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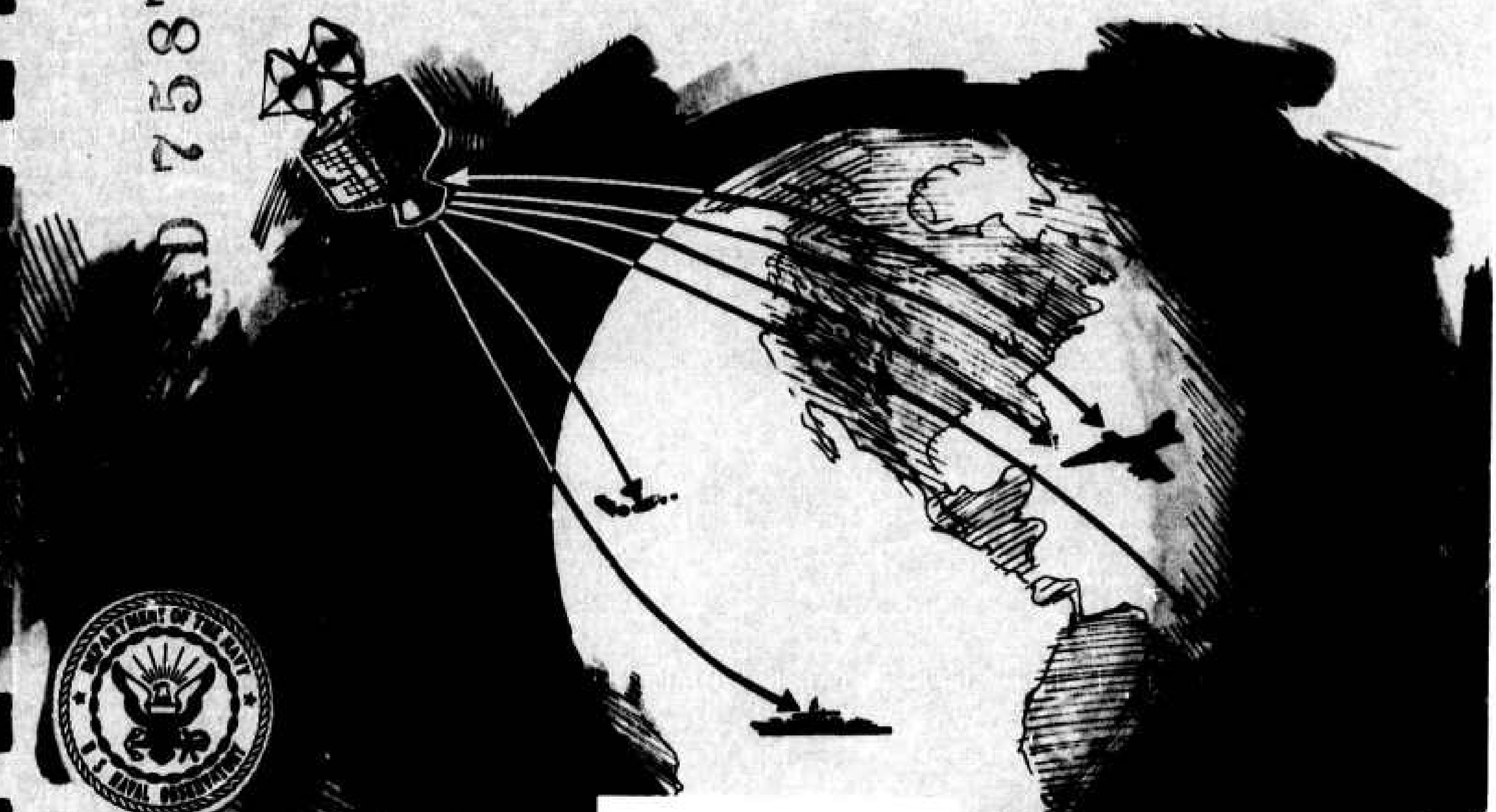
PROCEEDINGS OF THE ANNUAL DEPARTMENT OF DEFENSE PRECISE TIME AND TIME INTERVAL (PTTI) STRATEGIC PLANNING MEETING (3RD). HELD AT WASHINGTON, D.C. ON 16-18 NOVEMBER 1971

Naval Observatory
Washington, D.C.

1973

PROCEEDINGS OF THE THIRD ANNUAL DEPARTMENT OF DEFENSE PRECISE TIME AND TIME INTERVAL (PTTI) STRATEGIC PLANNING MEETING



16-18 NOVEMBER 1971

FOREWORD

The Third Annual Department of Defense (DOD) Precise Time and Time Interval (PTTI) Strategic Planning Meeting, sponsored by the U.S. Naval Observatory was held November 16-18, 1971 in Washington, D.C., to accomplish the following objectives:

- Exchange of practical information associated with PTTI.
- Review present and future requirements for PTTI.
- Review status of current and planned systems for PTTI dissemination.
- Acquaint systems engineers and/or managers with precise time and frequency technology and its problems.

Each presentation was invited and a status report was given concerning the various techniques and systems involving PTTI rather than presenting novel concepts and results in the pattern of professional engineering conferences.

Annual engineering conferences of the PTTI community are also held regularly under the auspices of the U.S. Army Electronics Command and are known as "The Annual Frequency Control Symposium, Atlantic City." Copies of those proceedings are available from Electronic Industries Association, 2001 Eye Street, N.W., Washington, D.C. 20006. Additional information is available from Dr. Erich Hafner, Leader, Frequency Control Devices Team, Electronics Technology and Devices Laboratory, U.S. Army Electronics Command, Fort Monmouth, New Jersey 09703.

The Annual DOD PTTI Strategic Planning Meetings supplement each other rather than repeat items on which there is little or no change to report. It is therefore recommended that interested persons consult the Proceedings of the Second Annual DOD PTTI Strategic Planning Meeting, December 10-11, 1970, Volume I (Unclassified) and Volume II (Secret), which are available from the Defense Documentation Center (DDC) as AD 881014-L and AD 514056-L, respectively.

This report contains a summary of PTTI topics discussed during the 16-18 November 1971 meeting. The unclassified Conference Proceedings are contained in this volume for distribution. Copies of the classified presentations may be obtained by writing the U.S. Naval Observatory, Technical Officer, Washington, D.C. 20390.

Harold N. Acrivos
Precise Time Operations Officer
Time Service Division
U.S. Naval Observatory
Washington, D.C. 20390

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OPENING ADDRESS

by

Dr. Alan Berman

Dr. Berman is Director of Research, Naval Research Laboratory, Washington, D.C.

Good morning. On behalf of the Naval Research Laboratory, it is my pleasure to welcome you to the Third DOD Precise Time and Time Interval Strategic Planning Conference. One of my responsibilities is to welcome meetings that are held at NRL. This Laboratory is a busy place with all sorts of people meeting on all sorts of things. I'm usually a little hard put to think of what to say. One can always state the usual amenities, hope that the attendees will be comfortable, and state that you are sure they will have an interesting program. I find today's introduction to be easy to make because my early professional life was devoted to time standards and frequency measurement.

I was an impoverished graduate student in 1947 when I went to work for Professor I. I. Rabi in his Molecular Beams Laboratory at Columbia. At that time he entertained the idea that one could tell time by using the precession period of the cesium atom in a magnetic field. Needing an assistant to build an atomic beam machine for him, which would function as a frequency standard, he gave me a summer job designing an atomic beam cesium system, which could be used for this purpose. These plans were turned over to a gentleman at Oak Ridge who had it built. The machine actually functioned, and, in a sense, it was the first cesium clock that was built. The machine existed and was used for some years as a frequency standard. Eventually it was turned over to the Smithsonian Institution as an early frequency standard. You can see it today in the Hall of Science and Technology.

On a Sunday afternoon a few years ago, I took my children to the Smithsonian, and we inadvertently came upon this device. I very proudly pointed out to my five-year old son that I had designed it and that it was the first cesium frequency standard. He looked at the device and then at me and said, "Gee, that sure is an olden time frequency standard, isn't it, Dad?" I was crushed.

Until I had the simple joys of becoming a Laboratory Director, I spent most of my life worrying about problems related to precise time and frequency. I worked with Professor Kusch on the early measurements of the hyperfine structure anomaly in hydrogen and found that the problems of maintaining a decent frequency standard were much more difficult than measuring hyperfine structure anomalies in hydrogen cesium, rubidium, or thallium.

I have very recently had an experience relative to U.S. Navy sponsored research on frequency standards. During the first week in November 1971 I was in the Middle East, and I had occasion to visit an Israeli General. He was a real tough cookie--the sort of man who comes to work in fatigues and combat boots, with a machine gun thrown over his shoulder. If you go to Israel these days, people will start the small talk in the conversation with two things. First, they will give you a hard time as to why the U.S. is not giving Israel more F-4 Phantoms. The second topic invariably pertains to cesium clocks that Americans are flying around the world. Apparently this experiment received remarkable publicity in Israel. Israelis want to know why the American Navy spends money worrying about the relativistic twin paradox. True to form, the Israeli General rather bluntly told me that in Israel they only had money to do relevant research and they did not mess around with clocks. In the meantime, standing next to him was a very polite young engineering aide of the gruff General, and he said, "But General, we do do research in this country on time." Somewhat surprised, the General growled, "Why do we?" The aide said, "Well, we have problems with cryptology, we have problems with time difference of arrival of signals, and we have problems with our aircraft collision avoidance." He then enumerated 10 or 12 additional areas where the Israeli and, for that matter, all modern military establishments need precise time and time interval measurements. The General finally admitted defeat and grunted, "Yeah, I guess so, but at least we don't measure the age of twins."

In any case, I do think the work you are doing is important to the U.S. Navy. Your program is remarkably impressive, and I'm looking forward to hearing as much of it as I can in the next three days. If there is any way we can make you comfortable, be sure to talk to one of the natives here, and we'll do everything we can to make your stay useful. Thank you.

INTRODUCTION TO THE PROCEEDINGS

by

Capt John Hankey

CAPT John Hankey is Superintendent of the U.S. Naval Observatory, Washington, D.C.

I would like to welcome you to the conference on behalf of the Naval Observatory. I also want to thank the Naval Research Laboratory, especially Dr. Berman, for the opportunity of holding this conference in their very nice facilities here. I would also like to extend to you an invitation to visit the Naval Observatory, which is located in Northwest Washington, D. C. It is a site of considerable physical attraction and it is also a site that contains a certain amount of equipment and material which I think you would find of interest, even in the daytime. By the way, before I proceed, LCDR Atwood would be more than happy to arrange a tour of the Observatory for you if you will leave your name with him at any time during the next couple of days.

Time has always been a subject of considerable concern to our culture. This is very plainly evident in all the proverbs, sayings, and maxims that have enriched not only our language, but also many previous ones. Time is not only as important to us as it was to our ancestors, but it is going to become even more so. The fact, of course, is that the number of time-ordered systems is increasing, at an almost astronomical rate. I must confess that when I first came to the Naval Observatory my experience of time was not much better than that of the Israeli General to whom Dr. Berman referred when he welcomed you here. Thanks to Dr. Winkler and his assistants, I have been exposed to a rather liberal education on time and time interval. I find myself almost a one-man crusade occasionally when talking with my line contemporaries and superiors, convincing them that time is important--even more important than is implied by the motto on our old sun dials, *It is later than you think.* But since time is important, I am not going to waste very much of yours by giving you any personal reminiscence. Instead, I'm going to proceed to introduce our first speaker -- a Naval officer of considerable technical background, particularly following his receipt of the Masters Degree in Science at the Massachusetts Institute of Technology in 1946. Since that time, Admiral Schneider has had a variety of highly responsible positions in technical areas, in the Bureau of Aeronautics, the Naval Air Technical Development Command, the Bureau of Naval Weapons, and the Naval Air Systems Command. Currently, he is serving as the Vice Commander of the Naval Electronic Systems Command. It is my pleasure to introduce Admiral Schneider.

TIME AND FREQUENCY STANDARDIZATION

by

RAdm R.J. Schneider

RAdm R. J. Schneider, USN, Vice Commander, Naval Electronics Systems Command, Washington, D.C.

I take great pleasure in coming over to these rather hallowed halls of the Naval Research Laboratory. May I remind you that our Naval Observatory, which CAPT Hankey represents, is perhaps hallowed squared. It is one of the real beginnings of scientific endeavor in the United States. There has been a common Naval tradition across the wide world going back into the 1200, 1300, and 1400 period of history when the Dutch, the Portuguese, and the British Navies became prominent. They ran into a very substantive need for fairly accurate time, that is, if they wanted to get back home to the wife and kids. Some of you may remember the famous stories of trying to find a chronometer, and how they looked and what they were like when first built, and how they cheated the chap that finally made it work, for some 10 or 15 years, out of his stipend, and that's a story in itself. Like most great inventors, he finally got his money just as he was about to die.

I am not an expert on these things, I am an ordnance man, missile and fire control educated. But in the course of a rather misspent Navy life, I constantly have run into bits of science here and there. I can recall working with Dr. Draper at M.I.T. when we were first postulating the possibility of an inertial navigation system, and frankly, that was treated with the same credibility as a chap who might have been talking to a college physics group in the mid-40's, exploring the possibility of uranium fission.

I well remember at the PG school when my physics professor took an afternoon off to talk to us about these oncoming possibilities and we laughed at him. Of course that was about 1943, but it wasn't very long after that when we had some very positive proof that it was not anything to laugh about. Underneath all of this is basic science and the very tight little specialty you're here to work with and contribute to. I must say that we have come a long way from the water clock, the sand clock, and the hourglass, to the things that we are doing now. Precise time measurement is absolutely fundamental in modern communications and navigation and many other areas of modern life. This technology requires a degree of precision that has always seemed unobtainable. Because the Navy has recognized its importance, it has vigorously taxed its budget with the pressure necessary to support this technology. In turn, these improvements have fed back into such systems as LORAN-A, LORAN-C, OMEGA, and a worldwide communication network--not to mention the cipher and security systems, in which one mistake made at a nanosecond rate renders all the output thereafter worthless.

To address the bare fundamentals, it is essential to remember that almost every standard used is time-relevant, as shown in Figure 1. Even man has a time-relevant base. In past attempts to measure accelerations, a system was considered respectable if it could measure down to parts in 10^8. But today, even a "poor man's inertial system," a system that the average commercial airplane can afford, as opposed to a full military system, is being built regularly. It is visualized that one can eventually get a still cheaper system (for, perhaps $1,000 or $1,500) that will provide fundamental navigation for the pilots of the $50,000 to $100,000 machines that are regularly killing people around the country, because they are where they do not belong or because they are not where they think they are.

It is obvious that all these fundamental quantities, even in the electrical worlds, are time-related. Some question remains as to whether

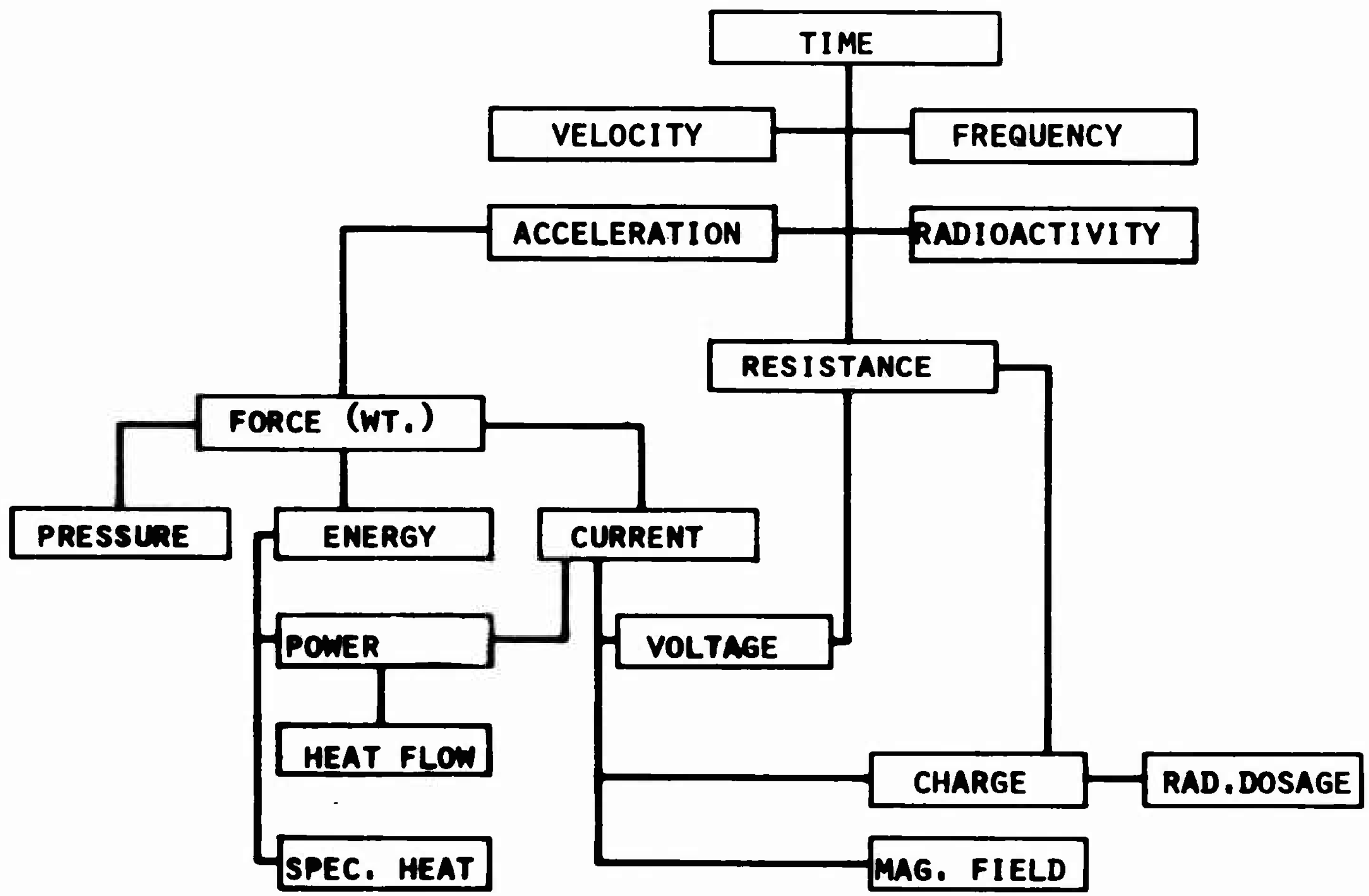

Figure 1. TIME

resistance is time-related, per se. It is known that electrical current is a time measure domain of Qdt, therefore it can be said that $E = IR$ or $R = \frac{E}{I}$, which gets into a time base, depending on how the standard is set.

The timing precision that has been required tends to follow a pattern along the lines shown in Figure 2, which illustrates the accomplishments of the time specialist, or scientist, who devotes himself to this field. Accomplishment is achieved in clumps, and the result is a step function where a jump is made. That is to be expected--the jumps from a wristwatch to a chronometer to a cesium clock are significant.

At the same time, in the normal role of nature, invention tends first to follow what is available and then to drive the system; the requirement often is established by the capability. At the present time, innovative ideas to move that line up are scarce, and, as a result, in the 1980's the requirement may be driving the technology instead of technology pulling the requirement up to it, unless there is another breakthrough.

Is there a quantum of time, as there is a quantum of everything else? Is there finally a spot where one cannot have half an interval? It is hard to visualize one part in 10^{24}. In postulating a protective defense system against an inertially navigated ICBM, it was figured that if the Earth could be moved roughly 100 to 150 miles off its normal rotation axis, the bomb would not get the message and would go on in inertial space coordinates to land off target. But the number of 45,000-pound-thrust jet engines required to move the Earth off its axis was about 10^{24}, an enormous number of engines. But then, if the Earth's axis could be shifted in less than 15 minutes, the bomb would overfly or underfly, but all the people would be flat on their faces. We must push on in pursuit of accuracy, because one can predict right now that the technology needs may well overrun technology accomplishments if the current pace is maintained.

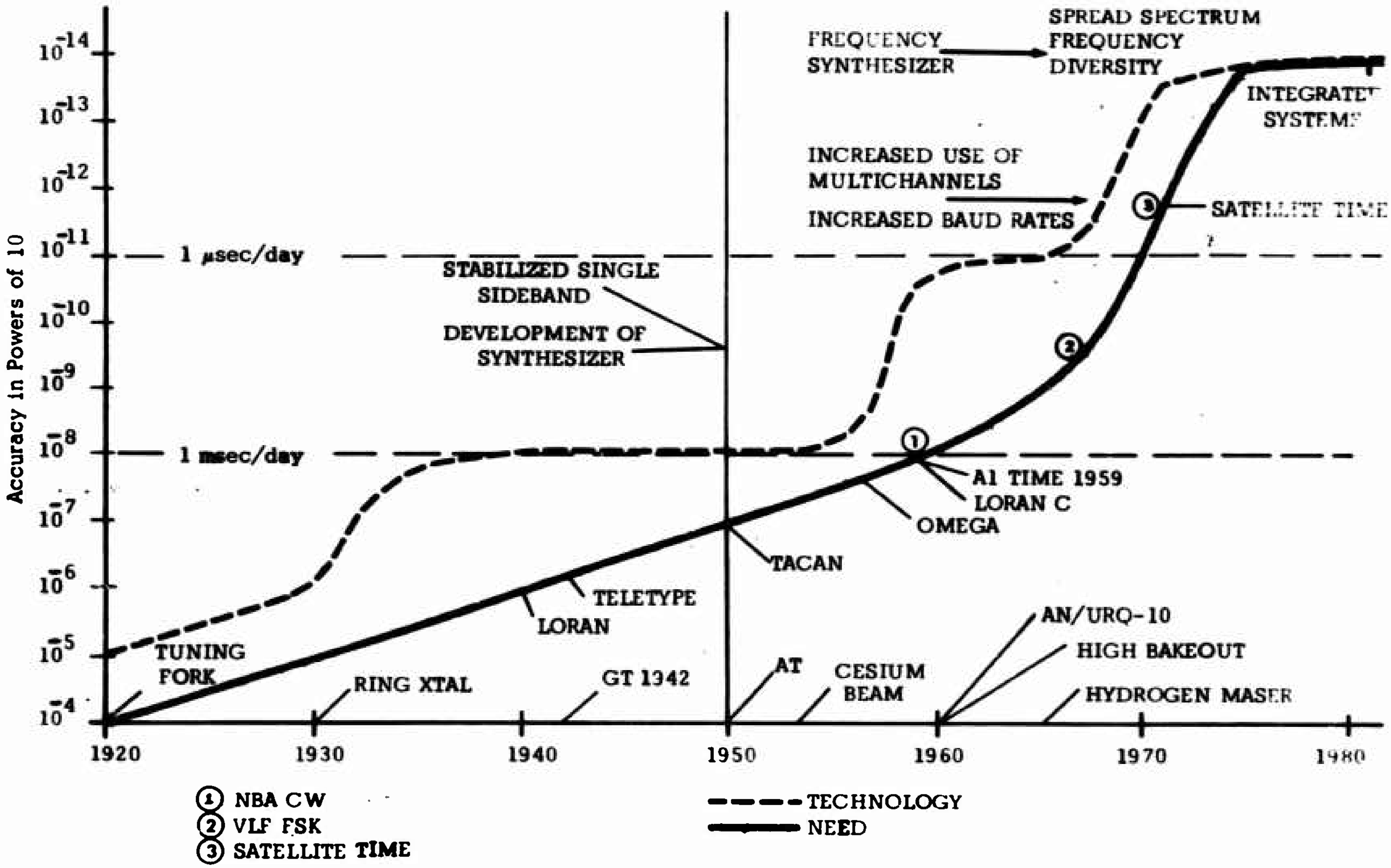

Figure 2. TIMING — NEED VERSUS TECHNOLOGY

The contemporary instrument for accurate time checking measurements is the cesium clock. We fly these clocks around the world as needed. When the courier flies his clock, his errors are computed at one end; he takes the clock from station to station (Figure 3), and against it as his standard, measures everyone else's time as he goes by. He then returns home, which closes the loop, and then advises each station of its current error situation. One does not merely put the key in the machine and move the hands up, because that screws up the works, figuratively, just as it does on a chronometer. The clock is left alone, but the error is established.

However, flying clocks around (Figure 4) has become a nuisance, since airplanes are subject to highjacking and couriers carrying electronic equipment are regarded suspiciously at various borders. A somewhat better system is now evolving.

This plan is, in part, shown in Figure 5. The digital systems operating in the communication world can transmit time within their own capability; the defense satellite communications system becomes such a system. As a result, the problems created by foreign custom agents, flight schedules, airport staffs, and aircraft failures are eliminated. Attention can also be redirected to any given site by a proper use of antennas and satellite communication. The system is currently operational, more or less, claiming a time signal accuracy to one-tenth of a microsecond on the network from the Naval Observatory, coming out of Brandywine to the DCSC terminal at Camp Roberts, California, then out to Oahu, and over to Germany and Guam.

The next step is to transfer this time to the local users. The first effort is being made at the Naval Communications Station, Wahiawa, Hawaii; this operation was surveyed the first week of October.

The system is a little complex (see Figure 6), but the main point is that once the time signal is brought into the local station, the local user can process it, and use it to update his own equipment, and then provide this additional service for various supporting equipment. The

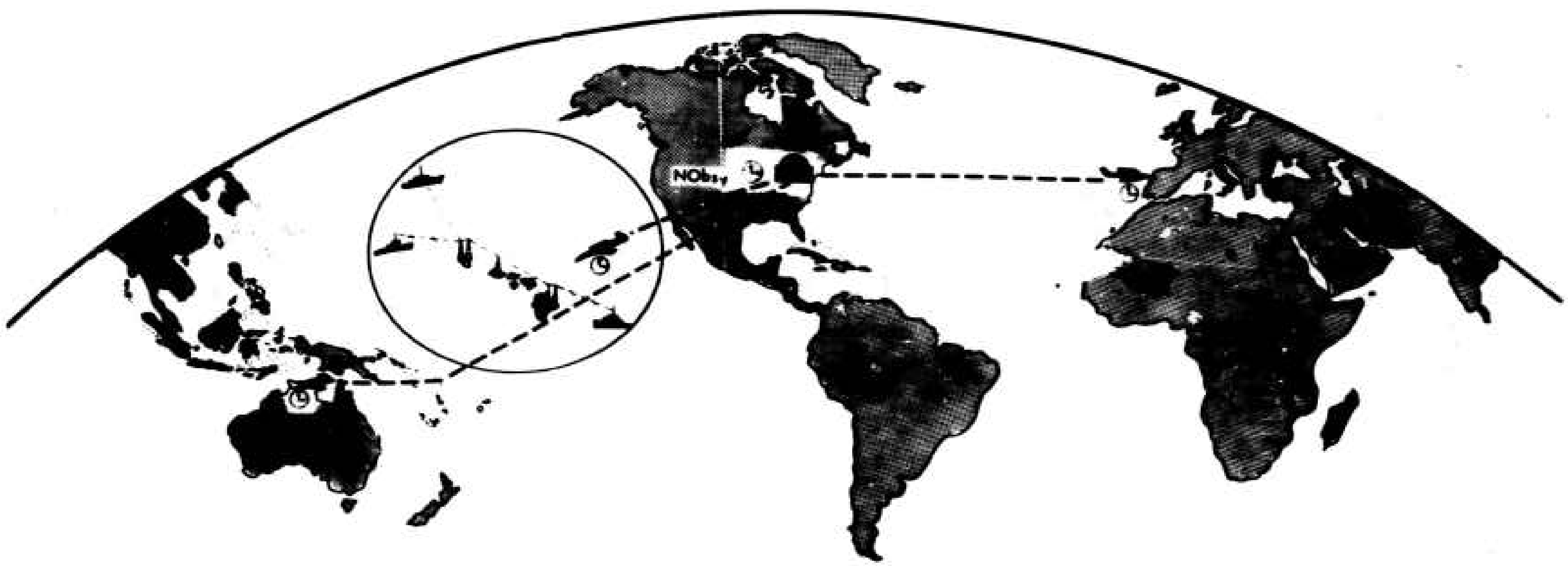

Figure 3. PRECISE TIME SYNCHRONIZATION SERVICE (PTSS) WORLD DISSEMINATION

Figure 4. CESIUM CLOCK STRAPPED IN FIRST CLASS AIRLINE COMPARTMENT

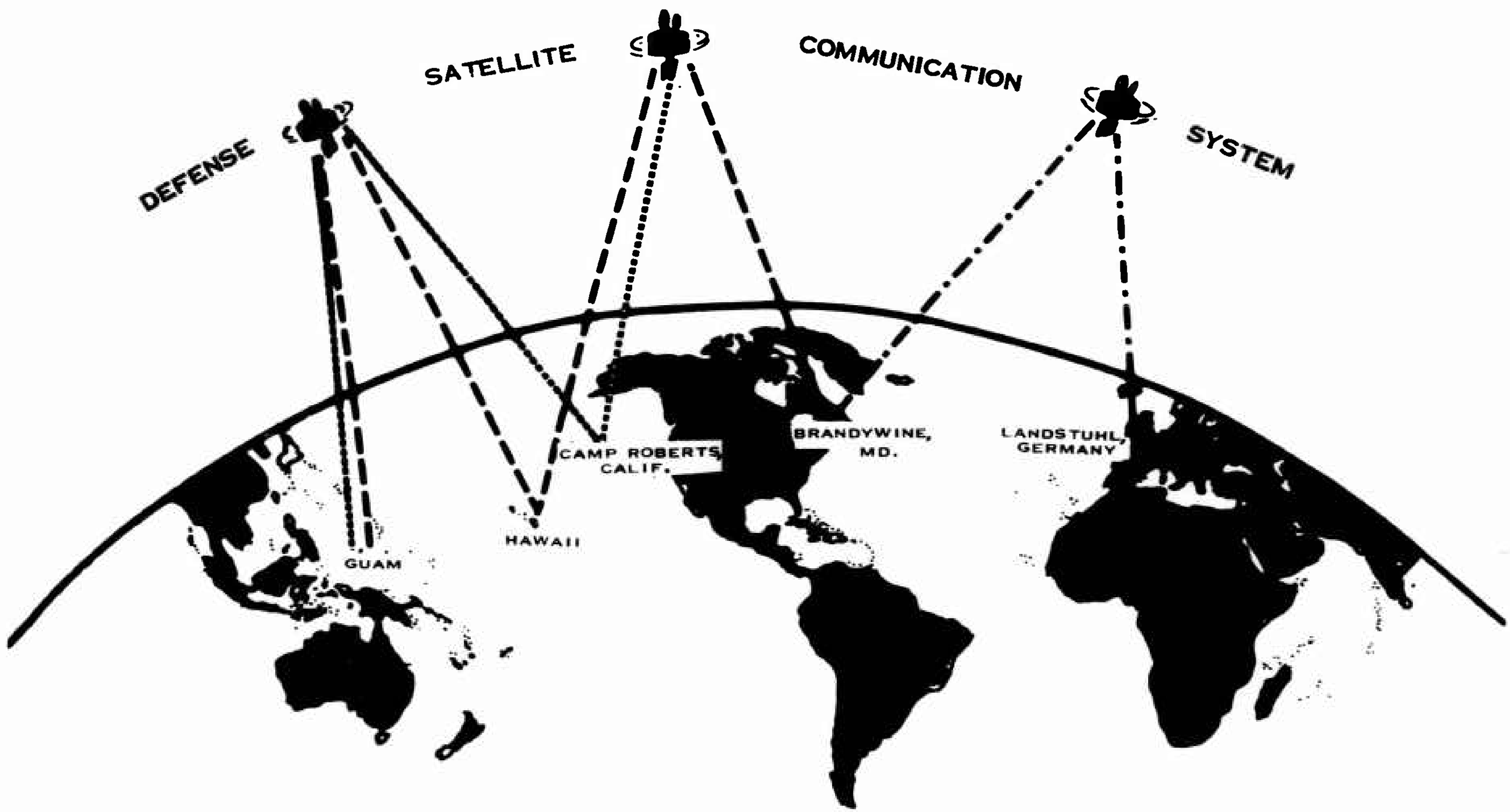

Figure 5. PRECISE TIME AND TIME INTERVAL (PTTI) WORLD DISSEMINATION

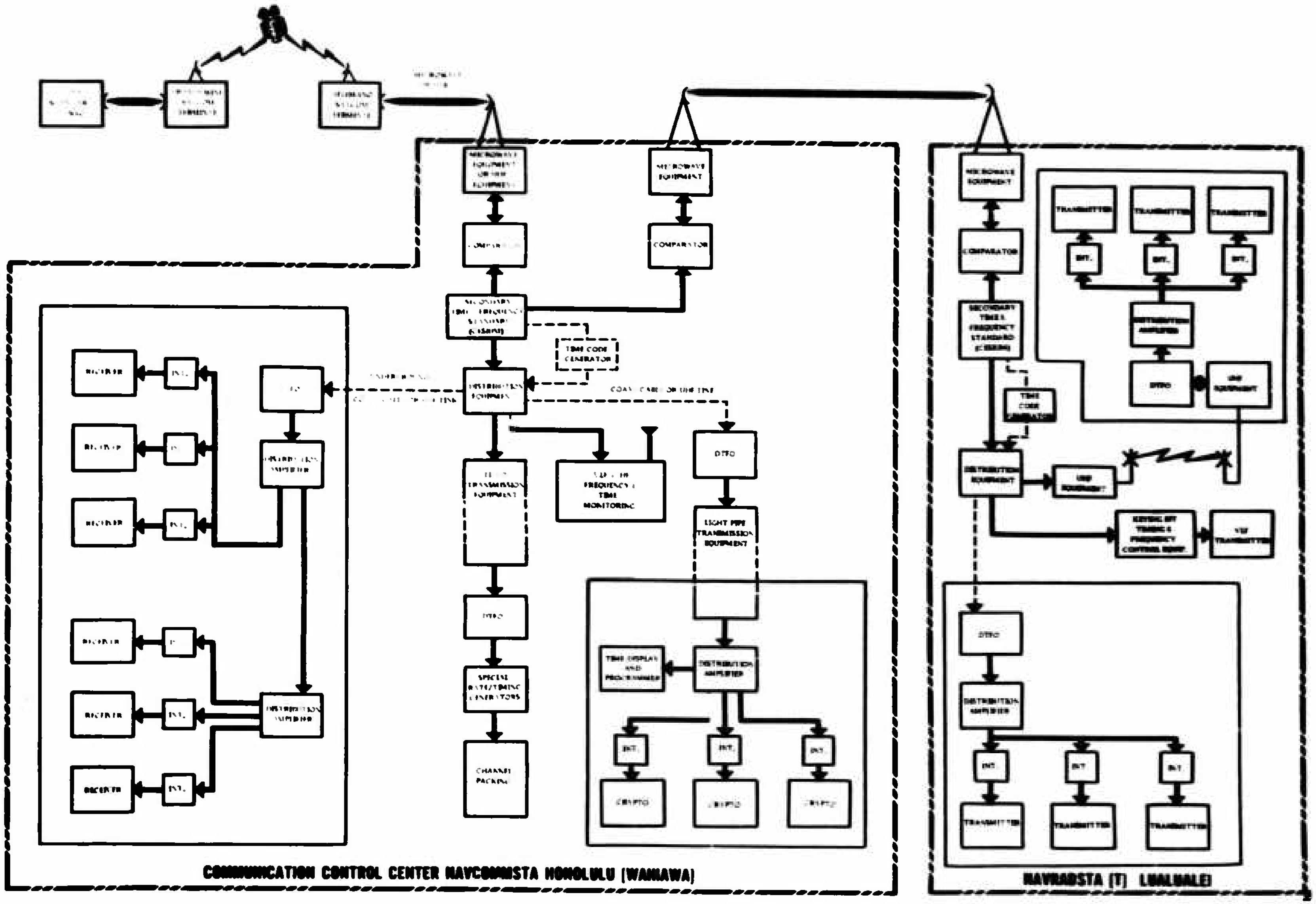

Figure 6. PRECISE TIME AND FREQUENCY LOCAL DISTRIBUTION FOR NAVCOMMSTA

system will provide inexpensive, relatively reliable, all-weather, sea and air navigation improvements, just because of the availability of precise time and time interval. The modern navigation system is already fairly accurate, but unprecedented accuracy, almost beyond the immediate needs, is achieved by pushing one order of magnitude higher.

Some current uses of precise time and time interval applications are shown on Figure 7. The VLF transmissions are used to site Navy ships, and the oil companies are also using them to site their oil drilling rigs. As synchronization of all these platforms is enhanced, many of the time losses in calibration will be eliminated and many of the restraints of the previous systems disappear.

It might be mentioned here that the digital data rates under good control can perhaps go up from 2400 baud to as high as 9600 baud or better; however, the accomplishment of these rates directly depends on absolutely accurate knowledge of the baud-to-baud time rate. International color television transmission also depends on this knowledge; i.e., to bring in real time color television at both ends, the oscillators and color separators must all be accurately synchronized.

Some potential uses of precise time and time interval applications are shown in Figure 8. It is now envisioned that once the system is pretty well operative, users will have relatively simple equipment to take advantage of it. The capabilities of a new and simple collision avoidance system will encompass more than safety considerations, which are so essential and are becoming more so as the air traffic increases. In a sense the system will help decrease the traffic problems or help absorb the traffic because of better time control and better guarantees that the aircraft operator will obey precisely the instructions of the air controller and that the FAA controller will have a higher degree of confidence for using his time spectrum availability relative to his runways. For example, when pilots are being brought aboard an aircraft carrier at between 20- and 30-second intervals, the pilot who is 5 seconds late sends a 5-second transient

- **NAVIGATION/SHIP POSITIONING**
  - OMEGA
  - USE OF VLF TRANSMISSIONS
  - PRECISE SITING FOR OIL DRILLING
- **INCREASED EFFICIENCY OF POINT-TO-POINT DIGITAL COMMUNICATIONS**
  - REDUCED LIMITATIONS ON SYNCHRONIZATION
  - DIGITAL INCREASE 2400 - 9600 BAUD POSSIBLE
  - REDUCED TRANSMISSION LENGTHS
- **PRECISE CRYSTAL OSCILLATORS, SYNTHESIZERS**
- **RATING OF OSCILLATORS**
- **COLOR TV TRANSMISSION/RELAY**

Figure 7. PRECISION TIME AND TIME INTERVAL APPLICATIONS

- **EFFECTIVE COLLISION AVOIDANCE SYSTEMS FOR AIRCRAFT**
  - SAFETY
  - INCREASED AIRPORT CAPACITY/FEWER LANDING DELAYS
- **REDUCED COSTS FOR SKIN PAINT RADARS**
- **MORE EFFICIENT USE OF THE RADIO FREQUENCY SPECTRUM**
- **FURTHER LONG LINES COMMUNICATION EFFICIENCY**
  - RECENT RATE INCREASES NOTED
- **INFORMATION SYSTEMS**
  - LINKAGE OF COMPUTERS
  - REDUCED BUFFERING
- **TIME CORRELATION OF DISTANT GEOLOGIC/GEODETIC/ASTRONOMIC EVENTS**
- **THROUGH IMPROVED SYNCHRONIZATION, COMMUNICATION SYSTEMS WITH**
  - ANTI-JAM/LOW INTERFERENCE QUALITIES
  - LOW COST SECURE SYSTEMS FOR POLICE OR INDUSTRY

Figure 8. POTENTIAL PRECISION TIME AND TIME INTERVAL APPLICATIONS

down the chain and out to 30 airplanes; the 5-second delay may eventually entail an emergency airborne refueling for the thirtieth plane.

It is now believed that the radar skin-paint approach so commonly used may decrease in importance, perhaps almost to the point of obsolescence, when an airplane can accurately report its position. The skin-paint radar, which just closes the loop on relative motion, is a pretty expensive installation at airports and many other operations, where it presently is the final unit that links the relativity of all people in the grid together.

Higher precision would also lead to better use of the RF spectrum. At the present time radio operators are filling 3,000 kHz bandwidths with the human voice, speaking at from 250 to 330 words a minute. That is a poor use of 3 kHz when right now 1200 words a minute are pumped out with 10 or 12 simultaneous teletype circuits operating in the same bandwidth, and there is absolutely nothing technical to prevent a rate 3 to 4 times higher. Theoretically, one could go almost 6 times that, but the system noise level keeps the rate to 4,500 to 5,000 words a minute. When these machines of precise time control are built and working exactly to a part in 10^{11}, an almost infinite number of words can be put on the telephone or communication net by going back to codes instead of ciphers, which would envision a memory that's infallibly accurate. One could preposition anything in the memory--even the entire Bible if it were so prearranged that, when "dit da" was sent that meant the Bible, and both sender and receiver could read it. So there is really no fundamental limitation by bandwidth, if one has control of time at the computer level, both input/output end, and of memory.

A great many people are finding themselves very much involved in time. The astronomer and the geophysicist are now more accurate with their solar activity work and their correlation of earthquake information because of precise time. Reference is made to the possibility of low-cost security systems for both public and private sector communications, which, again, would be dependent on decoding and encoding, so that the common link is to know where one is at exactly the same time as somebody else who is far away. This goes right back to the navigator who tried to work longitude from a reference that he controlled only by knowing his time, and we are back to the chronometer where it all began.

The current worldwide distribution of precise time and time interval is shown in Figure 9.

In several ways, past requirements were well supported by those old fashioned multi-millisecond broadcasts. Many have read the familiar WWV, NSS, and NAA time signals, which replaced the old custom of shooting a noon gun in every major port, by which every ship in the harbor could check its chronometer. But our past requirements have been superseded by requirements far, far above this order of magnitude, now in parts of a microsecond, where a few milliseconds used to be good enough. For this moment and possibly for the next 5 to 8 years, it can be said that the technology of the present capability is in step with any forseeable requirement; however, this matching pace may not continue. The next step toward a greater precision comes up that S-curve of learning with great difficulty, but it is certainly a worthwhile challenge.

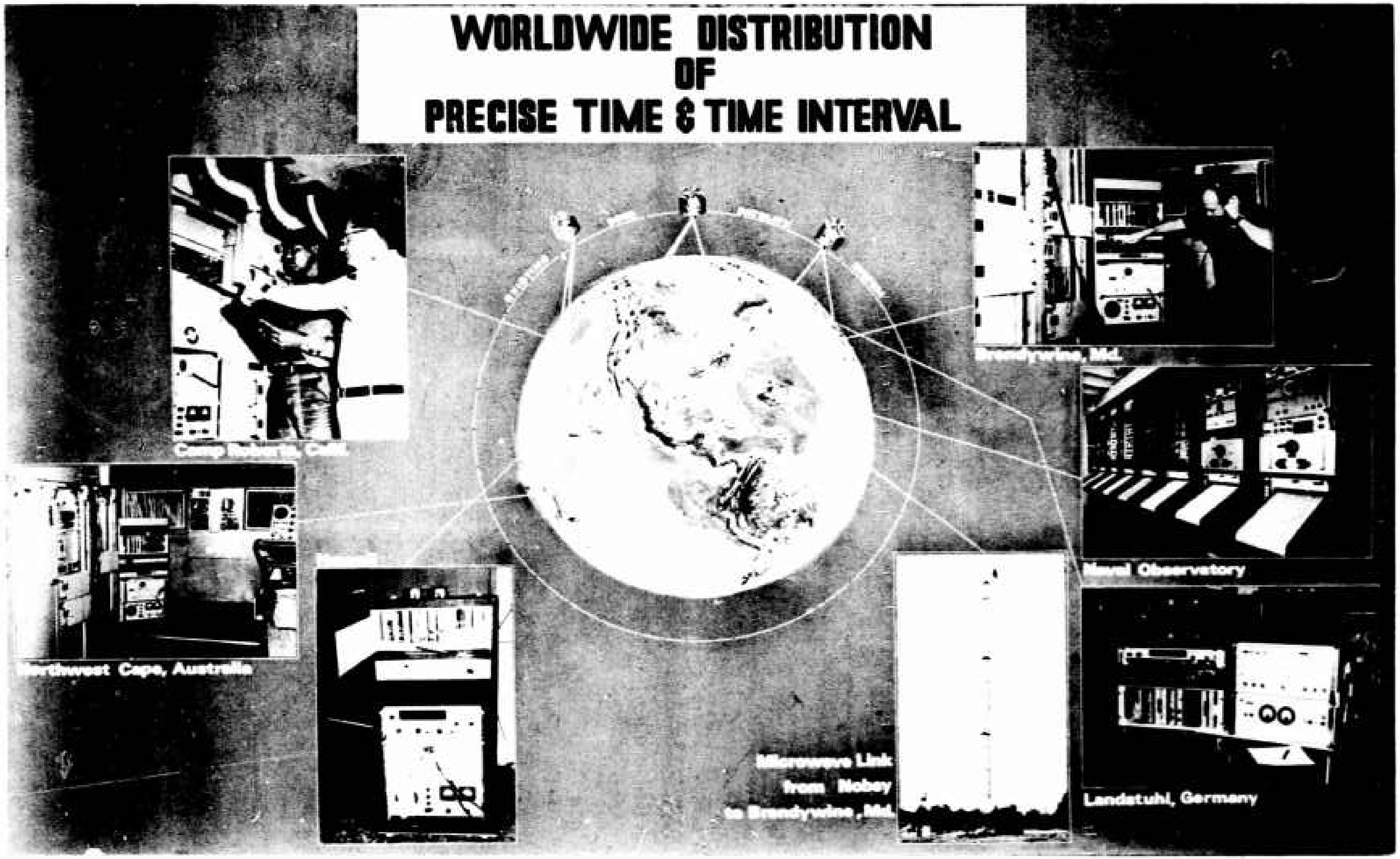

Figure 9. WORLDWIDE DISTRIBUTION OF PRECISE TIME AND TIME INTERVAL

THE INCREMENTAL PHASE SHIFTER AND PRN TIME TRANSFER

by

Dr. R.B. Kershner

Dr. Kershner is Space Development Department Head, Applied Physics Laboratory, Silver Spring, Maryland.

An experiment is being planned which will be run early next summer from a satellite under development by the Applied Physics Laboratory for the Polaris people of the Navy. The satellite is basically an experimental satellite to determine the feasibility of some of the techniques planned for an eventual second generation replacement of the current operational Transit navigation satellites at some future date. It is clear that technology will ultimately move to where the current Transit satellites leave something to be desired, although they are still meeting all existing requirements and are continuing to operate exceptionally well--much to the dismay of the current commercial producer, who never gets the opportunity to launch any because the ones that are up there keep running. The oldest of the current operational series was launched just over four and one-half years ago. Whereas no one intends to go up and shoot them down, the advance of technology will ultimately make them obsolete. The techniques that look applicable and desirable for an alternate second generation replacement are being studied with certain specific classified objectives in mind; however, these will not be discussed because of their classification. Certain other technical possibilities are being explored because of their potential usefulness in a second generation system.

The two pertinent techniques that will be discussed are, first, a method of recognizing arrival time of the signal with very much greater precision than is currently possible with the present Transit satellite and, second, a method of steering the frequency of the oscillator, which is still a good crystal oscillator, by command from the ground. In other words, this is a frequency synthesizer which is able both to move the frequency of the crystal oscillator to a given predecided value and to compensate for the aging of the crystal by incorporating a rate of change of frequency to stabilize the frequency at a standard value. If this is done in the satellite, there is no longer a need to treat frequency as another unknown in any computation so the interval over which it is necessary to observe the signals in order to get a good navigation fix can be reduced. This has obvious specific military interest, as well as general scientific interest.

The new satellite will retain the items shown in Figure 1 in the white boxes, which are currently in an operational Transit satellite. There are a crystal oscillator and a frequency multiplying chain which ultimately provide 400 megahertz and 150 megahertz as the two basic transmitted frequencies. A phase modulator will be used which is exactly like the present one to modulate the transmitted frequencies $\pm 60^{\circ}$ at a very low rate and provide coded information transmitted from the satellite. This coded information describes the satellite location--the ephemeral data. This information, together with the doppler shift observed on the signals at the receiving end, which has been corrected for refraction by the use of two coherent frequencies--150 megahertz and 400 megahertz--adds up to a precision fix on the part of the user.

The new devices that are being introduced into the satellite are shown in gray boxes. There are two devices: a pseudo-random noise modulation capability and an incremental phase shift synthesizer. The pseudo-random noise modulation capability consists of a code generator (in the largest box) driving phase modulators on each of the two frequencies.

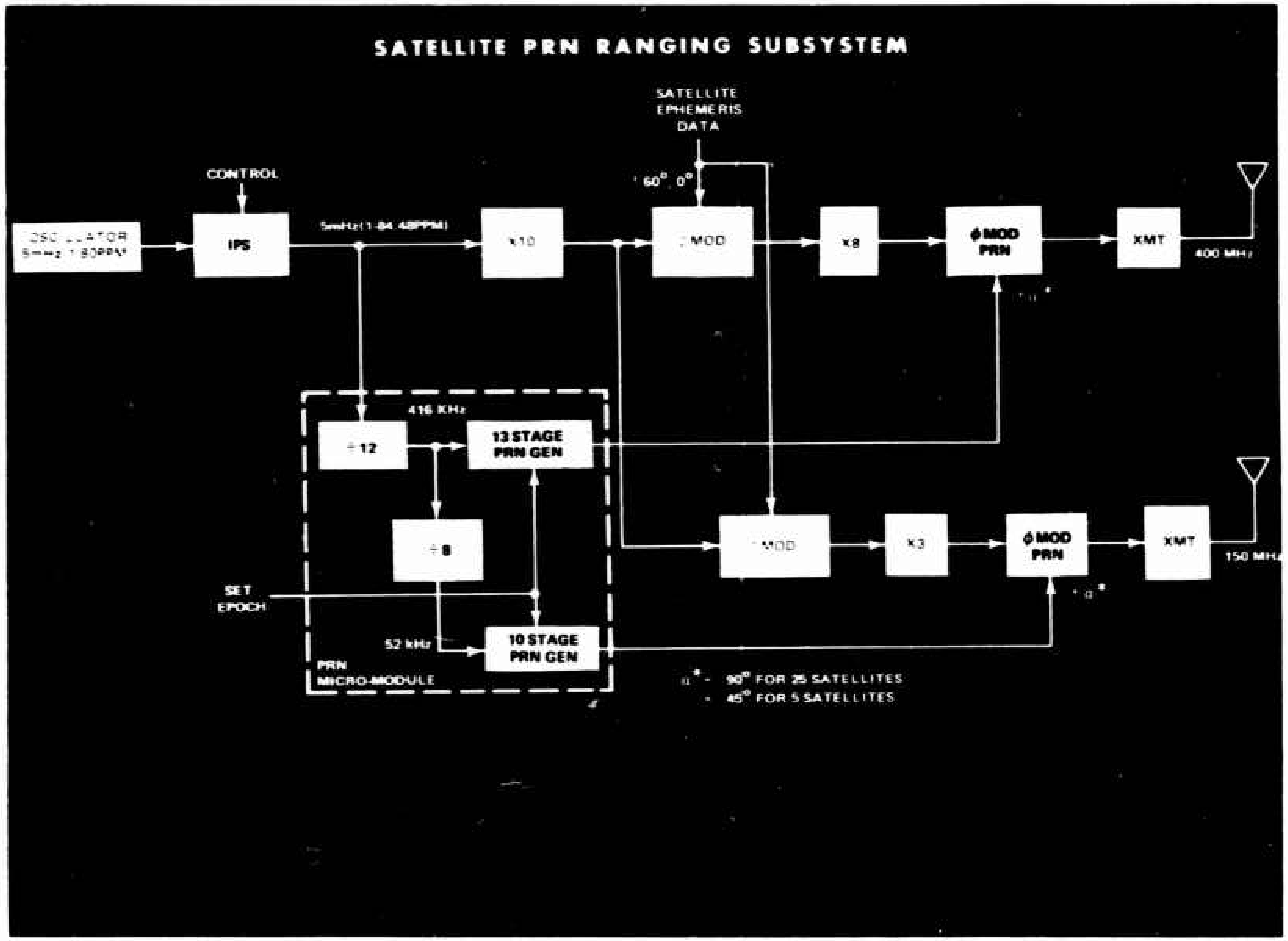

Figure 1. SATELLITE PRN RANGING SUBSYSTEM

This device puts a rapid phase modulation on the output of the signal, thereby effectively spreading the spectrum. It is a straightforward spread technique; a rather normal PRN method. This allows the recovery of the signal by reconstructing the phase modulation and the PRN code at the receiving end. Once synchronization is attained, there is an epoch recognition which uses statistics on a very large number of pulses rather than being dependent on the ability to recognize a single timing pulse with precision. This results in a precise synchronization of the ground receiver to the received signal. The other device that is being introduced is the incremental phase shifter (IPS). It is the PRN and the phase shifter that will be described with most of the discussion being on the incremental phase shifter. We are using one of the simplest ways to generate a PRN code.

1.0 PSEUDO RANDOM NOISE

As shown in Figure 2, there are four boxes, or stages, marked A, B, C, and D. At the start there are binary "ones" in each of them. On each clock pulse, whatever is in A goes to B, whatever is in B goes to C, and whatever is in C goes to D, but a zero goes into A if the contents of C and D are the same, and a one goes into A if the contents of C and D are different. So, on line D there are four ones, those would be the contents of A, B, C, and D, then each next digit is a 0. The entire code is generated with only four stages; this example would provide a 15-bit long PRN code in the sense that the correlation of the whole code with itself is 15 and repeats every 15 clock periods. However, the correlation of the code with any displaced-position translation of itself is near 0, namely either 1 or -1. There is roughly 1/15th of the auto-correlation with itself when the code is in any displaced position and this is the pseudo-noise characteristic. We generate a code of this nature but with many more bits, of course; this example is simply a very short code of the same type.

15 BIT PRN CODE

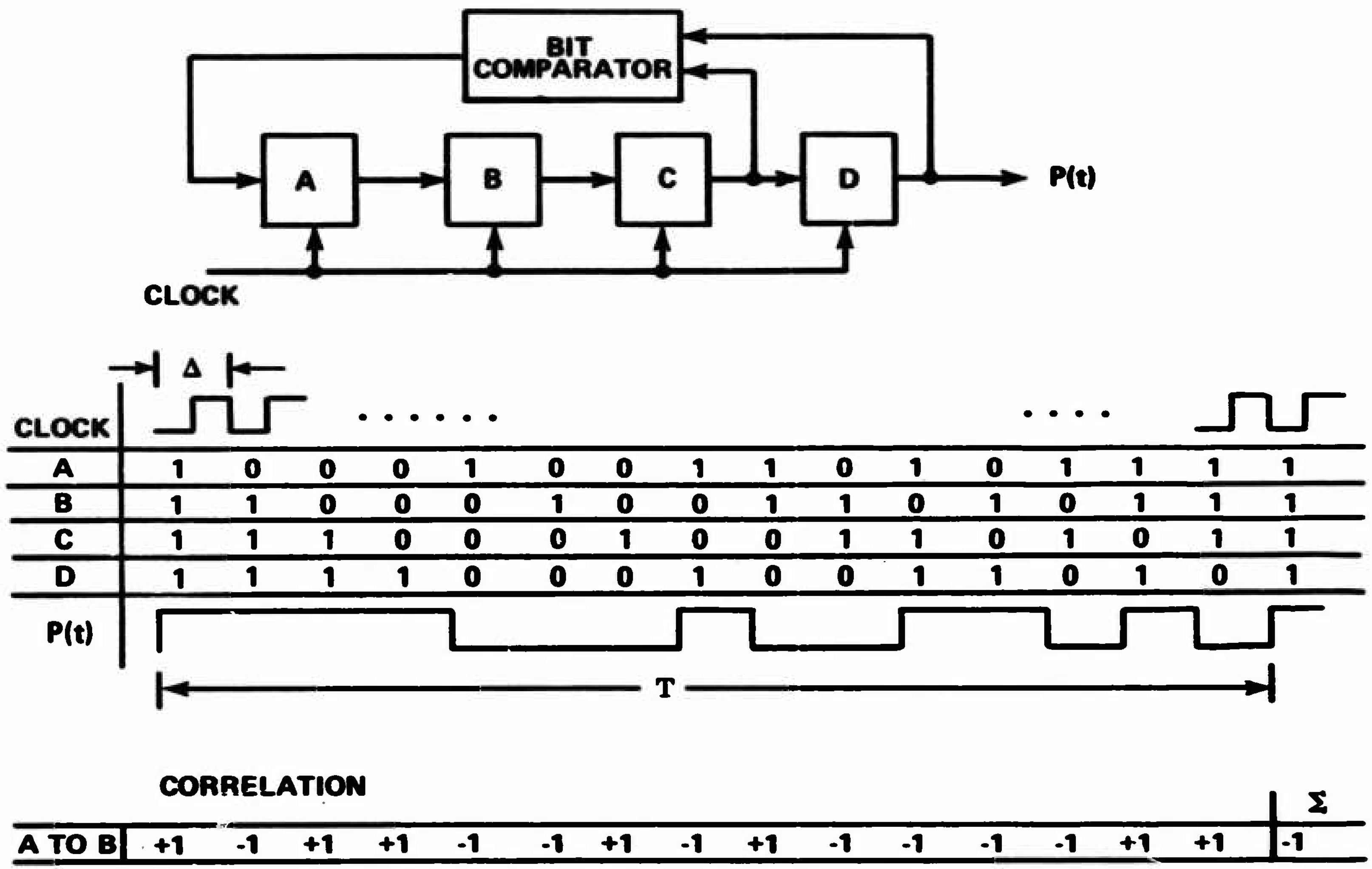

Figure 2. 15-BIT PRN CODE

Figure 3 shows a PRN digital generator for use in the satellite. It should be noted that it is really a very small device.

Figure 4 shows the code generator together with the phase modulator that produces the actual phase modulation on the output signals. The unit shown is the one required for 400 megahertz, and, incidentally, it is flight hardware.

A similar device for the 150 megahertz is shown in Figure 5; it is really the only modification to a standard Transit satellite that is required in order to provide the random noise capability. There are two options, depending upon the amount of phase modulation that is to be introduced: when $\pm 90^{\circ}$ is introduced, the spectrum is totally spread and the carrier is completely suppressed; when a lower modulation level, such as $\pm 45^{\circ}$ is used, as in this first experiment, there is the advantage that half of the carrier is still there so that the receivers can still be operated in the old-fashioned way of tracking the carrier. At the same time, if one wishes to receive the PRN, it is also there and has half of the power in that mode. So essentially, the satellite radiated power is being split, half of it in the carrier, half of it in the PRN; and it can be used either way, which is extremely convenient for experimental purposes. It also enables one to simplify the synchronization or acquisition problem associated with the pseudo-random noise code.

Figure 6 shows the spectrum that is created with the protruding carrier 3 dB lower than it would have been if the PRN modulation were not used; also note that the power distributed by the PRN modulation is approximately 40 dB down from the coherent carrier. Therefore, unless you have the right PRN code, you do not know it is there at all.

Through funding support from the Naval Air Systems Command an AN/SRN-9 satellite navigation receiver is now being modified to recover the PRN code. A block diagram of the existing modified navigation receiver is shown in Figure 7.

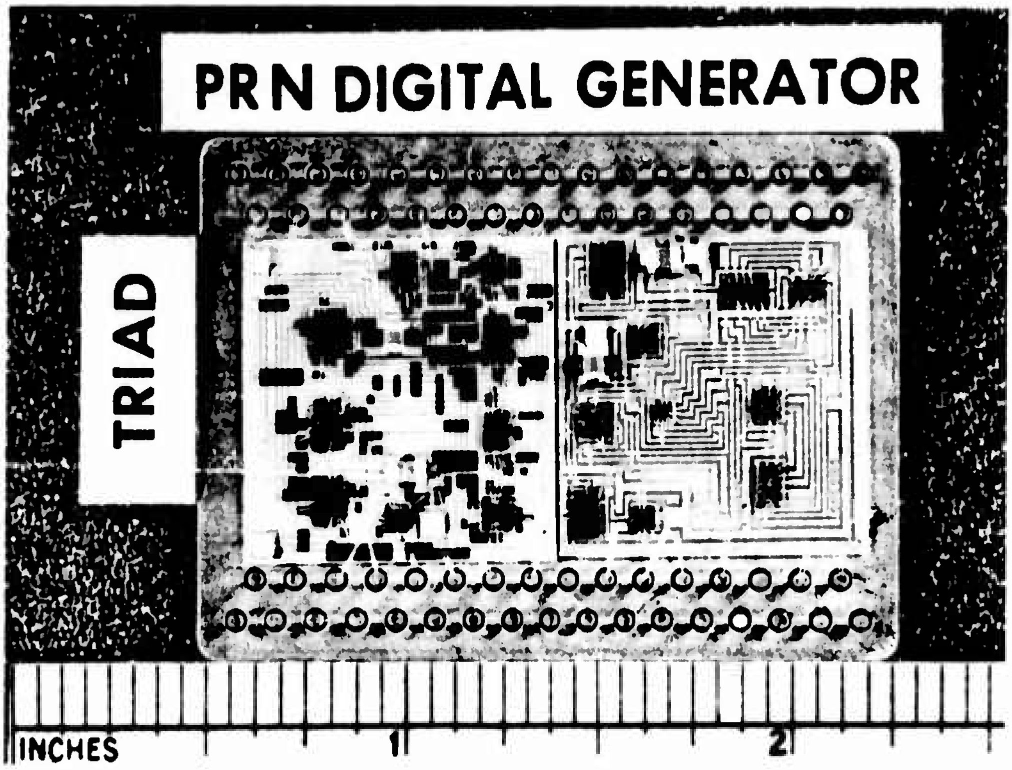

Figure 3. PRN DIGITAL GENERATOR

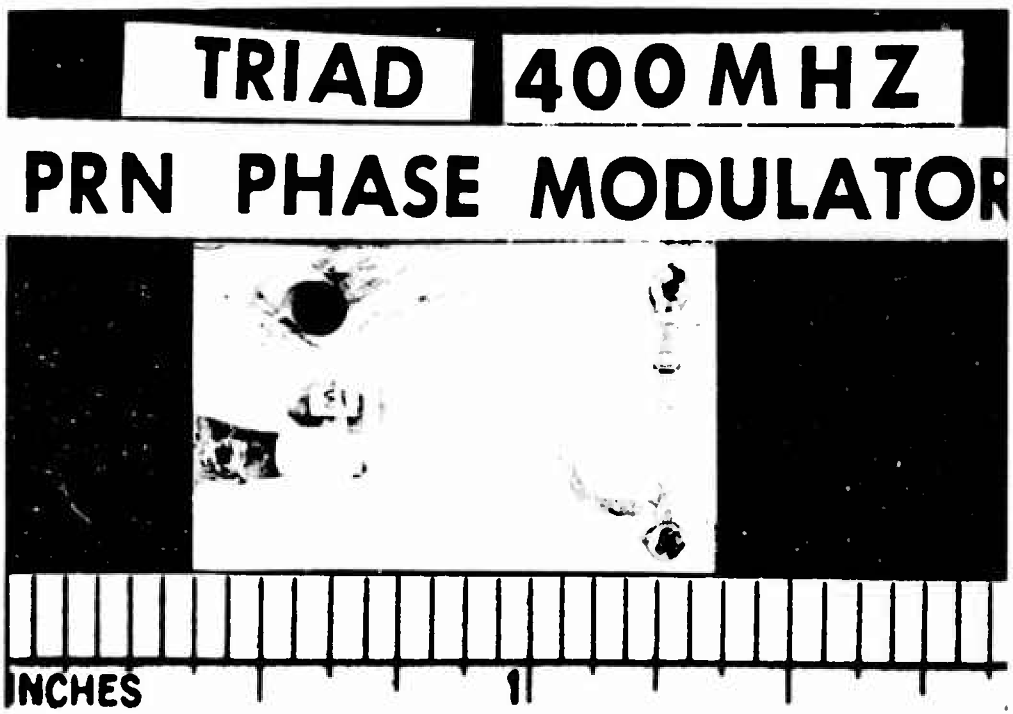

Figure 4. PRN PHASE MODULATOR

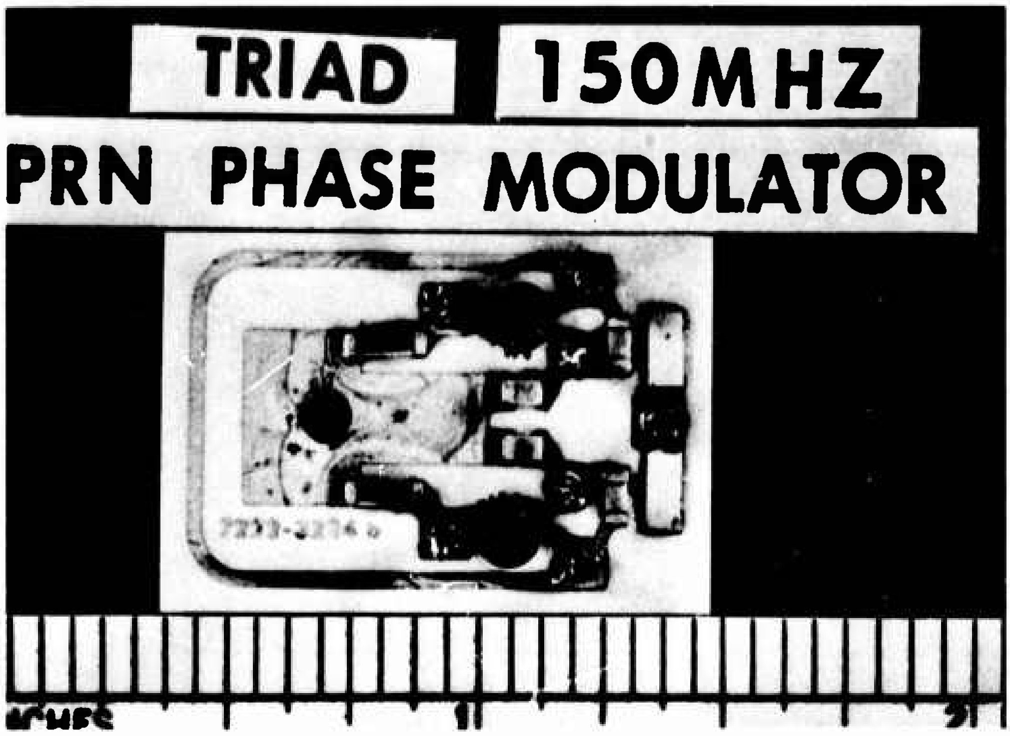

Figure 5. PRN PHASE MODULATOR (150 mHz)

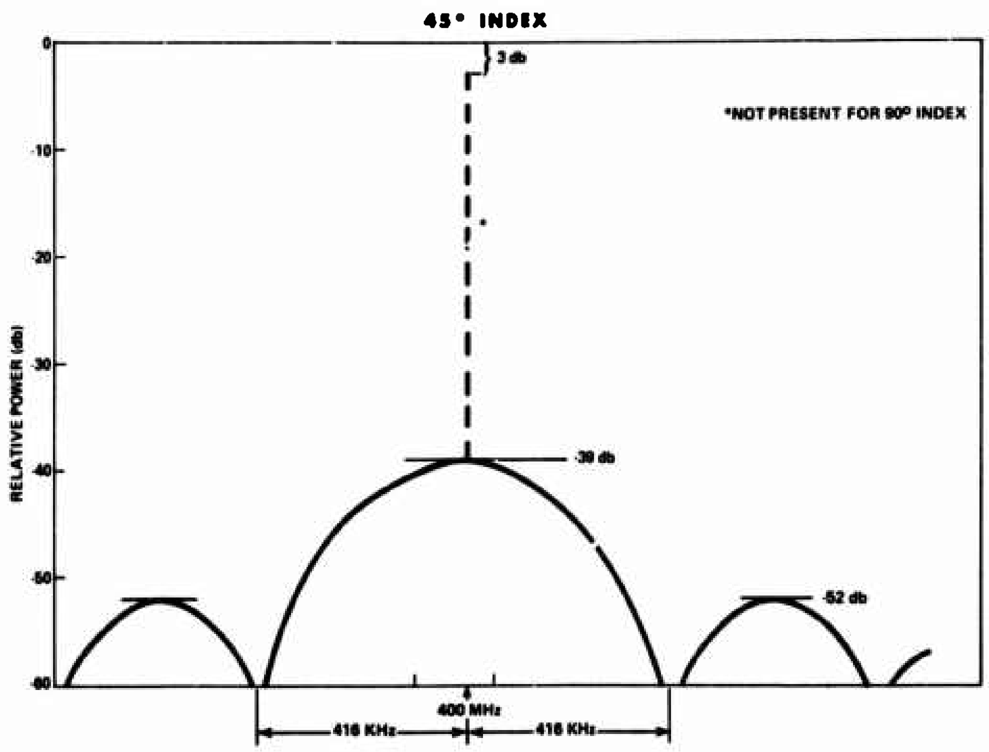

Figure 6. RF POWER SPECTRUM AFTER PRN MODULATION (45° Index)

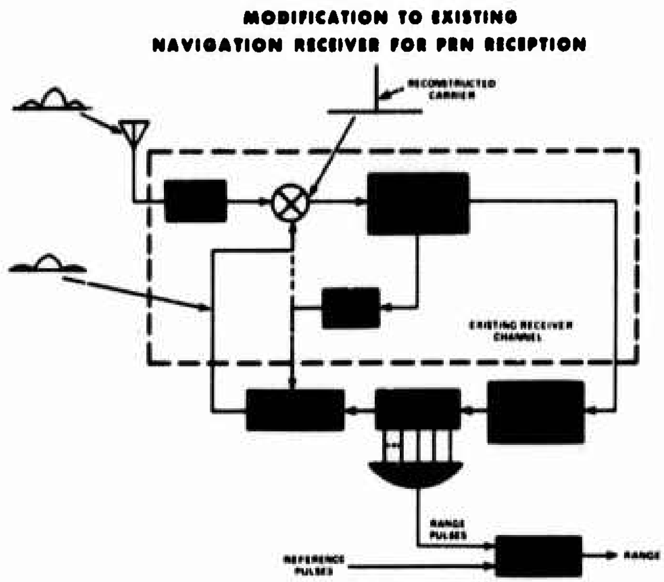

Figure 7. MODIFICATION TO EXISTING NAVIGATION RECEIVER FOR PRN RECEPTION

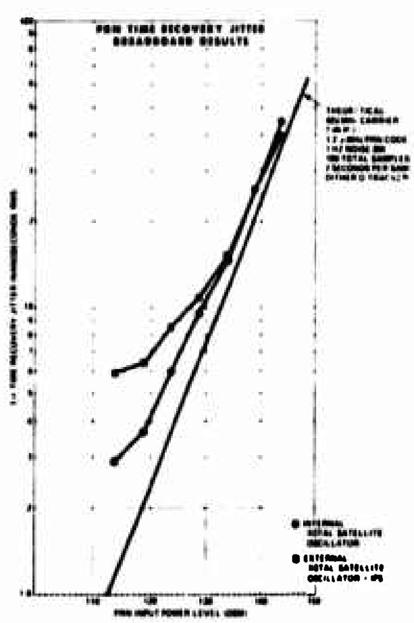

Figure 8. PRN TIME RECOVERY JITTER BREADBOARD RESULTS

Figure 8 shows results of some breadboard tests of the PRN equipment that has been built and incorporated into the experimental satellite which is called TRIAD, because it is made up of three interconnected bodies. The TRIAD satellite with PRN modulation allows the recovery and recognition of the epoch in the nanosecond region.

2.0 INCREMENTAL PHASE SHIFTER

The incremental phase shifter shown in Figure 9 is a somewhat larger device and is a means of synthesizing a frequency, or rather of shifting the frequency of a given oscillator by a small, carefully controlled amount; an amount that can be controlled digitally, so that one can send a digital signal to the satellite and say, "this is exactly the amount I wish this frequency shifted," and it will proceed to do that. It is done through the use of phase shifters operating on the 5 megahertz signal of the basic reference oscillator by taking out or putting in multiples of exactly 1.8 electrical degrees. There are two phase shifters working in cascade to make 200 steps per cycle of 5 megahertz; one has 25 steps of 1.8° or 1 nanosecond at 5 megahertz; the other, 8 steps of 45° or 25 nanoseconds at 5 megahertz. A digital word can control the rate at which these advance or retard the phase and, by putting in proper satellite remote command, and can make anything from extremely small, extremely slow frequency changes to very substantial ones.

Figure 10 shows these 1.8° steps for a total of 200 of them to complete one cycle and the continuation of the process from cycle to cycle.

Figure 11 shows how time can be controlled by steering the rate of the oscillator. If one is counting out this oscillator and putting out time ticks, and if the time ticks are not running at a satisfactory rate, one can simply steer the frequency of the oscillator to a point which produces time ticks at the rate desired. It should be noticed that the variations in time provided by this method of frequency correction are in the 20 picosecond

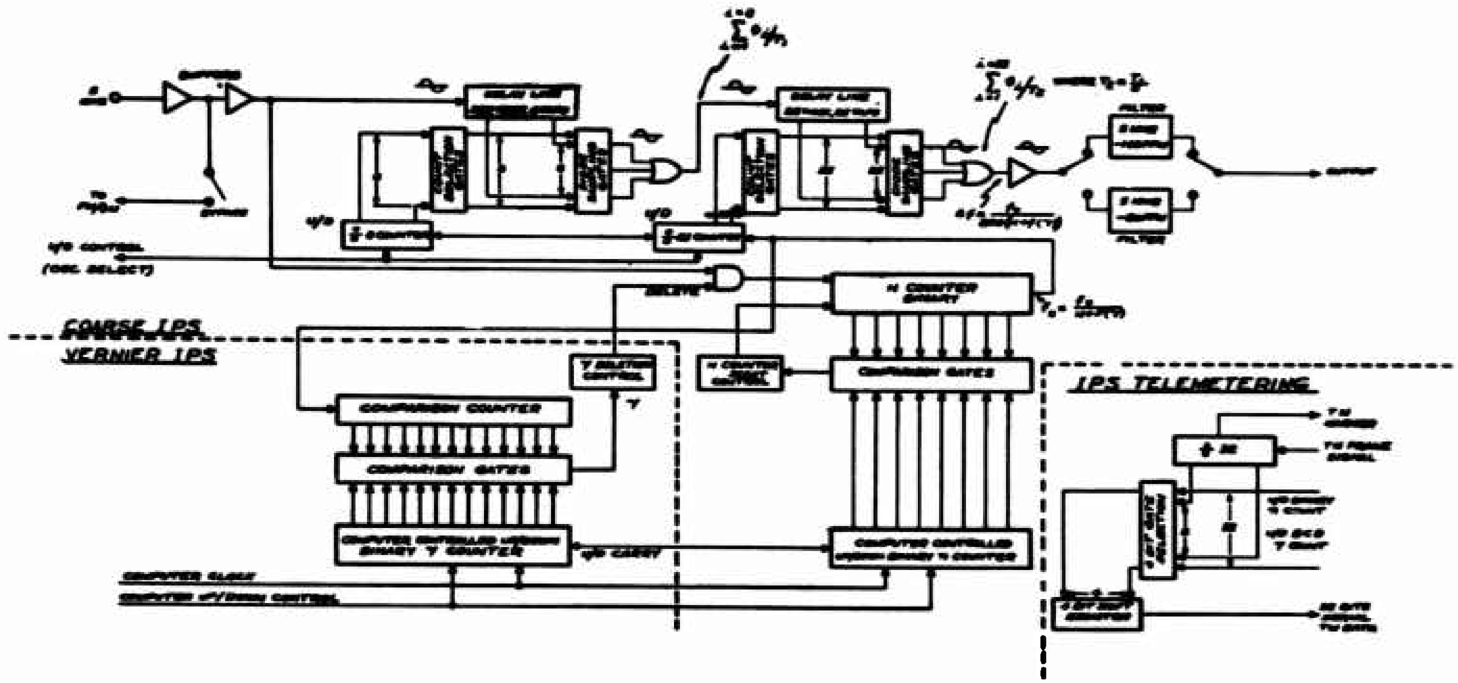

Figure 9. INCREMENTAL PHASE SHIFTED SYSTEM BLOCK DIAGRAM

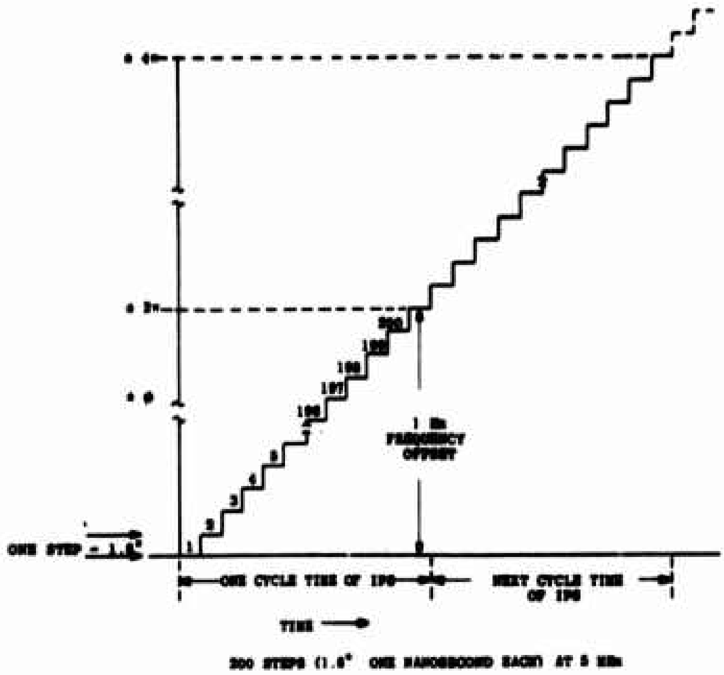

Figure 10. IPS PHASE STEPS

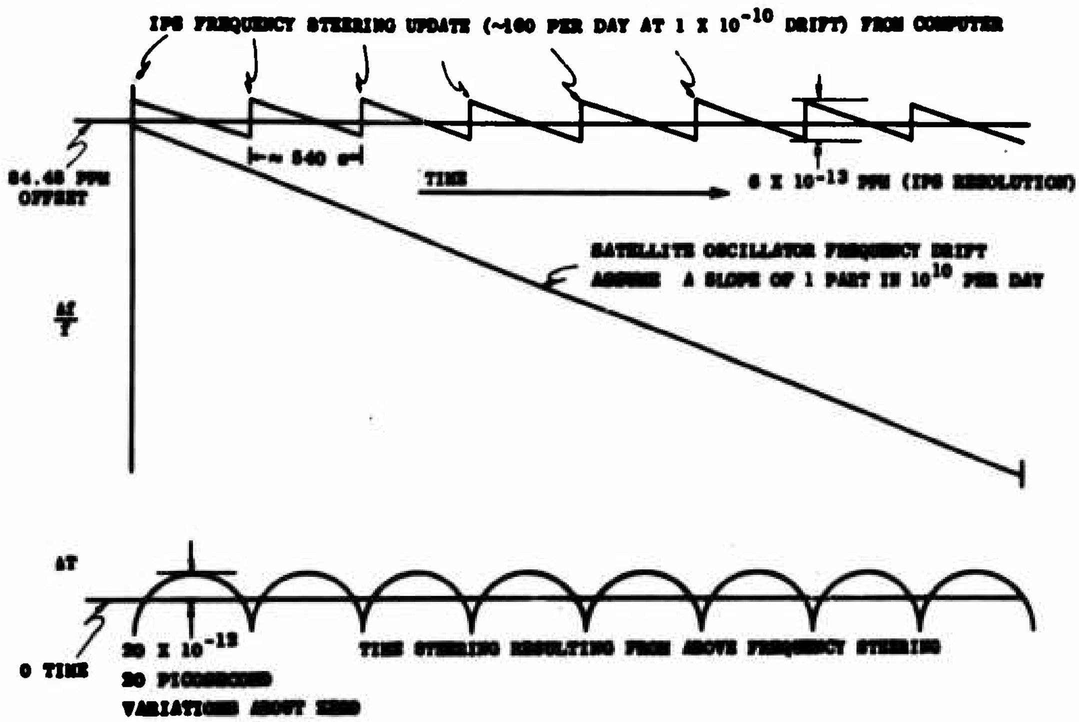

Figure 11. IPS FREQUENCY AND TIME STEERING

level, so that for time correction to the nanosecond level, this is a completely acceptable method of operation.

The IPS specifications are as follows:

Output frequency

5 megahertz - 145.51 ppm adjustable in steps of 6 parts in 10^{13}.

5 megahertz - 84.48 ppm adjustable in steps of 8 parts in 10^{13}.

Epoch adjustment precision $<$ one nanosecond.

Power - 1.3 watts

Weight - 0.7 pounds

Volume - 42 cubic inches

We have two different offsets for the 5 megahertz: one offset provides the operational frequency and one is different from the operational frequency. The offset used depends on whether the satellite is used to provide navigation service or whether it is used in an experimental mode. There are slightly different resolution capabilities depending on the output frequency desired.

Figure 12 shows the breadboard which has been operating 6 to 8 months at the laboratory. Some of the experimental results are shown.

Figure 13 is a diagram of the IPS package; a photograph was not available but it will be a box of about 4 inches by 7 inches by 1-1/2 inches in the TRIAD satellite.

In order to find out its basic performance, it is necessary to know the magnitude of noise generated within the device itself. To measure the noise level, we essentially beat a cesium standard oscillator against itself by operating two clocks from the same standard. One clock obtained its signal straight through a divider chain; the other went through the IPS and a separate divider chain. Therefore any noise produced by the IPS would show up on that output and the time differences should differ from 0 by the

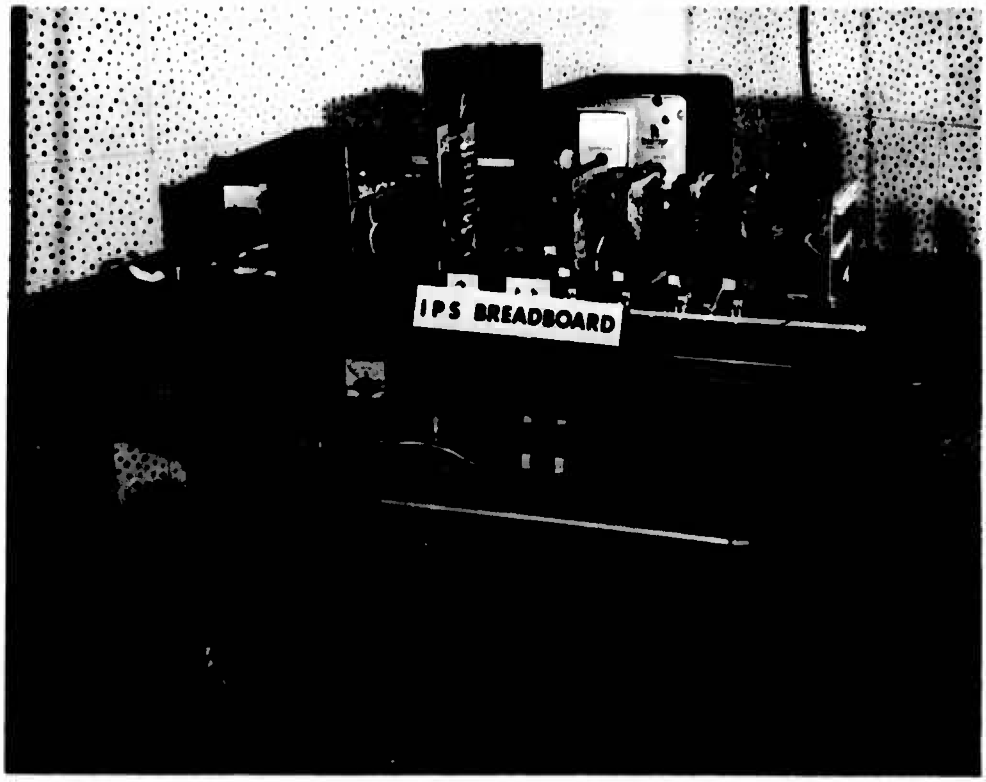

Figure 12. IPS BREADBOARD

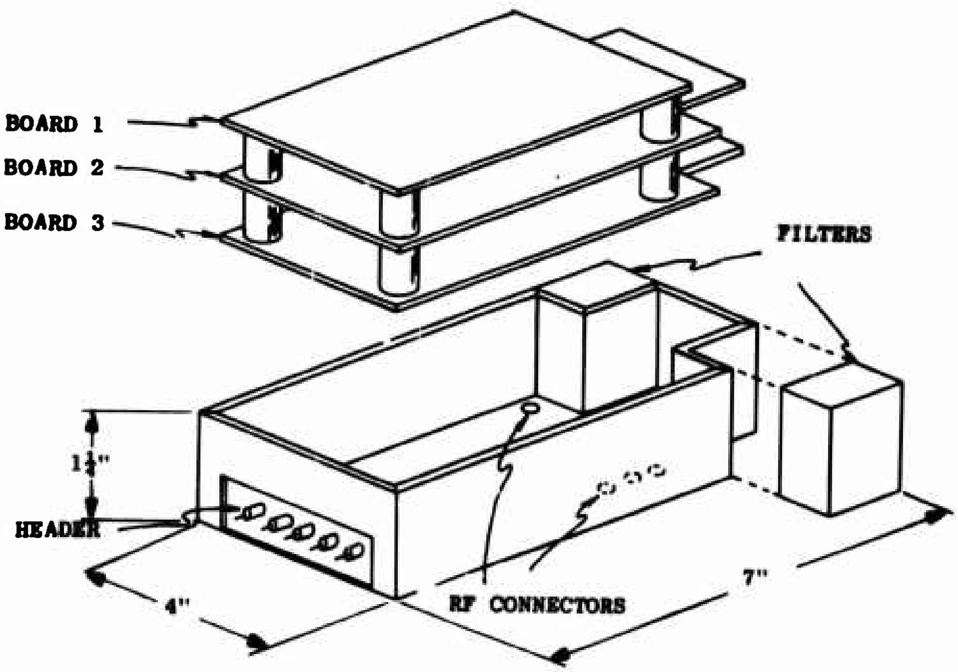

Figure 13. IPS PACKAGE

amount of the noise input of the IPS unit. The time differences were measured by a computer counter.

It can be seen in Figure 14, on a scale on which 10 nanoseconds is shown as a fairly substantial number, that the total IPS instrument noise is certainly well under a nanosecond.

Figure 15 shows the basic minimum adjustment step of the IPS; that is, time of error of ±50 nanoseconds a day. It can be seen that the instrument noise level is so far under the basic minimum adjustment step that instrument noise is not a problem.

The next thing tried was to actually correct for the drift of a crystal oscillator-driven clock relative to a clock driven by one of the cesium standards by inserting the appropriate rate in an IPS unit to modify the crystal oscillator frequency. Figure 16 shows the time comparison, which was well under the 100 nanoseconds level, but due to the non-predictable frequency drift rates of the crystal oscillator, the time error could not be kept under 50 nanoseconds. This is inherent in what that particular crystal oscillator was able to do. It should be noticed that the period of time was about 3 days; these time errors are fairly small departures from a constant time rate, but they are not extremely rapid in fluctuation.

The same sort of test was made using two different cesium standards--Serial #121 and Serial #450. First they were directly compared against each other to see what the basic difference in their offsets and rates were. Figure 17 shows that the difference in frequency resulted in a time error rate of approximately 30 nanoseconds an hour. You will notice the scale is pretty large; the total scale is a full microsecond.

An attempt was then made to synchronize by putting in a 30 nanosecond per hour correction with the incremental phase shifter. In Figure 18, the scale is changed so that instead of a microsecond, 100 nanoseconds is full scale, and on this scale a fairly substantial jitter can be seen. However, this is not nearly as much as was shown by the crystal oscillator

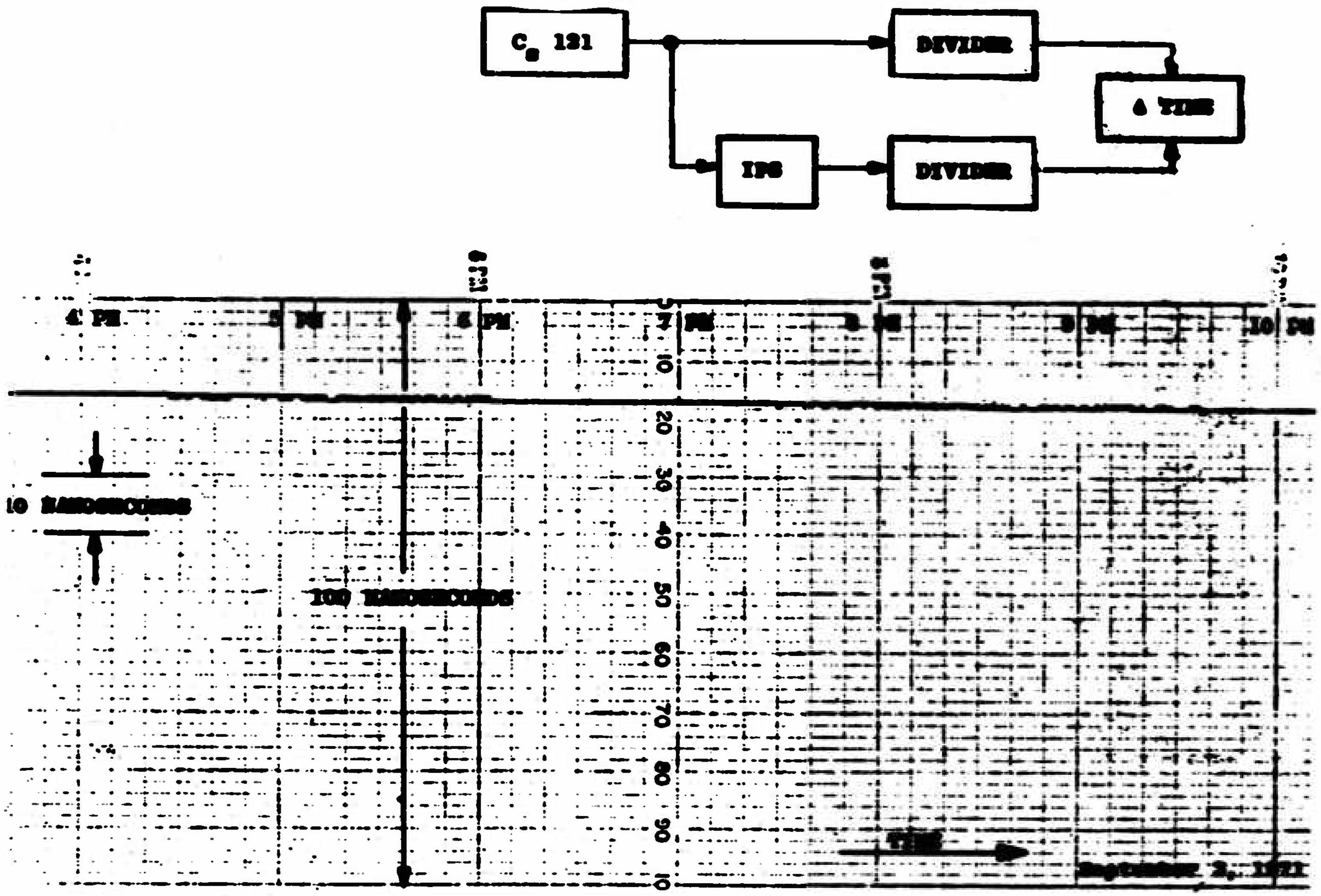

Figure 14. CESIUM (SN 121) VS. IPS (OFFSETTING CESIUM (SN 121)) IPS INSTRUMENTATION NOISE

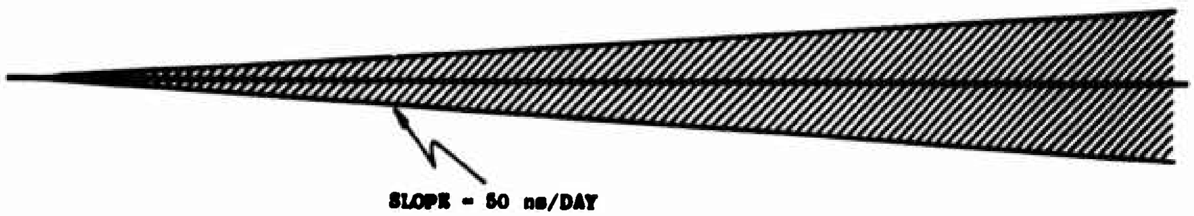

Figure 15. MAXIMUM TIME ACCUMULATION DUE TO SMALLEST INCREMENT OF IPS

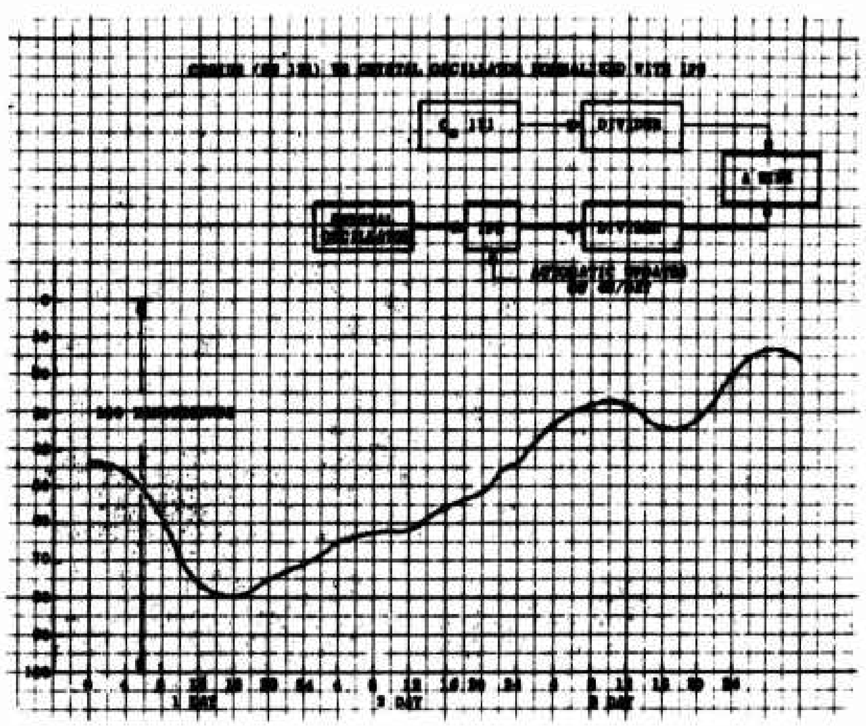

Figure 16. CESIUM (SN 121) VS. CRYSTAL OSCILLATOR NORMALIZED WITH IPS

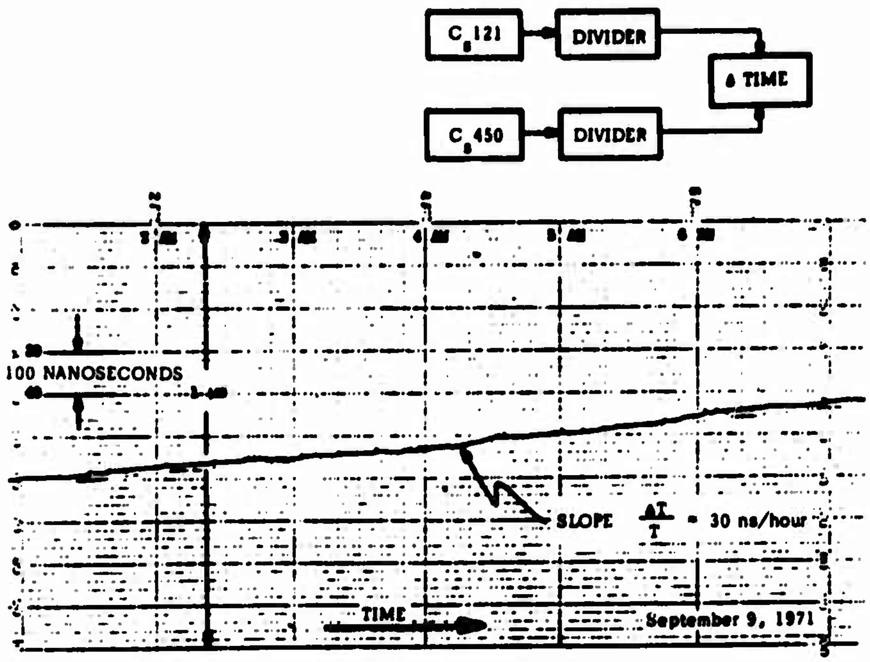

Figure 17. CESIUM STANDARD (SN 121) VS. CESIUM STANDARD (SN 450)

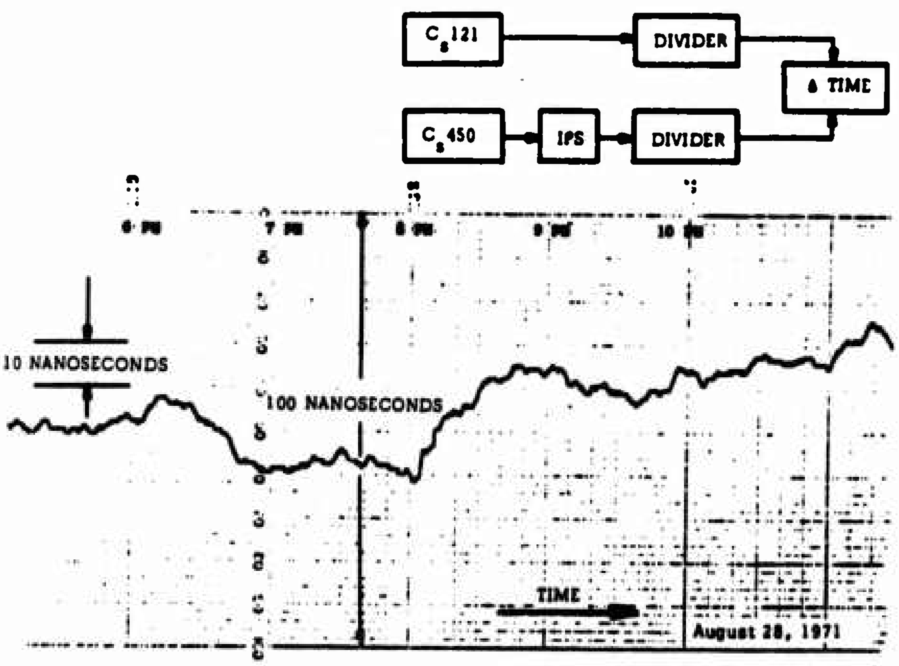

Figure 18. CESIUM (SN 121) VS. CESIUM (SN 450) IPS CONTROLLED - WORST CASE

where it was necessary to go to a factor of 10 larger scale. In Figure 18, the data shown are for the worst period time observed for a period of about 4 hours on August 28.

At other times, results were observed as good, as shown in Figure 19, in the behavior of two cesium standards. One cesium had been moved in frequency by IPS to agree with the other cesium. For a period of 4 hours they kept time errors at about the nanosecond level.

A summary of what seems to have happened so far with the use of the incremental phase shift oscillator and PRN time recognition at the laboratory is shown in Table 1. We can steer the frequency of a crystal oscillator to provide a clock correct to better than 100 nanoseconds over 3 days. We know that the basic instrumentation noise of the IPS itself introduces a time error of approximately 3×10^{-10} seconds, on a short-term basis, and that the cumulative time error is less than 50 nanoseconds per day for a specific fixed frequency setting of IPS. IPS can correct the drift rate of a crystal oscillator to the degree that the drift can be predicted. An improvement in the effective drift rate of 50:1 has been demonstrated.

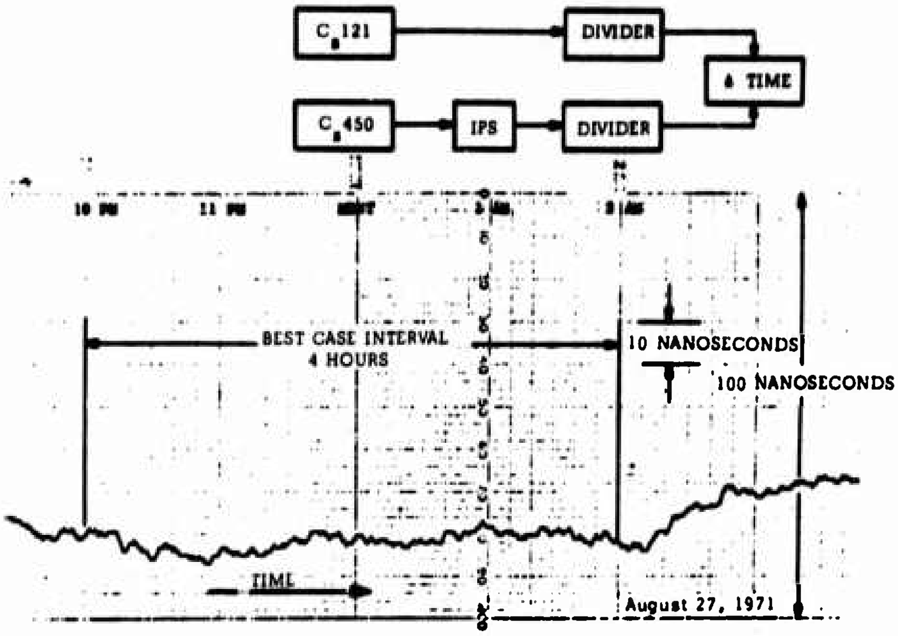

Figure 19. CESIUM (SN 121) VS CESIUM (SN 450) IPS CONTROLLED - BEST CASE

Table 1. APL TIME NORMALIZATION CAPABILITY

1. CESIUM STANDARD AT APL NOW DRIFTS AT 864 x 10^{-9} sec/day.
2. DEMONSTRATED: CRYSTAL OSCILLATOR FREQUENCY STEERED WITH THE IPS BREADBOARD TO THE C_s STANDARD TO < 100 x 10^{-9} sec. OVER 3 DAYS. CRYSTAL DRIFT RATE OF > 6 x 10^{-11}/day or 5 x 10^{-6} sec/day (50:1 IMPROVEMENT).
3. DEMONSTRATED: IPS INSTRUMENTATION NOISE ≈ 3 x 10^{-10} sec. SHORT TERM JITTER.
4. CUMMULATIVE TIME ERROR OF IPS FROM MINIMUM STEP ADJUSTMENT; 50 x 10^{-9} sec/day FOR FIXED FREQUENCY IPS SETTING.
5. CUMMULATIVE TIME ERROR < 1 x 10^{-9} sec/day BY DUTY CYCLE OF IPS LEAST SIGNIFICANT BIT.
6. IPS CAN CORRECT OSCILLATOR DRIFT TO THE ABILITY TO PREDICT THE DRIFT RATE. 50:1 HAS BEEN DEMONSTRATED.

DISCUSSION

DR. WINKLER: Dr. Kershner, do you anticipate any difficulties for the coming changeover in frequency on 1 January because you are not going to have these phase shifters in service yet, and you will have to tune your crystals?

DR. KERSHNER: No basic technical difficulty, no. There is still some discussion with the Navy Astronautics Group who run the current Transit program as to exactly how they are going to do it. There are several possible ways. Technically there is no reason for having any trouble. Because human beings are involved, there is a question, however, whether or not everything will get done right, and on time. But it is possible to cope with the problem. The only real trouble is tracking over periods of time for which data are obtainable before and after.

MR. LIEBERMAN: Do you anticipate much degradation when it is in the satellite?

DR. KERSHNER: In general, they behave better in the satellite than they do on the ground because of the much nicer and more controlled environment. We have seen no sign of real degradation. Generally, after they've been in orbit for about 4 or 5 days, they settle down very nicely and you get a very calm and rather steady and predictable aging rate which holds quite well. We do, once in a while, see a sudden shift, one part in 10^{11}, and it just happens and nobody knows why but then it goes on as before. This has happened on not most, but many, of the oscillators in satellites. That's the only freakish performance; it's very rare and very intermittent. Generally they behave better than on the ground.

MR. CHI: I have heard many times that the crystal oscillator behaves better in space. Do you have any explanation or any simulation results in the laboratory which could account for it?

DR. KERSHNER: I have no proof of this. I think a strong factor is the fact that you simply cannot get a human being within 400 miles of it. Also, the basic environment in a satellite is very carefully controlled. It's easy to have extremely good temperature control and your power conditioning is under quite good control and the situation is totally repetitive. If it survives a month or so, it has seen essentially everything it's ever going to see. There are more sources for power transients, for temperature changes, and so forth in the typical laboratory than there are in the satellite. It's easier to realize a good thermal design in the satellite than in the laboratory. A very good vacuum for a multilevel vacuum system is readily available in the satellite.

MR. CHI: You don't feel that the zero gravitation field might have some effect in relaxation of the crystals?

DR. KERSHNER: The fact that the vibration level is essentially zero in the satellite certainly cannot hurt. I think if you had a steady 1 G you'd be just as well off as having a steady zero. In the laboratory you have 1 G $\pm$ some fraction of vibration that cannot be totally isolated, and that surely isn't as healthy an environment as a steady acceleration of zero or any other amount. The satellite is just a very comfortable place.

TIMING RECEIVER FOR TIMATION SATELLITE

by

Roger Easton

Mr. Easton is Head, Space Metrology Branch, Naval Research Laboratory, Washington, D. C.

This paper presents a brief review of the various methods of time dissemination and a discussion of the timing receiver developed for use with the Timation satellites.

Four time transfer possiblities are listed in Figure 1. LORAN, OMEGA, and TV are suited for a fixed master-fixed user situation; user navigation is required for the fixed master-moving user. This report is concerned with items 3 and 4: when the master and/or the user are moving, precise knowledge of their locations is necessary.

There are two very closely related ways of time dissemination today: radio and navigation. Historically, the moons of Jupiter were used to obtain the first measurements of longitude. Later, the moon was used in a navigation system in which time could be determined to about 30 miles (a little over a minute). Time dissemination today uses the hyperbolic stations, LORAN and OMEGA, and satellites, which make possible the two-way ranging and passive ranging systems.

The satellite has four advantages: (1) well-known position; (2) line-of-sight signal, which allows the use of UHF; (3) worldwide coverage; and (4) a celestial navigation solution identical to the one used in celestial navigation for 200 years (see Figure 2). The diagram indicates the observer on a ship and his method of measuring the range to the satellite. He knows the radius of the Earth and the distance from the center of the Earth to the satellite. Triangulation gives him the angle θ, the same angle a celestial

1. Fixed Master-Fixed User

    LORAN
    OMEGA   to fixed stations
    TV

2. Fixed Master-Moving User

    User Navigation

3. Moving Master-Fixed User

    Master Navigation

4. Moving Master-Moving User

    Navigate Both Master and User

Figure 1. TIME TRANSFER POSSIBILITIES

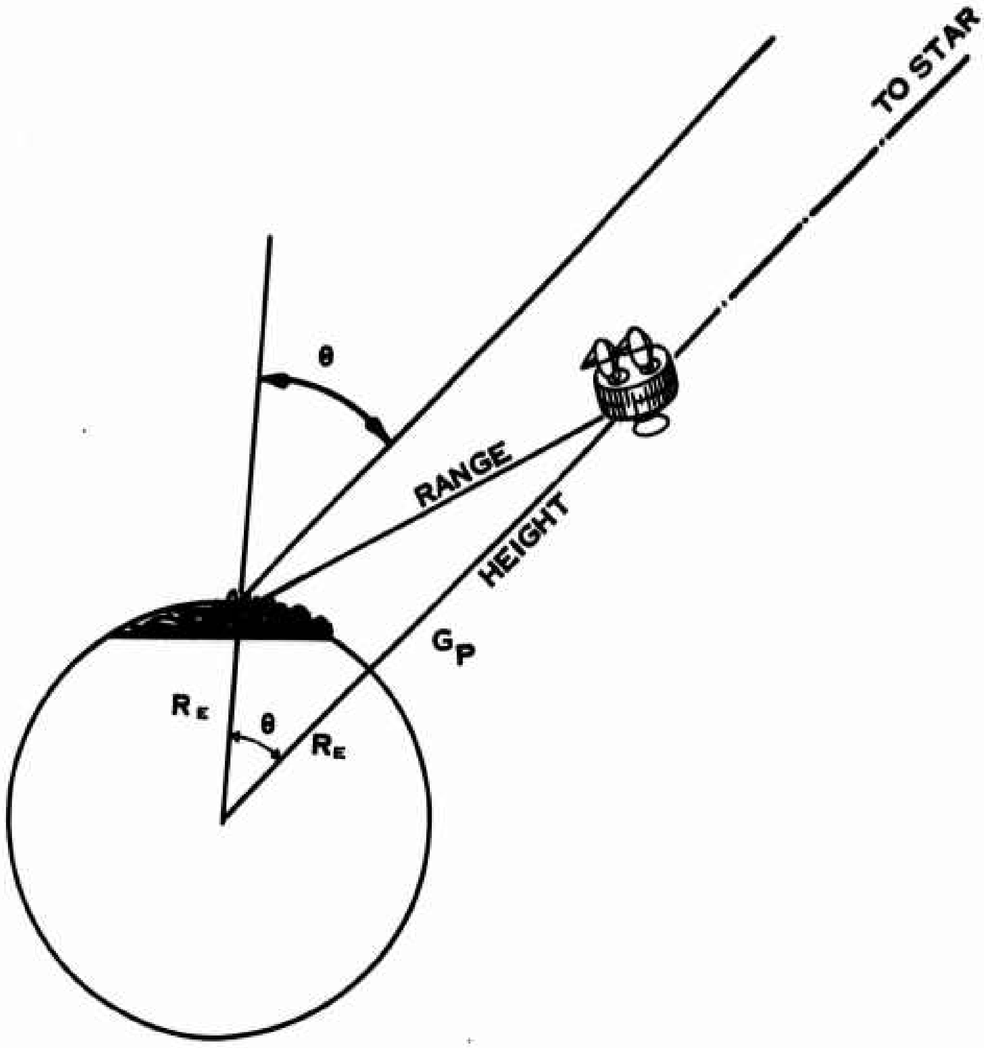

Figure 2. TRANSFORM TO CELESTIAL NAVIGATION

navigator would have used to observe a star in the same geographical position of the satellite.

Figure 3 is a diagram of range measurement by phase measure. The satellite has a clock (in this case, a 100-kHz clock) that is counted down: 100, 10, 1, .1 kHz. The observer has a similar clock. The signal from the satellite is received by the observer who then compares the phase of the 100 kHz received to his own 100 kHz to get a phase reading; he repeats this step for the other frequencies. If the satellite clock is synchronized to the observer clock, this phase reading gives a measurement of the time delay between the satellite and the observer.

Figure 4 is a schematic of the actual procedure, measured in 6800, 920, 18, and 8.6, 10 microseconds, with 100-cycle, 1000, and 10,000 microseconds countdown. The satellite clocks and the navigator clocks are synchronized in this case. However, by the time this signal gets from the satellite to the navigator, his clock has changed because it took 6800 microseconds for the signal to arrive. The phase comparison for the first clock is .68 of a cycle, which gives a rough reading of 6800 microseconds. For the second clock, the reading is .92, so it should read 6920 microseconds. For the third clock the reading is .18, so it should read 6918 microseconds, and for the fourth clock it is 8.6, so it should read 6918.6 microseconds.

Figure 5 is an intercept chart invented a hundred years ago by St. Hilaire, a French naval officer. The precomputed chart shows the assumed position, the direction of the satellite at 16 minutes past the hour and the computed time delays from the satellite at 16 minutes past the hour (10,870 microseconds). Thus, one can plot the predicted satellite positions for these times, compute the distance from the satellite to the assumed position, and convert this to time delay.

Figure 6 shows a fix determined on the intercept chart. At 16 minutes past the hour the time delay is read, a right angle is drawn, and a line of position (LOP) is established. Other LOP's are drawn in similar fashion.

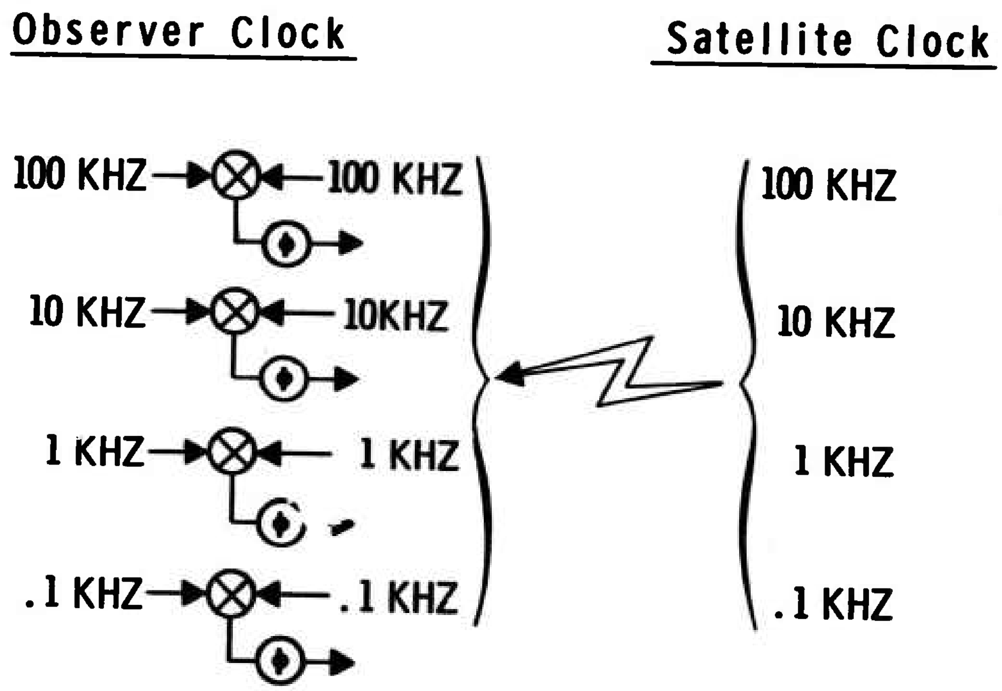

Figure 3. RANGE MEASUREMENT BY PHASE MEASUREMENT

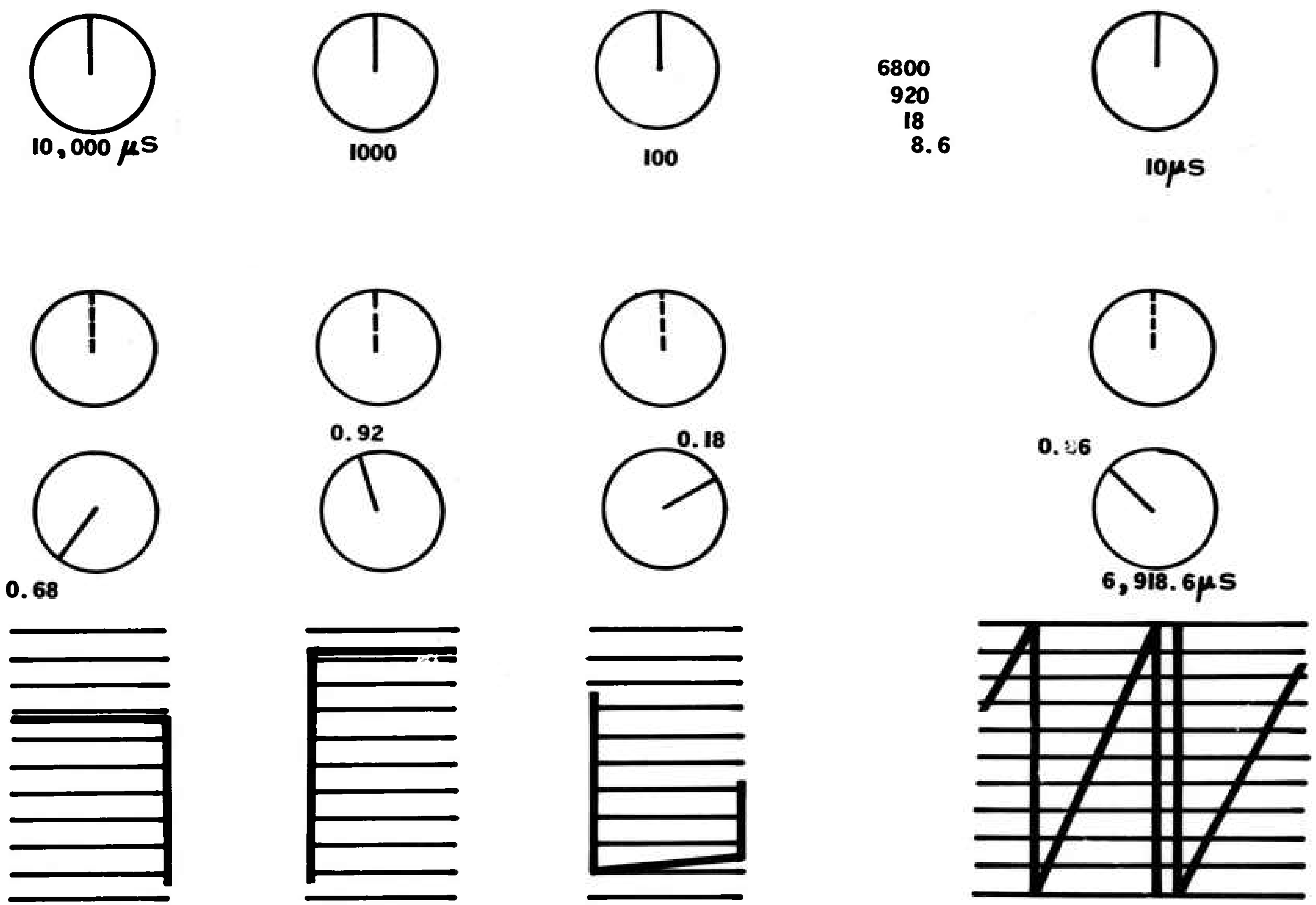

Figure 4. SCHEMATIC PROCEDURE

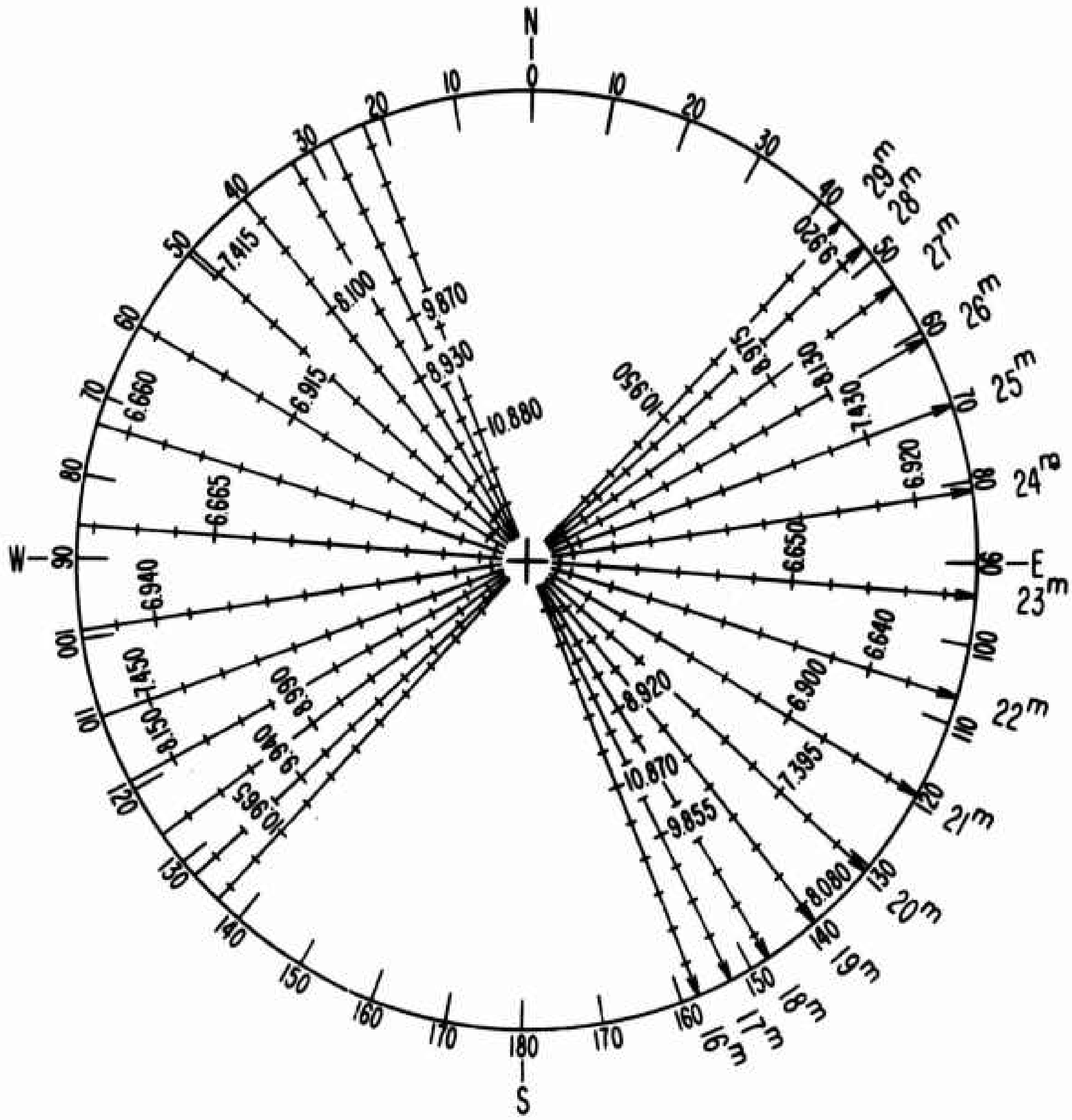

Figure 5. PRECOMPUTED INTERCEPT CHART

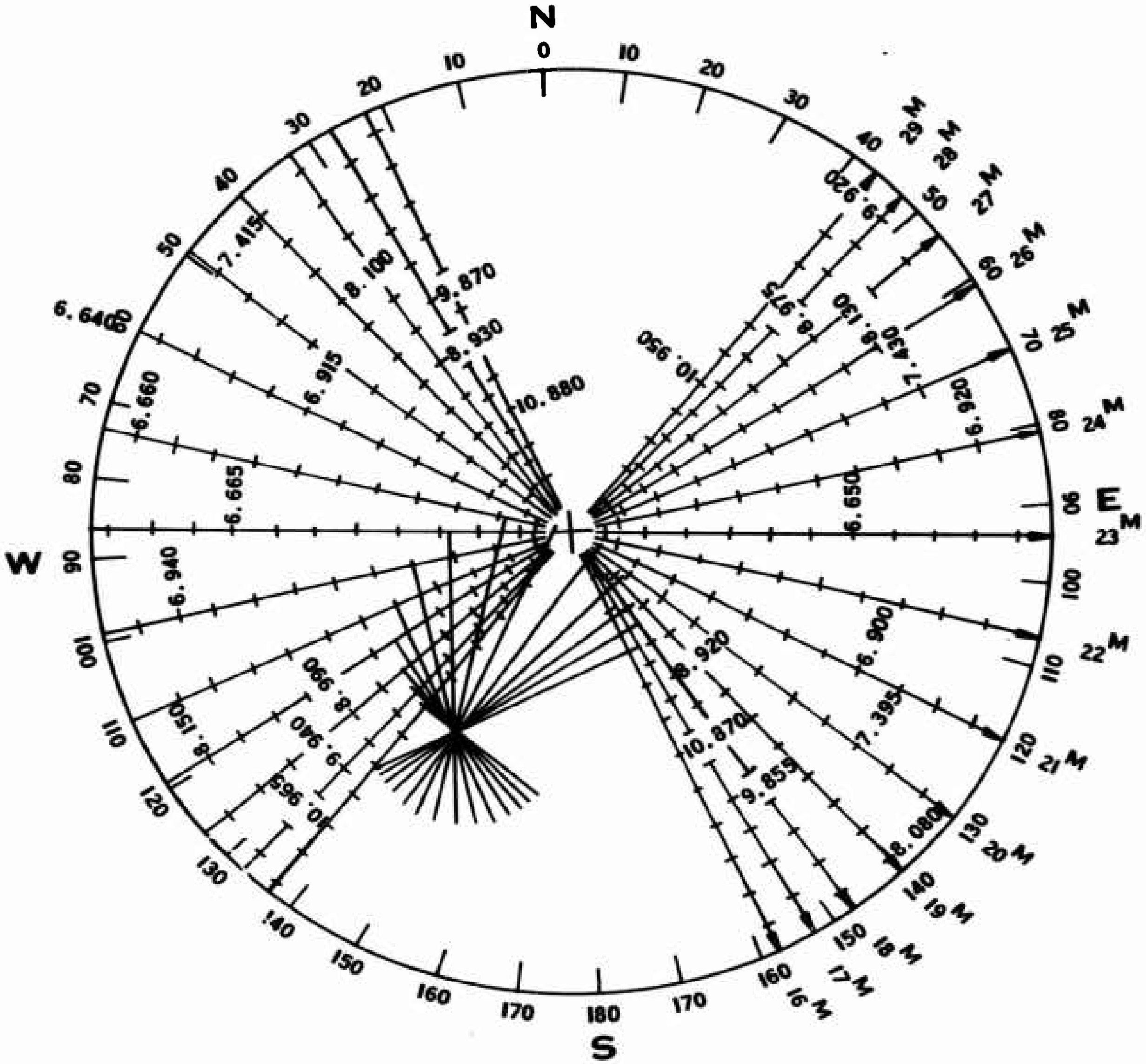

Figure 6. FIX DETERMINED ON INTERCEPT CHART

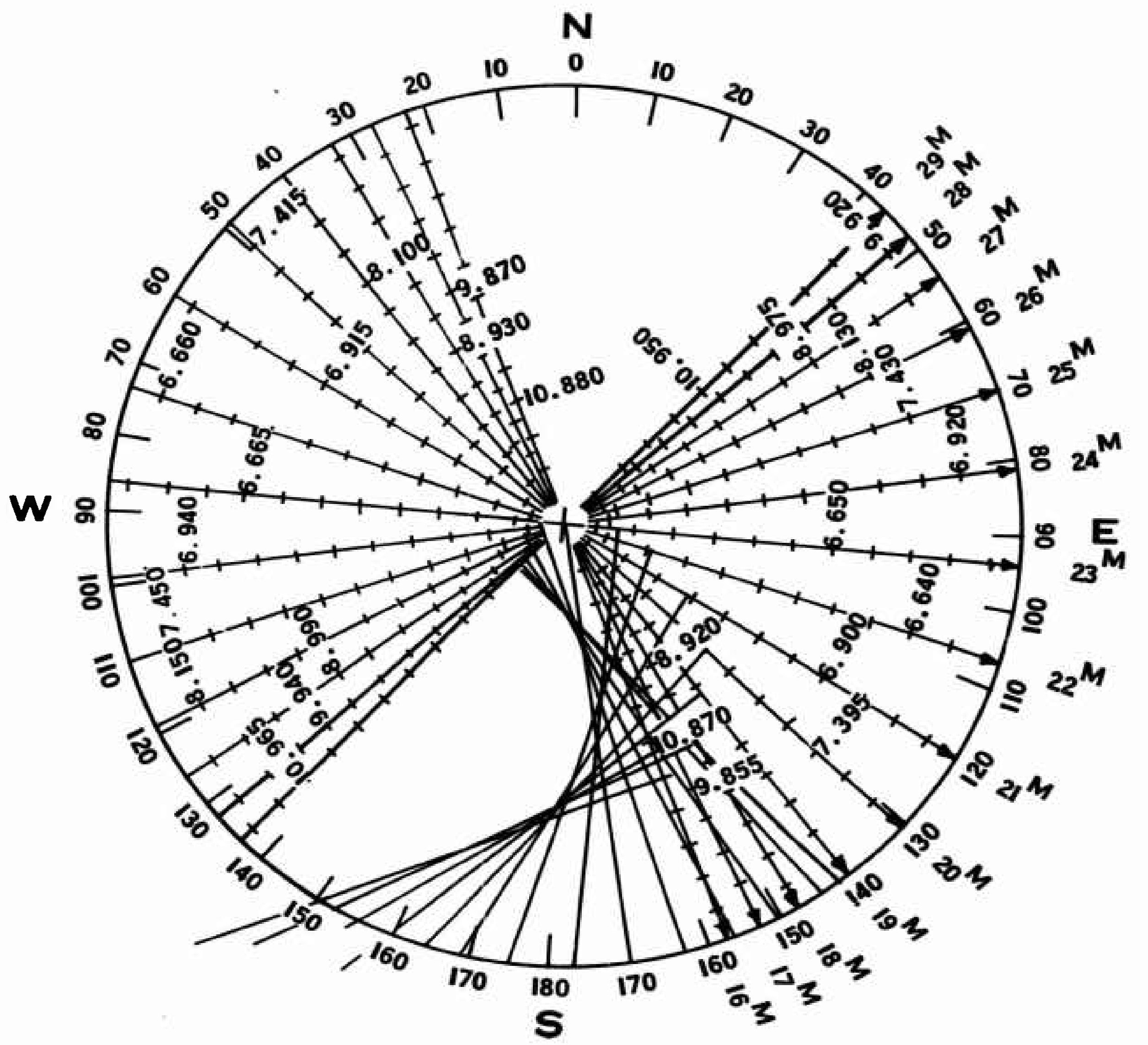

Figure 7. INTERCEPT CHART SHOWING EFFECT OF SYNCHRONIZATION ERROR ON PLOT

If there are no errors, the fix is perfect. But more often than not, the result will be similar to that pictured in Figure 7, an intercept chart showing the effect of synchronization error on plot, which is identical to having an instrument error for a celestial fix. The navigator is at the center of the arc of the circle, and the radius is his time error between his clock and the satellite clock. Thus the use of this technique allows both navigation and time transfer.

Figure 8 is a picture of the satellite in current use, Timation II. It was launched over two years ago on the aft rack of an agena. Table I lists the characteristics of Timation I (which failed after two years because of the failure of the gravity gradient boom), Timation II, and Timation III (scheduled for December, 1972).

Table 1.

TIMATION SATELLITES			
	#I	#II	#III
Launch Date	31 May 1967	30 Sept 1969	Proposed
Altitude	500	500	7500 n. mi.
Inclination	70^o	70^o	96^o
Weight	85 lb	125 lb	360 lb
DC Power	6 W	18 W	50 W
Frequencies	400 MHz	150&400	400,1600 MHz
Max Mod Freq	100 kHz	1 MHz	8 MHz
Osc Stab	$3pp10^{11}$	$.5\text{-}1pp10^{11}$	$1\text{-}2pp10^{12}$

Figure 9 shows the aging rates of the oscillators on Timation I and II. When the crystal oscillator on Timation II (which is tunable from the ground) was launched into space, it had a positive aging rate, 2 parts in 10^{11} per day. This rapidly decreased to more than minus 4 parts in 10^{11}

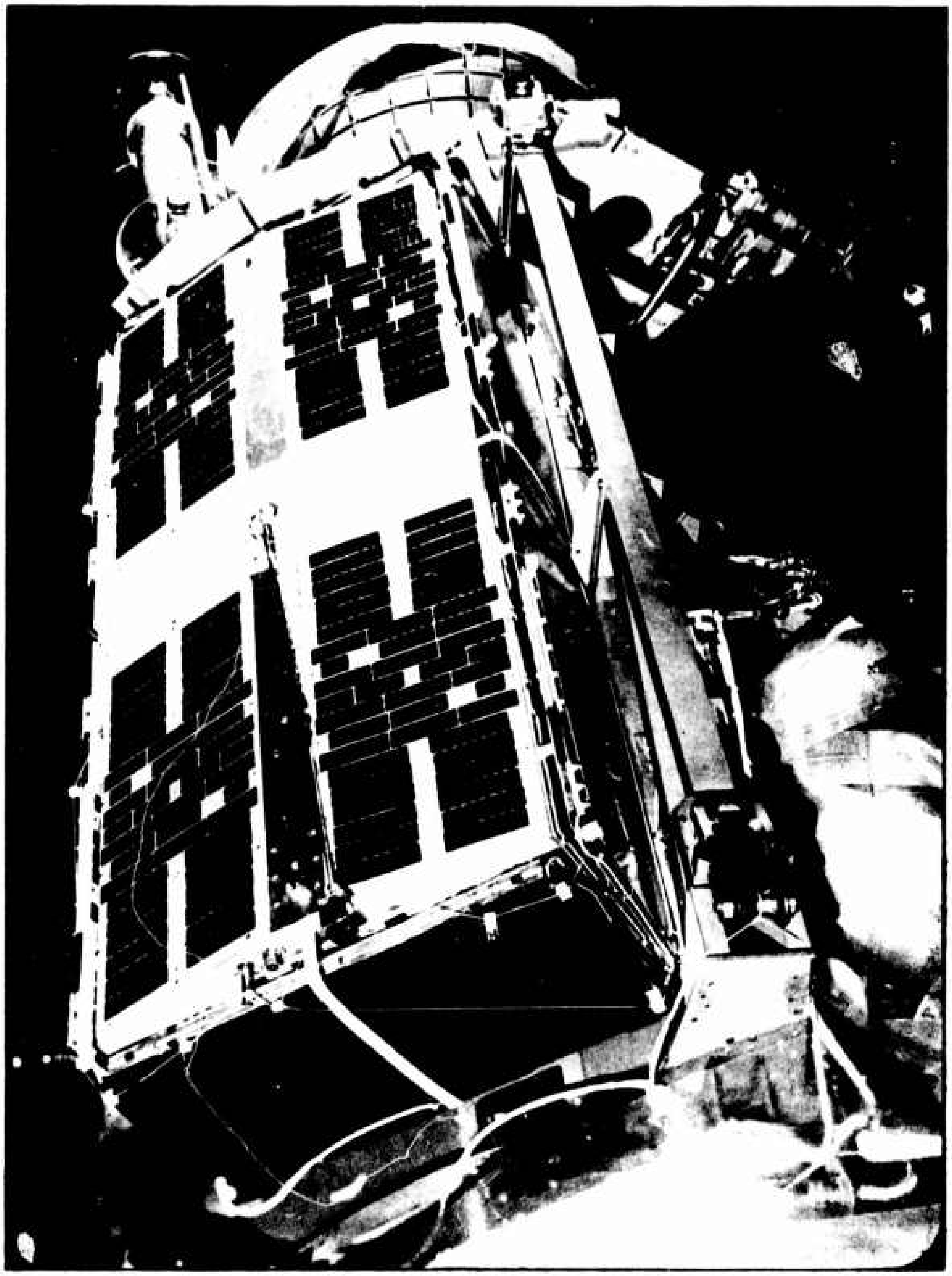

Figure 8. TIMATION II

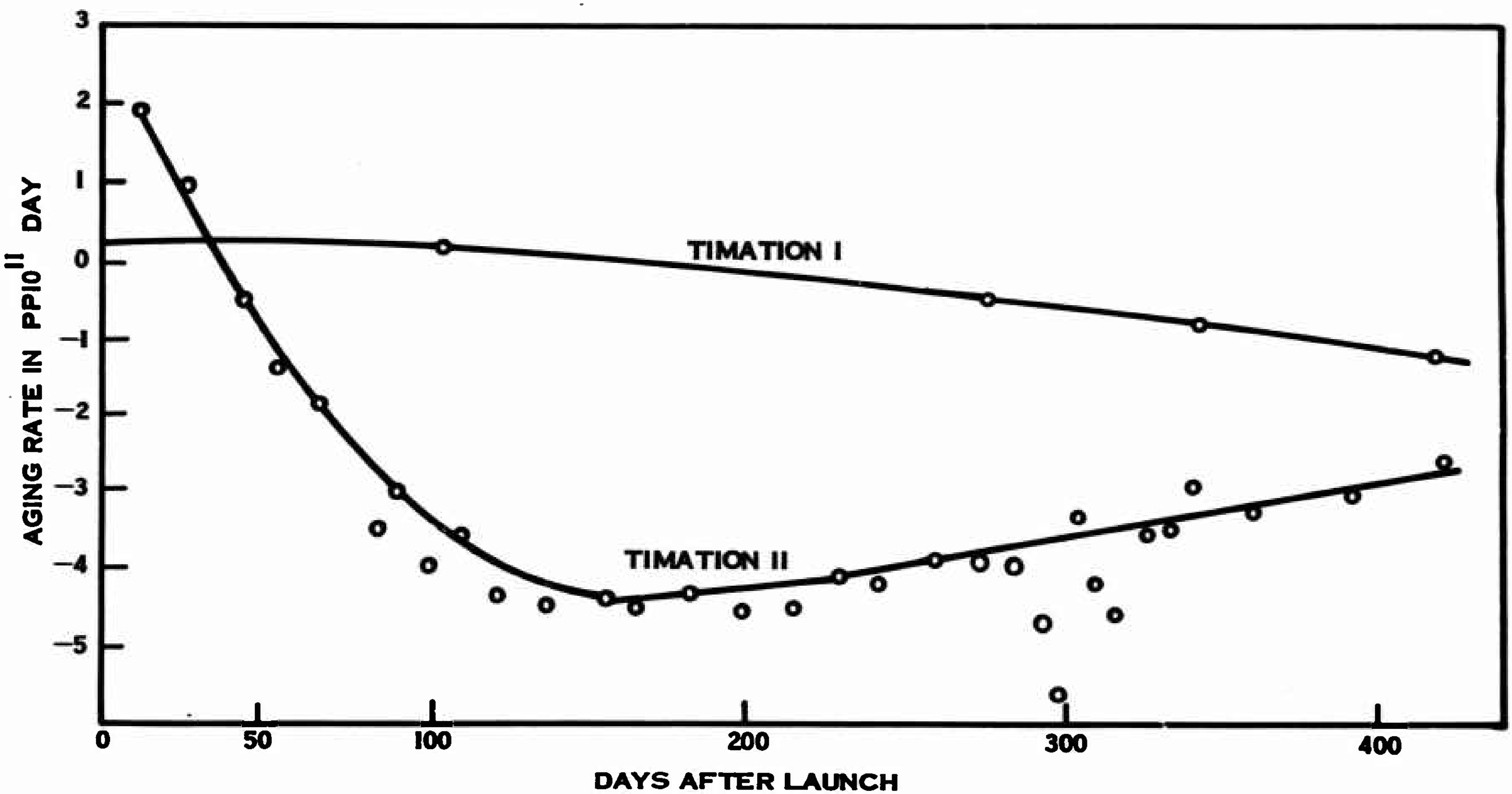

Figure 9. AGING RATES OF CRYSTAL OSCILLATOR

and has now come back up to minus 2 parts in 10^{11} per day. This would not be expected from any ground measurements. The rate of Timation I started as a much lower rate and gradually became more negative. The difference was caused by proton bombardment on the crystal; the reason for the different shapes of the curves is that Timation I had a much higher positive coefficient when it was launched and the proton bombardment (largely proton,some electron) compensated for it almost directly, thus the almost zero aging rate. Timation II had a much lower aging rate and the protons overcompensated for it, which caused the highly negative aging rate for part of the time. It was determined that the rate was largely caused by protons because Timation II had a lead shield that shielded out the electrons, and it still had almost the same rate that would have been expected without the lead shield.

Figure 10 is a schematic of Timation III. It is a large satellite, 5 feet in diameter, with a double gravity gradient boom and antennas on both ends, so no matter which way the gravity gradient captures, it can operate. At this altitude the gravity gradient takes about 3 weeks to stabilize, so it is not desirable to turn it over very often.

Figure 11 is a photograph of the 400-megahertz time dissemination receiver. It is designed to resolve ambiguities; i.e., it makes a reading, carries the reading on, resolves the ambiguity in steps of time, and reads out the time delay directly.

Figures 12 and 13 are graphs of time measurement errors made by the timing receiver, which illustrate that the occasional error made by the device can usually be corrected .

Figures 14 and 15 are graphs comparing time measurement errors made by the NRL-RCA receivers.

Figure 16 charts satellite clock errors with 4- and 6-day predictions. Data received from the Naval Weapons Laboratory on the orbit ephemeris

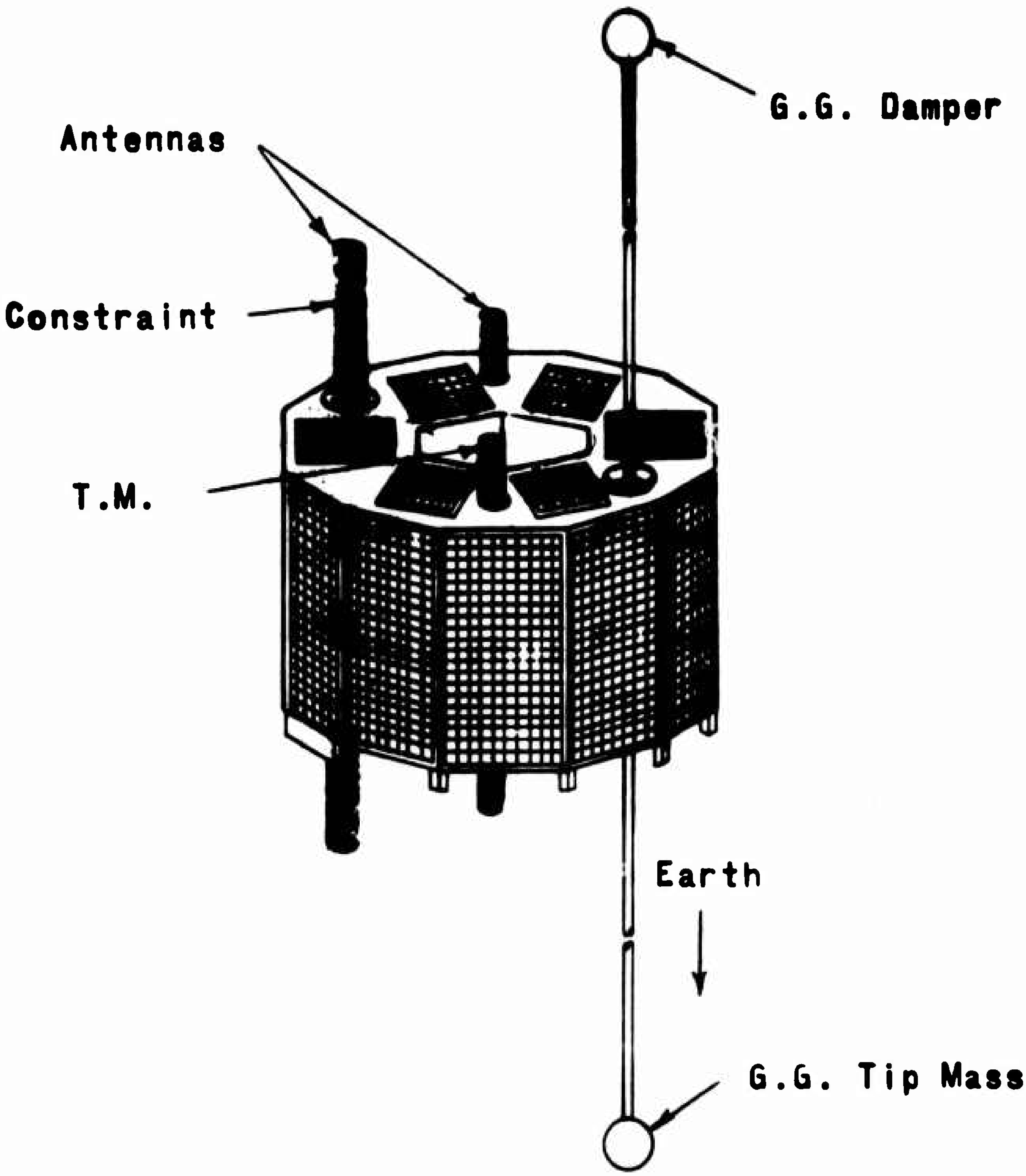

Figure 10. TIMATION III ORBIT CONFIGURATION

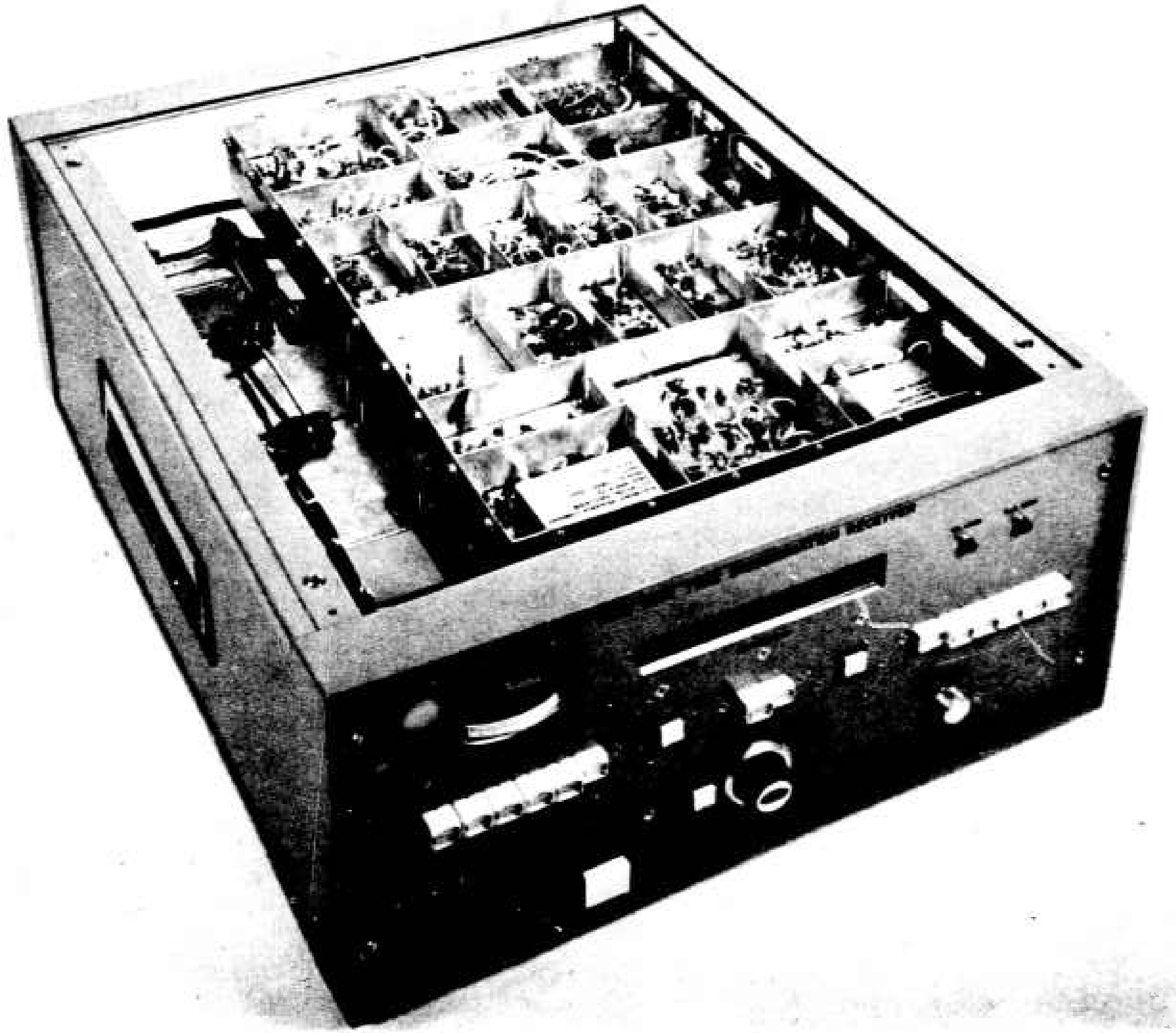

Figure 11. 400 MEGAHERTZ TIME DISSEMINATION RECEIVER

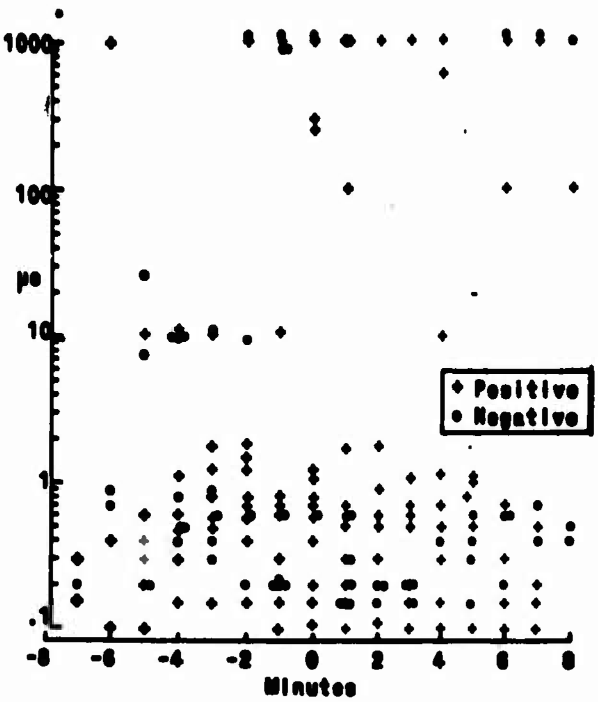

Figure 12. TIME MEASUREMENT ERRORS

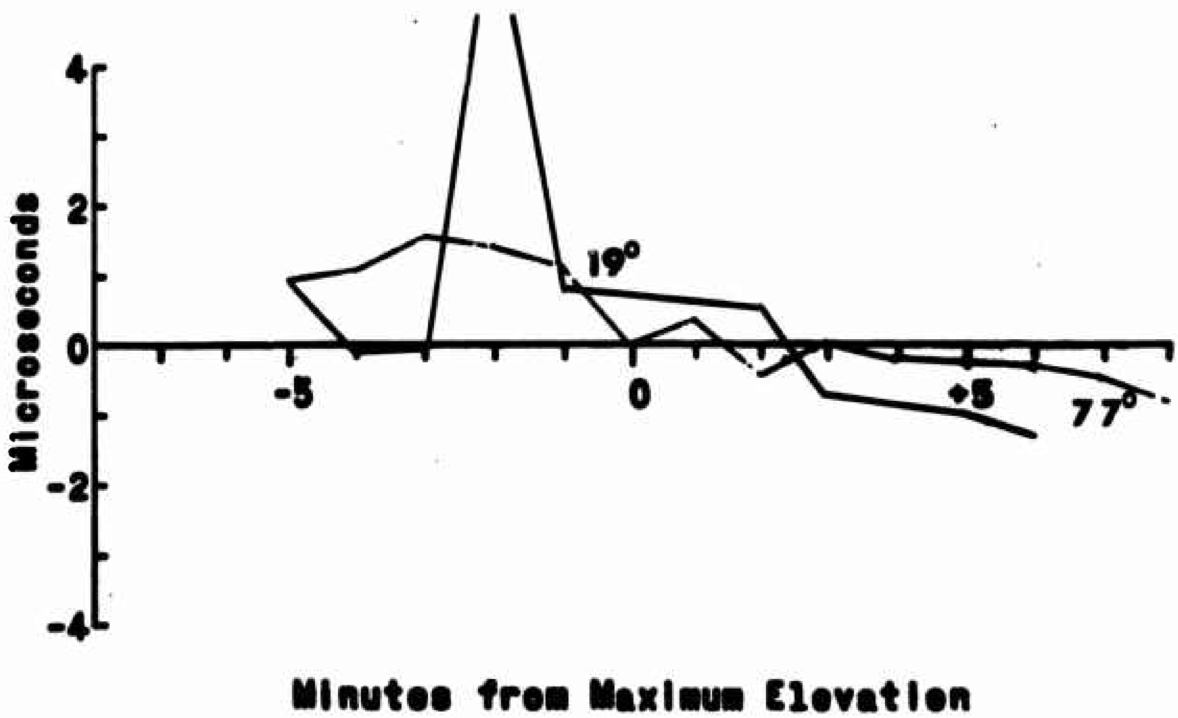

Figure 13. TIME ERRORS FOR PASSES ON 12 NOVEMBER

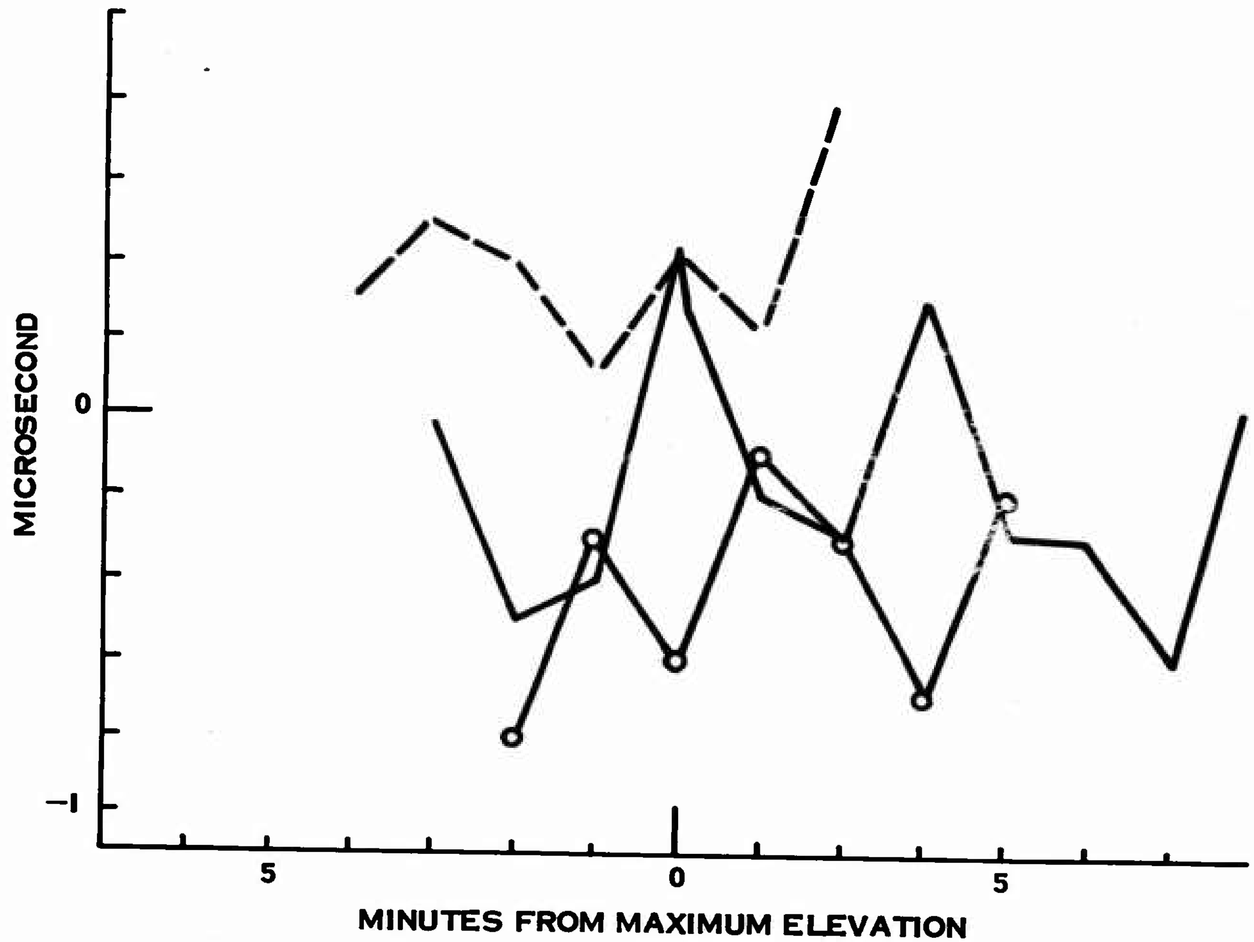

Figure 14. NRL-RCA RECEIVER COMPARISON

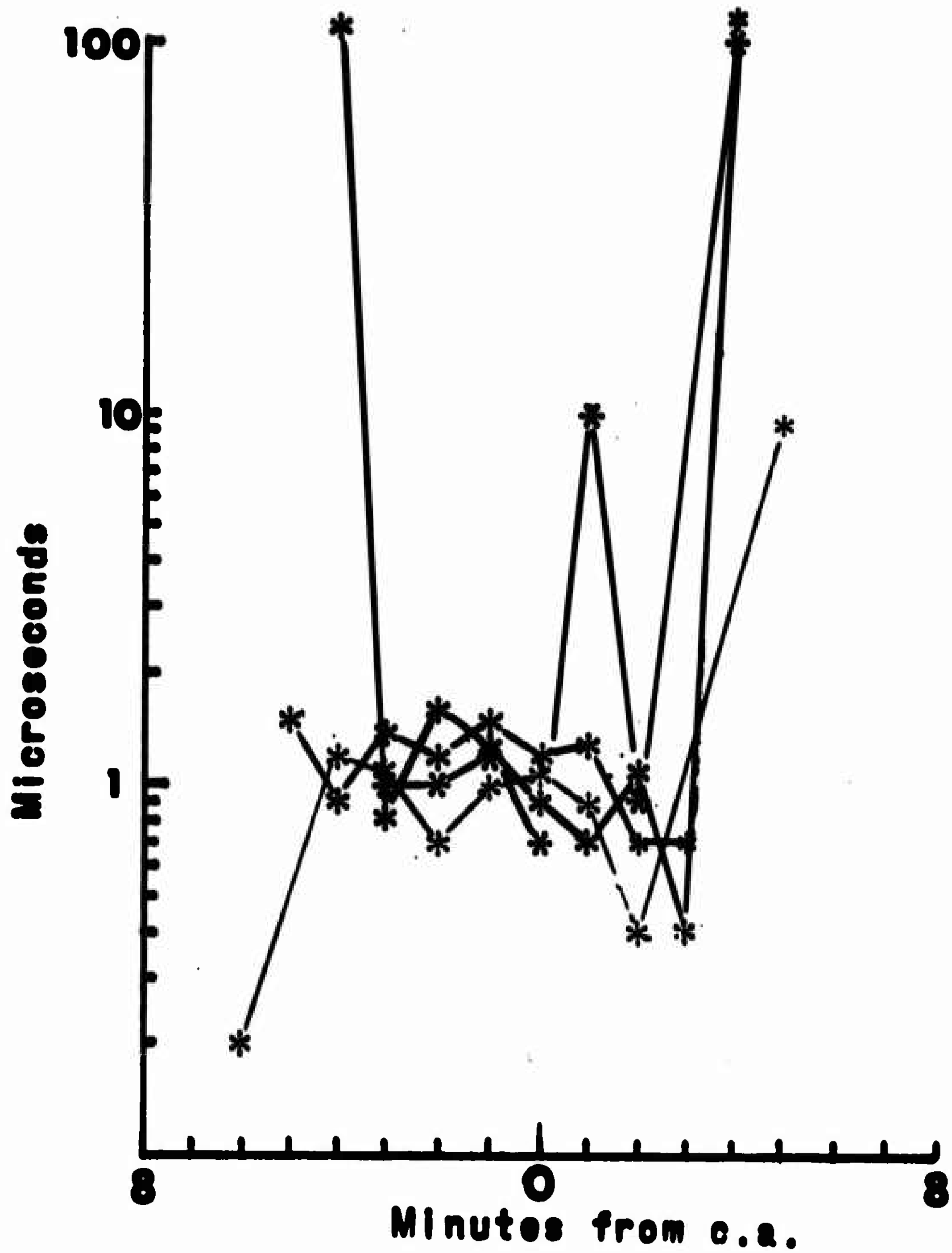

Figure 15. TIME MEASUREMENT ERRORS NRL-RCA

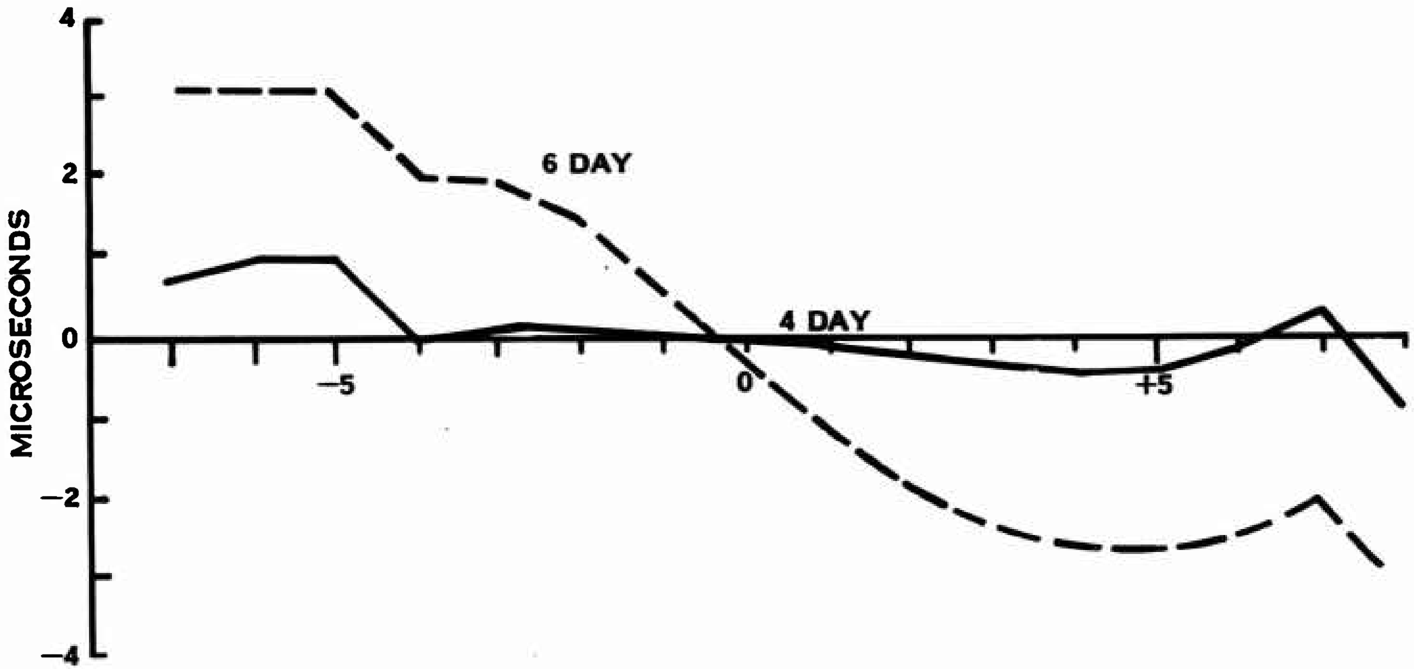

Figure 16. CLOCK ERRORS WITH 4 AND 6 DAY PREDICTIONS

were 4 and 6 days old; with the 4-day old data, the maximum error was a little more than a microsecond, and with the 6-day old data it was between 3 and 4 microseconds.

Five steps are taken for routine satellite clock update: (1) The satellite position is determined by use of TRANET, a tracking net for geodetic satellites operated by PM 16 of the Navy. TRANET looks at the satellite as though it were a doppler satellite, sends the data to the Applied Physics Laboratory, where they are processed somewhat and then sent to the Naval Weapons Laboratory, which then gives predictions on where the satellite will be and post-dictions on where it was. (2) The Naval Weapons Laboratory computes the time delay from the satellite to the stations in question (e.g., NRL). (3) The local clock is compared to the master clock, which is ultimately compared to the Naval Observatory Clock. (4) Time delay from the satellite is measured. (5) By measuring these time delays on sequential days, the clock drift of the satellite (which is now about 2 parts in 10^{11} per day) is obtained.

Three steps are taken to obtain time transfer measurement. (1) The time delay from the satellite to the stations is computed. (2) The time delay is measured and compared with the computation. (3) The oscillator drift measurement is used to correct the times of the remote station, if it is a considerable distance away from the master station.

Figure 17 shows the predicted positions of the satellite pass for 16 November 1971, and Figure 18 gives the calculated and observed delays.

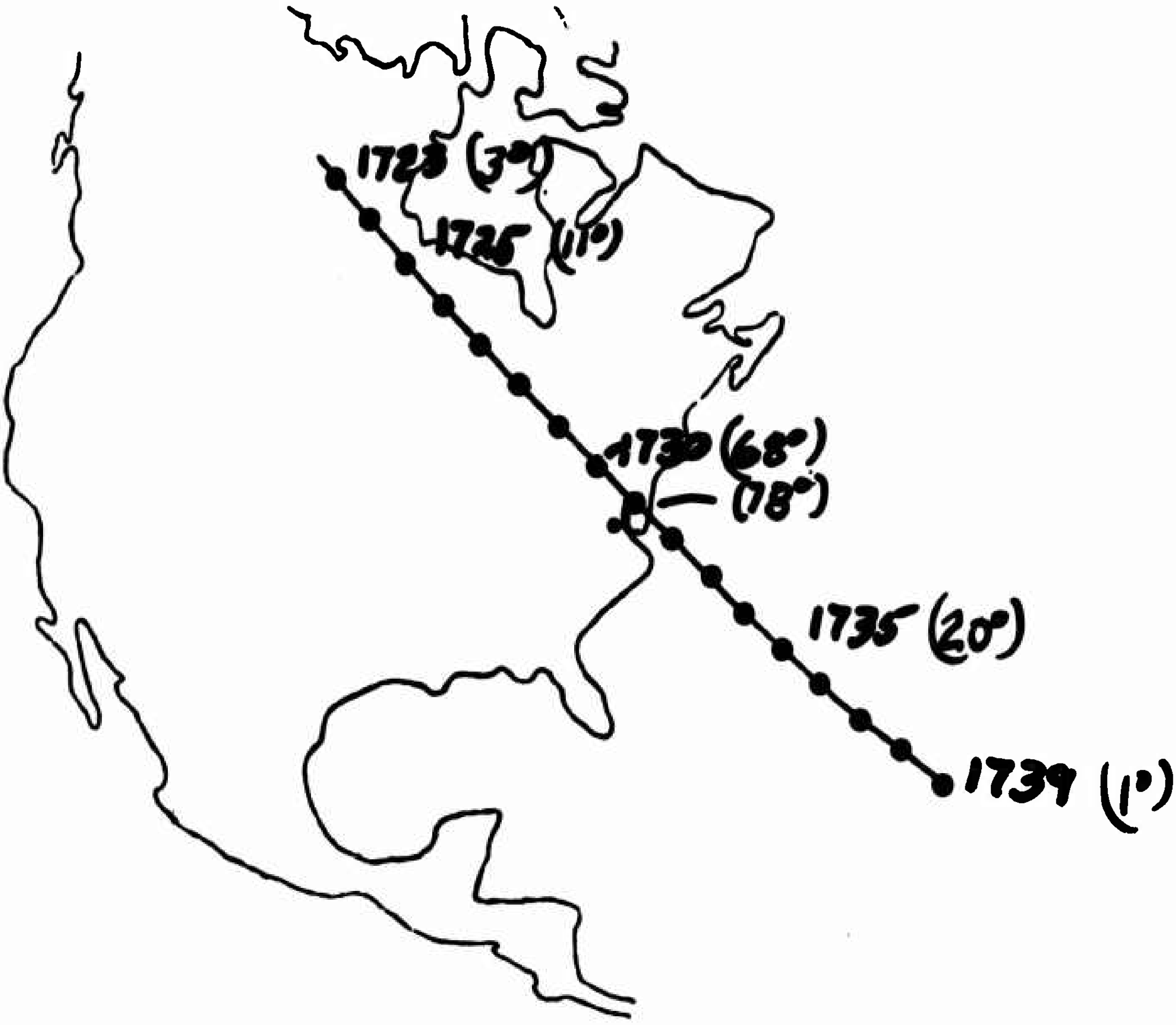

Figure 17. SATELLITE GROUND TRACK FOR 16 NOVEMBER 1971 PASS

	Observed	Calculated	Δt		Observed	Calculated	Δt
1723		10,554.49		1731	2,154.88	3,155.11	-1000.23
1724		9,299.41		1732	2,674.11	3,674.81	-1000.70
1725	8,159.11	8,057.93	101.22	1733	4,548.72	4,549.80	- 1.08
1726	6,944.29	6,843.25	101.04	1734	5,613.15	5,614.28	- 1.13
1727	5,680.19	5,678.50	1.69	1735	6,784.34	6,776.82	+ 7.52
1728	4,609.06	4,607.65	1.41	1736	7,990.26	7,991.64	- 1.38
1729	3,719.47	3,718.44	1.03	1737	9,233.29	9,234.72	- 1.43
1730	3,172.70	3,172.23	.47	1738	10,491.34	10,492.42	- 1.08
				1739	11,254.39	11,756.32	- 1.93

* calculated is underlined; observed is not underlined

Figure 18. CALCULATED AND OBSERVED DELAYS*

DISCUSSION

LCDR POTTS: What are the error mechanisms that cause the ambiguities of 100 microseconds, 1000 microseconds in the reading?

MR. EASTON: It's just noise in the system from one place to another. The signal level we're using is not too high, and the noise makes us resolve the times wrong.

MR. GATTERER: If this were an operational system available to anybody, what would it cost a user to receive this signal at the various accuracy levels? What would it cost in terms of equipping and setting up in the first place? What would it cost in terms of manpower to operate?

MR. EASTON: We've heard figures all the way from, say, a dozen receivers like this for something like $20,000 each. And if you were in the thousands category; for instance, you had a real navigation system going and you wanted down to the fairly cheap system, which would be a single frequency system, we've heard figures below $1000. If you went to the best, two frequencies, why of course, you're going to a higher value. But somewhere between $1000 and $20,000, depending on the number you want, I think it is a reasonable span, anyway.

MR. GATTERER: What about manpower?

MR. EASTON: It takes one man to read off the data once you get it set up. It's not a big manpower problem.

MR. WILCOX: I'm wondering about the gravity gradient boom; just how does that compensate for the gravity gradient?

MR. EASTON: The gravity on one end of the boom is different from the gravity on the other, and, since there's very little drag or anything else at that altitude, by having a damper in one tip mast, you can damp out the effect of gravity. It will give you a two-axis stabilized satellite, either pointing toward the Earth or away, depending on which way you want to look at it.

DR. REDER: I'm puzzled by those curves which you showed on the aging of the crystal. You say it's because of protons?

MR. EASTON: That's correct. That's what we think it is.

DR. REDER: How long is this satellite in orbit?

MR. EASTON: The second one has been just over two years, and the first one, four years.

DR. REDER: Well, did you notice any change in the aging rate during a proton flare of the sun?

MR. EASTON: No, and we probably wouldn't. We wouldn't have enough sensitivity to notice that.

DR. REDER: Well, the proton flares have an increase in flux rate, in some cases up to two or three thousand.

MR. EASTON: Right, but we have quite a few errors in our measurement and we haven't noticed it. Possibly we could.

MR. BARNABA: You mentioned this oscillator in your Timation II satellite, parts in 10^{12}. Could you describe that?

MR. EASTON: Well, it's just a crystal oscillator which, hopefully, is, you know, the-state-of-the-art, much smoother grind, much higher temperature bake-out, much higher vacuum, and carefully selected from a large number. Right now, it doesn't look like we'll get one part in 10^{12}; two parts in 10^{12} is probably as good as we will do.

MR. LIEBERMAN: I noticed that you have a single satellite up for both II and III. Are you going to have clusters, or just single satellites?

MR. EASTON: Well, that gets into the whole DOD navigation area. How many and whether they will go into a new navigation system are still undecided questions.

TIME AND FREQUENCY ADJUSTMENT ON THE LORAN-C SYSTEM

by

LCDR Cyrus E. Potts

LCDR Potts is with the Systems Development Branch, Electronics Engineering Division, U.S. Coast Guard Headquarters, Washington, D. C.

This paper describes the time and frequency adjustments which are presently being made on the Loran-C system and those which will be made when some newer, more sophisticated equipment has been installed. Last year, the Loran-C system used as a medium for the dissemination of precise time and time interval was discussed in some detail, and is available in the proceedings [1]. This paper concerns itself with time and frequency performance and adjustments on the Loran-C system.

As a brief review, a Loran-C chain consists of a master and two or more secondary stations, as shown in Figure 1. In the hyperbolic navigation mode, constant time differences (between receipt of master and secondary station signals) form lines of position which are hyperbolas. A user measures the time difference between receipt of the master and secondary signals and determines a line of position. This measurement is repeated for another master-secondary pair. These measurements then establish a position in the Loran grid.

The basic characteristics of the Loran-C system are:

- Center frequency of 100 kilohertz with a bandwidth of 20 kilohertz.

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1 C. E. Potts, "Precise Time and Time Interval (PTTI) Dissemination via the Loran-C System," Proc. Precise Time and Time Interval (PTTI) Strategic Planning Meeting, Volume 1, December 1970, pp. 32-54.

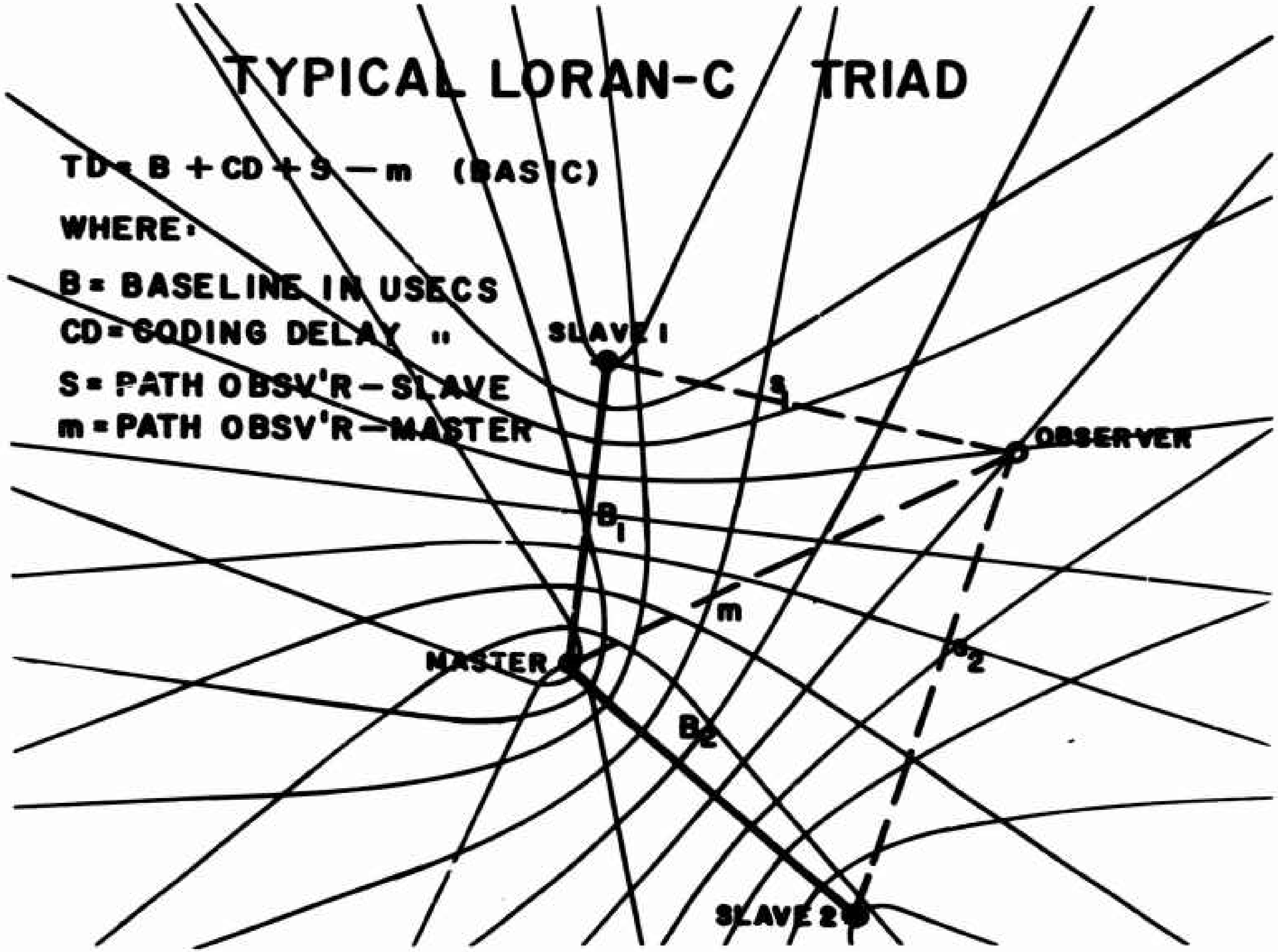

Figure 1. TYPICAL LORAN-C TRIAD

- Pulse leading edge which approximates the expression: $e(t) = t^2 \epsilon^{-\alpha t}$.

- Eight pulses per group (separated by 1000 microseconds) except for the master station which transmits a ninth pulse 2000 microseconds after the eighth pulse as an identifier.

- Group Repetition Interval (GRI) which varies from approximately 50,000 microseconds to 100,000 microseconds, chosen to maximize the signal-to-noise ratio for a given coverage area.

- Secondary stations synchronized to the master station in carrier phase, usually to a tolerance of 200 nanoseconds (3σ).

Loran-C coverage is a little difficult to describe since one needs to specify whether the interest is in hyperbolic navigation coverage, range-range (rho-rho) navigation coverage, or time and frequency dissemination coverage. An example of the types of coverage is presented in Figure 2 for a Loran-C triad (3-station chain). The hyperbolic navigation coverage is indicated by the fully cross-hatched area. The user must receive the signals from all three stations and the crossing angles of the hyperbolas must be large enough to permit accurate fixes. For rho-rho navigation the user need only receive the signals from any two stations, thus the coverage area is greater as indicated by the shaded area. A user interested in time or frequency need only receive one station so the coverage for this usage is that bounded by the outermost circles.

There are two types of time dissemination services provided by Loran-C. The first is a single pulse per second (1 pps) transmitted by Universal Time Coordinated (UTC) synchronized Loran-C master stations. The second type service is provided by the Loran-C pulse groups, the first pulse of which is synchronized periodically with the Universal Time Second (UTS, a second on the UTC scale). A null ephemeris table published by the U. S. Naval Observatory (USNO) tabulates the times that

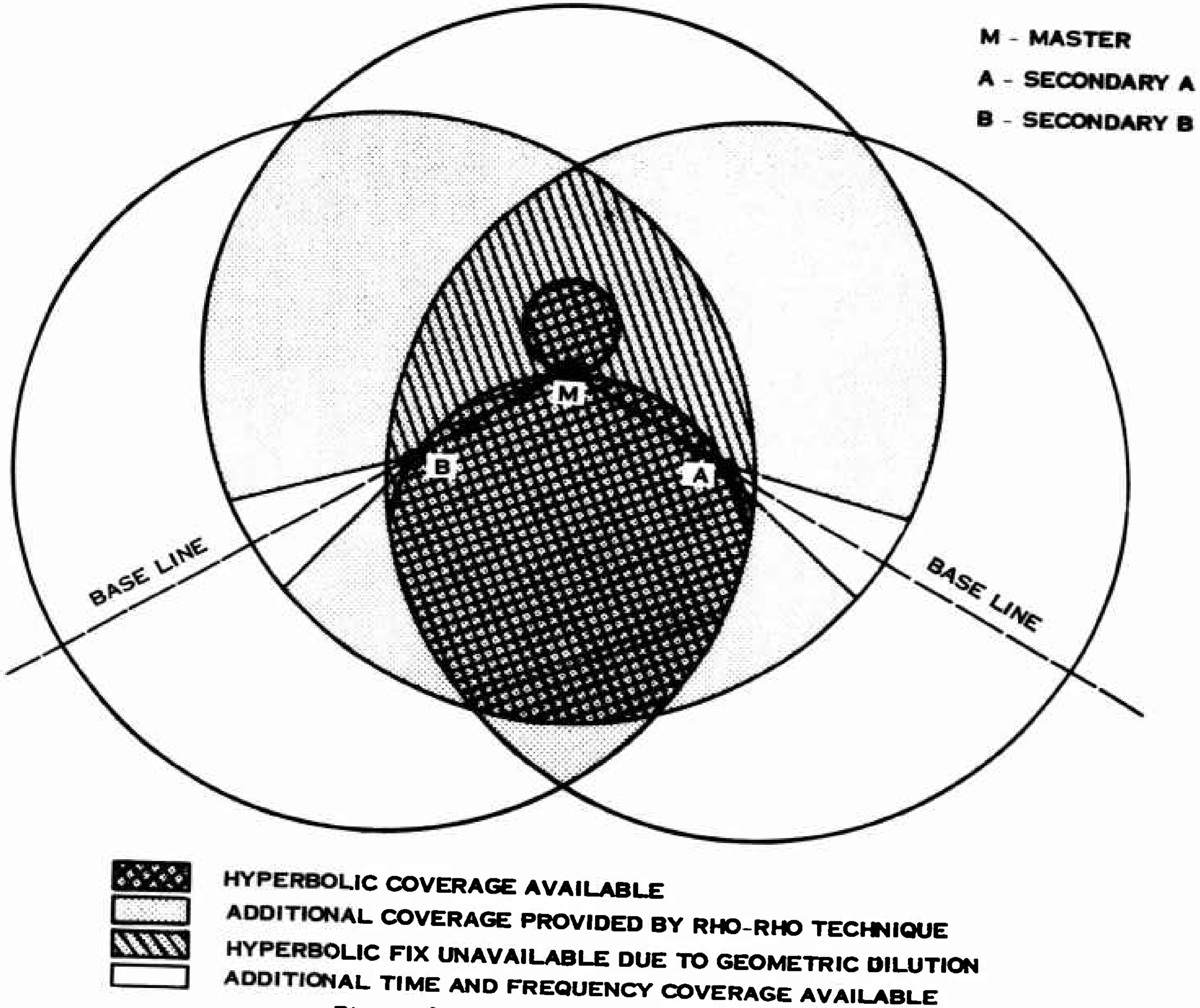

Figure 2. LORAN-C COVERAGES

the Loran-C pulse groups are coincident with the UTS. Null ephemeris tables for any Loran-C rate are available from the USNO upon request. Figure 3 illustrates the timing of the Loran-C pulse groups.

The instrumentation system shown in Figure 4 would be used to recover time information from the Loran-C 1-pps transmissions. This type of instrumentation is used when the user is within range of the master station and in an area where the signal-to-noise conditions are favorable. If the user is fairly close to the master station the band pass filter may not be necessary. The RF information is presented to the oscilloscope vertical amplifier and the oscilloscope is triggered by the user's clock at a 1-hertz rate (1-pps). The oscilloscope trace starts coincident with the user's clock pulse and the Loran-C 1-pps transmission appears later on during the sweep. The elapsed time between the start of the trace and the occurrence of the Loran-C 1-pps will be the sum of: the propagation delay from the Loran-C transmitting antenna to the user's site, any receiving equipment delay, the Loran-C phase value for that day, and the user's clock error. Since the first three factors may be ascertained readily, the remaining factor provides the user with his clock error.

To utilize all eight pulses within the Loran-C pulse groups, a little more equipment is required as shown in Figure 5. In this case, a counter is triggered by pulse occurring at the Loran rate and synchronized to the USNO null ephemeris tables. The stop triggers to the counter also occur at the Loran rate and are phase locked to the received Loran-C signals. The time interval counter displays the sum of: the propagation delay from the Loran-C transmitting antenna to the user's site, the receiving system delays, the Loran-C phase value for that day, and the user's clock error. If the signals from a secondary station are being received and tracked, the reading also includes the emission delay of the secondary station (published constant delay). Thus, the user's clock error is readily determined.

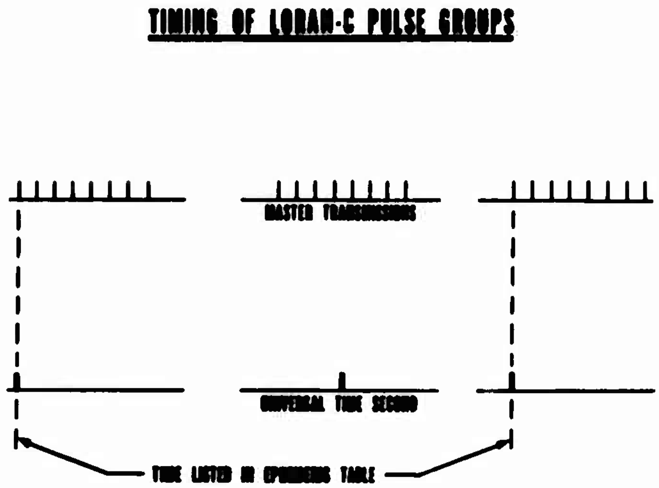

Figure 3. TIMING OF LORAN-C PULSE GROUPS

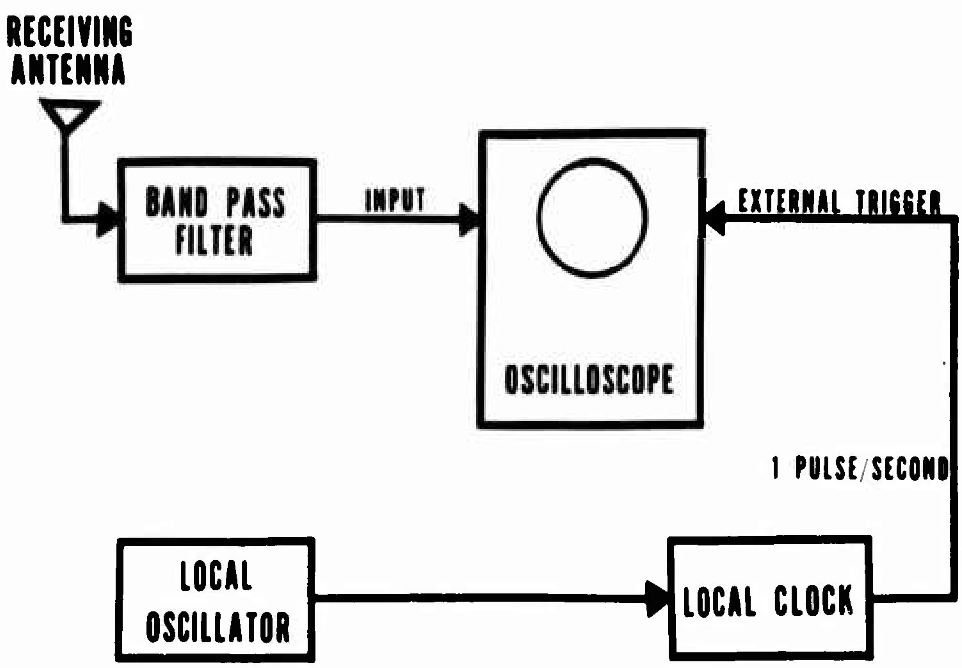

Figure 4. INSTRUMENTATION FOR ONE PULSE/SECOND SYSTEM

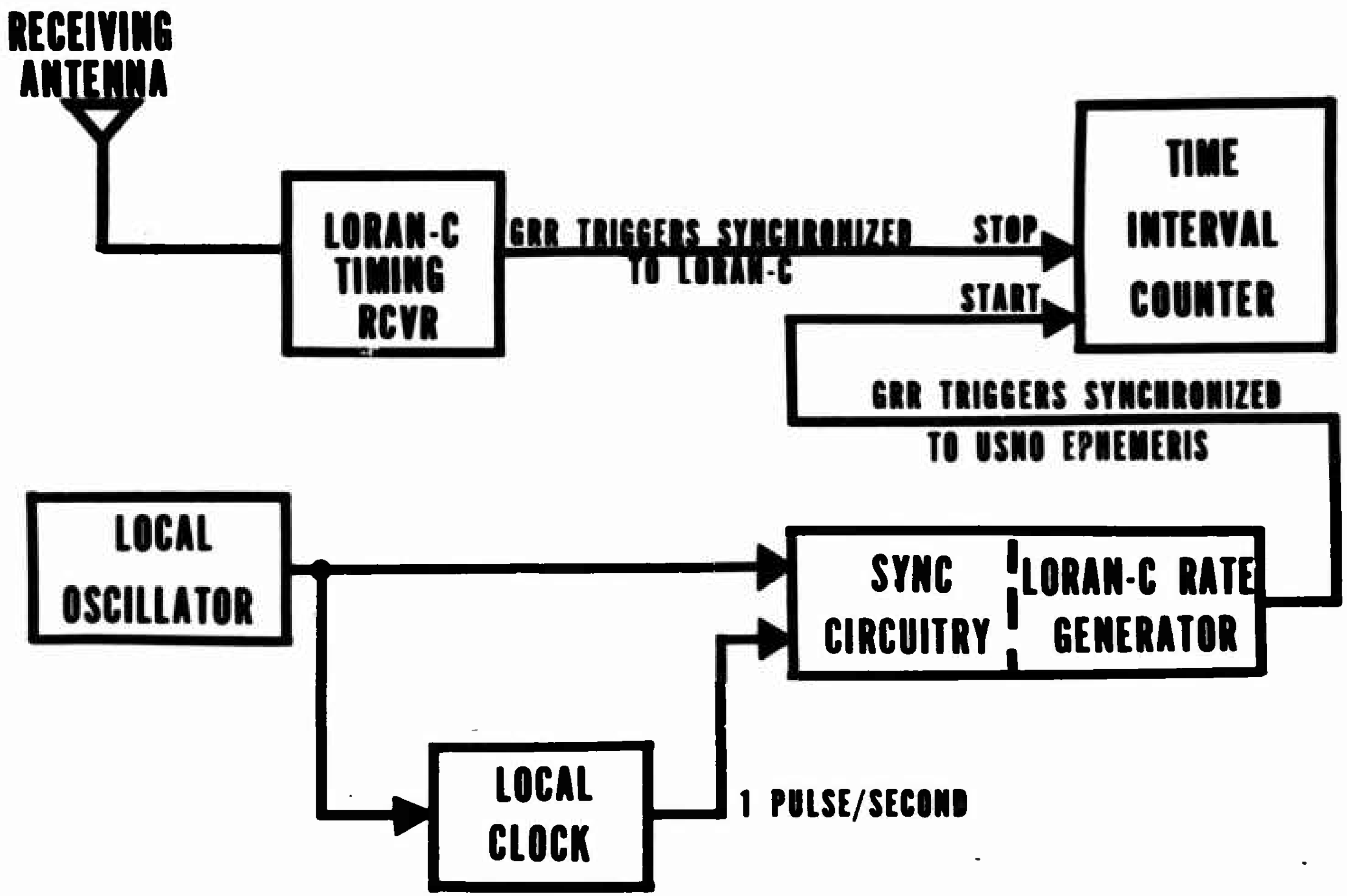

Figure 5. INSTRUMENTATION FOR UTILIZATION OF LORAN-C PULSE GROUPS

The daily Loran-C phase values are published by the USNO and indicate the time relationship between the individual Loran-C chain transmissions and the USNO master clock (UTC(USNO)). A plot of these published (USNO Daily Relative Phase Values, Series 4) values provides a user with valuable historical information on the frequency offset of the Loran-C chain with respect to UTC(USNO), and the time relationship 'UTC(USNO) - Loran-C Chain' (daily phase value) which he needs for calculating his own clock error. Table I shows the results of an analysis of the published daily phase values for six of the Loran-C chains. Periods were chosen which were free of adjustments or malfunctions and linear regressions were performed on the data. The mean value and the slope were removed, then the standard deviation and the frequency offset of the chain with respect to UTC(USNO) were calculated. The results of the standard deviation calculation are illustrated in Figure 6 where the standard deviation is plotted versus the number of days contained in each sample period. The results indicate that the expected value is 0.28 microseconds. The significance to the user is that he knows (if he has a little data history on the Loran-C chain he is using) that the expected value for a particular day's measurement is within 280 nanoseconds of the previous day's value, or of any previous value projected into the future using the calculated Loran-C chain frequency offset.

The results of the data analysis with respect to the Loran-C frequency offset are illustrated in Figure 7. The mean value for all the sample periods was 6.1×10^{-14} and the standard deviation was 5.9×10^{-13}. Note that in only three cases did the frequency offset exceed 1×10^{-12}. The significance to the user is that he can compare his frequency standard to the received Loran-C carrier phase and be assured that the Loran-C 100-kilohertz frequency is within 1×10^{-12} of UTC(USNO). If the user compiles a little data history he can compute the frequency offset of his standard

Table I. RESULTS OF ANALYSIS OF PUBLISHED LORAN-C DAILY RELATIVE PHASE VALUES

CHAIN	PERIOD	NO. OF DAYS	$\sigma(\mu s)$	$\Delta f/f (x10^{-13})$ USNO - LORAN-C	R*
U. S. EAST COAST	FEB 1 - JUN 30, 1968	151	0.28	-0.02	0
	JUL 1, 1968 - JAN 15, 1969	199	0.45	3.6	.97
	JAN 16 - MAR 30, 1969	74	0.18	-0.6	0
	MAR 31 - AUG 25, 1969	148	0.38	-3.6	.96
	AUG 26 - NOV 1, 1969	68	0.19	5.7	.98
	NOV 2 - DEC 12, 1969	41	0.11	-7.4	.99
	DEC 13, 1969 - FEB 12, 1970	62	0.28	1.3	0
	FEB 13 - JUL 7, 1970	145	0.40	5.2	.98
	AUG 8 - SEP 17, 1970	41	0.08	-11.6	1.00
	SEP 18 - DEC 31, 1970	105	0.12	1.0	0
	JAN 1 - FEB 28, 1971	59	0.21	5.3	.97
	MAR 1 - JUN 7, 1971	99	0.13	-3.8	.99
	JUN 11 - AUG 20, 1971	71	0.15	-6.7	.99
NORTH ATLANTIC	JAN 1 - JUN 30, 1970	181	0.40	3.4	.96
	JUL 1 - NOV 18, 1970	140	0.30	0.05	0
	NOV 19, 1970 - SEP 1, 1971	287	0.25	4.5	.99
NORWEGIAN SEA	OCT 15, 1968 - MAR 30, 1969	167	0.49	-3.1	.94
	MAR 31 - NOV 14, 1969	229	0.43	-3.4	.98
	NOV 15, 1969 - JAN 20, 1970	67	0.29	7.0	.97
	JAN 21 - APR 12, 1970	82	0.27	8.9	.99
	APR 13 - JUL 30, 1970	109	0.35	-4.4	.96
	JUL 31 - DEC 31, 1970	154	0.30	-7.6	.99
	JAN 1 - FEB 28, 1971	59	0.25	-1.8	0
	MAR 1 - MAY 31, 1971	92	0.21	-4.4	.98
	JUN 1 - JUL 5, 1971	35	0.21	-7.5	.96
	JUL 6 - SEP 1, 1971	58	0.27	-0.07	0
MEDITERRANEAN SEA	NOV 1, 1969 - FEB 12, 1970	104	0.40	0.3	0
	FEB 12 - JUN 16, 1970	125	0.33	2.8	.92
	JUN 24 - OCT 3, 1970	102	0.39	5.1	.96
	OCT 4 - DEC 25, 1970	74	0.27	-5.2	.96
	DEC 28, 1970 - FEB 28, 1971	63	0.23	-1.5	0
	MAR 1 - MAY 11, 1971	72	0.22	-6.6	.98
	MAY 12 - AUG 30, 1971	111	0.33	-0.6	0
CENTRAL PACIFIC	FEB 11 - MAR 31, 1970	49	0.17	1.8	0
	APR 13 - MAY 26, 1970	44	0.30	7.3	.94
	MAY 27 - JUL 19, 1970	54	0.15	-1.9	0
	JUL 20 - OCT 30, 1970	103	0.25	6.1	.99
	OCT 31 - NOV 30, 1970	31	0.15	14.8	.99
	DEC 8, 1970 - MAR 19, 1971	102	0.21	5.9	.99
	MAR 23 - JUN 22, 1971	92	0.45	6.9	.98
	JUN 23 - AUG 12, 1971	51	0.14	4.1	.97
NORTHWEST PACIFIC	MAY 1 - JUN 15, 1971	46	0.11	-7.1	.99
	JUN 16 - SEP 2, 1971	79	0.17	12.2	.99

*R IS THE LINEAR REGRESSION CORRELATION COEFFICIENT. COMPUTER PROGRAM FAILURE TO YIELD THE CORRECT VALUE DUE TO THE VERY SMALL SLOPE INVOLVED IS SIGNIFIED BY 0. R=1 INDICATES A PERFECT FIT OF DATA POINTS TO THE LINEAR EXPRESSION.

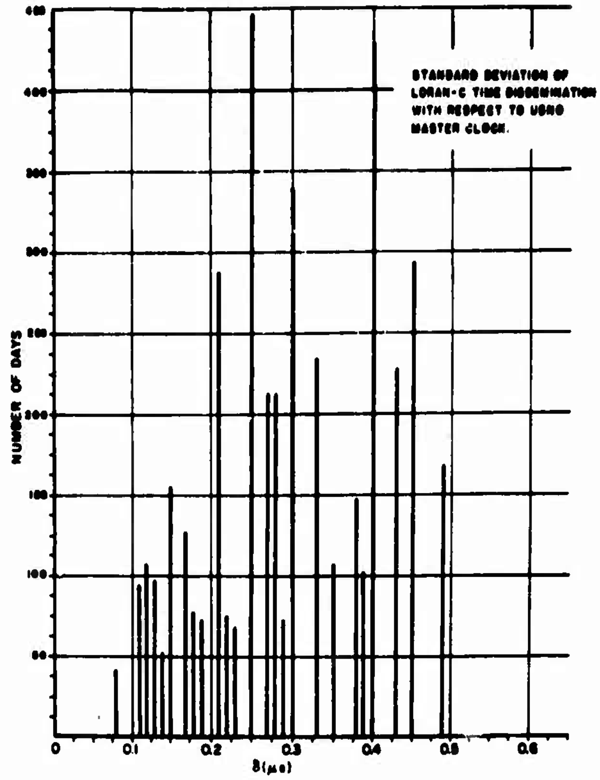

Figure 6. STANDARD DEVIATION OF LORAN-C TIME DISSEMINATION WITH RESPECT TO USNO MASTER CLOCK

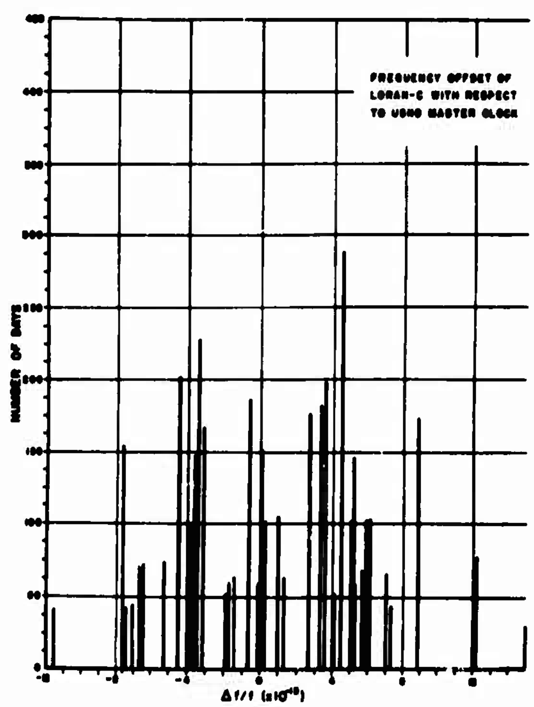

Figure 7. FREQUENCY OFFSET OF LORAN-C WITH RESPECT TO USNO MASTER CLOCK

with respect to UTC(USNO) to within a few parts in 10^{13} using the Loran-C system as a transfer medium. At the present time, all of the Loran-C stations are equipped with two or more cesium standards.

Two types of adjustments are made to the Loran-C transimssions to maintain certain tolerances with respect to the USNO master clock. By agreement between the Department of Defense and the Department of Transportation, the U. S. Coast Guard is acting as an agent of the U. S. Naval Observatory for the dissemination of precise time and time interval via the Loran-C system. Currently, the tolerance on time dissemination is ± 15 microseconds, and there is no tolerance on time interval (frequency) dissemination. Although the time tolerance is ± 15 microseconds, an attempt is made to keep the Loran-C chains within ± 5 microseconds of UTC(USNO), other operational commitments not withstanding. Figure 8 illustrates one type of adjustment made to the transmissions. In this case the plot of daily phase values shows the particular Loran-C chain transmitting early with respect to the USNO master clock. The frequency of the Loran-C chain is higher than the USNO master clock as evidenced by the fact that the chain is transmitting earlier each succeeding day. Near the middle of the plot the chain is seen approaching the -5 microsecond tolerance and a step retardation of the phase is introduced (noted as N microseconds) to place the transmissions near the other extreme of the tolerance. N, of course, may be any value, but is typically an integer, 10 or less. This step in phase is always announced in advance by the Naval Observatory in the Series 4 Bulletins. Note that after a time step the chain frequency remains as it was before the step.

Figure 9 illustrates the second type of adjustment made to the transmissions. In this case the frequency is adjusted to maintain the time tolerance. The adjustment is accomplished by adjusting the C field of the on-air cesium standard at the Loran-C master station. The smallest adjustment that can be made at present is approximately 5×10^{-13}, and

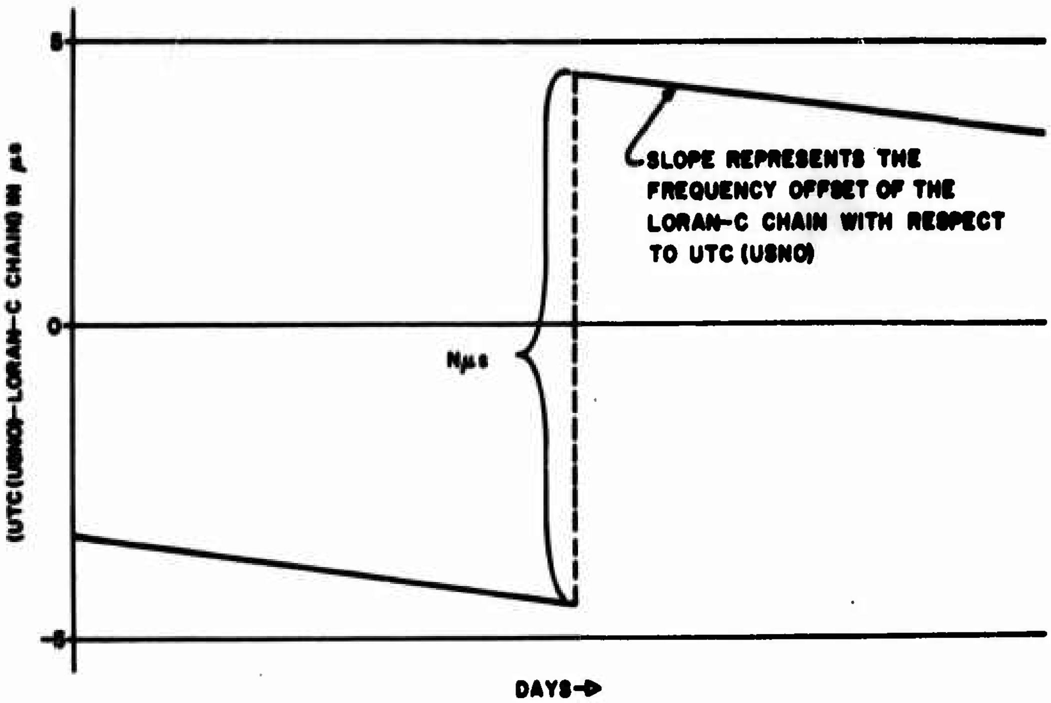

Figure 8. LORAN-C SYSTEM TIME ADJUSTMENT (Present)

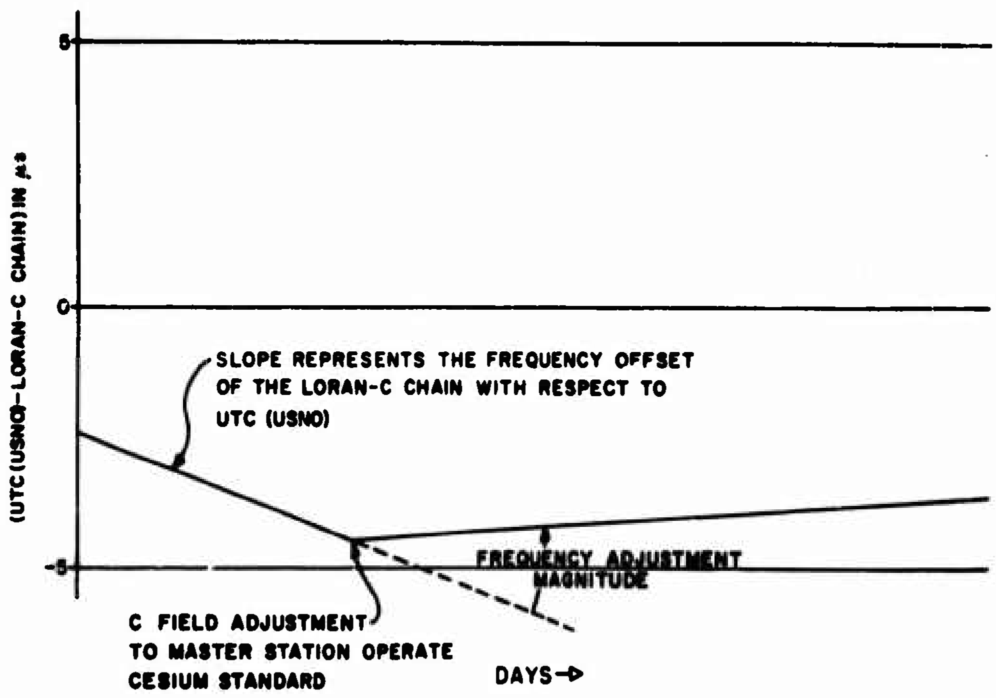

Figure 9. LORAN-C SYSTEM FREQUENCY ADJUSTMENT (Present)

with respect to UTC(USNO) to within a few parts in 10^{13} using the Loran-C system as a transfer medium. At the present time, all of the Loran-C stations are equipped with two or more cesium standards.

Two types of adjustments are made to the Loran-C transimssions to maintain certain tolerances with respect to the USNO master clock. By agreement between the Department of Defense and the Department of Transportation, the U. S. Coast Guard is acting as an agent of the U. S. Naval Observatory for the dissemination of precise time and time interval via the Loran-C system. Currently, the tolerance on time dissemination is $\pm$ 15 microseconds, and there is no tolerance on time interval (frequency) dissemination. Although the time tolerance is $\pm$ 15 microseconds, an attempt is made to keep the Loran-C chains within $\pm$ 5 microseconds of UTC(USNO), other operational commitments not withstanding. Figure 8 illustrates one type of adjustment made to the transmissions. In this case the plot of daily phase values shows the particular Loran-C chain transmitting early with respect to the USNO master clock. The frequency of the Loran-C chain is higher than the USNO master clock as evidenced by the fact that the chain is transmitting earlier each succeeding day. Near the middle of the plot the chain is seen approaching the -5 microsecond tolerance and a step retardation of the phase is introduced (noted as N microseconds) to place the transmissions near the other extreme of the tolerance. N, of course, may be any value, but is typically an integer, 10 or less. This step in phase is always announced in advance by the Naval Observatory in the Series 4 Bulletins. Note that after a time step the chain frequency remains as it was before the step.

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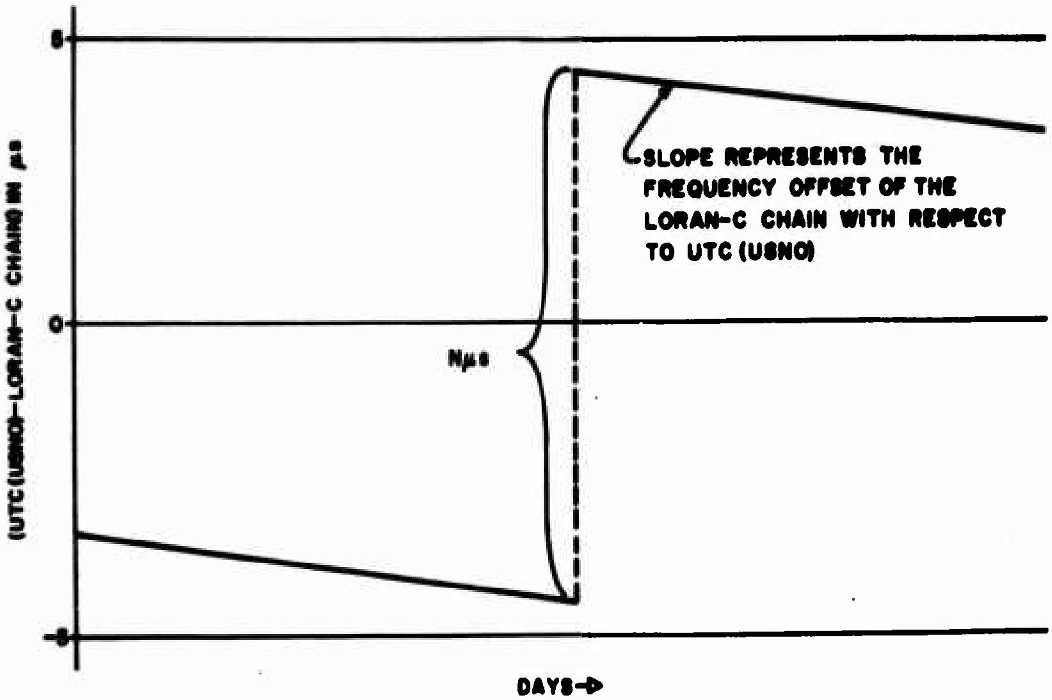


Figure 8. LORAN-C SYSTEM TIME ADJUSTMENT (Present)

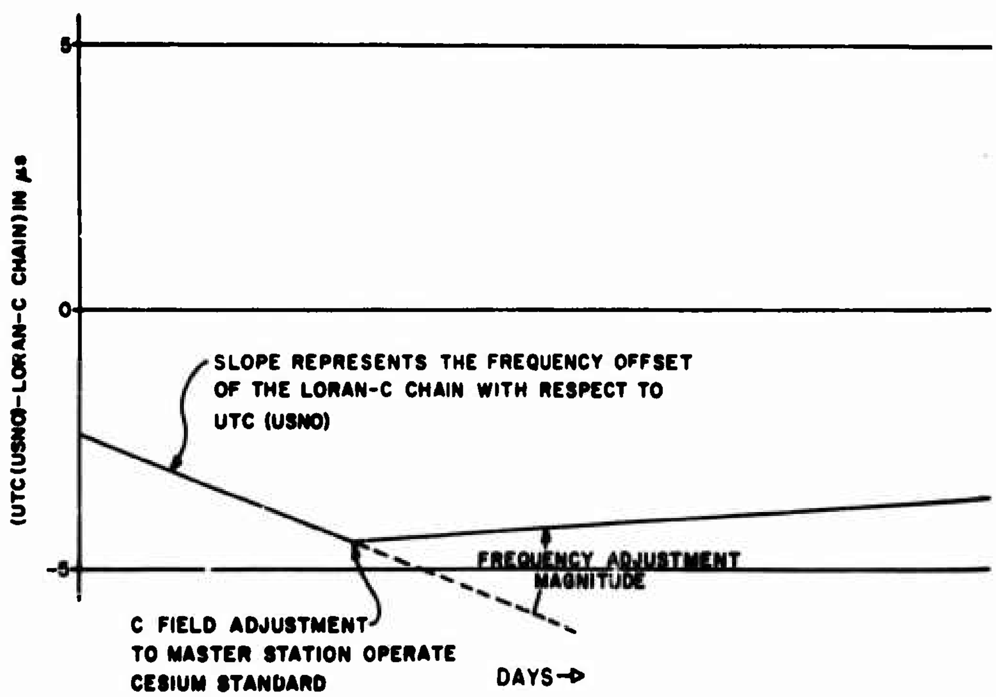
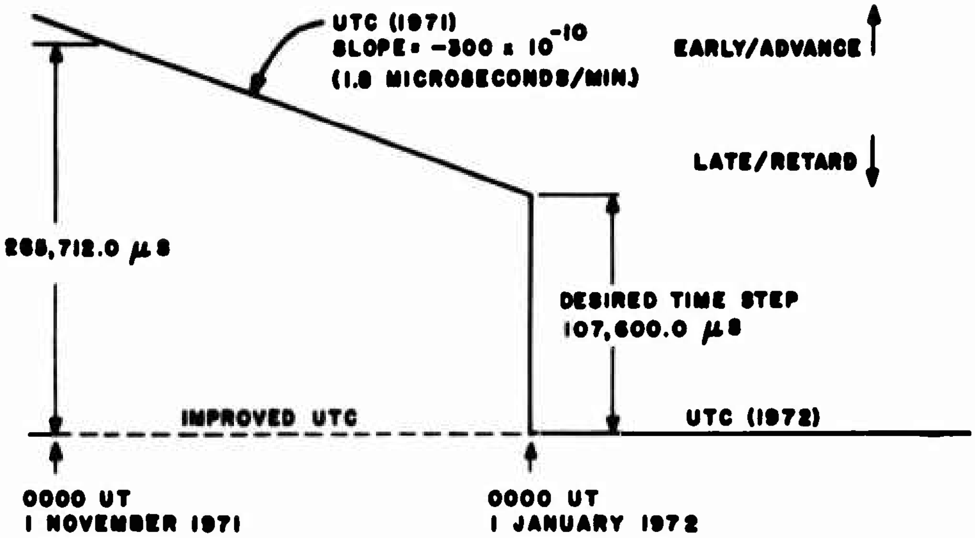
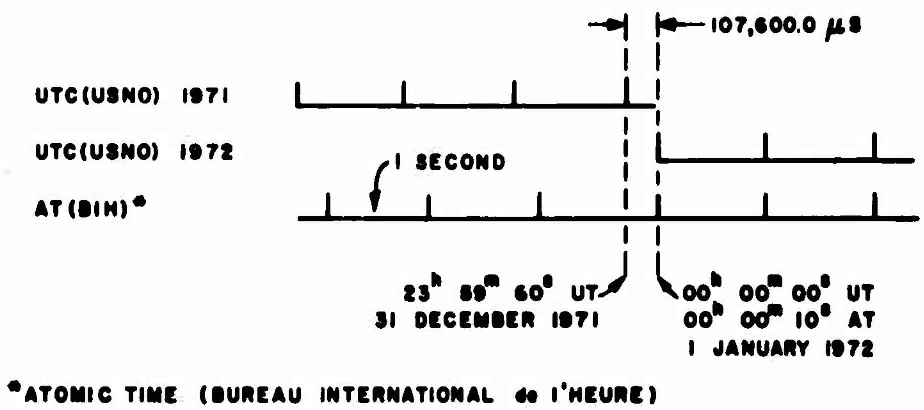


Figure 9. LORAN-C SYSTEM FREQUENCY ADJUSTMENT (Present)



UTC vs IMPROVED UTC TIME SCALE RELATIONSHIP



RELATIONSHIP BETWEEN UTC, IMPROVED UTC AND AT.

Figure 10. RELATIONSHIP BETWEEN UTC, IMPROVED UTC AND AT

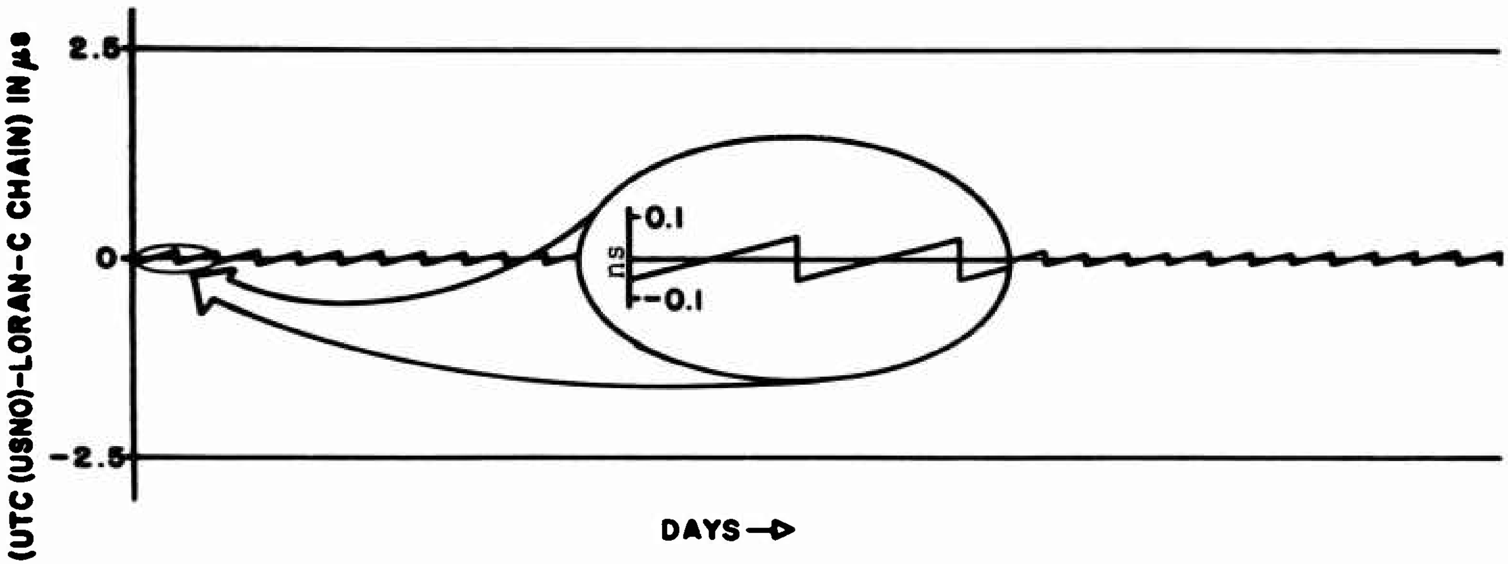


Figure 11. LORAN-C SYSTEM TIME AND FREQUENCY ADJUSTMENT (FUTURE)

multiples thereof. Loran-C chain frequency corrections are typically 5×10^{-13} or 1×10^{-12}, seldom greater.

Since 1966 the UTC scale has been offset -300×10^{-10} in frequency with respect to atomic or ephemeris time. On 1 January 1972 that offset will be removed and a retardation of 107,600 microseconds will be made to the time scale. In essence the old UTC scale is ended on 31 December 1971 at 23 hours, 59 minutes and 60.1076 seconds and a new scale is started. This is depicted in Figure 10. The new scale is started such that the start coincides with the AT(BIH) scale at the moment when the AT(BIH) scale is 00 hours, 00 minutes, and 10 seconds. At this particular instant the Loran-C chains will all change frequency by removing the 300×10^{-10} offset from the cesium standards and at the same time they will introduce a time retardation of 107,600 microseconds. To a user the step will appear to be different for each Loran-C chain. This is because the Loran GRI is less than the time step. For example, consider the case of the East Coast chain which has a GRI of 99,300 microseconds. When the time step is effected, the pulse groups will appear to have moved the difference between 107,600 and 99,300 microseconds (8,300 microseconds) and to have undergone a phase code reversal. (Alternate pulse groups are phase coded differently to reduce the effects of skywave contamination.)

In the future, time and frequency adjustments will be effected in a different manner. Both will be effected by introducing very small phase steps (on the order of 0.5 nanoseconds) periodically to compensate for the slight frequency offset of the on-air cesium standard with respect to the USNO master clock. This also ensures that the time tolerance will not be exceeded, as illustrated in Figure 11.

Synchronization of all the Loran-C chains to UTC has been approved by DOD for fiscal 1973. When the synchronization has been accomplished the new time tolerance will be $\pm$ 2.5 microseconds with respect to UTC(USNO). This will enable most users to employ the system without the need for knowing the daily phase value.

DISCUSSION

LCDR SEELY: What does the 2-1/2 microsecond figure represent? How was that established? You said it was DOD-established.

LCDR POTTS: I suspect that was a very conservative figure arrived at and agreed upon by both Coast Guard and DOD representatives. Dr. Winkler may have some specific comment.

DR. WINKLER: The reason for five microseconds tolerance is actually an Air Force requirement to provide time to within five microseconds. That figure has been in existence for several years and was provided by issuing corrections to the Loran-C actual reception. It is the intent of these new procedures to assure that you pick up time in real time without having to resort to correction tables. This represents a control problem. I believe part of your question was answered in one of the slides of Dr. Kershner, where you saw two cesium standards beating against each other. The principle was exactly the same as that which will be applied in Loran-C, and the tolerance within which you can keep is determined by the statistics or the average behavior of the frequency standards in use. If you deal with cesiums and you can measure or issue a control command once a day, the frequency variations are going to be in the order of 2 parts or 3 parts in 10^{13}; that is, about 40-50 nanoseconds which is a 1-rms figure. With improved cesium standards you could keep it smaller but is that really necessary? As LCDR Potts said, what the Coast Guard and Observatory are trying to do is to keep all of these chains on time as well as we can and as economically as we can. But since each correction requires at least one message to go to several addressees, we do not want to do that more frequently or more accurately than our users require. At the present time, as LCDR Potts has said, we will try to keep within 2.5 microseconds of the Observatory master clock in all of the synchronized chains; that is, the North Atlantic chain, the Norwegian Sea chain, the Northwest Pacific chain, the Central Pacific chain, and the East Coast chain. If increased precision becomes necessary it could be provided; it simply would mean that we would have to send more messages more frequently. In order to justify that, we must know what the requirements are. Please tell us.

LCDR POTTS: Maintaining the chain very close to UTC and frequency has a benefit for range-range navigation mode users as well. They do not particularly desire to have frequency changes in the new system; they would not really see a frequency change. They would just see a system which maintained itself coherent with the universal coordinated time scale.

OMEGA TIME TRANSMISSIONS AND RECEIVING REQUIREMENTS

A. R. Chi, L. A. Fletcher, and C. J. Casselman

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A. R. Chi, L. A. Fletcher, and C. J. Casselman

Mr. Chi is with the Goddard Space Flight Center of the National Aeronautics and Space Administration, Greenbelt, Maryland 20771.
Mr. Fletcher is with the OMEGA Project Office, PME-119, Naval Electronics Systems Command, Arlington, Virginia 20360.
Mr. Casselman is with the Naval Electronics Laboratory Center, San Diego, California 92152.

1.0 INTRODUCTION

The possibility of using VLF signals for time transmissions became evident when the received signal phase was found extremely stable over long distances. Morgan and Baltzer, Fey and Looney, and Chi and Witt were among the first to pioneer (in the early 1960's) the use of a dual-frequency technique to transmit time on VLF carriers.

In 1965, National Bureau of Standards (NBS) (with NASA/GSFC's support) had completed the modification of an experimental transmitter, WWVL, to transmit at 10-second alternations, the dual VLF carriers at 20.0 and 20.5 kilohertz. The radiated power was relatively low, approximately 2 kilowatts. To reduce the frequency dispersion effect, the frequency separation was soon changed to 100 hertz at 19.9 and 10.0 kilohertz.

Between December 1966 and June 1968, NASA (with the cooperation of NBS and RMS Engineering, Inc., and others) conducted several field tests of time reception of WWVL transmissions, in its Space Tracking and Data-Acquisition Network (STADAN). Portable crystal clocks and a cesium frequency standard were used during these trips to measure the propagation delays. Because of the requirements for phase control of the two signals at the transmitter and the phase stability of the receivers, it was soon found that the cycle number identified at each receiving station varied between ± 2 cycles, and could vary by as many as five cycles in some remote sites. In the early 1960's, OMEGA stations at Hawaii and Forestport, New York, were used to conduct lane-resolution studies using 200-, 500-, 1000-, and 2000-hertz frequency separations. In the late 1960's, the dual-frequency time-transmission technique was tried in the OMEGA station, Forestport, and also in Europe. Results of studies made on these tests convinced the experimenters that the technique was, indeed, sound and feasible for implementation, if the instrumentation phase errors at the transmitters and in the receiver design is reduced sufficiently to allow positive cycle identification, leaving only propagation error predominant.

2.0 THEORY OF DUAL-FREQUENCY TIME TRANSMISSION

Let t_0 be the time of the emitted signals at the transmitter for F_1 and F_2 and t_r be the received time of the signals relative to a clock at a receiving site. Then

$$t_r - t_0 = T_p + \Delta t_c \tag{1a}$$

$$= t_p + \Delta t_p + \Delta t_c \tag{1b}$$

$$= t_p + \Delta t \tag{1c}$$

where

T_p = total propagation delay

t_p = calculable propagation delay at a given time

Δt_p = propagation delay anomaly

Δt_c = clock difference

Δt = $\Delta t_p + \Delta t_c$

Equation (1a) can also be written

$$T_p + \Delta t_c = n\tau_a + \left(n_1 + \frac{\Delta\phi_1}{2\pi}\right)\tau_1 \qquad (2a)$$

$$= n\tau_a + \left(n_2 + \frac{\Delta\phi_2}{2\pi}\right)\tau_2 \qquad (2b)$$

where n, n_1, and n_2 are integers

$$\tau_a = k\tau_b = \frac{k}{\Delta F}, \text{ k being an integer}$$

$$\tau_b = \frac{1}{\Delta F} = \frac{\tau_1\tau_2}{\tau_2 - \tau_1}$$

$$\Delta F = F_1 - F_2$$

$$\tau_1 = \frac{1}{F_1}$$

$$\tau_2 = \frac{1}{F_2}$$

$\Delta\phi_1$ = phase difference of F_1 relative to a local clock

$\Delta\phi_2$ = phase difference of F_2 relative to the same local clock

From Equations (2a and (2b), one gets

$$\frac{n_1 + \frac{\Delta\phi_1}{2\pi}}{n_2 + \frac{\Delta\phi_2}{2\pi}} = \frac{\tau_2}{\tau_1}$$

Subtracting 1 from both sides of the equation and multiplying by $\frac{1}{\tau_2}$, one gets

$$\frac{n_1 - n_2 + \frac{\Delta\phi_{12}}{2\pi}}{\left(n_2 + \frac{\Delta\phi_2}{2\pi}\right)\tau_2} = \frac{\tau_2 - \tau_1}{\tau_1 \tau_2} = \frac{1}{\tau_b} = \frac{k}{\tau_a} \quad (3)$$

where $\Delta\phi_{12} = \Delta\phi_1 - \Delta\phi_2$

Substituting Equation (3) into Equation (2b),

$$T_p + \Delta t_c = \left\{n + \frac{1}{k}\left[(n_1 - n_2) + \frac{\Delta\phi_{12}}{2\pi}\right]\right\}\tau_a \quad (4a)$$

$$= \left\{nk + \left[(n_1 - n_2) + \frac{\Delta\phi_{12}}{2\pi}\right]\right\}\tau_b \quad (4b)$$

Rearranging Equation (4b), one gets

$$T_p + \Delta t_c - n\tau_a = \frac{n_1 - n_2 + \frac{\Delta\phi_{12}}{2\pi}}{\Delta F} \quad (4c)$$

From Equation (4c), one can see that T_p and Δt_c are directly related to $\Delta\phi_{12}$ and inversely related to ΔF.

3.0 CYCLE IDENTIFICATION

Time is recovered from the identification of a particular cycle of a carrier signal and the phase difference between the two received carrier signals. Therefore, it is important not only to know the cycle identification but also $\Delta\phi_{12}$ relation as a function of time.

The cycle identification is achieved with the knowledge of the propagation path delay, T_p. This propagation delay can also be measured directly through the use of a portable clock.

Using Equations (1), (2), and (4), one gets

$$n_1 = \frac{1}{\tau_1}(t_p - n\tau_a) + \left(\frac{\Delta t}{\tau_1} - \frac{\Delta\phi_1}{2\pi}\right) \tag{5a}$$

$$n_2 = \frac{1}{\tau_2}(t_p - n\tau_a) + \left(\frac{\Delta t}{\tau_2} - \frac{\Delta\phi_2}{2\pi}\right) \tag{5b}$$

$$n_1 - n_2 = k\left[\frac{1}{\tau_a}(t_p - n\tau_a) + \left(\frac{\Delta t}{\tau_a} - \frac{\Delta\phi_{12}}{2\pi k}\right)\right] \tag{5c}$$

$$= \frac{1}{\tau_b}(t_p - nk\tau_b) + \left(\frac{\Delta t}{\tau_b} - \frac{\Delta\phi_{12}}{2\pi}\right) \tag{5d}$$

The first terms in the right-hand side of Equations (5) are constants and the second terms are time-dependent due to such factors as the instability of the propagation medium and the clocks.

Neither n_1 nor n_2 can be determined independently by Equations (5a) and (5b) since $\Delta\phi_1$ and $\Delta\phi_2$ are time-dependent especially during sunrise and sunset hours and are also affected by the propagation disturbances. Additionally, the propagation time-delay anomaly, Δt_p, is not known and cannot be easily determined. For this reason, Equation (5c) or (5d) is used. In these equations, the relative phase difference of the two VLF signals at a receiving site is used in part to reduce the propagation effect on the signal phase of each received signal and to determine n_1 or n_2, based on some a priori knowledge of $n_1 - n_2$,* especially if an estimate of the propagation delay time can be made.

4.0 AMBIGUITY RESOLUTION

Because of the sinusoidal nature of the time-transmission technique used in the dual VLF transmissions, some ambiguous periods cannot be resolved without additional transmission of coarse time or the use of other techniques to resolve the ambiguity time. For clarity, we define the beat period, τ_b, as $1/\Delta F$, i.e., the time at which the phase of the two signals at F_1 and F_2 are coincident. Then $\Delta F = F_1 - F_2$ is the beat frequency. The ambiguity period, τ_a, is defined as the time at which the phase of the two signals are not only coincident but also occurs at the positive-going zero-crossing of the sinusoidal signals as shown in Figure 1.

Let

$$\tau_a = k_1 \tau_1 = k_2 \tau_2 = k \tau_b = \frac{1}{Q} \tag{6a}$$

where k_1 is the integer number of cycles of F_1 in τ_a, k_2 is the integer number of cycles of F_2 in τ_a, k is the integer number of cycles of ΔF in τ_a, and Q, i.e.,

$$Q = \frac{F_1}{k_1} = \frac{F_2}{k_2} = \frac{\Delta F}{k} \tag{6b}$$

is the largest common divisor of F_1 and F_2.

---

* From Table 2, $n_1 - n_2 = 0, 1, 2 \ldots k_1 - k_2$.

signals. Therefore, it is important not only to know the cycle identification but also $\Delta\phi_{12}$ relation as a function of time.

The cycle identification is achieved with the knowledge of the propagation path delay, T_p. This propagation delay can also be measured directly through the use of a portable clock.

Using Equations (1), (2), and (4), one gets

$$n_1 = \frac{1}{\tau_1}(t_p - n\tau_a) + \left(\frac{\Delta t}{\tau_1} - \frac{\Delta\phi_1}{2\pi}\right) \tag{5a}$$

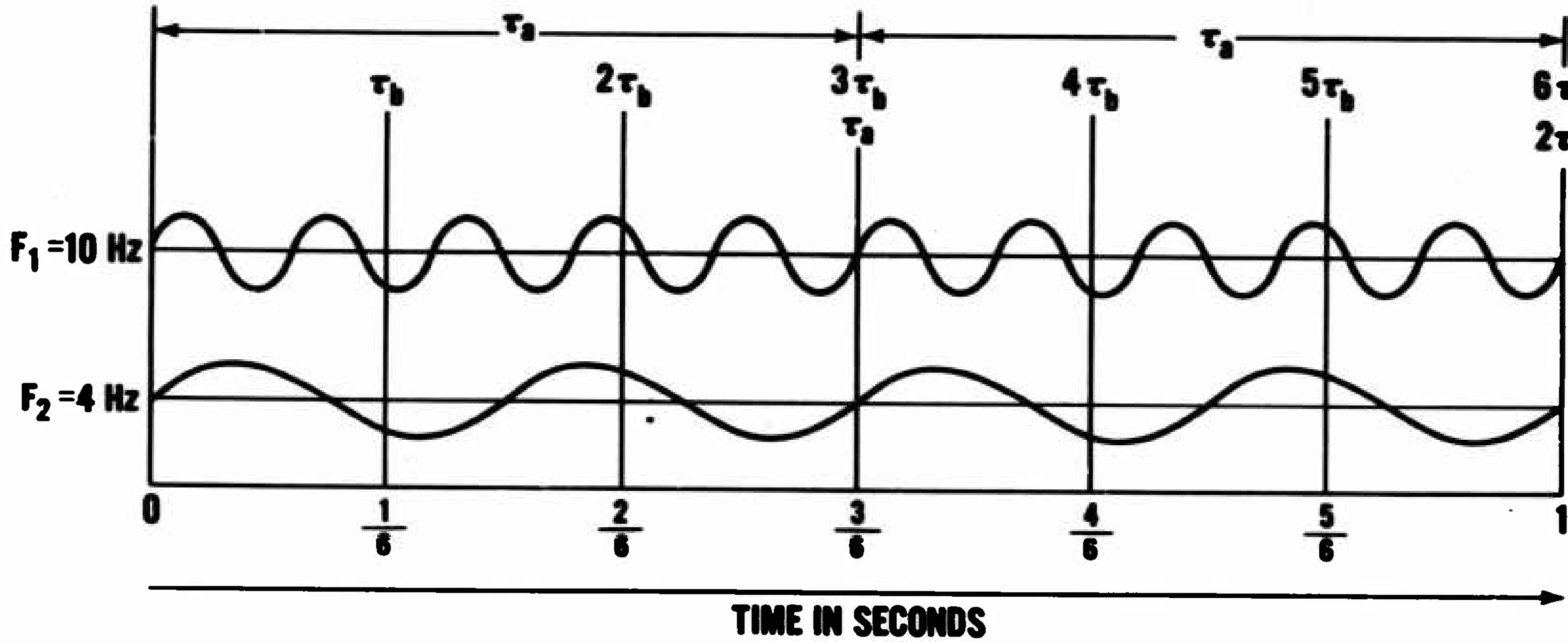
$$n_2 = \frac{1}{\tau_2}(t_p - n\tau_a) + \left(\frac{\Delta t}{\tau_2} - \frac{\Delta\phi_2}{2\pi}\right) \tag{5b}$$

$$n_1 - n_2 = k\left[\frac{1}{\tau_a}(t_p - n\tau_a) + \left(\frac{\Delta t}{\tau_a} - \frac{\Delta\phi_{12}}{2\pi k}\right)\right] \tag{5c}$$

$$= \frac{1}{\tau_b}(t_p - nk\tau_b) + \left(\frac{\Delta t}{\tau_b} - \frac{\Delta\phi_{12}}{2\pi}\right) \tag{5d}$$

The first terms in the right-hand side of Equations (5) are constants and the second terms are time-dependent due to such factors as the instability of the propagation medium and the clocks.

Neither n_1 nor n_2 can be determined independently by Equations (5a) and (5b) since $\Delta\phi_1$ and $\Delta\phi_2$ are time-dependent especially during sunrise and sunset hours and are also affected by the propagation disturbances. Additionally, the propagation time-delay anomaly, Δt_p, is not known and cannot be easily determined. For this reason, Equation (5c) or (5d) is used. In these equations, the relative phase difference of the two VLF signals at a receiving site is used in part to reduce the propagation effect on the signal phase of each received signal and to determine n_1 or n_2, based on



$F_1 = 10$ Hz

$F_2 = 4$ Hz

$Q = \frac{F_1}{k_1} = \frac{F_2}{k_2} = 2$

$k_1 = \frac{F_1}{Q} = 5$

$k_2 = \frac{F_2}{Q} = 2$

$k = k_1 - k_2 = 3$

$\tau_b = \frac{1}{\Delta F} = \frac{1}{6}$ sec

$\tau_a = k\,\tau_b = \frac{3}{6}$ sec

Figure 1. Ambiguity Period and Beat Period for Cycle Identification in Dual VLF Time Transmissions

Since

$$\frac{k_1}{k_2} = \frac{\tau_2}{\tau_1}$$

$$\left(\frac{k_1 - k_2}{k_2}\right)\frac{1}{\tau_2} = \left(\frac{\tau_2 - \tau_1}{\tau_1}\right)\frac{1}{\tau_2} = \frac{1}{\tau_b}$$

$$\therefore$$

$$k_2 \tau_2 = (k_1 - k_2)\,\tau_b = k\,\tau_b \qquad (6c)$$

Therefore

$$k = k_1 - k_2 \qquad (7a)$$

and

$$k_1 = \frac{F_1}{Q} \qquad (7b)$$

$$k_2 = \frac{F_2}{Q} \qquad (7c)$$

It should be mentioned here that the value of $(n_1 - n_2)$ in an ambiguity period takes $1, 2, \ldots k$. For a fixed location, $(n_1 - n_2)$ does not change with time if the frequency dispersion effect due to the propagation medium is accounted for or is assumed to be small. This is also one reason for selecting a small frequency separation between the two VLF carriers.

5.0 CYCLE WELLS

This concept was developed, in 1966, for grouping the cycle numbers which cannot be uniquely determined from the dual VLF transmissions. Cycle variation can be observed at a receiving site when the relative phase or differential phase of the two emitted signals at the transmitter cannot be controlled to a constant value or zero; when the phase-difference measurement in a receiver is nonlinear for the dual frequencies due to variations of environmental conditions, signal amplitude, and antenna orientation; and when there are large ionospheric disturbances causing large propagation delay variations (anomalies). When the combined errors are larger than $\frac{1}{2}|\tau_2 - \tau_1|$, the cycle number can be in error by Δn, when is time-dependent.

$$\Delta n = \frac{\Sigma\, \delta\, (\Delta \phi)}{\frac{1}{2}\,|\tau_2 - \tau_1|}$$

where $\Sigma\,\delta(\Delta\phi)$ is the combined phase errors mentioned above.

To account for these variations, the cycle determination from Equations (5) is quantitized into cycle wells with a width (or diameter) equal to the relative phase difference of one cycle of progagation for each signal, i.e., $|\tau_2 - \tau_1|$, and a wall thickness equal to the sum of the propagation delay anomaly and the relative phase control of the two frequencies at the transmitter, as shown in Figure 2.

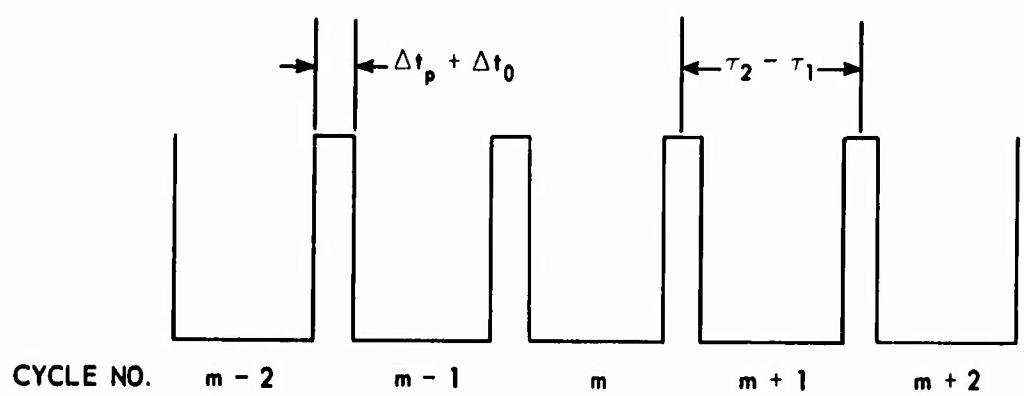


Figure 2. Cycle-Well Concept for Dual VLF Time Determination

6.0 TRANSMISSIONS AND RECEIVING REQUIREMENTS

Early in 1969, the U.S. Naval Observatory established an informal group, known as the OMEGA PTTI Advisory Group, to discuss details of the use of the OMEGA navigation system for the simultaneous dissemination of precise time.

This Group, after careful consideration of all aspects of the problems, made the recommendation which was accepted by the OMEGA project office in 1970. The recommendation was to implement the dual-frequency concept for time transmission in the OMEGA system. The frequency separation of 250 hertz was selected for minimum dispersion effect without placing too stringent phase-control requirements on the transmitters and receivers. The locations of the eight OMEGA stations, which form a global navigation system, are shown in Table 1. The dual frequencies proposed for each OMEGA station and the estimated date for beginning transmission are also given.

Figure 3 shows the 10-second OMEGA transmission sequence for the eight stations, labeled A to H. Three time segments are used for the transmission of navigation frequencies and the remaining five are reserved for time transmission and for transmission of intrasystem control data. The three segments labeled F_1 or F_2 (F_1/F_2) together with the two designated time segments for F_1 and F_2 form a coding format which can be used to transmit information at low rate. The present plan calls for 60 percent of the time to transmit intrasystem control data. The remaining 40 percent is still available for potential users to transmit other data.

Table 2 gives the pertinent data for cycle identification and ambiguity resolution for the OMEGA time-transmission frequencies. The last column in Table 2 gives the value of $\frac{1}{2}|\tau_2 - \tau_1|$. These data are important for cycle determination since an error of one cycle results if the combined errors (in phase control at the transmitter, the propagation delay due to medium, and phase stability and resolution in the receiver) exceed $\frac{1}{2}|\tau_2 - \tau_1|$.

Table 1

OMEGA Station Locations and Proposed Dual Frequencies for Time Transmission and Intrasystem Data Communications

STATION	STATION DESIGNATION	COORDINATES **		FREQUENCIES F_1/F_2* (KHz)	EST. COMPL. DATES
		LATITUDE	LONGITUDE		
HAWAII	C	21°24'20.67"N	157°49'47.75"W	11.55, 11.80	10 NOV 72
TRINIDAD	B	10°42'06.20"N	61°38'20.30"W	12.00, 12.25	73
LA REUNION	E	≈ 16°S	56°E	12.05, 12.30	73
NORWAY	A	66°25'15.00"N	13°9'10.00"E	12.10, 12.35	73
AUSTRALIA	G	SOUTHEASTERN REGION		12.75, 13.00	74
JAPAN (Tsushima Is.)	H	≈ 34°38'N	129°26'E	12.80, 13.05	73
N. DAKOTA	D	46°21'57.20"N	98°20'08.77"W	12.85, 13.10	1 APR 72
ARGENTINA	F	43°03'12.38"S	65°11'28.50"W	12.90, 13.15	73

* F_1 is the frequency, which is an integer multiple of 100 Hz, and F_2 is an integer multiple of 50 Hz.

**Mercury data.

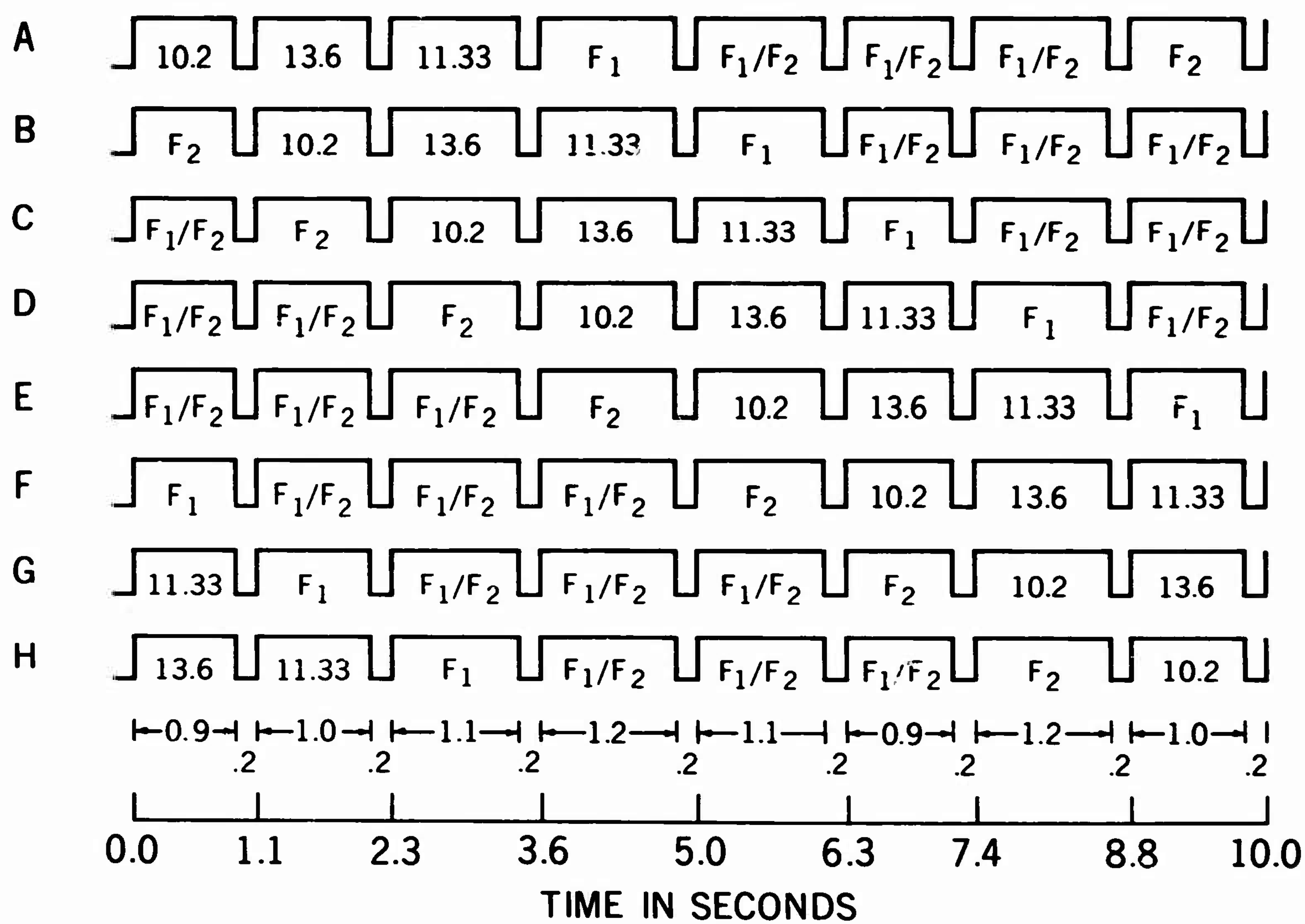


Figure 3. 10-Second OMEGA Transmission Sequence for Stations A Through H

Table 2

Pertinent Data for Cycle Identification and Ambiguity Resolution for the OMEGA Time-Transmission Frequencies

STATION	F_1	F_2	k_1	k_2	k*	τ_a ms	τ_1 (μs)	τ_2 (μs)	$1/2 \lvert \tau_2 - \tau_1 \rvert$ (μs)
A	12.100	12.350	242	247	$\lvert -5 \rvert$	20	82.64	80.97	0.84
B	12.000	12.250	48	49	$\lvert -1 \rvert$	4	83.33	81.63	0.85
C	11.800	11.550	236	231	5	20	84.74	86.58	0.91
D	13.100	12.850	262	257	5	20	76.33	77.82	0.74
E	12.300	12.050	246	241	5	20	81.30	82.98	0.84
F	12.900	13.150	258	263	$\lvert -5 \rvert$	20	77.51	76.04	0.74
G	13.000	12.750	260	255	1	4	76.92	78.43	0.75
H	12.800	13.050	256	261	$\lvert -5 \rvert$	20	78.12	76.62	0.75

*The negative value of $k = k_1 - k_2$ results if $\Delta F = F_1 - F_2 < 0$.

The phase of the dual frequencies for time transmissions relative to a second tick at each of the eight potential OMEGA stations will be held within 0.1 microsecond. The instrumentation phase error of the OMEGA time receiver under normal operating conditions will be less than 0.2 micro second. Using a simple arithmetic sum, the total phase instabilities contributed by the transmitter and the receiver is one-third of the required phase stability, $\frac{1}{2}|\tau_2 - \tau_1|$, for positive cycle identification. If propagation delay anomaly does not exceed two-thirds of the required phase stability, i.e., about 0.5 microsecond, then the cycle identification on a carrier frequency of the OMEGA system can be uniquely determined. The resolution of the received time, under typical conditions, should be the phase stability of a single VLF carrier, i.e., 1 to 2 microseconds. The OMEGA station epoch, as a goal, is to be maintained within $\pm$ 2.5 microseconds relative to the January 1972 UTC scale, i.e., the OMEGA station epoch will not follow the leap second adjustments.

7.0 A PROPOSAL: "TO TEST THE CAPABILITY OF THE OMEGA TIME-TRANSMISSION SYSTEM"

The Naval Electronics Laboratory Center, under NASA support, is currently developing an OMEGA timing receiver. The receiver is designed especially to reduce problems associated with positive cycle determination. The construction of the receiver is expected to be completed by April 1972. Those activities who are interested in precise time synchronization on a worldwide basis are invited to participate in the experiment or a field test to determine the capability of the OMEGA time-transmission system. It is hoped that enough receivers can be procured for placement at various locations such as one-half, one, one and one-half, and two times the average distance between two OMEGA stations. Those who are interested in the participation of this test should contact Dr. Winkler, U.S. Naval Observatory, or the authors of this paper.

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MINI MODEM FOR PTTI DISSEMINATION

by

J. A. Murray, Jr.

Mr. Murray is with the Time and Frequency Systems Unit, Naval Research Laboratory, Washington, D.C.

Precise comparisons of clocks are now regularly made over several Defense Satellite Communication System (DSCS) trunks employing communications modems that use high-speed pseudo-random codes. Under the primary sponsorship of the Naval Electronic Systems Command, the Naval Research Laboratory (NRL) is continuing the development program to extend the use of the technique to certain other stations that are not equipped with appropriate modems. The Army has also contributed to the development funding and will be furnished with a time transfer system between two of its satellite terminals.

While the development effort is directed mainly at satellite time transfers, the techniques and equipment may also be used in other communications systems, such as line-of-sight microwave links. The techniques are intended to make use of existing communication facilities in a non-interferring manner wherever possible.

Time comparisons were made over DSCS trunks using existing AN/URC-55 communications modems by monitoring certain points on their high-speed pseudo-random codes. The ability to recognize such a point on both ends of the circuit is equivalent to transmission of a very short pulse over the circuit. To make clock comparisons, the signals that are transmitted in both directions between the terminals are monitored by devices called time transfer units, which are inserted between the URC-55 modems and the clocks at both stations as in Figure 1. Accuracies in the order of 0.1 microsecond have been realized in long distance comparisons using this equipment, and several stations are served by the Naval Observatory time standard through single or multiple-hop satellite time comparisons.

The time transfer technique requires each station to transmit a pulse and to receive the pulse transmitted by the other station. At each terminal, the transmitted and received pulses are compared with the local clock. If half the sum of the two measurements taken at one station is subtracted from half the sum of the measurements made at the other station, the difference is the actual difference between the two station clocks (see Figure 2).

This relationship is valid if the propagation time $\tau_1 + \tau_2$ in one direction is equal to the propagation time in the reverse direction. When using the slow-moving DSCS satellites, the inaccuracy is less than 0.1 microsecond if the two transmitted pulses occur within approximately one second of each other. It is not necessary to control the timing of the transmitted pulses, in that case, except to have them occur at roughly the same time. An interpolation technique has been worked out for use when the transmissions cannot be approximately synchronized.

Figure 3 shows the CM-427 time transfer unit developed at NRL last year which automatically compares the transmitted and received pulses at each station with the local clock and yields a burst of pulses that is equal to half the sum of the two time intervals. This burst is totalized in an electronic counter that is used merely as an accumulator. The time difference between the clocks at the two stations, then, is simply the difference between counter readings at the two sites.

For time transfers between stations that are not equipped with the URC-55 modems, an experimental modem designed specifically for time transfer service was developed last year and was used successfully to make satellite time transfers. That model, intended only to demonstrate feasibility, has been redesigned, and the second version is near completion.

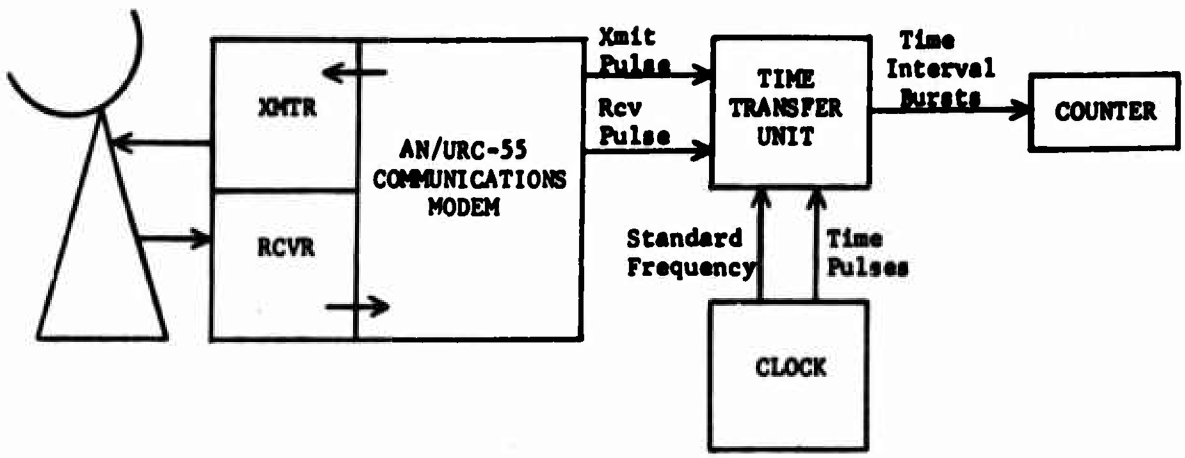

Figure 1. CONFIGURATION FOR TIME TRANSFER WITH AN/URC-55 MODEMS

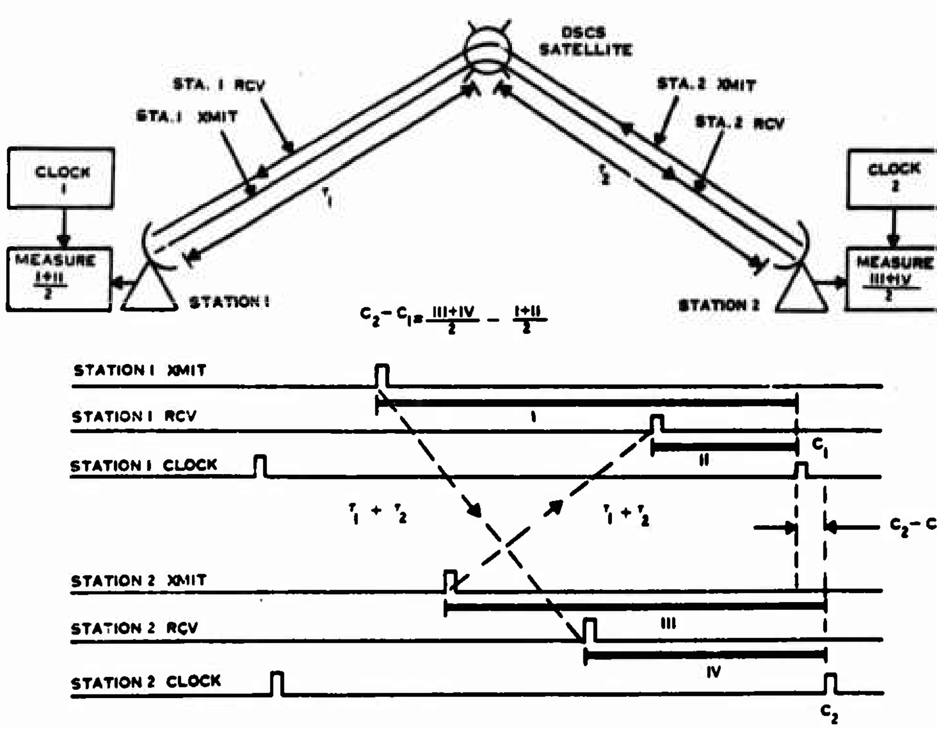

Figure 2. TIME TRANSFER TIMING DIAGRAM

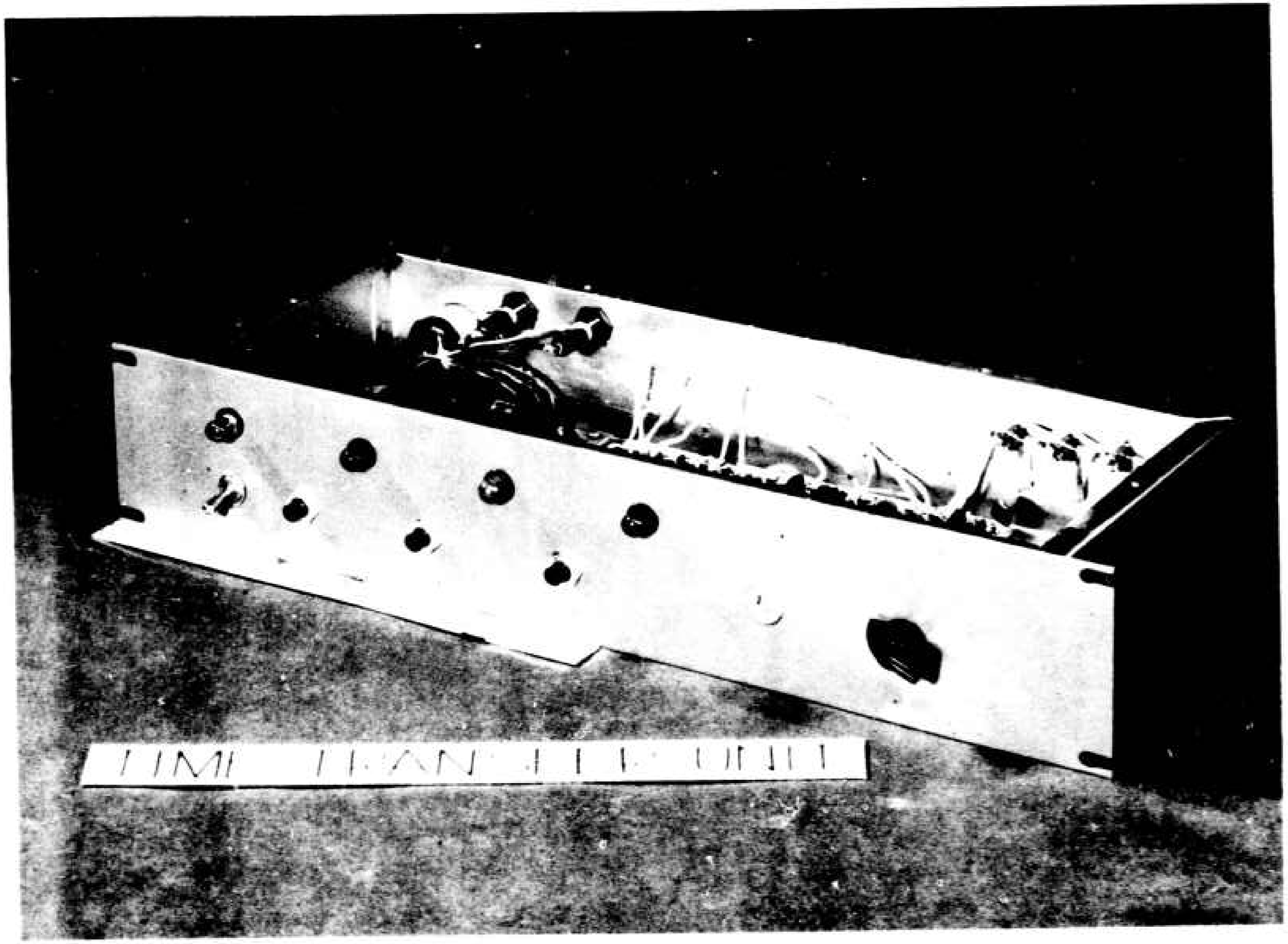

Figure 3. TIME TRANSFER UNIT

The improved model, shown in Figure 4, employs the same basic principles that were used in the original version. The improvements include the increased use of synthesized frequencies based on the local clock in place of crystal-controlled oscillators and increases in operating tolerances.

The design of the newer equipment has been made with a view toward the possible use of the modem over line-of-sight microwave links as well as in satellite systems. Two modes of interfacing are to be available. One is a 70-megahertz intermediate frequency connection. The other is a base-band interface for use in systems through which there is no frequency translation.

The modem transmitter at the bottom of Figure 5 normally provides a 70-megahertz output that is bi-phase modulated by the code generator. The code-rate oscillator function in the new modem is a synthesized frequency controlled by the accurate local clock.

Once during each cycle of the 8,191-bit code, an "all-ones" pulse corresponding to the "all-ones" state of the shift-register code generator is gated out. Several code rates will be available between 1.25 megahertz and 10 megahertz. At 10 megahertz, the code cycle is 819 microseconds long, and at 1.25 megahertz, the code cycle length is 6.5 milliseconds.

On command of an initiating pulse, the "polarity inversion sequence and all-ones gate" causes the code polarity to be inverted for one complete code cycle beginning at the next all-ones event. At the end of the cycle, an all-ones pulse designated as the "tranmit time tick" is gated out. The code then returns to its original polarity.

The receiver section of the modem in the upper part of Figure 5 contains a shift-register generator that produces a code identical to the one generated by the transmitter of the other station. The rate of the receiver code generator, however, is controlled by a variable rate frequency synthesizer that is automatically adjusted to acquire accurate alignment with the code modulation of the received signal.

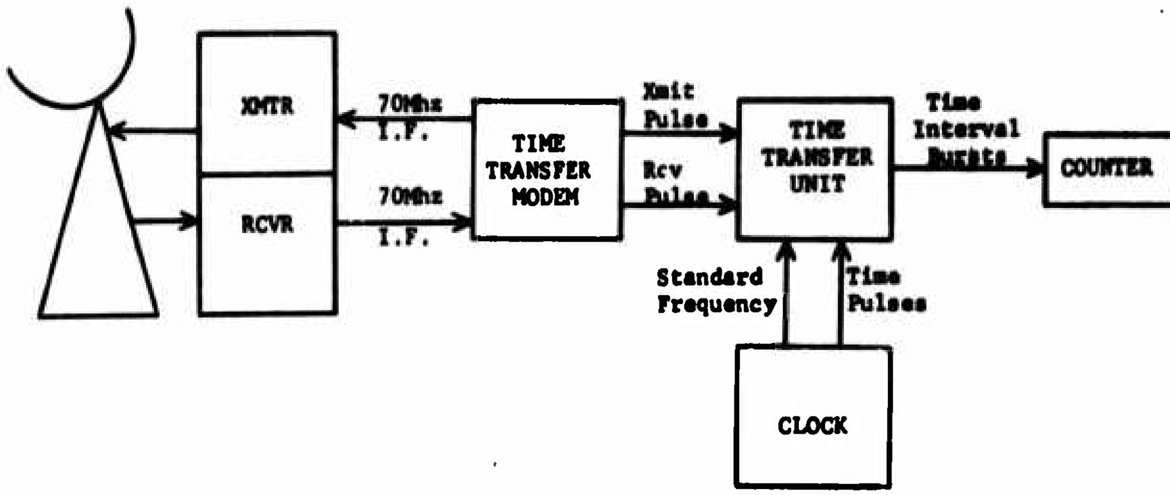

Figure 4. CONFIGURATION FOR TIME TRANSFER WITH TIME TRANSFER MODEMS

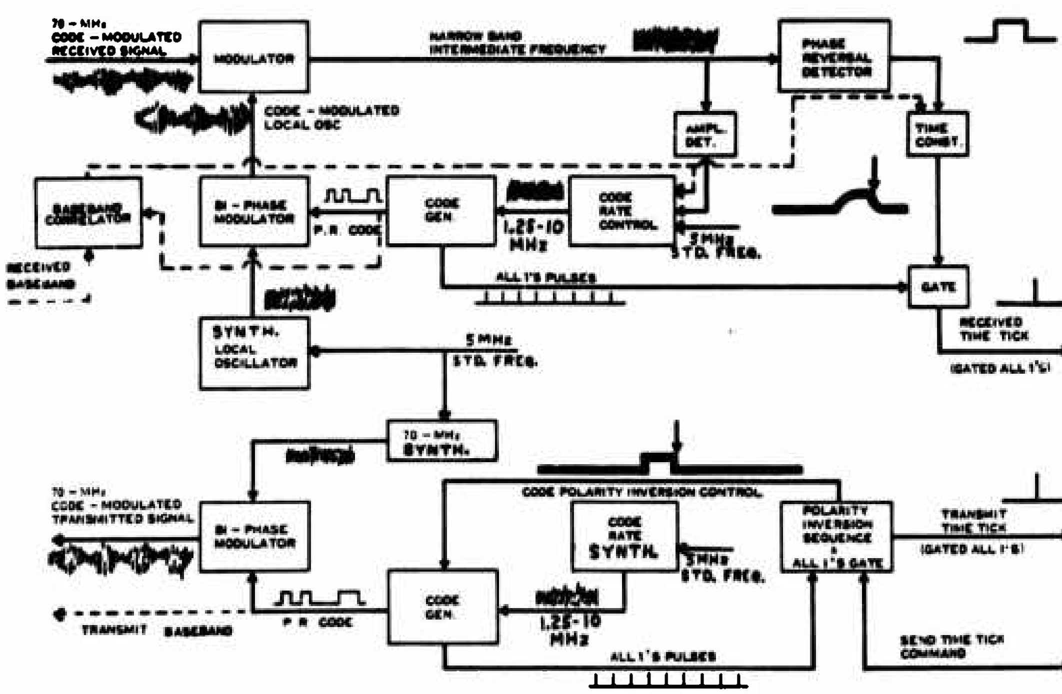

Figure 5. TIME TRANSFER MODEM TRANSMITTER AND RECEIVER

When alignment is achieved, the output of the bi-phase modulator is a nearly constant-phase (or narrow-band) intermediate frequency. The amplitude of this intermediate frequency decreases essentially to zero as code misalignment is increased to one bit (0.1 microsecond at 10-megahertz rate), and it is possible to maintain alignment to within a small fraction of a bit by maintaining peak amplitude. The code rate control, therefore, is designed to maintain peak output of the amplitude detector. Matching the codes is a narrow-band process that can be accomplished in the presence of large amounts of uncorrelated noise, and the modem may be operated at a level considerably below other signals occupying the same channels.

A phase-reversal detector, consisting of a phase-locked oscillator with a large time-constant loop, senses the reversed code cycle and gates out the succeeding all-ones pulse, which is the designated receive time tick.

Connections for baseband operation are shown by dotted lines in Figure 5. This arrangement bypasses all of the 70-megahertz circuits in both transmitter and receiver. The filtered output of the baseband correlator, which reaches a peak output when the receiver code generator is aligned with the received signal, is applied to the code rate control. Detection of the inverted code cycle is simply a matter of sensing an amplitude or polarity change in the correlator output.

Considerable simplification of the modem would result if its operation were restricted to the baseband mode. This might be done if the tests show the mode to be sufficiently useful.

As shown in Figure 6, one code is used for transmission in one direction, while a different code is used in the other direction. The receiver of one modem, therefore, ignores its own transmitter, even when the transmit and receive signals occupy a common channel.

In an experiment in which signals were sent simultaneously in both directions through a single coaxial line, it was possible to operate with a 20-db difference between transmitter outputs. This required, of course,

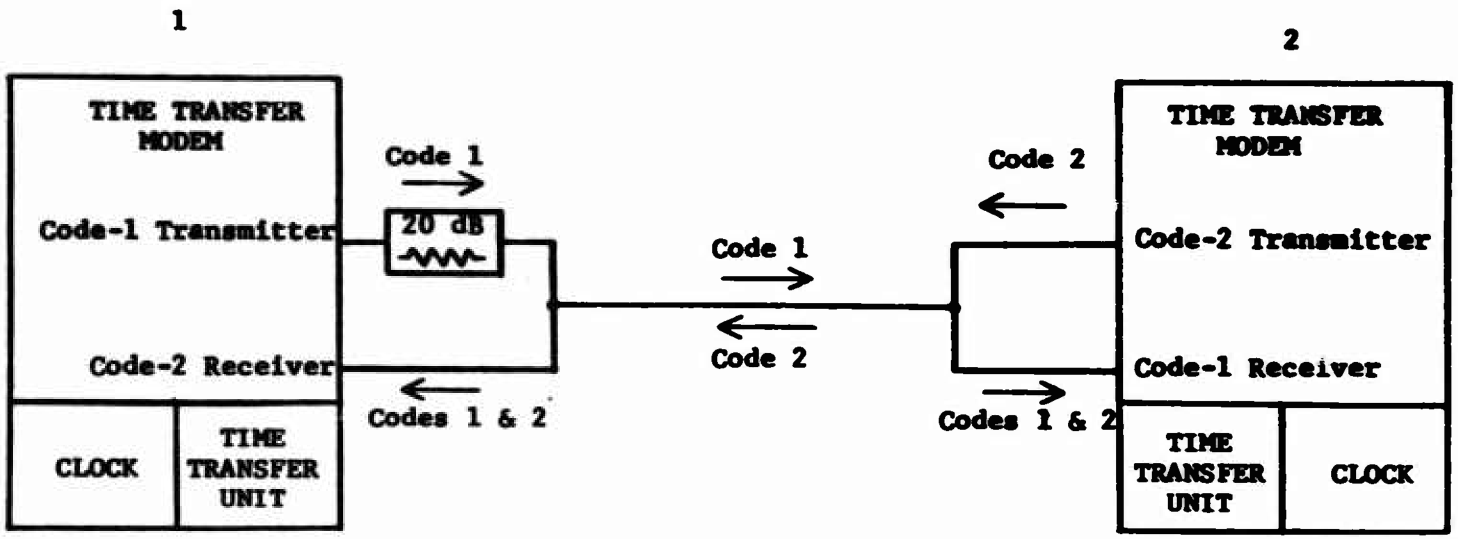

Figure 6. DUPLEX OPERATION OVER SINGLE COAXIAL LINE

that the transmissions in one direction operate 20 db below the pseudo-random interference generated by the other transmissions. Operation in the presence of continuous wave (CW) interference of the same order of magnitude has also been achieved in laboratory tests.

The total bandwidth of the modem 70-megahertz IF output is approximately 20 megahertz, as shown in Figure 7-A when used at its maximum, 10 megabit-per-second code rate. By selection of other rates, the IF bandwidth of the new modem may be reduced to as little as 2.5 megahertz as drawn in Figure 7-E. While potential resolution is reduced at the lower bandwidth, it is felt that the accuracy, exclusive of differential delays in the transmission medium, will remain in the range of one or two tenths of a microsecond, because the code matching in the modem receiver is maintained to within a fraction of a code bit.

The original time transfer modem produced only the spectrum of Figure 7-A. On certain satellite circuits, it shared the channel with a few relatively narrow-band communications circuits as shown in Figure 7-C. Since the spectrum of this modem is spread out over a large frequency range, the amount of power appearing in any of the narrow-band channels is quite small. A further reduction in interference to the communications channels is available because of the ability of the modem to operate significantly below their power level. This ability is of value particularly where the peak power of the transmission system is (or must be) limited.

The baseband output of the modem will appear as the spectra of Figure 7-B or 7-F. Two intermediate code bit rates of 5 and 2.5 Mbps will provide other bandwidths between those of Figures 7-B and 7-F. These spectra are simply those of the transmitter code generator. The signal would not be applied to systems in which the baseband is subjected to frequency translation, even though the baseband is later recovered, because phase uncertainty in the recovery could impair reception of the signal. The baseband signal might be used, however, with systems in which the baseband

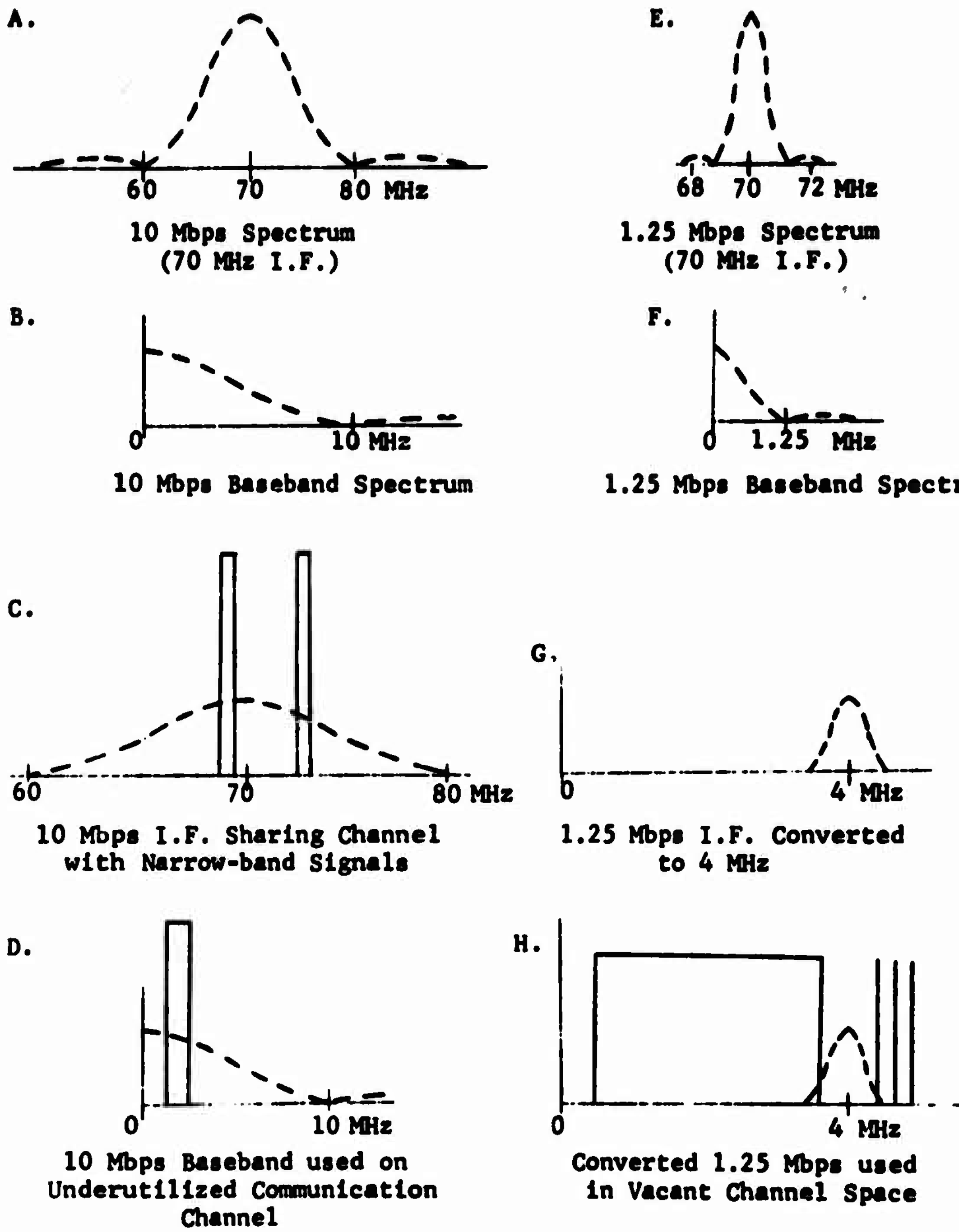

Figure 7. MODEM SPECTRA

directly modulates the amplitude or frequency of a carrier, and recovery of the baseband is accomplished at the receiver by a simple amplitude detector or frequency discriminator.

In systems such as those of Figures 7-C and 7-D, in which only a small portion of the channel is used for communications purposes, the density of the modem spectrum may be kept low and interference to the communications circuit may be minimized. However, as more communications channels are added within the range of the modem spectrum, the level of the wideband modem signal would have to be increased to maintain operation of the time-transfer system. This increase in signal strength would result in greater interference to each communications channel.

Vacancies or lightly occupied portions of a reasonably full channel might be used for time transfer by converting an IF spectrum of appropriate width to the region of the vacancy. The IF spectrum shown in Figure 7-E for example, might be translated by a simple converter to an appropriate spot such as the one shown in Figure 7-G and added to the communications system baseband as indicated in Figure 7-H at the lower right. The tolerances of the various communications components to the noise density produced by various parts of the time-transfer spectrum would govern its placement.

A local microwave link maintained by the Naval Electronics System Command will be used as a test bed for evaluation of the time transfer modem. Factors of interest include susceptibility of multiplexed voice channels, pilot tones, and control signals to the spread-spectrum time transfer signal and, conversely, the susceptibility of the time-transfer modem to the communications content of the link.

Figure 8 is a picture of the original modem. The time transfer modem was intended primarily for DSCS or other slow-moving satellites, but its tolerances may permit its use in other communications systems. The code generator feedback loop of the receiver, for example, is designed to acquire and

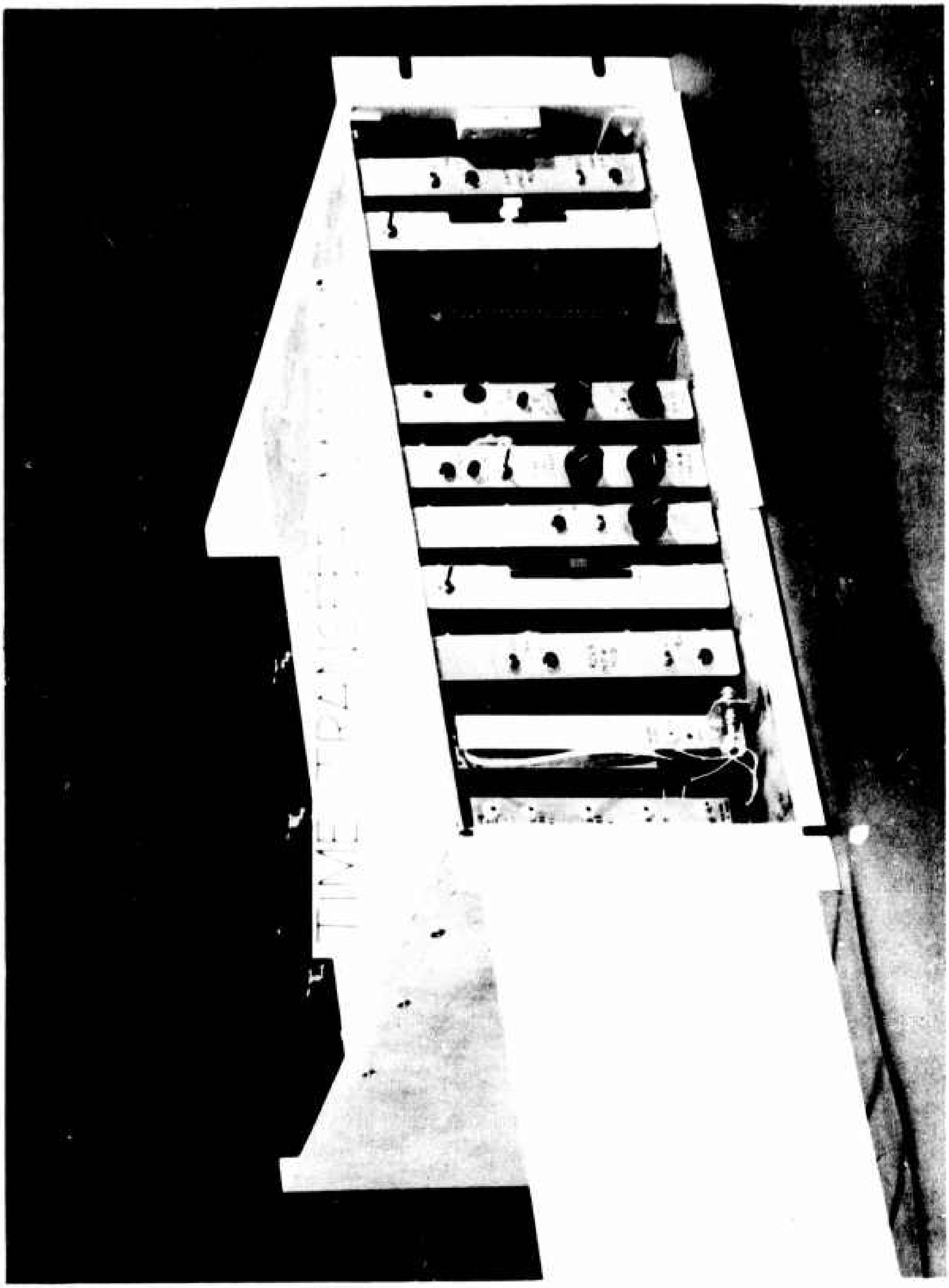

Figure 8. TIME TRANSFER MODEM

maintain lock on signals with Doppler shifts corresponding to a relative motion between stations as large as 1300 miles per hour.

The receiver can operate with offsets of the 70-megahertz input as large as ± 10 kilohertz. This tolerance is shared by Doppler shifts which are proportional to the transmission frequency and by frequency translation errors. A Doppler shift corresponding to a motion of over 600 miles per hour using X-band transmissions could be accommodated, for example, if there were no translation error. Defense Communication Satellite equipment and operating conditions fall well within these tolerances.

The new modem, which is 1-3/4 inches taller than its predecessor, will occupy a standard 19-inch panel space 8-3/4 inches high. The increased height permits continued use of some of the original printed circuit cards while providing an operating panel without requiring access to the cards for normal operating procedures.

Planned tests of the modem over satellite systems and a preliminary evaluation over the microwave test system will be completed in the next couple of months. Further evaluation of the modem in conjunction with other developmental PTTI elements may then be made in a proposed precise time and time interval test bed at the Naval Communication Station in Hawaii.

DISCUSSION

DR. WINKLER: This is a strategic planning conference, and there are several items which we ought to know and consider in our planning for further developments. First, there is one point which I found necessary to keep in mind in considering the uses of wideband channels for time transfer; that is, the bandwidth which is used determines the precision of time transfer, or resolution of time transfer. For resolution in the order of tenths of nanoseconds, one does need a bandwidth of tenths of megaseconds. On the other hand, the available or the used signal-to-noise determines the time which one needs to make a time transfer. Conceivably, by making the pseudo-noise code sufficiently long, one could make a time transfer using 10 to 30 seconds or one minute and operate 40-50 db below the level of other signals in the same channel. That is the principle which is really used here. When NRL originally proposed such a mini-modem development, everybody who participated in these discussions considered development of a unit which could be put into those satellite ground terminals which had no modems in order to use them for time transfer. In any such link you need a modem in both of the ground terminals involved, so we have to standardize. Fortunately, thanks to the Army Strategic Command, we are putting some modems into terminals, for example, at Camp Roberts. Camp Roberts' modem will also make that station available for time transfers to additional stations and those will need only one mini-modem. As the development went along, as Mr. Murray has explained, it became evident that that modem will find much wider use than originally planned and I would like to encourage everyone who can see a possible application in his system to please let us know about that. If we go into a production of five modems, it would be extremely useful to know that maybe five or ten more are needed.

MR. MURRAY: With UHF, I think that there are some conceivable problems. Multipath effects could conceivably cause a false lock in a system of this sort. It's probably best used where the signal is relatively concentrated by directional antennas, but I don't think that we should rule this out, since there may be ways around it. We haven't investigated that particularly yet. Other means can be used requiring a possibly longer synchronizing procedure which might be used on UHF.

VLF PHASE TRACKING FOR PTTI APPLICATION

Dr. F. H. Reder

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by

Dr. F. H. Reder

Dr. Reder is Chief, Antennas and Geophysical Effects Research Technical Area, Electronics Technology and Devices Laboratory, U.S. Army Electronics Command, Fort Monmouth, New Jersey.

1.0 PURPOSE OF PAPER

The purpose of this tutorial paper is to give a short review of some basic facts about VLF propagation for PTTI applications, and to discuss equipment problems and the effects of ionospheric disturbances.

2.0 SOME BASIC FACTS ABOUT VLF PROPAGATION

For the theory of VLF propagation one may consult the books of Budden[1] and Wait[2]. Practical aspects may be found in the VLF Radio Engineering book by Watt[3].

VLF waves propagate in the wave guide provided by the ground and by the ionospheric shell. When close to a transmitter it is convenient to describe observed phenomena by means of ray theory. Beyond the distance of 1,000 kilometers or so, it is advantageous to use mode theory with a mode being one of the solutions of Maxwell's equations for a bounded propagation medium.

Normally, we have to worry only about the first- and second-order modes. These modes differ by three important parameters: (1) their phase velocities (the higher the mode number, the higher the phase velocity);

(2) their attentuation rates (below 25 kilohertz, the higher order modes normally have higher attenuation per megameter); (3) their excitation functions (at a given time of the day one mode is better excited by a transmitter than the other). For many applications, one can use the simple flat-earth model with infinite conductivity on the ground and in the ionosphere. If greater precision is desired, a spherical model should be used, with appropriate approximations for the ionospheric conductivity as a function of height and with inclusion of the geomagnetic field. A very useful approximation for the ionospheric conductivity is given by an exponential function depending on some reference height and a gradient. Pertinent tables have been published by Wait and Spies[4] for determining phase velocity, excitation function in db and loss in db/Mm as functions of reference height and gradient. Normally one assumes for daytime propagation a reference height of 70 Km and a gradient of 0.3 Km^{-1}, and for nighttime a reference height of 90 Km and a gradient of 0.5 Km^{-1}.

For many applications of VLF there are some simple rules of thumb by which one can interpret observed phase and amplitude anomalies.

One rule is that any natural disturbance (except a solar eclipse) lowers the reference height. That means the phase velocity will go up for both the first- and the second-order modes whereas the amplitude for the first-order mode may go up or down depending upon frequency and the amplitude of the second-order mode always goes down. When the gradient increases, which seems to be the usual case in a disturbance, the phase velocity decreases for all modes, and the amplitude increases (the latter is understandable because with a larger gradient the ionosphere is denser and, therefore, has less leakage). From this it can be seen that if a disturbance occurs, there are two phase effects which oppose each other: the height reduction will increase the phase velocity, and the increase of the gradient will decrease the phase velocity. However, the decrease is negligible when compared to the opposing increase so, as a general rule, whenever the ionosphere comes down the phase velocity will increase. Amplitude anomalies, on the other hand, are not so easily predictable. Below about 18 kilohertz, e.g., solar X-ray bursts may either cause signal enhancement, no discernible change or signal loss, depending on signal frequency, path direction and location, and flare spectrum. Above 20 kilohertz it is quite safe to predict signal enhancement for solar X-ray flares, regardless of path geometry.

In the event that there is more than one mode present, it is possible to handle the explanation of many phenomena with a simple vector model.[5] The two mode phasors are computed for the given path, e.g., by using the tables of Wait and Spies.[4] Then the phasor of the second-order mode is added to the phasor of the first-order mode. If there is an ionospheric disturbance, the phasor of the first mode will advance in phase by a certain amount, and the phasor of the second mode will advance by a larger amount. Depending on the original positions of the two phasors with respect to each other, an ionospheric disturbance can cause a large variety of VLF anomalies. There can be an amplitude increase or decrease with practically no phase change, or a phase delay or advance with almost no amplitude change, or any combination of the two.

Another important point is that when a path crosses either a very huge mass of ice or a permafrost area where the electric ground conductivity is low, propagation losses are substantially increased.[5,6] Therefore, one should avoid a path which crosses Greenland or the Antarctic ice.

If one is located as close as 1,000 kilometers or less to a transmitter, one may actually have more trouble in data interpretation than if one is farther away, because the EM field will then consist of a ground wave, an ordinary skywave, and an extraordinary skywave, which is just too much for the ordinary operator to handle. So if it is necessary to pick a VLF signal for PTTI applications, it often is better to select a transmitter which is more than 1,000 kilometers away.

3.0 RECEPTION EQUIPMENT

Figure 1 shows a typical VLF setup. It includes a voltage regulator, an emergency power supply (batteries), a frequency standard (Rubidium standard in this case), two receivers, and a multichannel recorder. The antennas (loop, whip or long-wire) are not shown. There are many potential trouble areas, and most of all there are lots of tempting control knobs. It is a very good idea to follow the principle: keep your hands off, once everything works properly. For example, at Fort Monmouth we have a cesium beam frequency standard which we have not touched since March, 1967, except for retuning the Xtal about every three months. This is probably one important reason why it is still working so well after almost five years of operation.

A problem with loop antennas is that of waterproofing. A loop is supposed to be electrostatically shielded by an aluminum tube around it. This tube has to have one gap otherwise the VLF field could not be picked up. At the same time, the tube must be rain-tight, which is accomplished by a nonmetallic fitting over the gap. Although the manufacturer claims that the loops are rain-tight, in practice they are not. Exposure to sun, cold, rain, snow and ice, makes the joints between aluminum tube and non-metallic gap material and the seal of the tuning box leaky. As a consequence, the tuning box will fill up with water and the signal output will decrease. The solution is to cover all joints with a plastic cover which should be open at the bottom to let condensed water get out.

Whips must be protected from dirt splashings on the base insulator. Also, a good counterpoise (6 radial copper braids) should be maintained to avoid signal variations due to change of ground moisture.

Cables should not be left lying on the floor where people may step on them and either damage connectors or break their outer shields. Cable connectors are, ot course, a major trouble source. Their contacts may corrode, their pins may get loose, etc.

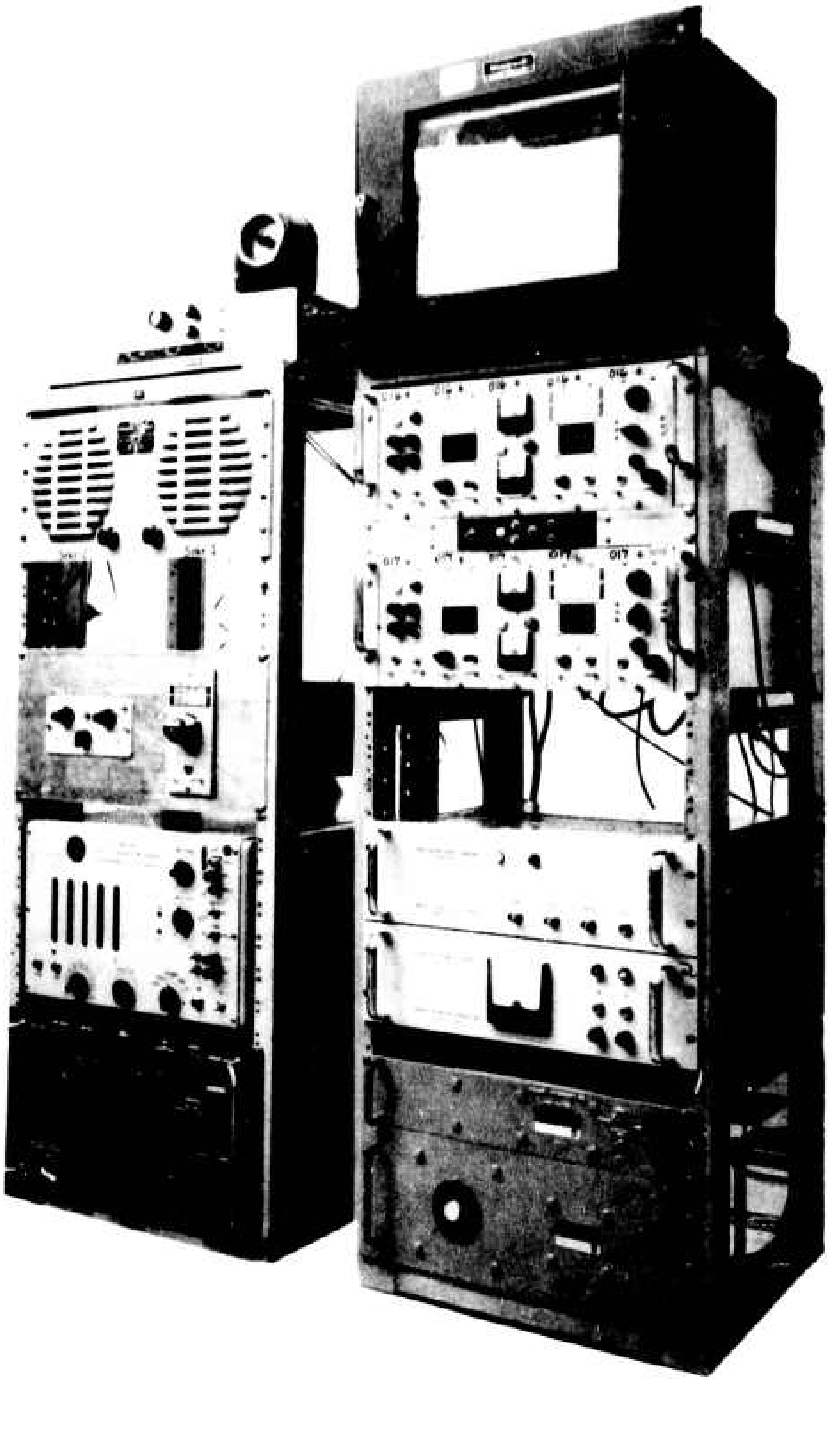

Figure 1. TYPICAL VLF RECEIVER SETUP

One of the most frequent failure sources in a receiver with a modular construction are the plugs between modules and chassis. Therefore, when the receiver fails, the first thing to do is to pull out one by one all the modules and push them right back. In about 80 percent of the cases, this may correct the problem.

The recorder shown in Figure 1 has excellent reliability and precision, but its 10-millivolt full-scale-sensitivity requires great care to avoid ground loops. It is our experience that such ground loops are particularly difficult to avoid if the receivers are connected to standby battery supplies (which is a must to avoid phase jumps during power failures). One indication of such a problem is nonlinearity of the recorder scale. Another indication is that the scale does not go to zero because of the presence of a stray voltage. To avoid this trouble, it is advisable to fasten all equipment needed for the recording tightly into one metal rack. Sometimes it helps to connect appropriate ground terminals of the DC supplies, receivers and the frequency standard by a reasonably heavy copper braid (but too many ground connections may be self-defeating).

A last remark on reception equipment: always use an RF filter in the front-end of the receiver, because the signal you tracketh may not be what thou thinketh. (Can be mirror signal of something else.)

4.0 TRANSMITTER PROBLEMS

Figure 2 shows an example of transmitter phase jumps which we have had in the past (NAA, NPG, NPM and GBR trackings). The distinct jumps occurred when the transmitters switched between FSK and CW, because one mode of operation required an extra filter. The example marked NPM-Fairbanks is taken from a 1964 recording of NPM at Fairbanks. We were, at first, extremely happy because it happened to be that the period of this oscillation was about four minutes, and this period was thought to be a typical period for electron precipitation. Fortunately, we took a look at records of NPM

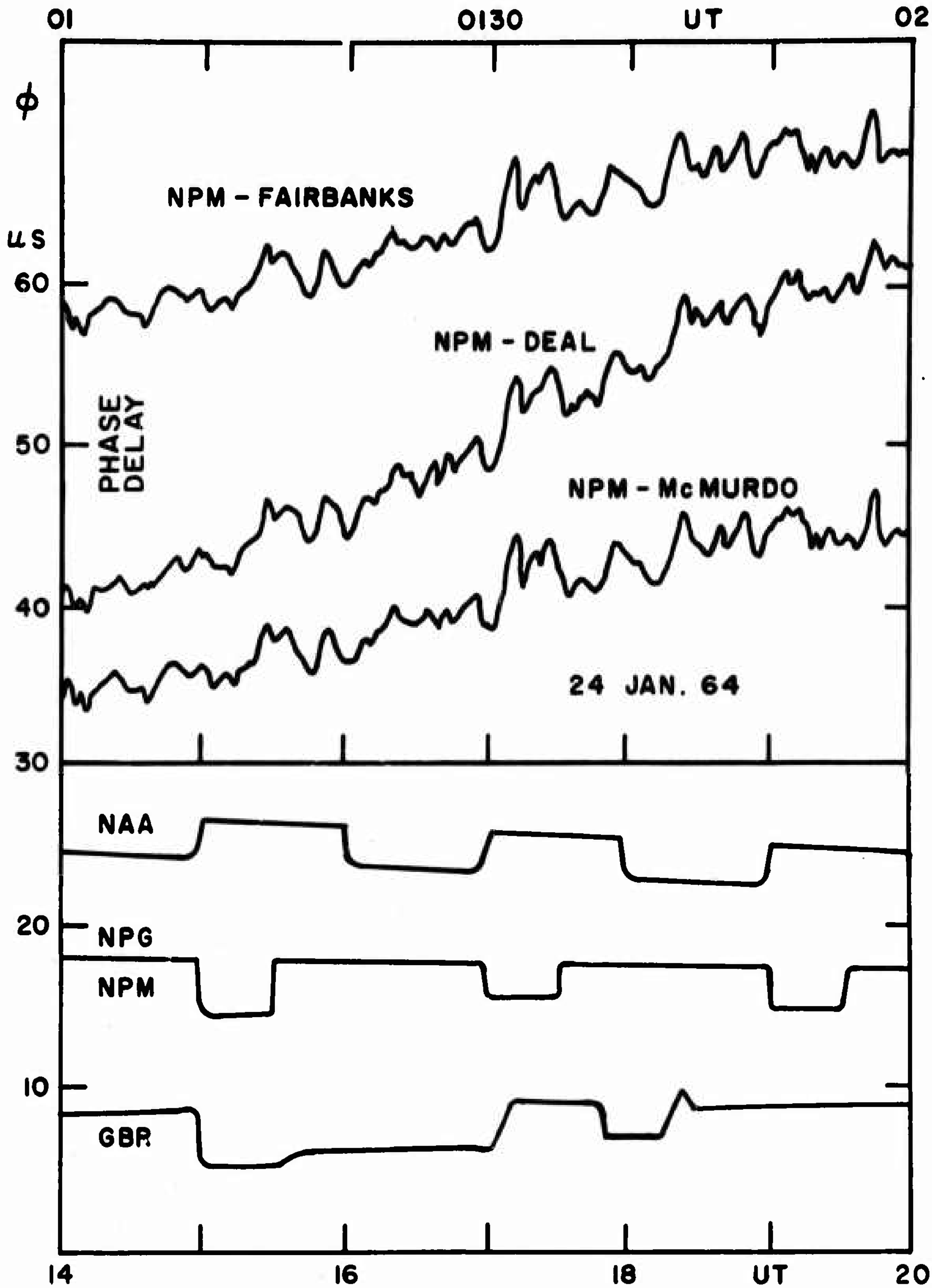

Figure 2. EXAMPLES OF TRANSMITTER PHASE INSTABILITIES

taken simultaneously at Deal, and at McMurdo and we found identical variations. So an electron precipitation effect was unlikely. The explanation given by the transmitter crew was that these phase variations were probably caused by wind gusts at the NPM transmitter. At that time NPM had no automatic phase control to eliminate such variations.

5.0 SIGNAL INTERFERENCE

Another VLF problem is interference. There are three kinds of interferences. The first one is transmitter interference which is illustrated in Figure 3. It appears from the phase of GBR-BRI as if there was either some ionospheric disturbance in progress or there was some problem with the transmitter. However, if one also looks at the amplitude record, one notices that the amplitude recording was saturated. This proves that the problem was not with the GBR transmitter, because the transmitter would have had to turn out about ten times as much power as normally to achieve this effect. It can then be concluded that this was a case of temporary signal interference. The middle section of Figure 3, labeled NBA-Tokyo, shows interference oscillations on phase, and coordinated oscillations on amplitude with amplituide minima coinciding with the moments of maximum phase changes. At the bottom of Figure 3, there is a good example of the lack of properly coordinated frequency allocations. In this case, two transmitters were regularly emitting on the same frequency: MSF on 60 kilohertz in the UTC time scale, and WWVB on 60 kilohertz in the atomic time scale (difference: 300×10^{-10}).

In addition to transmitter interference, there is also mode interference and antipodal signal interference. Both will be discussed later.

6.0 DIURNAL PHASE VARIATIONS

For the following discussion, it is to be noted that our recordings indicate phase advances in negative (downward) direction (because the ionospheric reference height decreases during disturbances).

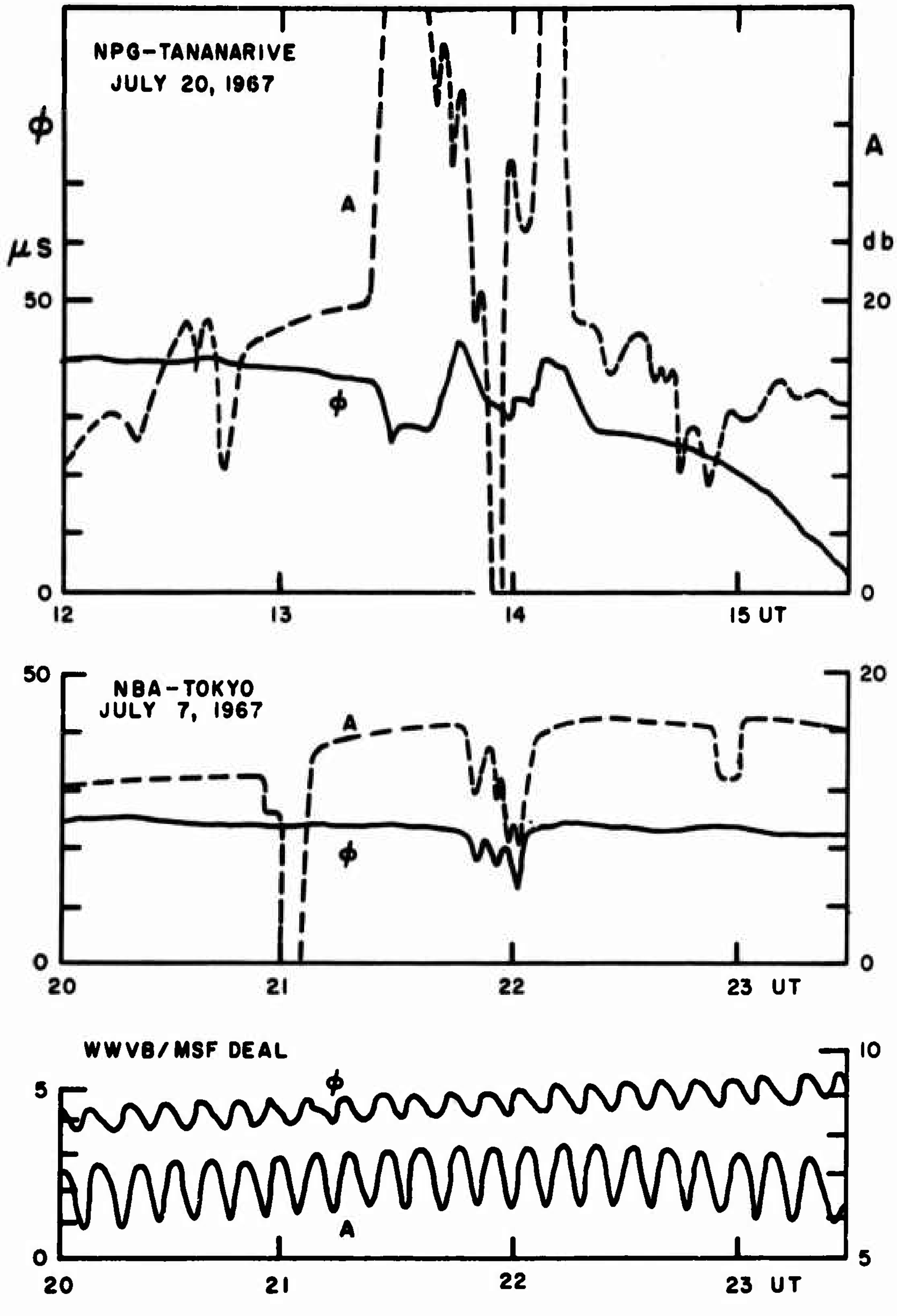

Figure 3. EXAMPLES OF VLF SIGNAL INTERFERENCE

Figure 4 illustrates some typical diurnal phase patterns. More or less sharply defined phase changes occur during sunset and sunrise at the path terminals. The dashed curves pertain to the standard deviations with respect to 14-day averages. The plot, NPM to Deal (summer) shows during the morning hours (0800-1600) mode interference effects typical for VLF frequencies above 18-20 kilohertz. The second-order mode which is excited near the transmitter gets converted at the solar terminator into a first-order mode which interferes with the first-order mode passing through the terminator. As the terminator moves, the two first-order mode phasors observed at the receiver site rotate with respect to each other, causing a series of amplitude minima and phase steps.[7]

In order to understand these diurnal phase patterns, it helps very much to have available sunlight-twilight-night charts[8,9] plotted for two week

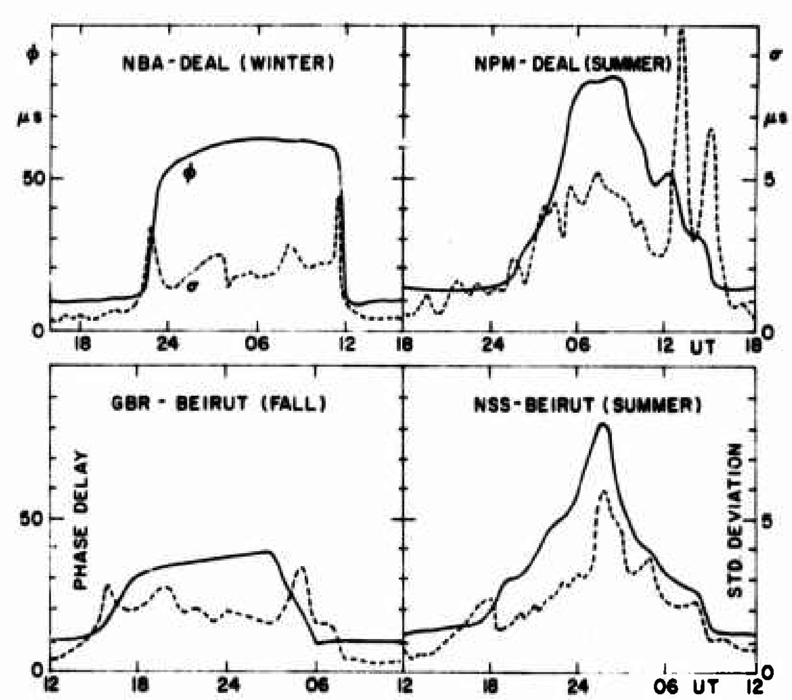

Figure 4. SOME TYPICAL DIURNAL PHASE PATTERNS AND STANDARD DEVIATIONS

intervals with a map overlay (Figure 5). To find out at what times the sun will rise on a particular path, one plots the path on the map overlay -- for intance, NPM to Sao Paulo -- picks the terminator chart for the right date, lays the map over the chart and turns it until one of the path terminals passes through the terminator. Then the time the sun will rise or set will be indicated by the angular position of the map overlay with respect to the terminator chart (time scale along circumference of chart is not shown in Figure 5).

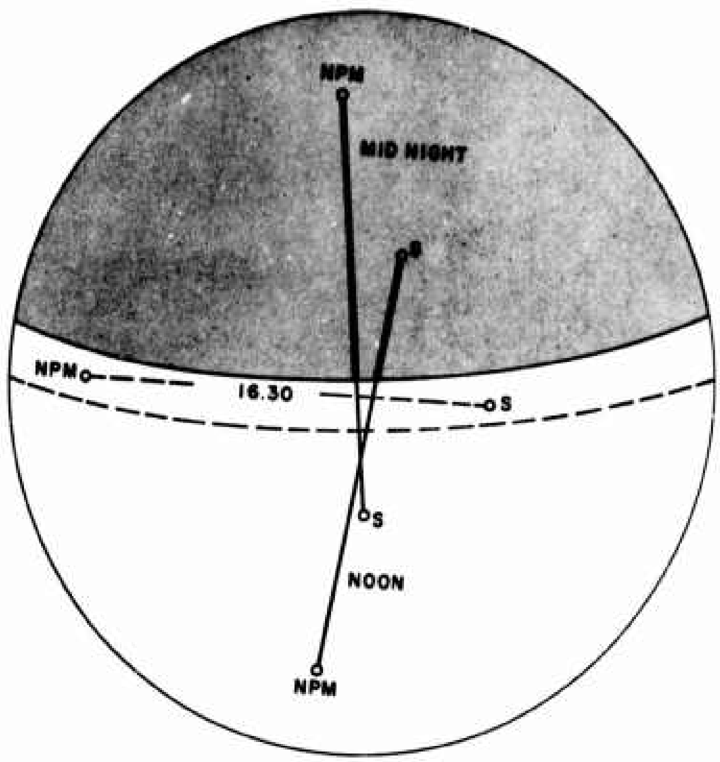

Figure 5. EXAMPLE OF A VLF PATH LOCATION WITH RESPECT TO SOLAR TERMINATOR (S Stands for Stockholm)

Figure 6 proves that these mode interference effects can also be present in the evening.

A very undesirable consequence of mode interference is shown in the lower part of Figure 7. In the evening the pattern develops apparently in a normal way (indicating a phase delay). At nighttime the phase becomes usually a little more disturbed. Then in the morning, instead of returning

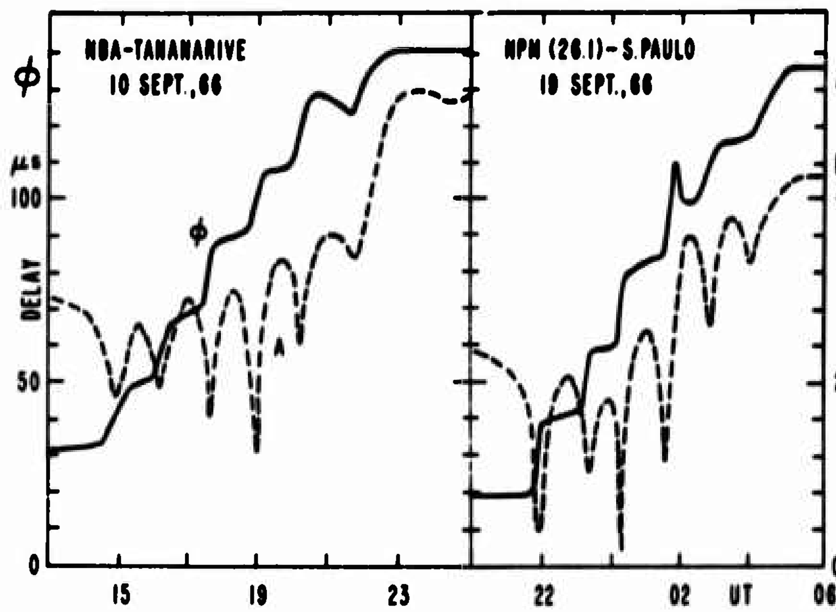

Figure 6. MODE INTERFERENCE DURING EVENING SHIFT

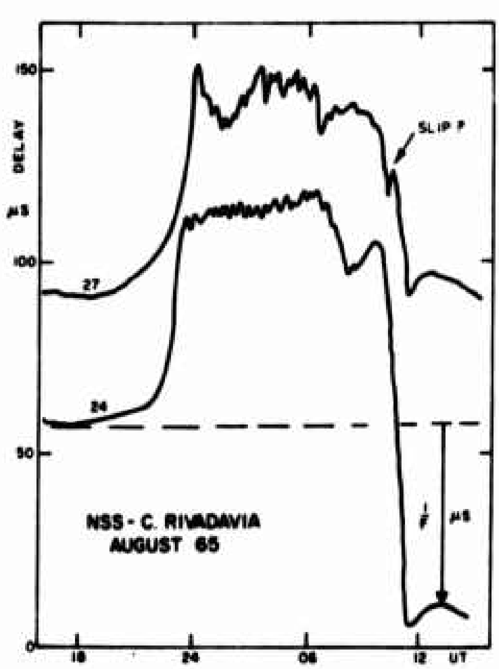

Figure 7. EXAMPLE FOR PARTICULAR MODE INTERFERENCE OBSERVED ON NSS-C (Rivadavia)

to the level of the previous day as one would expect, the phase undergoes an additional cycle advance before settling down for the daytime. Such a cycle advance due to mode interference is not much of a problem if one has a good reference standard, but otherwise it can be a lot of trouble. The only consolation is that it is known that the correction has to be exactly one cycle.[5]

Figure 8 depicts a case of mode interference observed on NAA-Deal (Fort Monmouth), a path of medium length (1,000 kilometers). Depending on the ionospheric activity and depending on the season, almost any pattern can be observed: phase advance in morning and delay in evening (#4, normal), advance in morning and evening (#13), delay in morning and evening (#5), and delay in morning, advance in evening (#10, reversed pattern).

Another undesirable feature occurs on some transmissions crossing the magnetic equator. For instance, Figure 9 shows the diurnal phase pattern of Haiku (12.2 kilohertz) to Brisbane, Australia in comparison with the normal diurnal patterns observed at Tokyo and Deal.[5] The diurnal shift observed at Brisbane is much smaller than expected. Of course, one thinks immediately cycle slips occurred at about 0700 and 1800 and ought to be corrected . But if one corrects the night portion by 1 cycle the diurnal pattern will be too high. So one has a choice of whether one wants the pattern to be too low or too high.

Figure 10 gives an example of a path which is just so long that the first-order and the second-order modes are almost equal in amplitude and nearly out of phase with each other during the night. One observes then two phasors at the receiver site which almost cancel each other. Then the slightest ionospheric disturbance can cause relatively big phase changes. As a result, nighttime phase may either show a "cave-in" or a "blow-out" (not shown in figure), with the phase difference being again exactly 1 cycle.

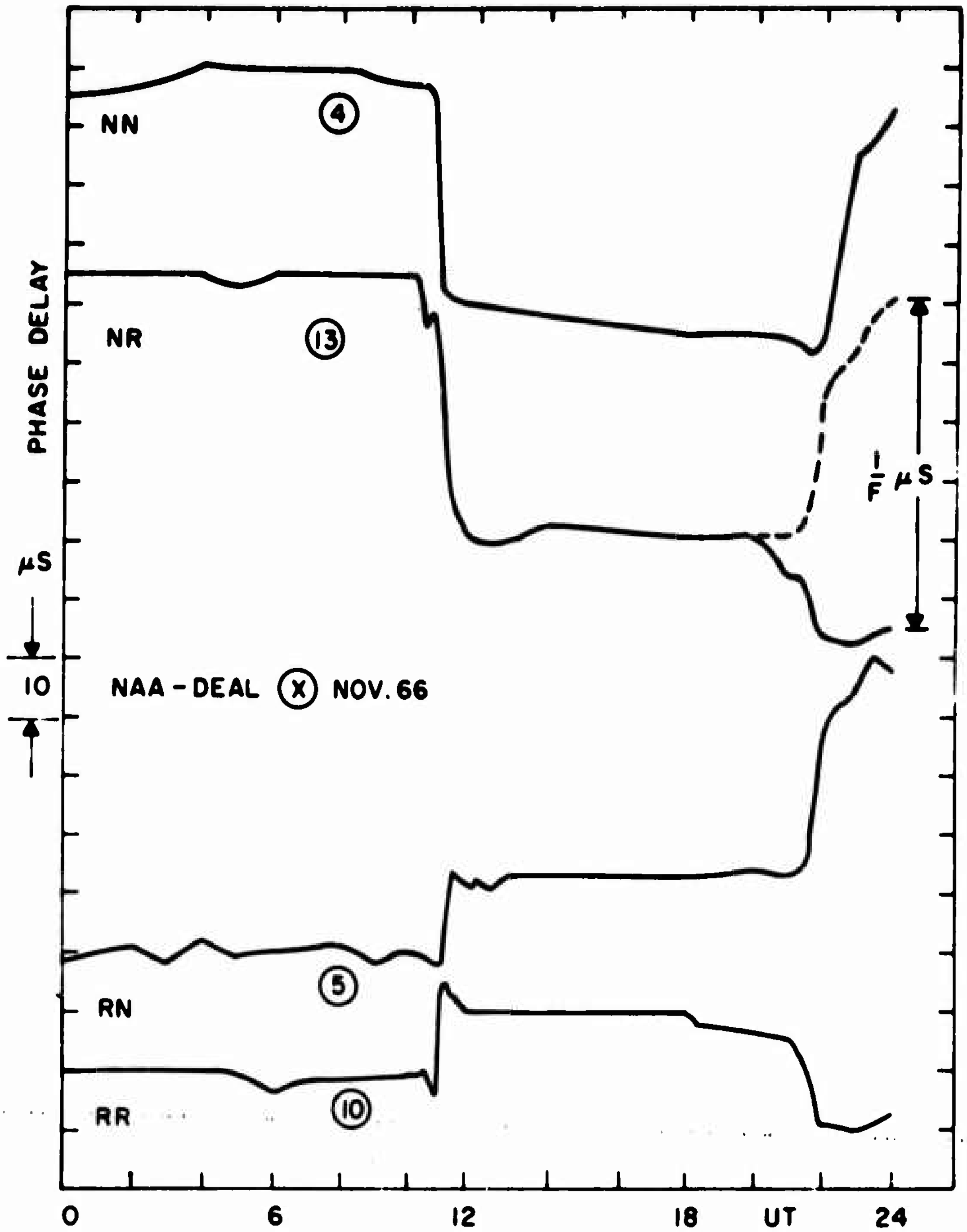

Figure 8. VARIETY OF DIURNAL PHASE PATTERNS ON NAA-DEAL

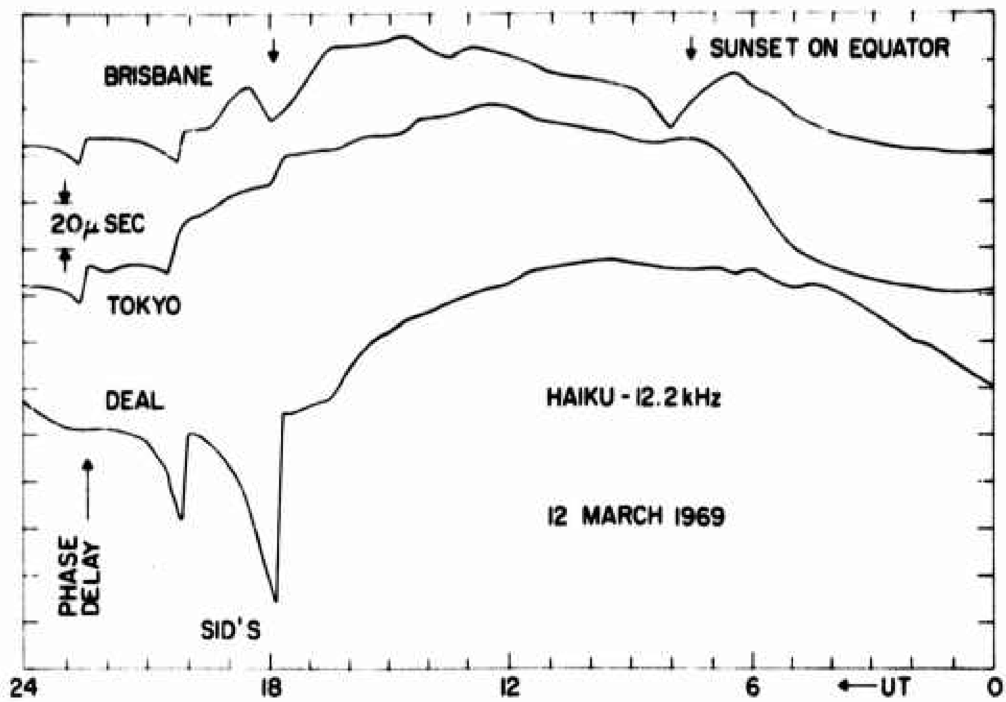

Figure 9. PECULIAR DIURNAL PHASE PATTERN OF NPM-BRISBANE AS COMPARED WITH THOSE OF NPM-TOKYO AND NPM-DEAL

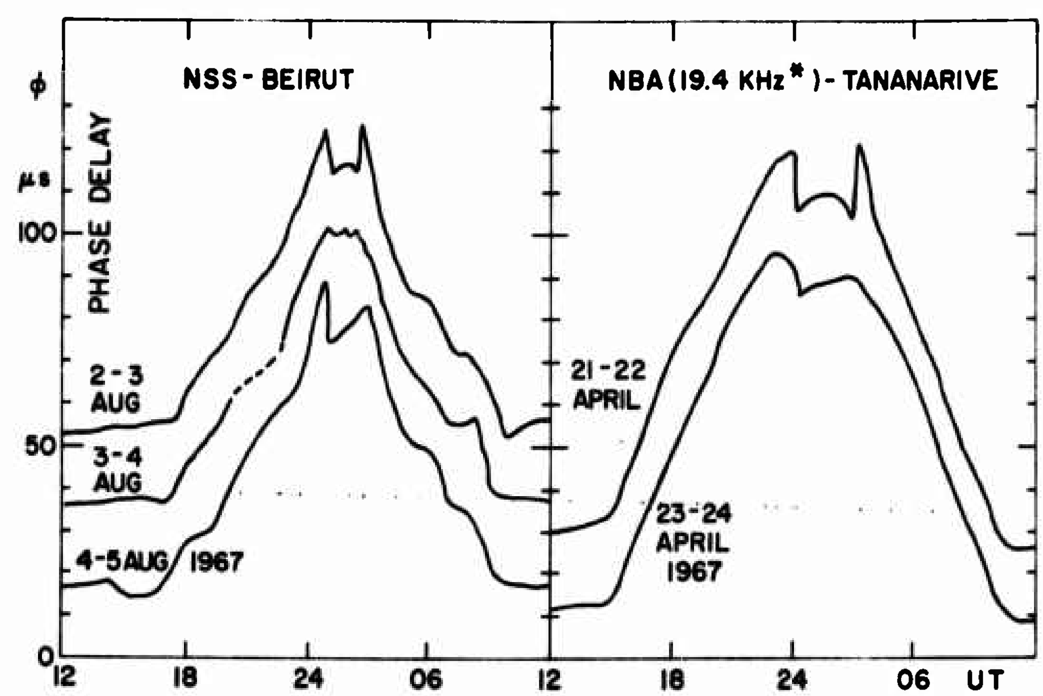

Figure 10. EXAMPLES FOR MODE INTERFERENCE DURING NIGHTTIME ON PATHS FOR WHICH FIRST- AND SECOND-ORDER MODES ARE ALMOST EQUAL IN STRENGTH AND OUT OF PHASE WITH EACH OTHER

An example of the so-called "morning layer"[10] is shown in Figure 11. If one has a signal path which passes through the morning terminator almost simultaneously along its entire length, one observes a temporary additional phase advance which will typically last for about 90 minutes, before the phase will reach its regular daylight value. The advance, for instance, of GBR to Cordoba, Argentina, is of the order of 10 microseconds. On the path from NBA to Fort Monmouth, it is of the order of a maximum of 5 microseconds. The anomaly is caused by a temporary excess of electrons in the lower ionosphere and will be the larger the longer the path is and the faster the entire path crosses the terminator.

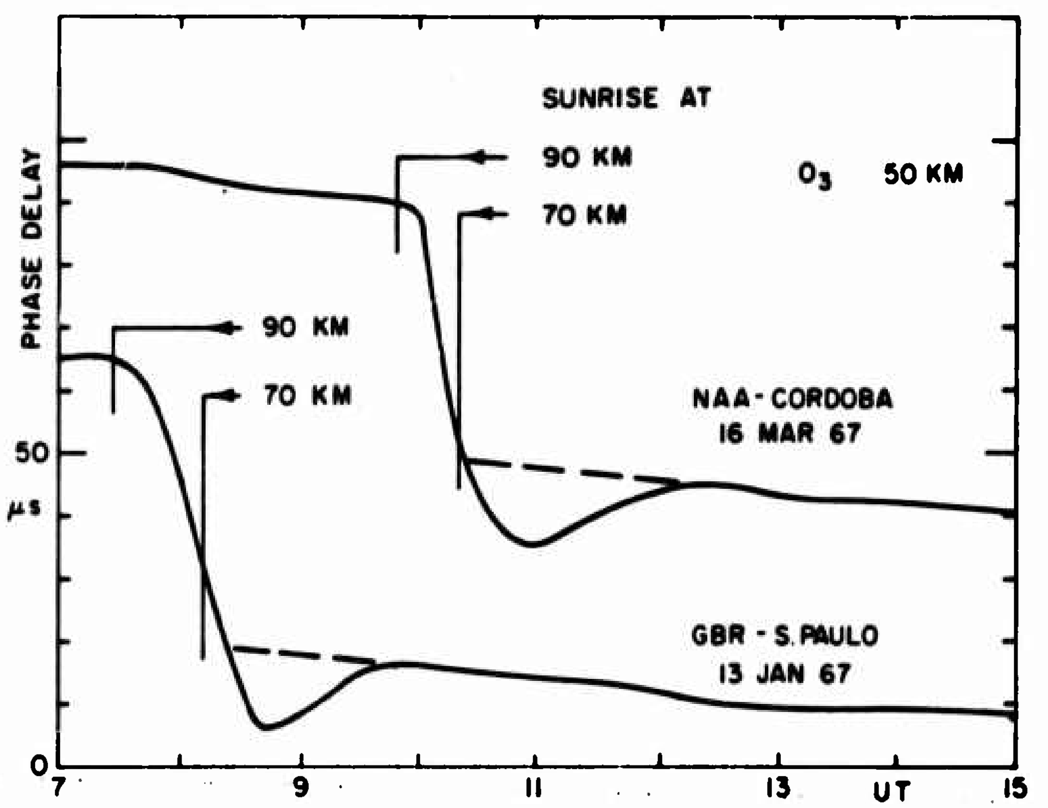

Figure 11. EFFECT OF SUNRISE LAYER ON VLF PHASE

Figure 12 gives an example of antipodal interference. The short path runs across Greenland; the long path runs across the Antarctic ice cap. In

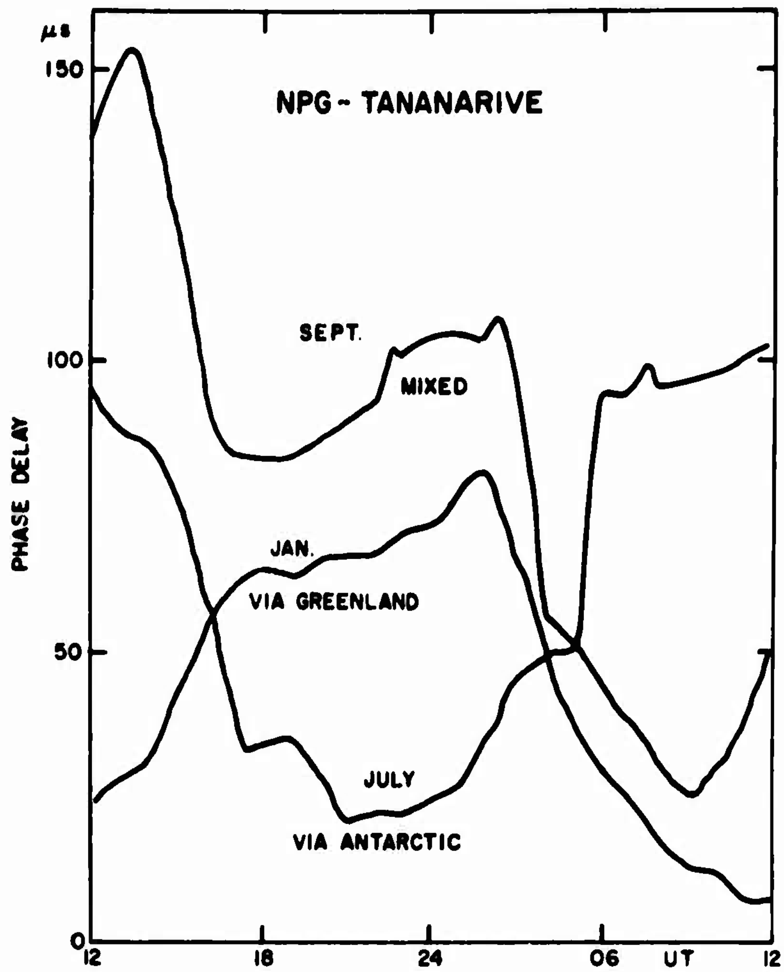

Figure 12. ANTIPODAL INTERFERENCE ON NPG-TANANARIVE

summer when Greenland is in sunlight, the attenuation over Greenland is extremely strong -- approximately 20 to 30 db. This signal is then cut off and the signal to Madagascar comes from NLK via the Antarctic which is in night, and therefore, the losses are not so high. In winter it is just the other way around: Greenland is in night and so it affects the signal only slightly, while the Antarctic is in daylight and cuts off the long-path signal. During spring and fall both signals are present at Tananarive. Reading from the top of Figure 12 down, the first curve pertains to September (mixed); the second curve to January (signal from Greenland only); and the third curve to July when the signal comes only via the Antarctic. Consequently, the January and July patterns are out of phase with each other. We see that the huge ice masses act as season-triggered filters.

7.0 DISTURBANCES

The upper left part of Figure 13 depicts some typical phase and amplitude anomalies caused by sudden ionospheric disturbances (SID's) due to solar X-ray flares.[11] As expected for single-mode signals which are free of antipodal interference, the phase always advances. In this example, the amplitudes increased. However, as mentioned before, amplitude will definitely be enhanced only at frequencies above 18-20 kilohertz. E.g., the signal GBR-Tananarive usually (but not always) indicates an amplitude decrease during an SID.

The upper right-hand part of Figure 13 demonstrates frequency dependence of VLF phase anomalies due to SID's: the lower the frequency, the larger the anomaly. For instance, on 29 December 1968, Haiku 10.2 to Deal deviated by almost 80 microseconds, Haiku 13.6 to Deal by about 50 microseconds, whereas the NPM 23.4 kilohertz to Deal anomaly was only 20 microseconds. All three paths are of equal lengths. The NLK 18.6 kilohertz-Deal anomaly was smaller again because this path is considerably shorter.

The lower part of Figure 13 illustrates what can happen to long-path signals on a day of very high solar activity. SID's followed one another all day long and the phase of Aldra 12.3 kilohertz -- Tananarive was advanced by an average of 20 microseconds during the time 0500Z to 1200Z.

If at all possible, one should never record phase alone, but always phase and amplitude. How advisable this is for proper interpretation of VLF phase anomalies is illustrated by Figure 14. On 2 September 1967, the SID at about 2040Z is clearly indicated by a phase advance and amplitude increase with distinct peaks and typical recovery. The phase advance commencing shortly after 2200 hints at another SID but the lack of any amplitude

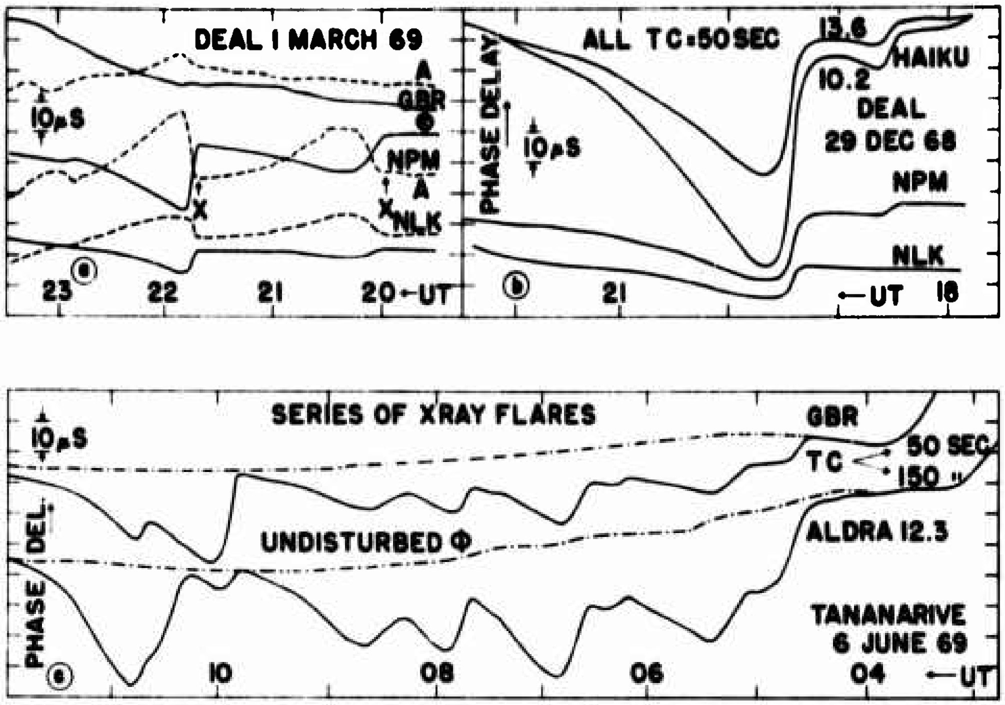

Figure 13. SOLAR X-RAY EFFECTS ON VLF SIGNALS

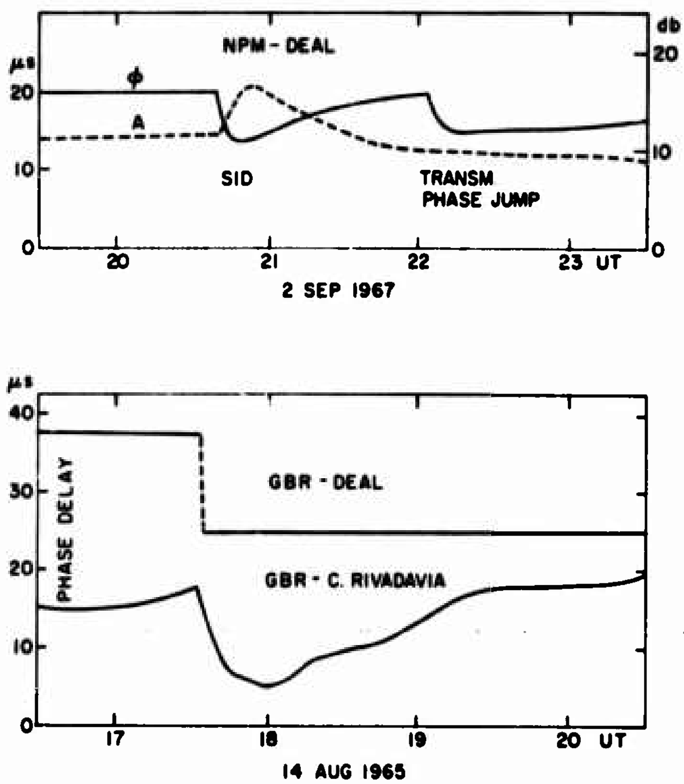

Figure 14. EXAMPLES FOR PHASE JUMPS CAUSED BY EQUIPMENT FAILURES BUT LOOKING LIKE SID'S

anomaly points to a transmitter phase jump. The GBR-C. Rivadavia (Argentina) phase anomaly on 14 August also has all the appearance of an SID, but the GBR-Deal recording clearly indicates a GBR phase jump. The onset is too sudden for an SID, there is no phase recovery and the amplitude shows no enhancement (typical for that path). Why does the GBR-C. Rivadavia anomaly look like an SID? Poor signal-to-noise ratio on this long path required use of an extra-long time-constant (150 sec), which rounded off the lower portion of the phase recording and the diurnal evening shift commencing slowly at 1700 and accelerating around 1800 provided a decieving simulation of the recovery of an SID. Had a reliable amplitude recording been taken at C. Rivadavia, it would have been obvious immediately that no SID occurred between 1700 and 1800 on 14 August 1965.

A short path, like Forestport 13.6 kilohertz-Deal (350 kilometers) can result in reversed SID's. Figure 15 is an example: GBR to Sao Paulo and Trinidad to Deal are paths longer than 3,000 Km and their SID's are normal (phase advance), while the SID's observed on Forestport-13.6 kilohertz-Deal are reversed (phase delay). This behavior can be explained by a phasor model using two modes as discussed before.

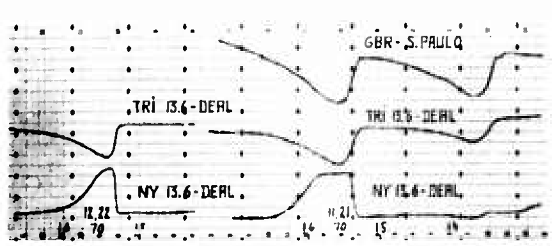

Figure 15. REVERSED SID PHASE ANOMALY ON FORESTPORT 13.6 KILOHERTZ-DEAL

Figure 16 shows some examples of electron precipitation effects. The electrons come directly from the sun or from the radiation belts and have been detected both at high and middle-latitudes. What is typical about them? Let us first take the path from NBA to Deal on 28/29 March 1966. At about 1908Z an SID occurred and it recovered within about 2.5 hours without discernible after effects. On the other hand, on GBZ and NPG to Deal we see the X-ray SID effects followed by new anomalies lasting to beyond 0300 on 29 March. Typically, electron effects last for several hours (two to eight and more). Another example for electrons is shown for 26/27 December 1966.

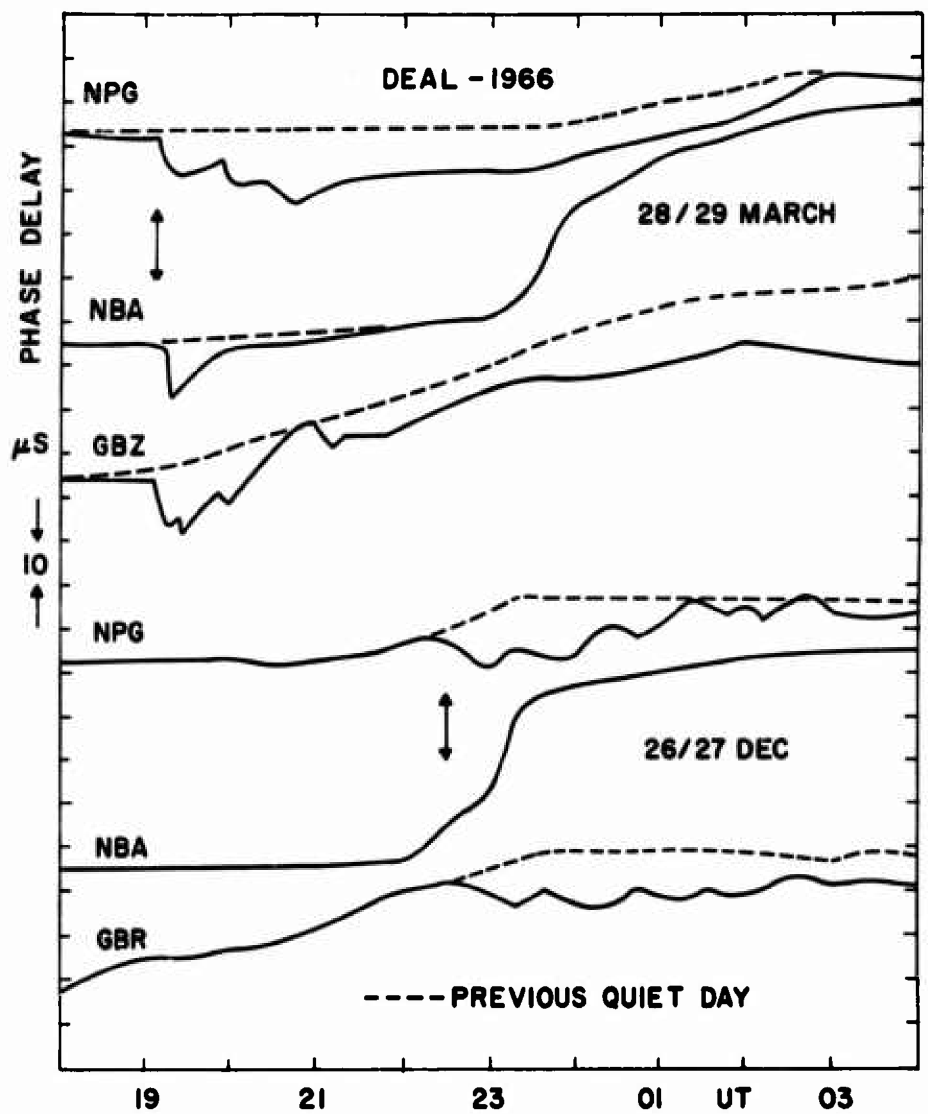

Figure 16. EXAMPLES OF ELECTRON PRECIPITATION EFFECTS

For PTTI purposes, one should avoid a polar path, because polar paths may be affected strongly by protons from the sun and these effects may last up to 10 days. Events of proton precipitation often lead to blackout of HF communication through the polar cap. Therefore, a proton precipitation event is called Polar Cap Absorption (PCA). Figure 17 shows some paths which are susceptible to protons. The ellipse represents approximately 62° geomagnetic latitude. Inside this so-called polar cap a VLF path will be disturbed by protons. If proton precipitation is accompanied by a magnetic storm, the ionospheric disturbances may spill over to lower latitudes and become noticeable on such paths as GBR-Deal, NSS-Beirut, etc.[6]

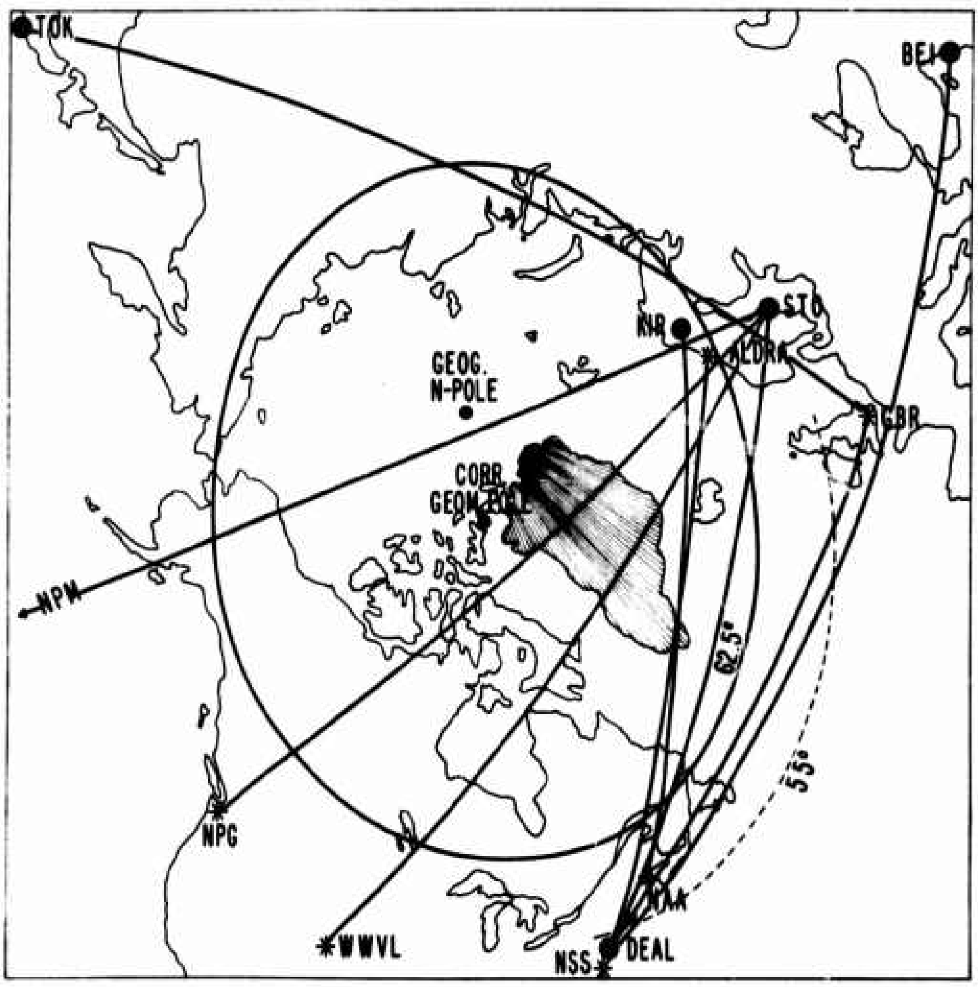

Figure 17. VLF PATHS THROUGH THE NORTHERN POLAR CAP

Figure 18 illustrates the dependence of PCA effects on path distance from the geomagnetic pole (center of polar cap). NSS to Stockholm has a large distance and one sees only a relatively small effect. NPM to Kiruna lies closer to the center of the polar cap and a more pronounced effect is evident. The WWVL to Stockholm path, shows a strong effect and NPG to Stockholm is the most disturbed. First of all, NPG-Stockholm passes close to the geomagnetic pole, and secondly, it runs across Greenland. Any ground with low electric conductivity will increase this type of anomaly. Figure 19 depicts the PCA effect of 18 November 1968 on the Omega signal Aldra 13.6 kilohertz to Deal. The onset was unusually abrupt -- peak phase deviation of 70 microseconds (100 microseconds on 10.2 kilohertz) was reached within 45 minutes -- and recovery took about six days.

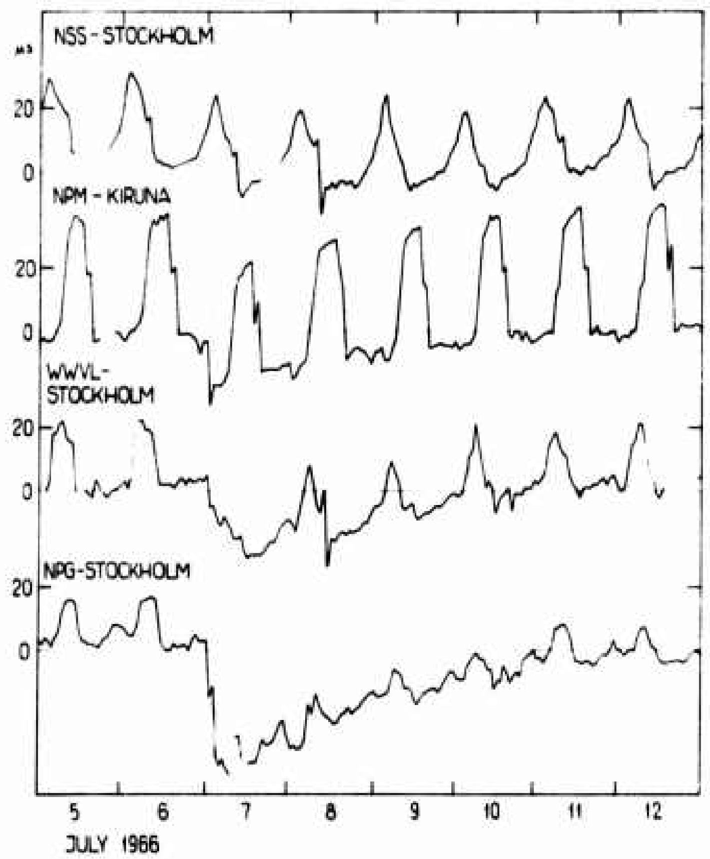

Figure 18. DEPENDENCE OF PCA EFFECTS ON PATH DISTANCE FROM GEOMAGNETIC POLE

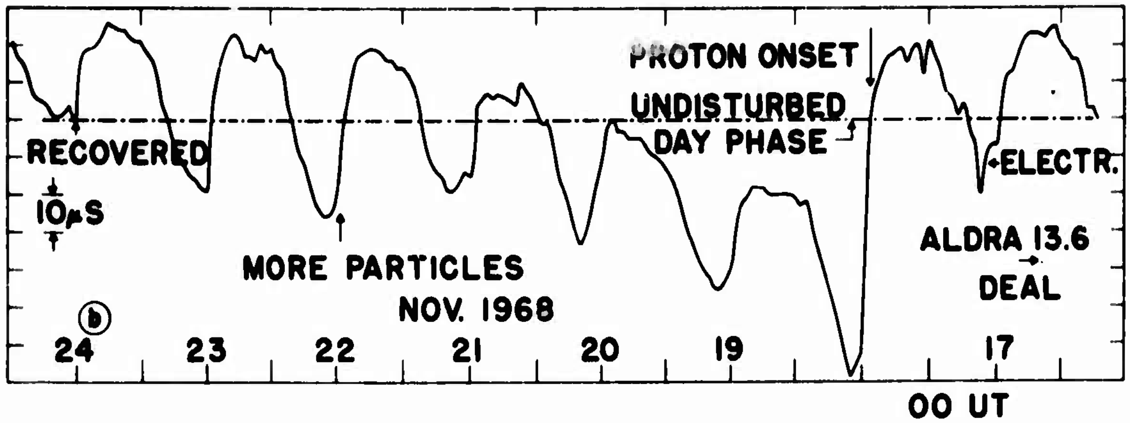

Figure 19. PCA OF 18 NOVEMBER 1968 AS OBSERVED ON ALDRA 13.6 KILOHERTZ-DEAL

8.0 LONG-TERM (SEASONAL) PHASE VARIATIONS

The excellent accuracy of Cs standards controlling VLF transmitters and receivers and the long-term behavior of the lower ionosphere are illustrated by the plots of Figures 20 through 23 which reproduce daily VLF phase values read at the moments of noon at the path centers. The plots are marked; e.g., by Deal-NLK instead of the more customary NLK-Deal in order to avoid errors in data interpretation. Deal-NLK means that the plot will have a positive slope if the frequency of the local standard controlling the receiver is higher than the frequency of the standard controlling the transmitter.

All plots reflect the strong ionospheric disturbances caused by the PCA's of 1968 (marked by arrows along the abscissas).

The Washington-NLK/NPG curves of Figure 20 point to an apparent seasonal lowering of the daytime VLF reference height during the period August-October. The total phase accumulation between the Cs standards controlling the Washington (US Nav Obs) and Deal receivers was only about 35 microseconds between 1 June 1967 and 31 January 1969, which is equivalent to an average frequency offset of the Deal standard of only -7×10^{-13}. (Note that our Cs beam standard was originally set up and adjusted as prescribed by the manual in spring 1967. No controls were touched since,

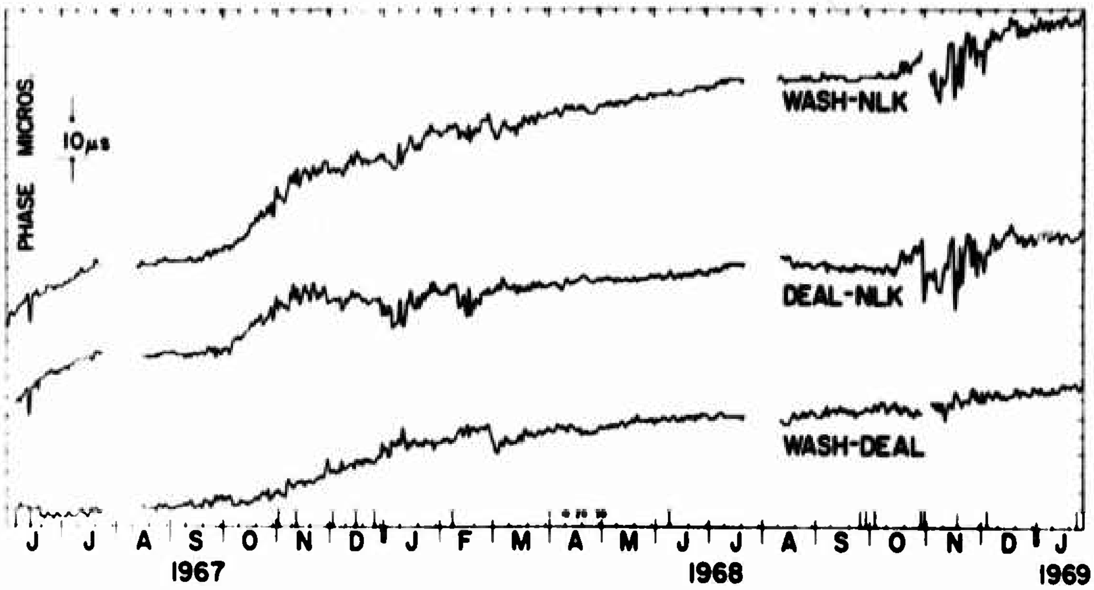

Figure 20. SEASONAL PHASE VARIATIONS OF NLK AT DEAL AND WASHINGTON

except that the driving Xtal oscillator was retuned about every 3 months without opening the servo loop).

Figure 21 shows NPM before and after cesium control was introduced. To the left of the line over 9 April 1968 the vertical scale is 20 microseconds, to the right it is 10 microseconds per major division. The improvement after the change-over to Cs control is obvious. As expected, the PCA effects on the polar signal STO-NPM are much larger than those on the mid-latitude signals Deal-NPM and Wash-NPM. Also, the seasonal variation of the STO-NPM signal phase is very pronounced because the polar region changes from continuous daylight in summer to continuous night in winter.

The seasonal plots of GBR (Figure 22) are included here to give an example for the case of an exceptionally strong PCA effect (40 microseconds) on the non-polar path GBR to Deal on 31 October 1968 (no reading of GBR was taken in Washington). The reason was the coincidence of the PCA with a strong magnetic disturbance which pushed the northern cutoff latitude of the protons far to the south.

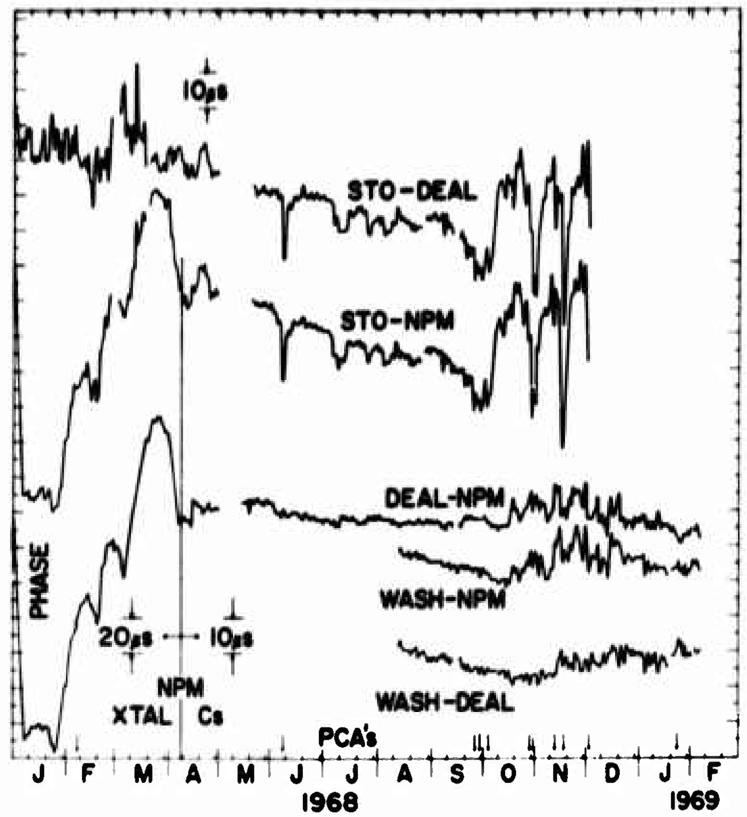

Figure 21. SEASONAL PHASE VARIATIONS OF NPM AT STOCKHOLM, DEAL, AND WASHINGTON

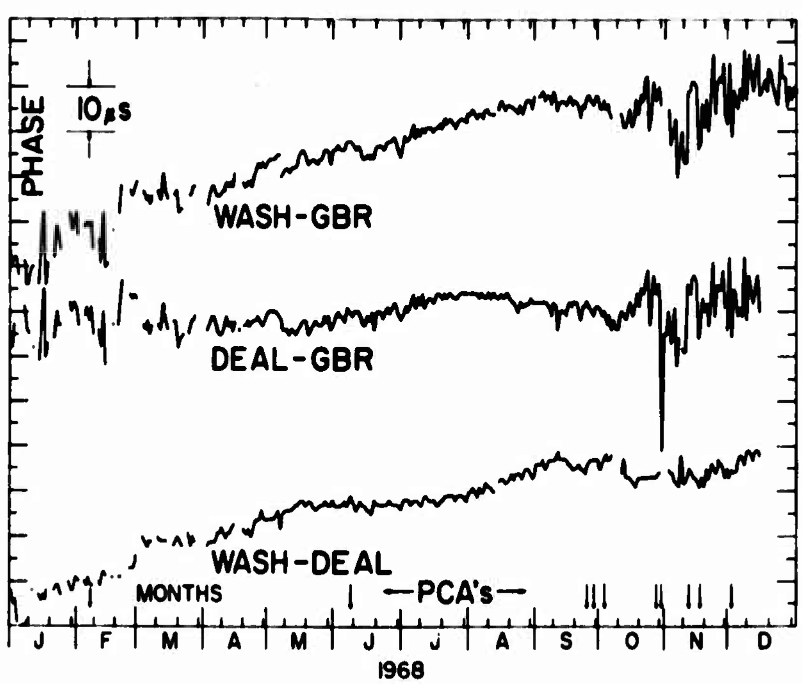

Figure 22. SEASONAL PHASE VARIATIONS OF GBR AT DEAL AND WASHINGTON

Figure 23 depicts midday phase values of Aldra 10.2 and 13.6 kilohertz as measured at Deal during 1967 and 1968. The signals at Deal were quite weak, but the seasonal variation caused mainly by the Arctic summer and winter in the transmitter area, and the strong PCA and electron effects are clearly detectable. The plot marked 3.4 (= 13.6-10.2) gives just the difference between the 13.6 and 10.2 phase readings. The plot marked "COMPOS" gives the phase of Pierce's composite wave[12] computed for his frequency parameter m = 2.25 from the 13.6 and 10.2 kilohertz phase readings. A comparison of the 2 lower plots indicates that this composite wave based on a very simple flat-earth model gives hardly an improvement over the difference (3.4) signal. However, it is expected that a more sophisticated[13] composite wave based on propagation data by Wait and Spies[4] will give considerable improvement in phase stability during ionospheric disturbances.

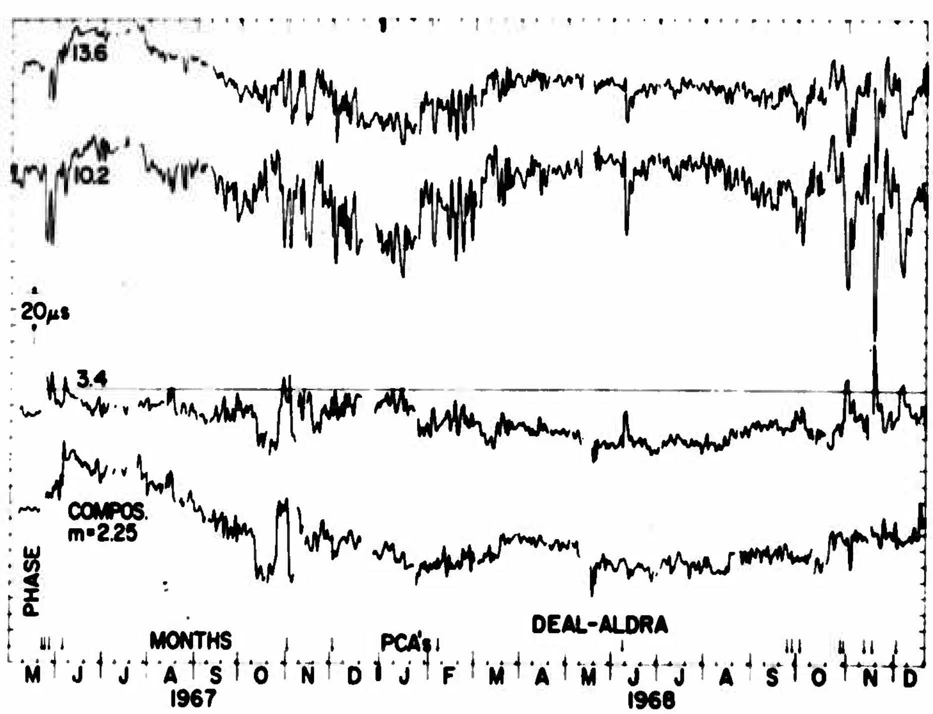

Figure 23. SEASONAL PHASE VARIATIONS OF ALDRA AT DEAL (10.2, 13.6, 3.4 Kilohertz and Composite Signal)

9.0 SUMMARY

What does one have to consider for the selection of the most suitable VLF signal for PTTI applications?

(1) Signal frequency: If one chooses a low VLF frequency (below 18 kilohertz), solar flare effects will be large, but one will in general not be plagued by cycle slips during morning and/or evening hours. If one chooses a high VLF frequency (above 18-20 kilohertz), solar flare anomalies will reduce in size but cycle slips become a real problem. So GBR-16.0, NAA-17.8, and NPG-18.6 kilohertz (> 1000 km) are good choices.

(2) Path length: Short paths have in general almost no or only small and abnormally-shaped diurnal effects, but phase stability is often inferior and anomalies may be more difficult to interpret because of ray or mode interference. On the other hand, very long paths (> 10,000 km) are associated with long periods of diurnal phase shift. Therefore, a path length between 3,000 and 8,000 km is desirable.

(3) Path orientation: N→S paths give shorter periods of diurnal shift than E→W paths, so the former ones are preferable. The possibility does exist of cycle jumps during those periods in a year when a N→S path passes through the terminator (morning or evening) simultaneously along its entire length (reason: diurnal shift occurs so rapidly that receiver cannot follow), but the critical periods last only a few days. If no N→S paths are available preference should be given to W→E paths since E→W paths give higher propagation losses due to the effect of the earth magnetic field on the ionosphere.

(4) Path location: The auroral zones and the polar caps, as well as areas covered by huge masses of ice or subject to permafrost conditions should be avoided.

As far as equipment is concerned, I would prefer:

(1) selection of equipment predominantly from the point of proven reliability;

(2) location of equipment in an unfrequented room (beware of knob twisters) which is temperature controlled to between 60°-$75^{\circ}F$;

(3) heavy emphasis on reliability of electric power (standby batteries, connected to all elements controlling signal phase is a must);

(4) multi-channel recorders with a paper width of more than 6 inches and recording of phase and amplitude on same paper;

(5) tuned loop antennas, properly protected from rain, snow, and ice;

(6) use of a separate loop for each receiver (there are exceptions);

(7) not to use preamplifiers (if I can avoid it) because they add complexity and may cause oscillations in antenna input circuit; and

(8) Cs standards over Rb standards and those over Xtal standards (who would not?). However, for those who cannot afford an atomic standard there is a consolation. If one's main concern is to retain an already synchronized (by portable clock, satellite, etc.) clock to within 50 microseconds throughout day and night or to within 10 microseconds during daytimes, one can drive the receiver with a moderately-priced Xtal standard and use the coherent (with VLF signal) 100 kilohertz output to drive the clock. The Xtal standard has then only to be near the transmitter frequency within the specified receiver tracking bandwidth. Offsets of 10^{-8} can easily be accommodated.

In conclusion I would like to say that during quiet ionospheric conditions the precision of long-distance standard-frequency transfer by means of VLF phase tracking is presently still limited by the precision of our equipment (including transmitter circuits) and not by the ionosphere. At least for daytime and the oblique incidence pertaining to long-distance VLF propagation, one can truly say that the quiet lower ionosphere is of an incredible stability from one day to the next.

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11.0 ACKNOWLEDGMENT

Figures 2, 3, 4, 6, 7, 8, 10, 11, 12, 14, and 16 are from Reference (5); Figures 9, 13, 19, 20, 21, 22, and 23 are from Reference (11).

Figures 17 and 18 are from Reference (6); Figure 5 is from Reference (9).

DISCUSSION

DR. WINKLER: I would like to make one more comment or, actually, put up a question, to see corroboration for some of the recommendations which have been made many times before. In spite of the apparent complication of tracking VLF for the purpose of maintaining time lock or frequency lock, it is still a very useful system and relatively inexpensive. But it appears to me that there are only two solutions. One is to have operators available at the station who know what they are doing and who must have a minimum amount of training, or to go to an entirely automatic system, as envisioned in the Omega Timing Procedures indicated this morning by Mr. Chi. I do not see how one can utilize VLF phase-tracking without either one of these, without trained operators -- well-trained operators, consciencious operators -- or fully automated equipment.

DR. REDER: Yes, I agree with that. There is one hope, however, and that is the possibility of reducing these anomalies and the diurnal shift by an improved Composite Wave Technique. The composite wave was originally introduced by Prof. J.A. Pierce of Harvard University. It consists of synthesizing the phase of a new signal (composite wave) from the measured phase values of two signals of different frequencies (e.g., 10.2 and 13.6 kilohertz) emitted by one transmitter in a time-sharing fashion. The synthesis is carried out in such a way that anomalies due to ionospheric changes are minimized. Pierce's original model used plane-wave propagation within a plane earth-ionosphere waveguide with infinitely conducting walls. This model was too simple to accommodate in a satisfactory manner both diurnal shifts and solar flare anomalies with one parameter setting. However, Dr. W. Papousek from the Institute of Technology, Graz, Austria (on invitational travel orders to our laboratory) recently showed that -- at least on paper -- the composite wave technique can be much improved by using the more realistic propagation data of Wait and Spies (exponential ionosphere).

DR. WINKLER: Could an improvement of the composite wave technique be accomplished by using three frequencies?

DR. REDER: Dr. Papousek has found that the realizeable phase measurement precision at least for the relatively low-power Omega signals makes the usefulness of adding a third frequency very questionable. The key to the method is dispersion. That is to say, the known change of phase velocity with frequency is utilized to compensate the anomaly observed at one frequency by the appropriately adjusted anomaly measured along the same path at another frequency. Since dispersion is not very large, the second frequency cannot be too close to the first else measurement errors will degrade too much the precision of the phase differences which are needed for computing composite-wave phase. If the frequencies differ too much, single-mode propagation cannot be maintained. Therefore, adding a third frequency makes either the frequency spacing too small and measurement precision too critical; or it requires consideration of propagation in at least two modes which introduces the need of taking mode amplitudes into account and that clearly becomes impractical.

PTTI RELATING TO THE VERDIN COMMUNICATIONS SYSTEM

by

L.S. Woznak

Mr. Woznak is Head, Information Processing Branch, TACAMO Division, Special Communications Project Office, Naval Electronics Systems Command, Washington, D.C.

Abstract

VERDIN is the Navy's VLF system to replace the present FSK modulation on our VLF and on some of our LF broadcasts. The first installations are starting this week with completion planned for 1975.

The frequency range of VERDIN is between 14 and 60 kilohertz. VERDIN operates in one, two, or four 50-baud channel modes. VERDIN has a number of modulation types, CW and FSK which will be used for compatibility with our present broadcast during the period of conversion to the VERDIN system; compatible shift keying (CSK), which can be detected either for phase or frequency and minimum shift keying (MSK) which is the primary mode of modulation in the VERDIN system.

The block diagram of the transmit system (Figure 1) is simplified to show components of the VERDIN system. The control unit is the interface with the outside world. It sends messages in and out of a stored program processor which is a special purpose digital computer with a 4k, 3-microsecond memory. The rubidium frequency and time standard controls both the frequency and the time within the control unit. Comprising the receiver terminal are the stored program processor, the demodulator, a radio receiver, and a frequency/time standard (Figure 2). The radio receiver can be used as a general purpose VLF receiver or it can be used with the demodulator for detecting the MSK.

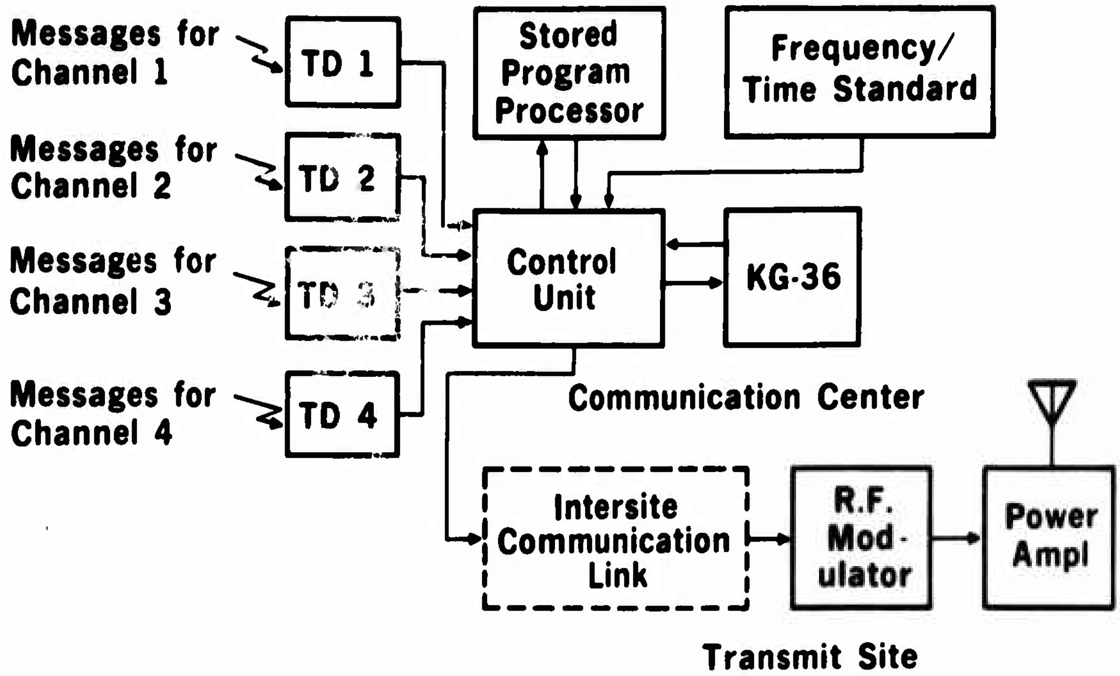

Figure 1. TRANSMIT SUBSYSTEM

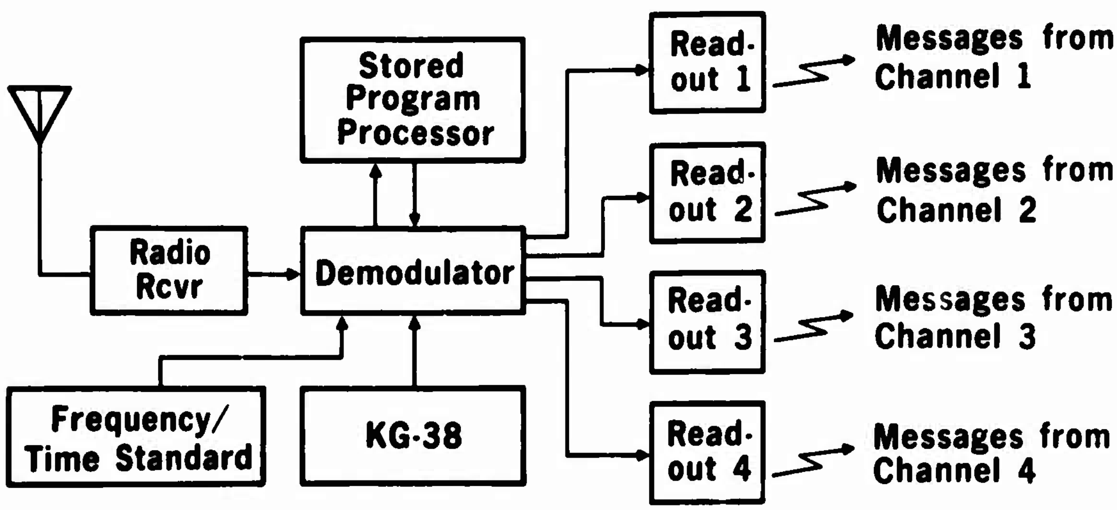

Figure 2. RECEIVE SUBSYSTEM

The stored program processor is used for synchronization and conversion of the output to a standard 7.0 low-level teletype code. Decryption is also done in the receiver terminal within the stored program processor. Again, the frequency and time standard provides accurate time within the system.

One of the main problems in a synchronous system, such as VERDIN, is synchronizing in a reasonable time. There is a tradeoff in system cost and complexity between searching for the signal over a large time uncertainty and maintaining time accurately. Figure 3 shows the cost relationship to increasing processor logic speed; as you increase the cycle time of your processor the cost curve increases fairly rapidly. If we did not have a time standard in VERDIN, we would have to search a time uncertainty of approximately ± 1 second. This would make the VERDIN system economically unfeasible and a decision was made to include a frequency and time standard in the system.

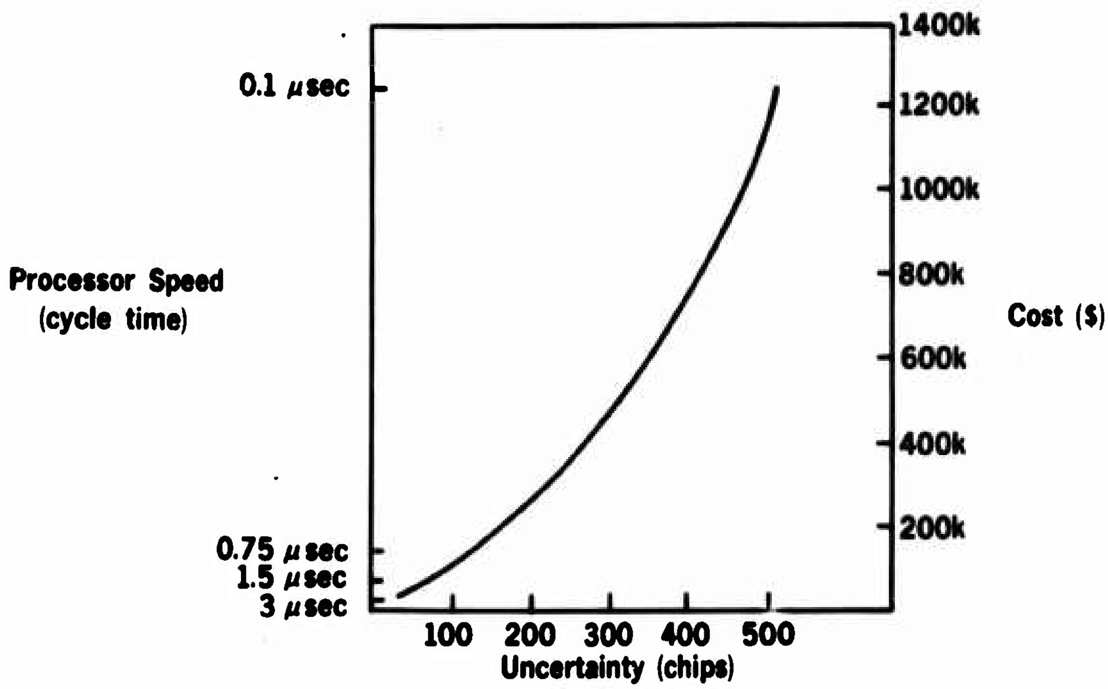

Figure 3. TIME UNCERTAINTY COSTS

In looking at the standards that were available, none were found to fit the VERDIN system very well. For the initial installations we were forced to select that which fit best into the system; however, in follow-on installations we plan to change the time standard to a design that is better integrated into the system. Figure 4 shows a comparison of the time standard that will be used in the initial and follow-on installations.

	INITIAL INSTALLATION	FOLLOW-ON INSTALLATION
Reference Cell	Rubidium	Cesium
Dimensions	H 5.22 in. W 17.0 in. D 16.0 in.	H 5.25 in. W 17.0 in. D 21.0 in.
Weight	44 lb + 10 lb standby battery	45 lb + 10 lb standby battery
Power	74 W (ac)* 50 W (dc) *with trickle charge into standby battery	90 W (ac)* 60 W (dc) *with trickle charge into standby battery
Standby Power	30 min int battery	30 min int battery
Clock	Mechanical	Electronic
Time Code	None	20-bit serial BCD

Outputs	Initial Front	Initial Rear	Follow-on Front	Follow-on Rear
5 MHz	1	4	1	4
1 MHz	1	1	1	1
100 kHz	1	1	1	1
1 pps	1	0	1	0
1 ppm	0	4	0	4

Figure 4. VERDIN FREQUENCY/TIME STANDARD CHARACTERISTICS

This complete report is classified SECRET and can be obtained only by written request to the U.S. Naval Observatory, Technical Officer, Washington, D.C. 20390.

THE NBS FREQUENCY AND TIME SATELLITE EXPERIMENT USING ATS-3

D. W. Hanson, W. F. Hamilton, and L. E. Gatterer

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by

D. W. Hanson, W. F. Hamilton, and L. E. Gatterer

Mr. Hanson, Mr. Hamilton, and Mr. Gatterer are with the Frequency and Time Dissemination Research Section, National Bureau of Standards, Boulder, Colorado.

1.0 INTRODUCTION

The work to be described is part of the National Bureau of Standards' (NBS) continuing effort to provide time and frequency information to a large number of users. This paper will discuss the current NBS time and frequency dissemination experiment using NASA's ATS-3 satellite. This work has been done partially supported by the Air Force Cambridge Research Laboratories.

2.0 CURRENT EXPERIMENT

The ATS-3 experiment is being conducted by the National Bureau of Standards operating under NASA's "User Experiment Program." Beginning on 1 August 1971, NBS began broadcasting the WWV time and frequency format from Boulder, Colorado, to the ATS-3 satellite, which then transponds the signals back to the earth. The uplink frequency to the satellite is 149.245 megahertz and the down link is at 135.625 megahertz. Figure 1 shows the transmit antenna at the Boulder Laboratories. It is a bifilar helix with 14-db gain and right circular polarization.

The signals transmitted from Boulder are frequency modulated and occupy a 30-kilohertz bandwidth. The signals are composed of voice

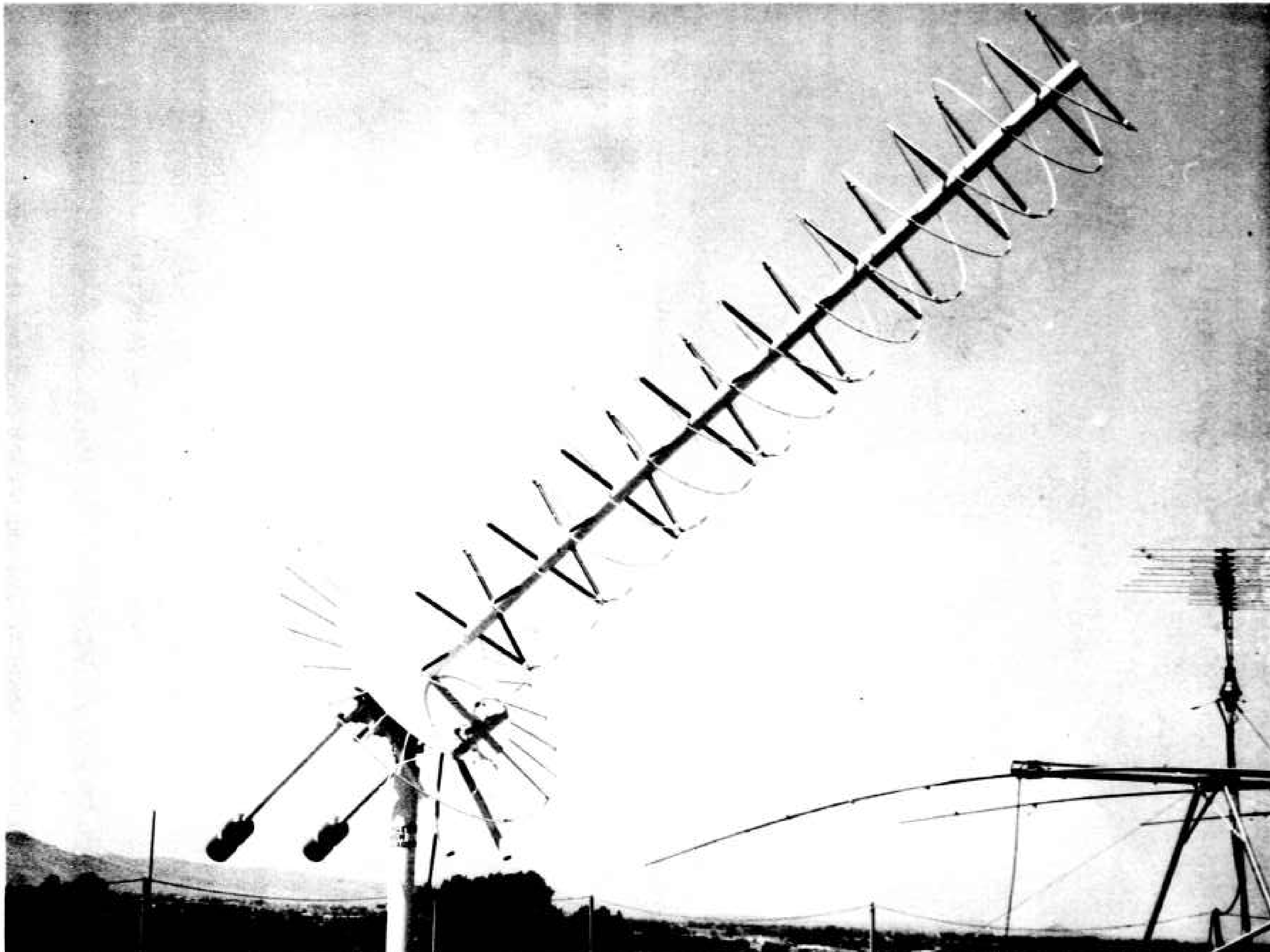

Figure 1. TRANSMITTING ANTENNA AT NBS, BOULDER COLORADO LABORATOREIS

announcements of time-of-day, ticks every second, tones, and a time code. These signals are referenced to the NBS UTC time scale. The broadcasts take place between the hours of 1700 to 1715 and 2330 to 2345 Greenwich Mean Time, Monday through Friday, excluding holidays. This experiment is scheduled to continue until 1 August 1972.

The ATS-3 spacecraft is in synchronous orbit and is presently stationed at approximately 70 degrees west longitude over the Equator. The output power from the spacecraft during these frequency and time broadcasts is approximately 10 watts fed to an 8 db gain, linearly polarized antenna or, + 48 db EIRP. The spacecraft antenna provides earth coverage as seen from synchronous altitude. In this case, the coverage includes North and South America, major parts of the Pacific and Atlantic Oceans, and a portion of Europe and Africa. In Figure 2 you will see a heavier line, or 5-degree elevation line, which approximates the periphery of usable coverage.

It has been a fundamental constraint in all NBS satellite experiments [1-4] that the user requirements for the reception and recovery of time and frequency signals be simple and inexpensive. Figure 3 shows the typical equipment used to receive the ATS-3 time and frequency signals. Shown are a 10-db gain Yagi antenna, linearly polarized, and an FM receiver. The receiver's noise figure has been improved by the addition of a transistor preamplifier to give a 5-db noise figure.

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1. Jespersen, J.L., G. Kamas, L.E. Gatterer, and P.E. MacDoran (1968), "Satellite VHF Transponder Time Synchronization," Proc. IEEE Vol. 56, No. 7, July 1968, pp. 1202- 206.

2. Gatterer, L.E., P.W. Bottone, and A.H. Morgan (1968), "Worldwide Clock Synchronization Using a Synchronous Satellite," IEEE Trans. Instr. and Meas., Vol. IM-17, No. 4, December 1968, pp. 372- 78.

3. Hanson, D.W. and W.F. Hamilton (1971), "One-Way Time Synchronization via Geostationary Satellites at UHF," IEEE Trans. Instr. and Meas., Vol. IM-20, No. 3, August 1971, pp. 147- 53.

4. Hanson, D.W. and W.F. Hamilton (1971), "Clock Synchronization from Satellite Tracking," IEEE Trans. Aerospace and Electronic Systems, Vol. AES-7, No. 5 September 1971.

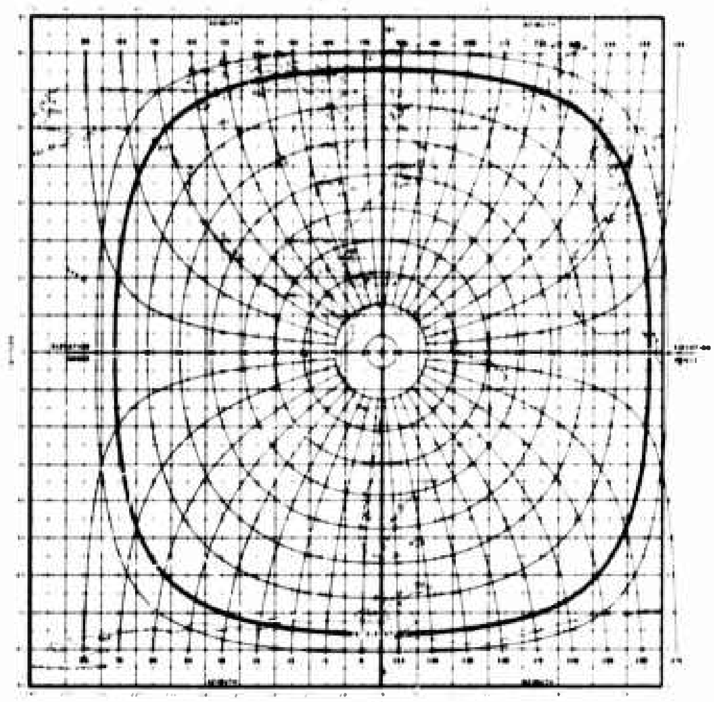

Figure 2. RECEIVER ANTENNA POINTING ANGLES

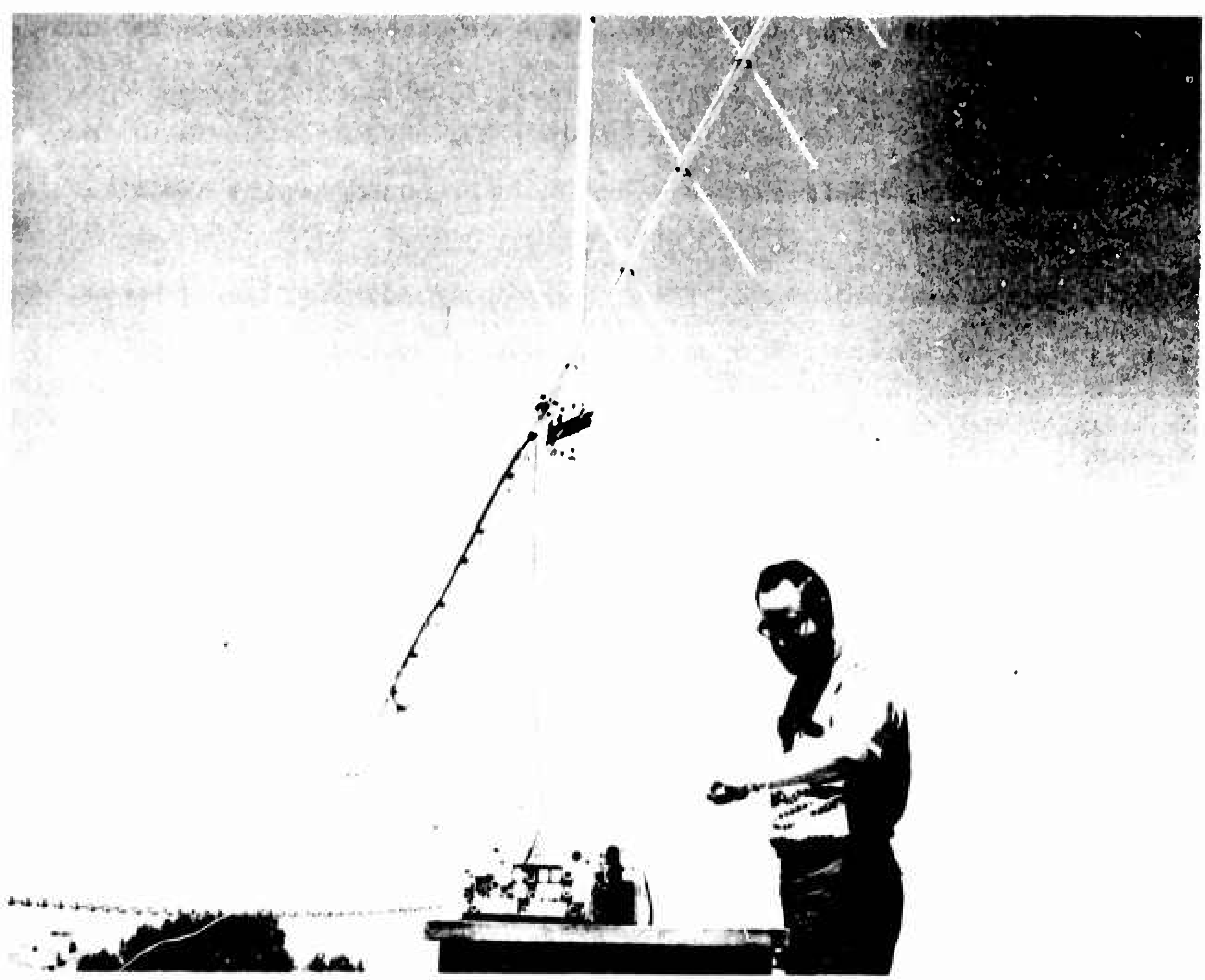

Figure 3. TYPICAL ATS-3 TIME AND FREQUENCY RECEIVING EQUIPMENT

We are now using a commercial circularly polarized receiving antenna, low-noise transistorized preamplifier (2.8-db noise figure) and FM receiver which sells for approximately $150. Figure 4 shows the received signals from ATS-3 as seen on an oscilloscope. This is the 1 pps tick and 600 Hz tone which is typical of the WWV format. Figure 5 shows an expanded view of the 1 pps tick as received at Boulder, Colorado. The propagation delay is very stable and the signals at Boulder have been free from any noticeable fading which allows for excellent timing resolution.

3.0 LEVELS OF SERVICE

We think of the ATS-3 experiment as offering three levels of service. The first level is obtained by simply listening to the ticks and voice announcements from the satellite. The signals leave Boulder on time and, because of the satellite's 38,000-kilometer altitude, the signals arrive back on earth delayed by approximately one-quarter of a second.

The second level of service is realized when one measures accurately the arrival time of the transmitted "ticks" relative to ticks of his local clock. Referring to Figure 5, by observing the positive going zero crossing of the first cycle of the tick, one is able, with visual averaging, to achieve 10 microsecond resolution in the time of that crossing relative to his local clock. At Boulder, with our local clock on time, we have been measuring the delays from Boulder to ATS-3 and back to Boulder, including equipment delays. If our local clock had not been on time, that difference would have been included in that "apparent" delay measurement. In order for our listeners to determine what the delay should be to their location, we have prepared contours of delay for the user of this experimental service.

Figure 6 shows the delay contours for the 1700-1715 GMT broadcast. If one wished to know the delay from Boulder to Washington, D.C., via ATS-3, he would look at the contour line which runs through Boulder and add it to

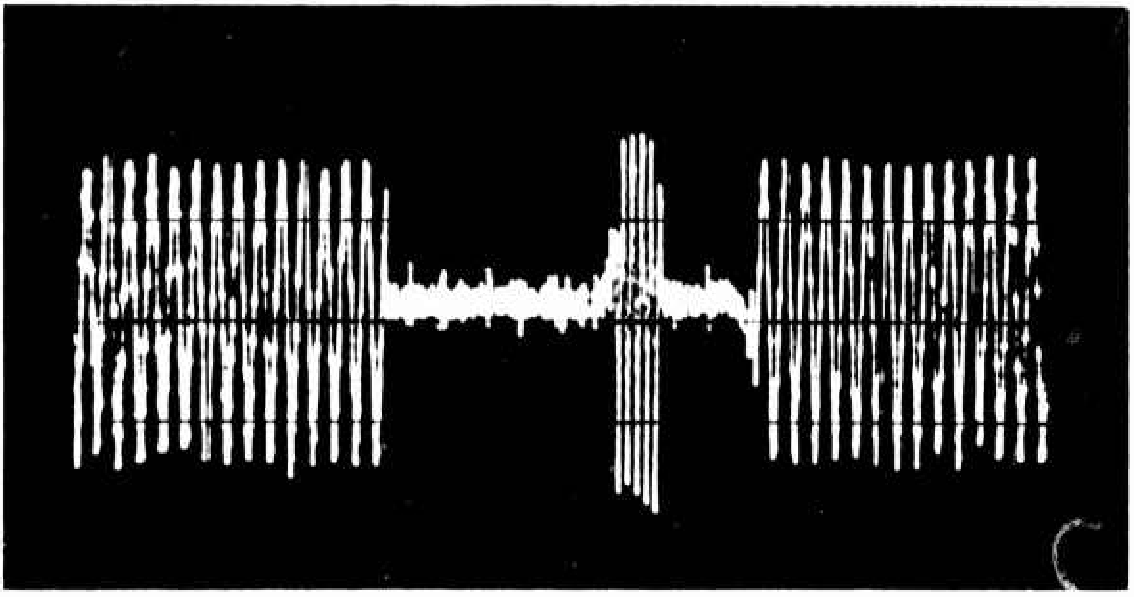

Figure 4. RECEIVED SIGNALS FROM ATS-3
(TICK AND TONE; SWEEP SPEED 10 ms/cm)

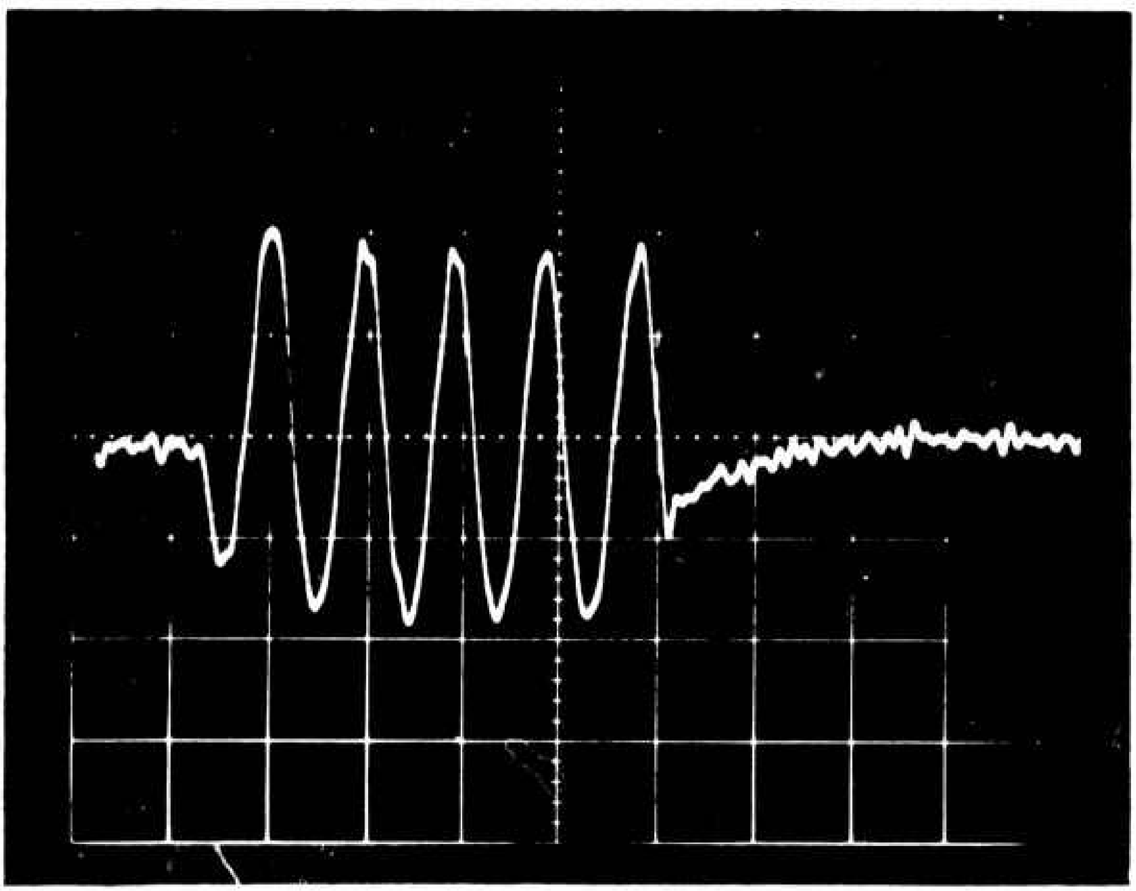

Figure 5. RECEIVED SIGNALS FROM ATS-3
(TICK; 1 ms/cm)

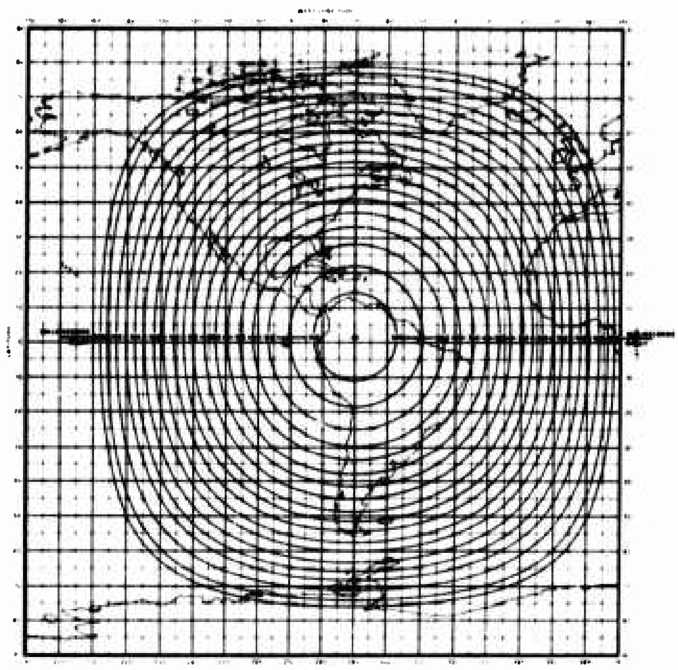

Figure 6. PROPAGATION DELAY 1700-1715 GMT

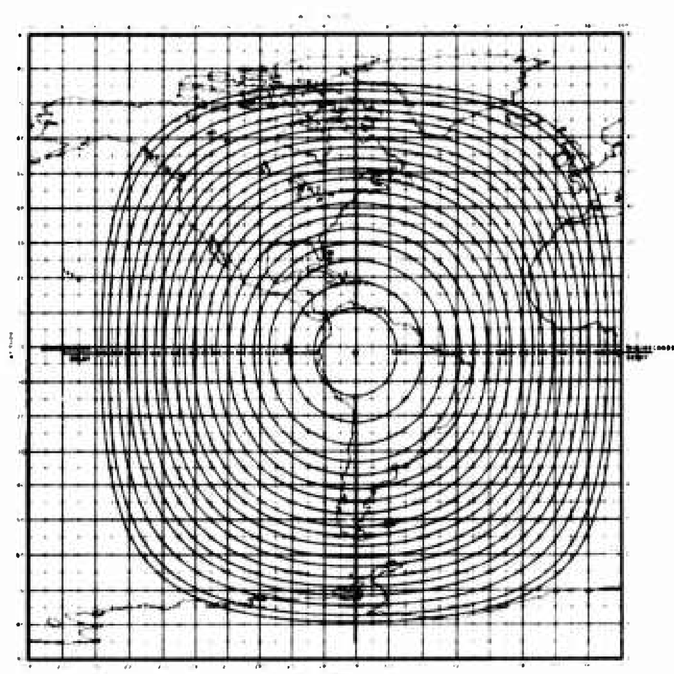

Figure 7. PROPAGATION DELAY 2330-2345 GMT

the one which runs through Washington, D.C. Figure 7 shows the delay contours for the 2330-2345 GMT broadcasts. These delay contours are generated from the orbital elements issued by NASA on ATS-3. From these elements we derive new contours monthly and publish them in the NBS Time and Frequency Services Bulletin.* In addition to the delay contours we include in the NBS Time and Frequency Services Bulletin contours of azimuth and elevation to enable our listeners to point their antenna at the satellite. Those contours are shown in Figure 2. It has been our experience that these delay contours allow timing to a few milliseconds. Figures 2, 6, and 7 were derived from NASA orbital elements issued for 23 October 1971.

The third level of service should be in effect by 1 January 1972. Our work with NASA's orbital elements has generally allowed us to predict the delays from Boulder to any point in view of the satellite to within 10 to 20 microseconds. To enable our listeners to benefit from this ability, we have designed a special purpose delay computer in the form of a circular slide rule. A prototype of this slide rule is shown in Figures 8a and 8b, which show the front and back of the rule, respectively. When we initiate this third level of service, we will broadcast by voice the satellite's longitude and latitude and a radius correction. The user will enter this information along with his longitude and latitude on the slide rule and compute the delay to his location to within 10 to 20 microseconds. This capability coupled with the path delay short-term stability should enable the user to obtain much better than a 50-microsecond timing.

A quantity of these slide rules are now being manufactured on a heavy plastic laminate. Since the program described is experimental, NBS requires

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* For duration of this experiment, booklets, slide rules, and bulletins are available upon request. Write National Bureau of Standards, Frequency-Time Dissemination Research Section, Boulder, Colorado 80302.

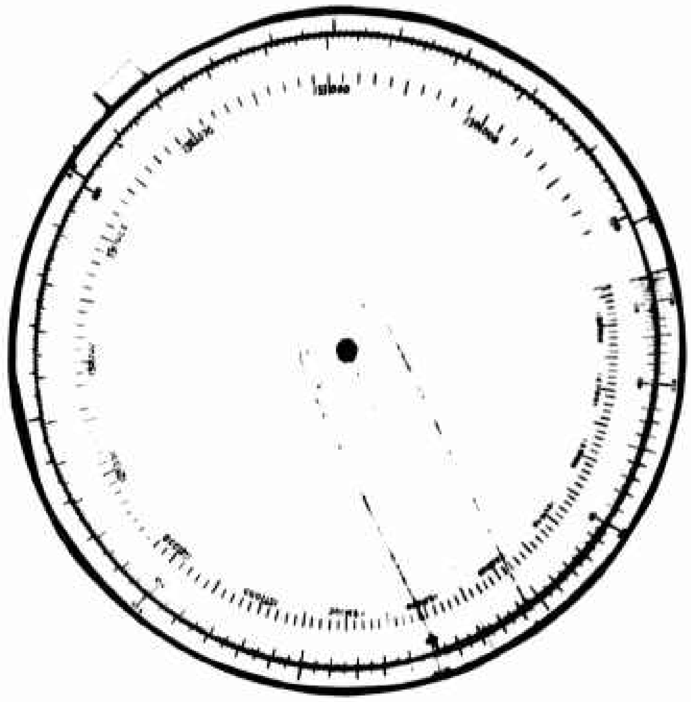

Figure 8a. PROTOTYPE DELAY COMPUTER (FRONT)

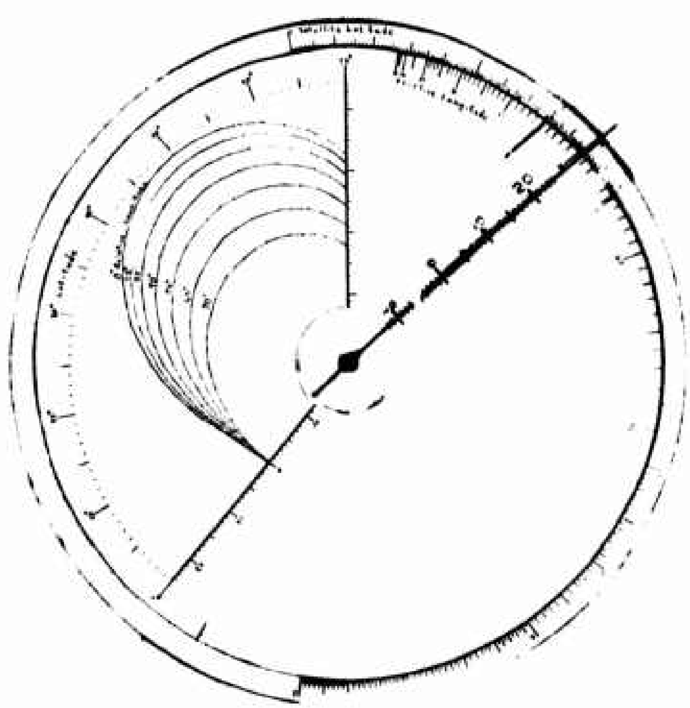

Figure 8b. PROTOTYPE DELAY COMPUTER (BACK)

data to verify its expectations. Anyone who has access to a good time reference and can provide NBS with data is being encouraged to use one of these slide rules when they become available. An informative booklet explaining this service is also available.*

Figures 9 and 10 show the results we have experienced at Boulder with the slide rule. The unbroken lines represent the delays obtained from the slide rule. The broken lines represent our measurements. The rms deviation over a period of months is less than 25 microseconds.

4.0 SUMMARY

In summary we believe that satellites can and will provide high accuracy timing to the public at low cost as NBS remains committed to that end.

* For duration of this experiment, booklets, slide rules, or bulletins are available upon request. Write National Bureau of Standards, Frequency-Time Dissemination Research Section, Boulder, Colorado 80302.

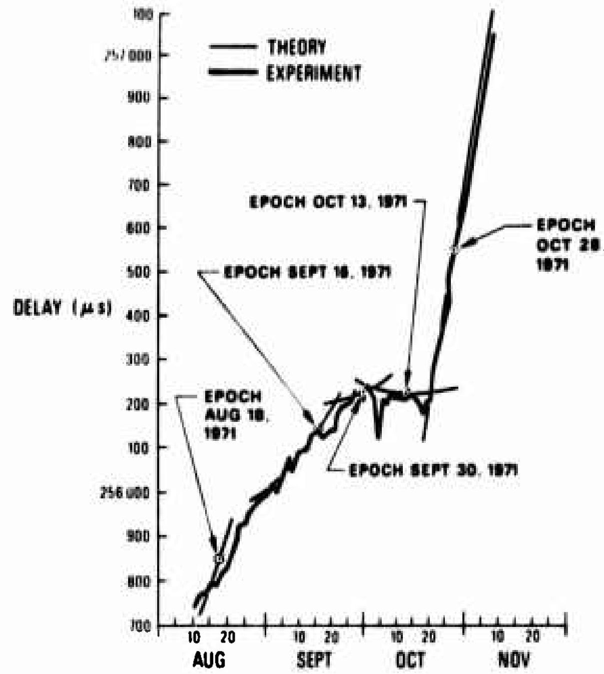

Figure 9. DELAY MEASUREMENTS AT NBS BOULDER FOR 1700 GMT

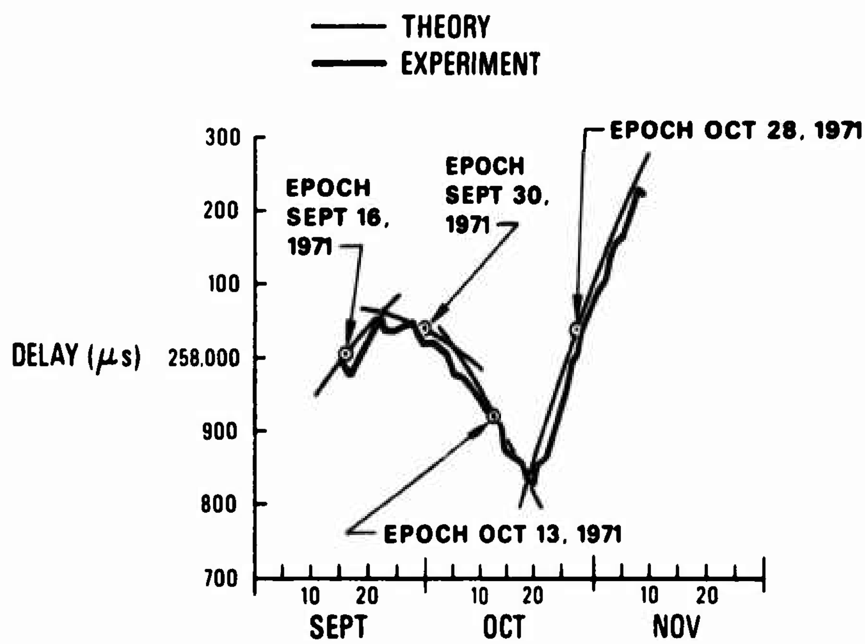

Figure 10. DELAY MEASUREMENTS AT NBS BOULDER FOR 2330 GMT

DSCS PTTI TRANSFER

by

Capt R.E. Enright

Captain Enright is DSC Program Project Manager, Defense Communications Agency, Washington, D.C.

This will be a discussion on the background and the future of the Defense Satellite Communications Program. I am going to give an introduction to our satellite system, where we are and where we are going.

The Defense Satellite Communications Program is currently operating with what we call the Phase One Satellite. They are very unsophisticated little satellites with a total power output of three watts. They only weigh about 100 pounds; they are spin-stabilized. They have an oddball shape for an equatorial drifting satellite (Figure 1), but these were originally designed to go into polar orbit. We now have 26 of these in orbit, 21 of which are working. These satellites are not controllable; we get beacon telemetry out of them but we can't turn them on, we can't turn them off, and we can't move them. They just drift up there at a rate of about 25 degrees per day.

Figure 2 shows our largest terminal which is the FSC-9. It was designed back in the days of SYNCOM and has been converted progressively since then. It will operate with a Phase One bird or a Phase Two bird. It is quite heavy because of the 60-foot dishes. We have two FSC-9's; one at Camp Roberts, California, the other at Ft. Dix, New Jersey.

Figure 3 shows the MSC-46 which is the "work horse" of our satellite system. We have 14 of these. They have 40-foot dishes and it is

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possible to move them. We moved one in a little over a week in Asmara, although the time normally quoted is 30 days. We are in the process of moving another one from Wildwood, Alaska to Taegu, Korea.

The TSC-54 is shown in Figure 4. It has an 18-foot equivalent antenna and is highly transportable. It can be folded up and put in an aircraft in about two or three hours. We have had them operating within two hours after off-loading from the aircraft. These can be moved, of course, to anywhere that a C-141 or a C-133 equivalent can operate.

Our new generation satellite is shown in Figures 5a and 5b. This is the Triple-7 bird, our Phase Two satellite, which is quite a bit more sophisticated than the Phase One. It is 9 feet in diameter, about 13 feet tall, and weighs about 1150 pounds. It has two steerable antennas; each has a beam width of about two and one-half degrees. The horns in the middle are the earth coverage mode antennas. The satellite generates about 500 watts. Each of the transmitters is powered by a 20 watt TWT. The actual flux density put out by those narrow beam antennas right now exceeds the flux density allowed by the ITU, so it may have to be reduced. This could provide, between big antennas, as many as 1200 voice channels of communications. On the other hand, if the earth coverage antennas were dedicated to two airborne terminals with 32-inch dishes, it would take the entire satellite to communicate one 2400-bit data channel. This satellite will serve for analog communications, digital data users, and it will serve such things as the wideband imagery and the Compass Link photography being sent back from Vietnam. Not being in competition with the commercial satellite people, we can run many different types of signals through it. If we were to acquire the wideband services through COMSAT right now, we would have a hard time paying the bill. COMSAT is now charging companies such as IT&T and World Comm about $4,000.00 per voice channel per month.

Figure 6 shows the terminal configuration which we have at the present moment and it is a point-to-point network. We are not very efficient; Northwest Cape cannot talk to Kwaijalien, Northwest Cape talks to Guam. Saigon talks only to Hawaii. Hawaii, however, relays to Camp Roberts.

The first two Phase Two satellites were launched November 2 from the Eastern Test Range, and about eight hours after the launch we had lost both of them. During the day, we recovered the serial number 2 satellite. It was a combination of software problems (they put the "A" program in the "B" computer) and a hardware fault in the satellite. The second satellite was recovered three days later by analyzing the hardware fault. Right now the hardware faults are under control; they still exist but we know how to work around them and at this moment, they do not cause any significant decrease in reliability. We exepct to test both satellites over the Los Angeles area (105^{o}W and 115^{o}W) for approximately 60 days, at which time the best of the two satellites will be drifted to the west to a position at 173^{o}E. The other satellite will be put over the Atlantic at 13^{o}W. However, that second satellite will be subject to additional testing through our terminals at Fort Monmouth and Fort Dix. Two of these terminals are training models; two of them are engineering models. Fort Dix is part of the engineering system but later it will become the backup terminal for our CONUS East.

Figure 6 shows those sites at which we now have the PTTI capability, or cesium standards. We have directed all the services to procure cesium standards for all terminals for two reasons. First is the advantage of not having to fly these standards around the world for calibration, and second we have in our system a spread spectrum device whose performance can be improved by use of these standards.

Now that the satellite has been described, I would like to discuss some of its advantages. We can operate in any sort of a mode with this satellite. In other words, we can go from earth coverage to earth coverage, transmit on earth coverage and receive on narrow beam, and vice versa. It has adjustable power output and a secure command and telemetry channel. Our hardware problem is in that secure system but it is under control.

Another advantage of this satellite over our current satellites is that although it will be geostationary, we can reposition it at 30 degrees per day, which is absolutely linear. In other words, we can reposition it 30 times at 1° per day or 15 times at 2° per day. It does not start to break down in linearity until you get down to below a tenth of a degree per day in positioning. One reason for this is that the repositioning device is a pulse jet type of thruster operating on hydrazene so one tells it how many pulses to shoot out and it gives the delta V to drift into various stations. Also sufficient fuel for the east-west station keeping and slow repositioning is now on board for seven years vice five years specified. Therefore, if everything else works out as well as the Phase One birds we can have these satellites around for quite some time. We can switch between all of the components within the satellite and we can control the gains and we can switch everything around and steer these antennas in addition to steering the satellite.

Figure 7 shows a very high performance 60-foot antenna. It is not transportable but it is recoverable. It is designed so that a crew of riggers can dismantle it in about two weeks and re-erect in about a month. It is all bolted together, there is no welding that would have to be done. The only thing that is not recoverable is the concrete foundation.

To accompany this is a new medium terminal shown in Figure 8. It uses the same antenna design as the AN/TSC-54. In the background you see the electronic van, maintenance and supply van and an operations van.

The vans for the heavy terminal look just like the vans for the medium terminal. As a matter of fact, you can see a pipeline coming out that contains the Servo control cable and the RF system. If you put a connector in the middle you can plug either antenna into either set of electronics. The basic difference between the two of them is the degree of redundancy in highpowered amplifiers and in some of the up and down converters. These terminals will be capable of transmitting as many as ten up channels and receiving twelve down channels, it is very versatile.

During this past summer, we conducted a serious study of what the post-1976 satellite would look like and no significant break throughs are expected between 1976 and 1978. However looking beyond that we see some very fancy satellites, possibly using the higher ranges - 15, 30, 40 gigahertz region - and we may have satellite-to-satellite link at EHF in the 60 gigahertz region.

This is the status of the Defense Satellite Communications System that will one day allow us to transfer time to all of our major bases around the world. The Navy is developing a family of shipboard terminals. The Air Force has developed an advanced development model of an airborne terminal.

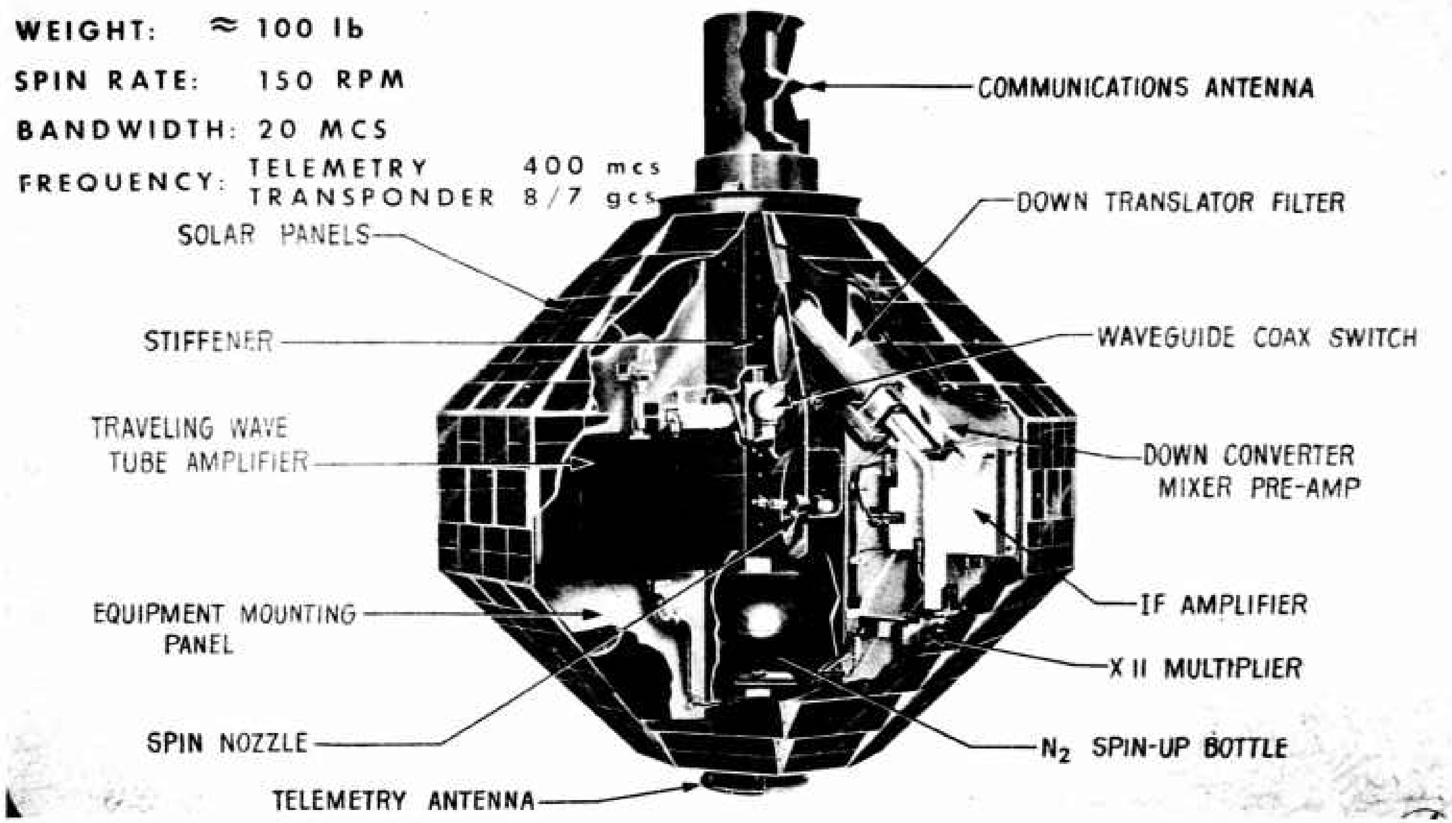

Figure 1. SPACE SUBSYSTEM - SATELLITE

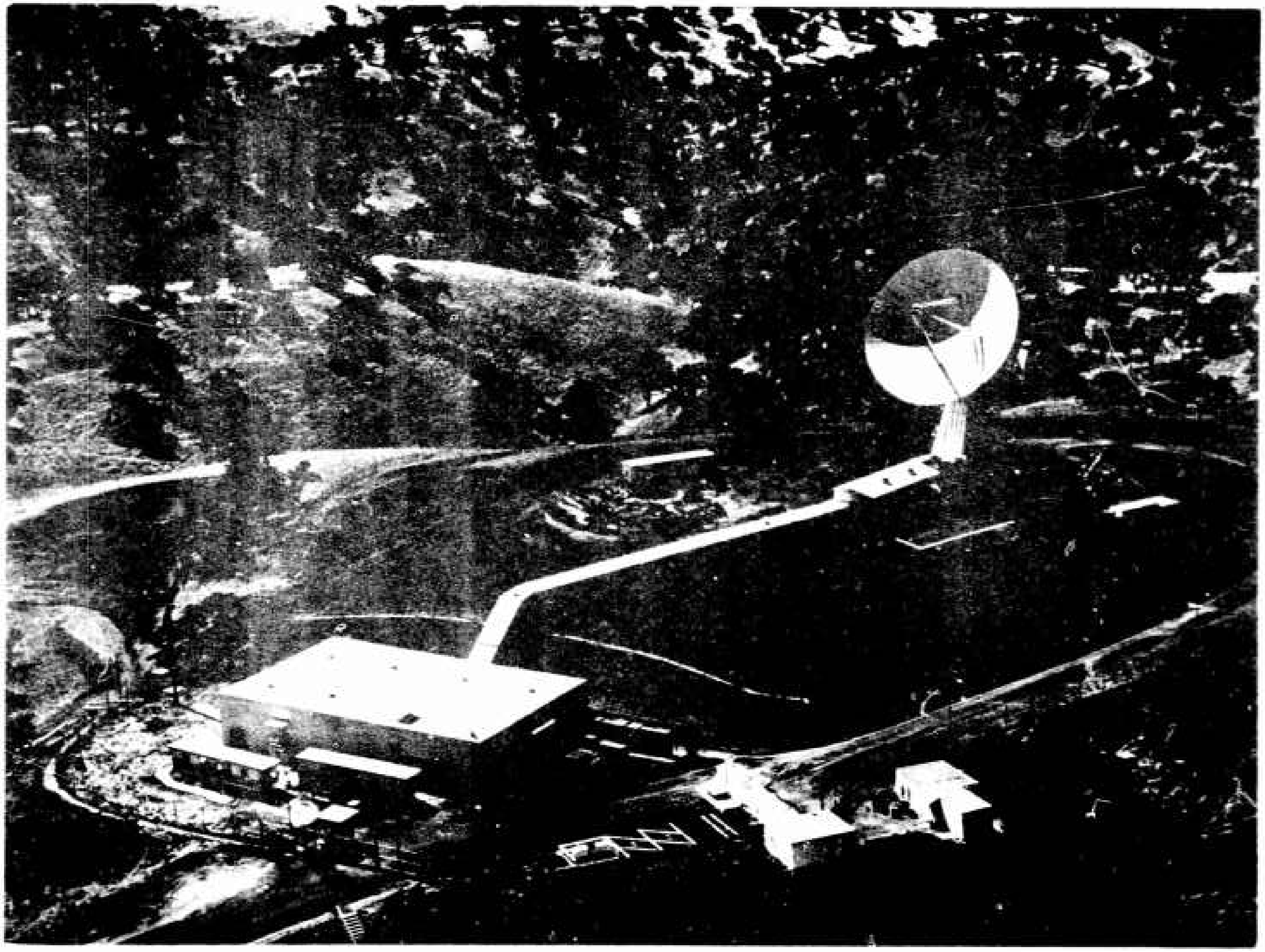

Figure 2. FSC-9 MODEL

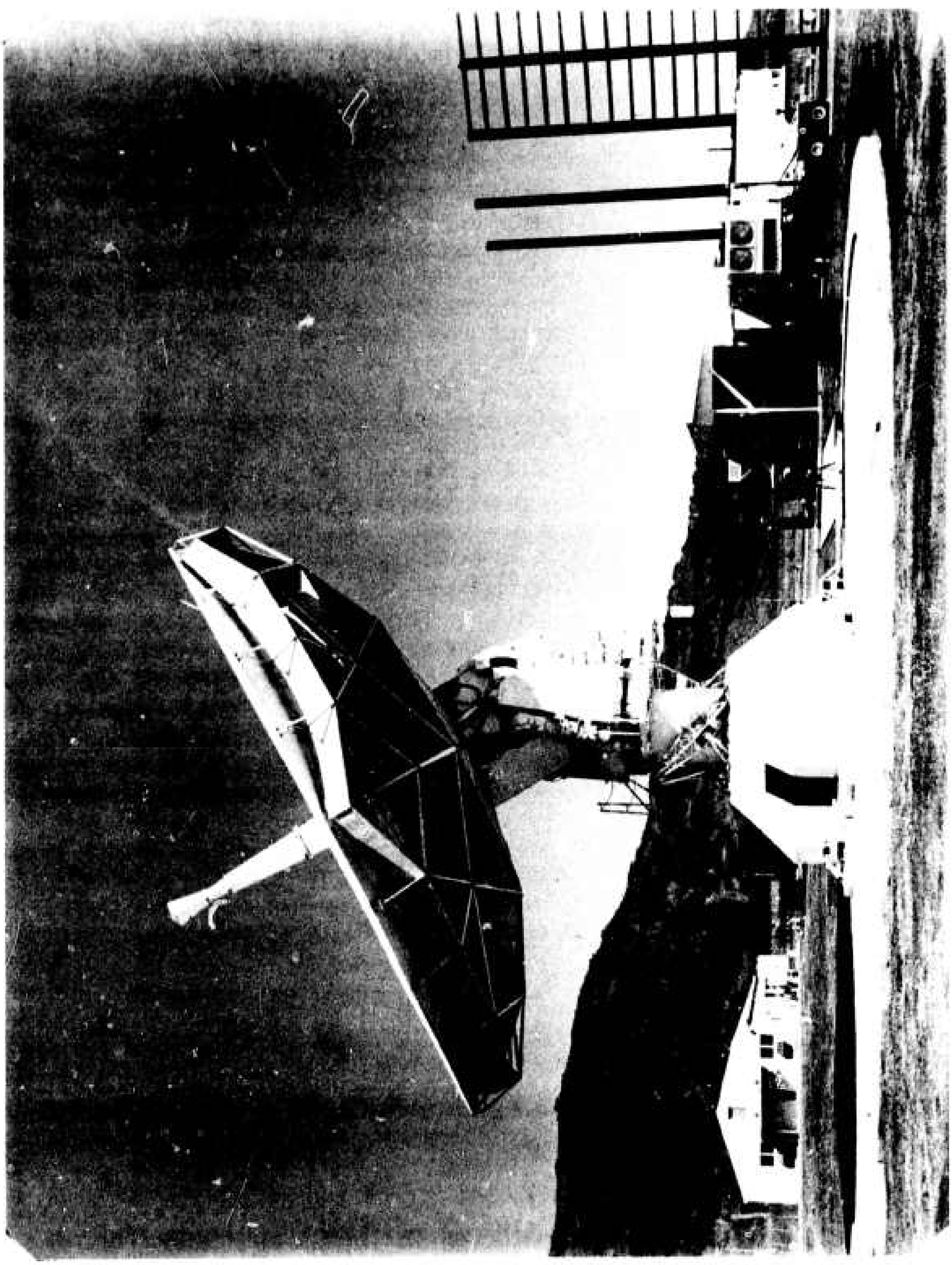

Figure 3. MSC-46 MODEL

Figure 4. TSC-54 MODEL

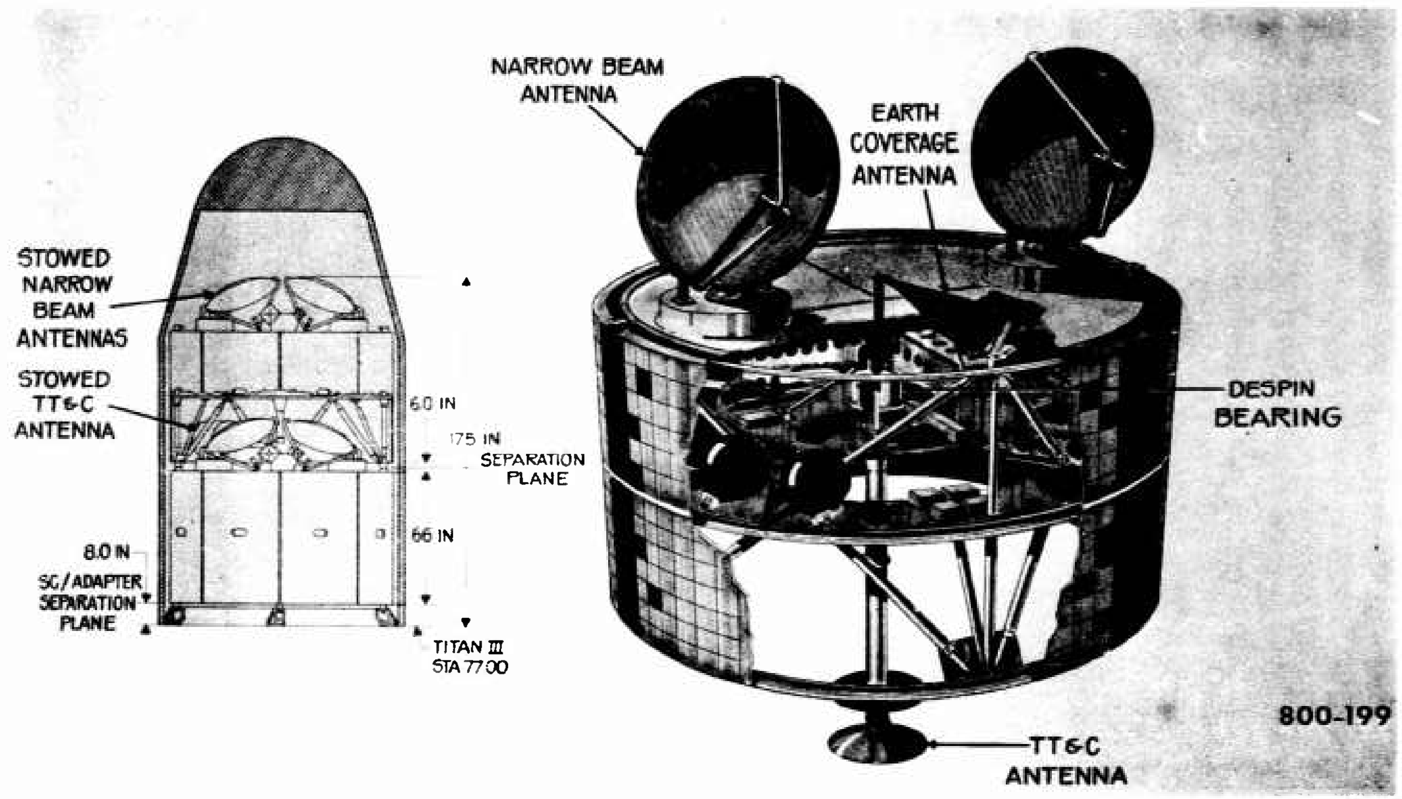

Figure 5a. INSIDE VIEW OF PHASE TWO SATELLITE

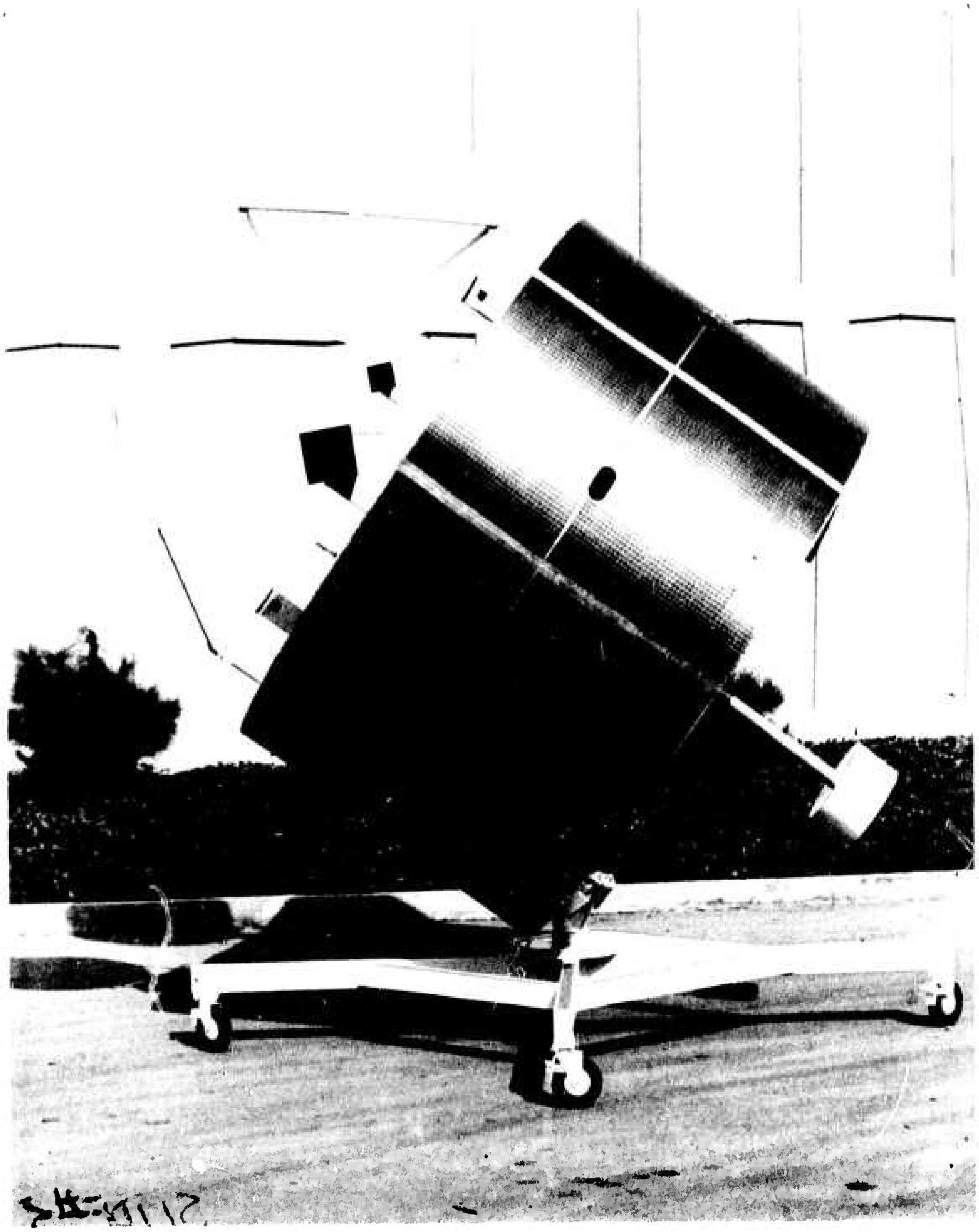

Figure 5b. OUTSIDE VIEW OF PHASE TWO SATELLITE

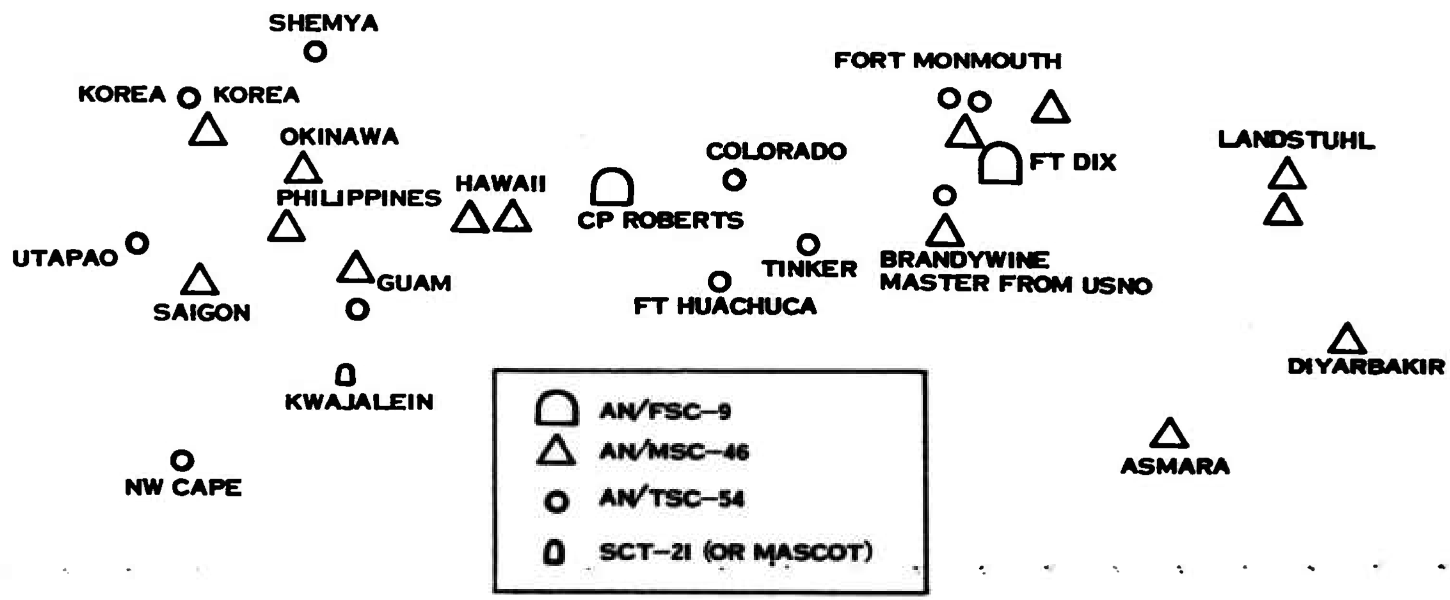

Figure 6. CONFIGURATION FOR PTTI OPERATIONS

Figure 7. HIGH PERFORMANCE 60-FOOT ANTENNA

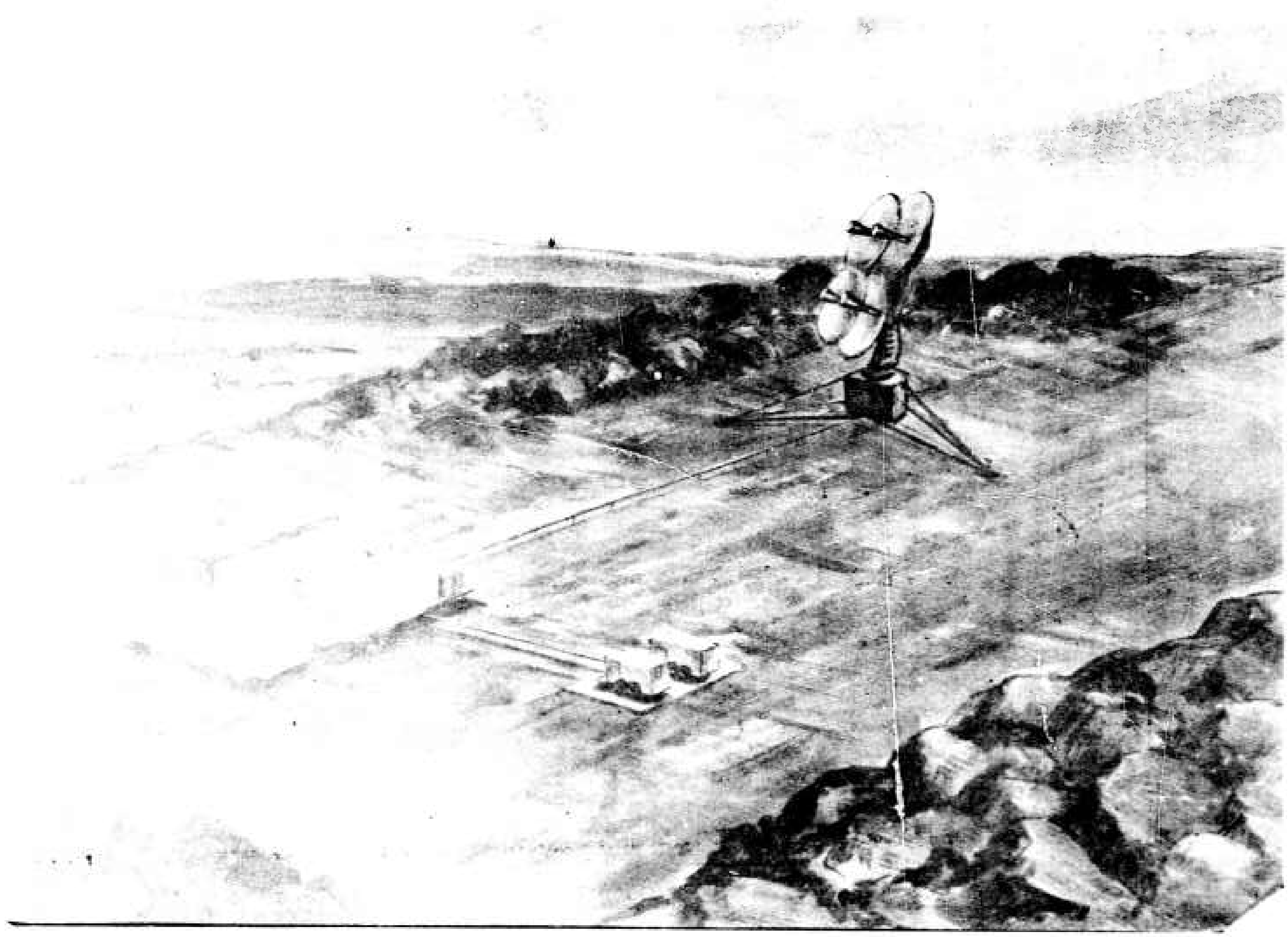

Figure 8. MEDIUM TERMINAL COMPLEX

DISCUSSION

CAPT ENRIGHT: I have a question for Dr. Winkler. Has anyone given consideration to the transfer of time internationally using INTELSAT.

DR. WINKLER:, Yes, in fact we have had several long discussions with INTELSAT. It appears, that they would consider transferring time, but only at a very high dollar cost. Apparently the configuration and the dedication of the various channels is so fixed that it would cause very severe operational problems. I wonder if Mr. Gatterer would not have some additional information.

MR. GATTERER: I expect that Dr. Winkler's conversations with INTELSAT are far more recent than any that I've had. I've been in communication in the past with COMSAT, and convinced myself of the feasibility of using their system for time transfers. I do agree that it appeared quite expensive unless we made use of things that would be free, such as the pilot tones themselves. However, for a base band transfer, it is quite expensive. Nonetheless, my expectation is that the only thing better than Loran-C would be a broadband satellite transfer. The only way that I can see to improve over the good time-transfer capabilities of Loran-C is by using INTELSAT. Therefore my expectation is that it would take place sometime in the future. Would you agree with that, Dr. Winkler?

DR. WINKLER: Not quite. I consider our immediate needs in DOD as somewhat more important at the moment. I feel that the Defense Satellite Communications System will satisfy most of our needs; certainly those which go to centers of activities located in strategic areas. In addition to that, we have a number of precise time requirements which are way outside any conventional operational area and must be satisfied by different means. I personally believe that approaches such as these indicated by Mr. Easton yesterday, or by Dr. Krishner will provide a truly worldwide capability. Possibly an improved tranist satellite will be provided which will allow a one-way dissemination of time to a user without any retransmission of signals. I also think that can be done relatively cheaply and you get around the complicated second step of distributing time from a ground terminal. In defense applications that is less of a problem than to go for international distribution. I have at least one promising thing in mind and that is that we may be able to make some time transfers with the British, using the DSCS, in the not too distant future. There is another implication, however, and I will come to that later in my talk about the UTC adjustments. That is, at any time we have to interface with international systems or systems operated by other nations, the question of which time scale is to be used and what kind of an operation will be adopted is a very important one.

PRECISE TIME/FREQUENCY FOR THE DEFENSE COMMUNICATIONS SYSTEM

by

Harold C. Folts

Mr. Folts is an Electronics Engineer at the Defense Communications Engineering Office, Reston, Virginia.

The role of Precise Time and Time Interval (PTTI) in the Defense Communications System (DCS) is becoming significant as a result of increasing digital transmission rates and advancing communication technology. Dynamic advances in PTTI technology are providing high degrees of precision with reliability. Therefore, it is now economically feasible to address the distribution and application of PTTI on a worldwide system basis.

During November 1970, DCEO and NSA conducted a field test to determine the effects of system timing accuracy variations on the performance of time division multiplexed (TDM) digital transmission trunks. The results showed that existing DCS timing facilities were not precisely on the same frequency and that these discrepancies had an adverse effect on the performance of the TDM circuits.

Action was then initiated to provide effective system timing to support the implementation of a TDM network. Further, it was recognized that all DCS station timing facilities should be analyzed to determine their present and potential ability to satisfy the present and future DCS requirements for precise timing and frequency.

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During this analysis, it was found that many independent efforts were being pursued in the transfer and application of PTTI, but no unified systems approach was being taken by anyone. Therefore, the Defense Communications Agency, in coordination with the Naval Observatory, established the Defense Communications Committee for Precise Time and Time Interval Policy (known as the Music Man Committee). The objective of this group is to develop a DCS PTTI subsystem concept that will not only satisfy current and future DCS PTTI requirements but will also provide the capability for serving other users within the DOD.

The primary motivation for providing precise timing facilities in a communications network is the need for the maintenance of frequency coherence between the transmission nodal points. Every nodal timing facility must be on the same frequency and must have the required degree of long-term stability. In addition, a major nodal point must not be dependent on any other nodal point for its timing reference. This arrangement allows the network to continue operation through diversified routes if a nodal facility fails. In addition, the retiming of digital signals at each node serves as a means of blocking low frequency oscillations and preventing other perturbations from propagating through each link of a tandem connection in a network.

The timing facilities that are currently employed in the DCS are adequate in their present applications since they are point-to-point transmissions using relatively low data rates. However, their specified performance is not easily maintained, and they have a limited capability to satisfy the more precise requirements in a worldwide network environment.

Figure 1 shows a widely used scheme in the DCS. It consists of triplicated crystal oscillators with stabilities ranging from 1×10^{-9} to 1×10^{-10} per day. These are calibrated against a standard VLF signal and can be manually adjusted to an accuracy of 1×10^{-10}. Experience in the field, however, has shown that this scheme is particularly vulnerable to

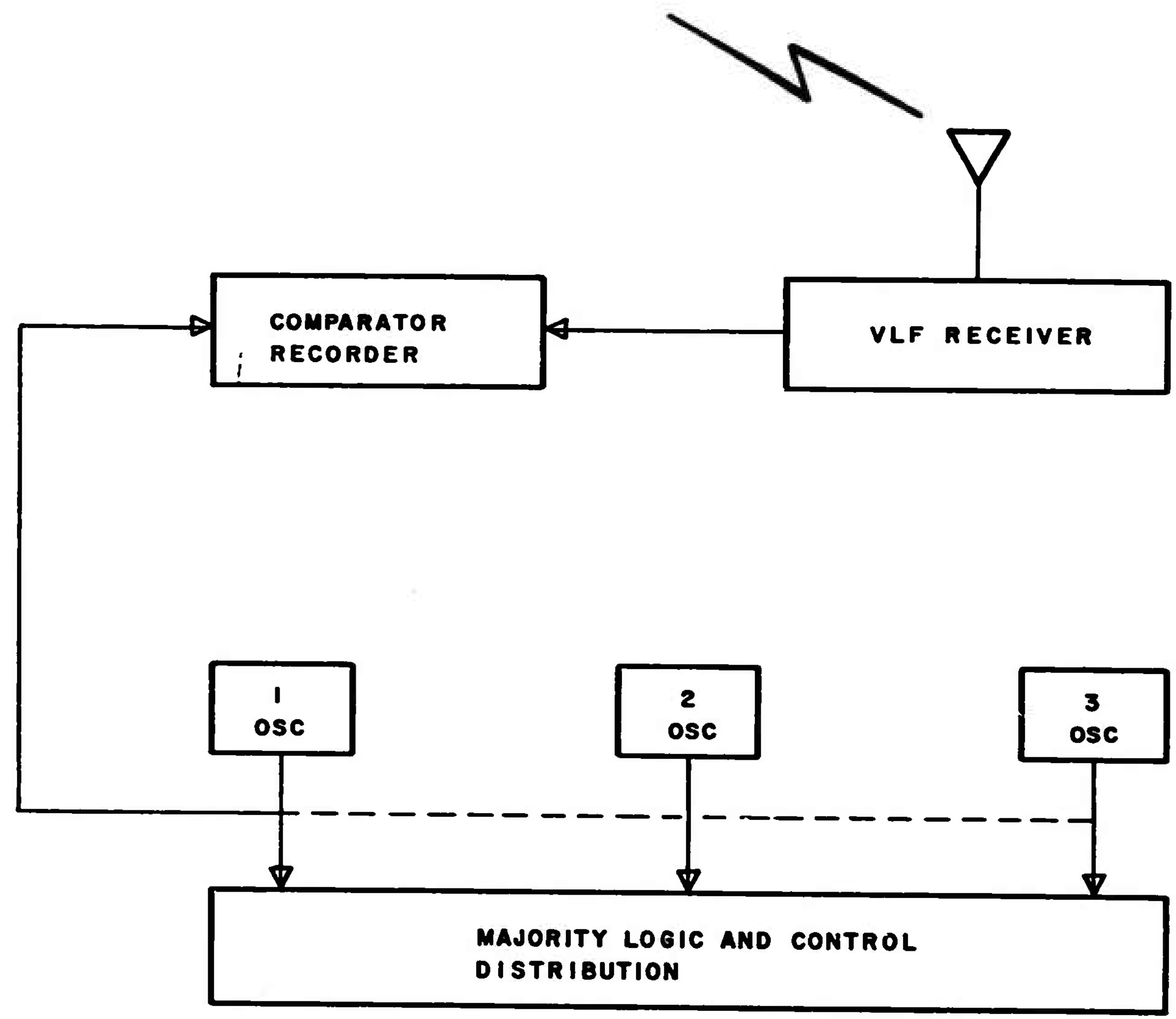

Figure 1. EXISTING MANUAL SCHEME

human error made in determining the corrections required and in making the oscillator adjustments. A high level of maintenance discipline is required to achieve optimum performance.

Another timing system in the DCS shown in Figure 2 uses phase locked oscillators which track either against timing recovered from a received data signal or against a reference derived from a rubidium frequency source. The data-recovered timing is subject to severe perturbation through the transmission media, which limits its performance. When a rubidium frequency source is used, periodic manual calibration against a precise standard is required to ensure continuing accuracy.

An approach that will overcome the limitations experienced with the existing timing facilities should provide for an automatic correction of station oscillators by use of a precise reference that is traceable to the master reference at the Naval Observatory. Advances in state-of-the-art time transfer techniques and electronic servo control of crystal oscillators now make it possible to maintain frequency coherence throughout a world-wide communication network to within 1×10^{-12} per day.

Figure 3 illustrates the concept of a typical precise timing facility at a major nodal point consisting of:

- A continuous precise reference source derived from the Naval Observatory master reference.

- An alternate precise reference source for applications where high accuracy reliability is required.

- Duplicated disciplined oscillators with state-of-the-art crystals and electronic servo control.

- A majority logic control, alarm, and distribution unit to serve as the nerve center. When the primary reference signal is lost, the alternate reference will be automatically switched into the system. Faulty units will be detected through the majority logic and alarm circuits.

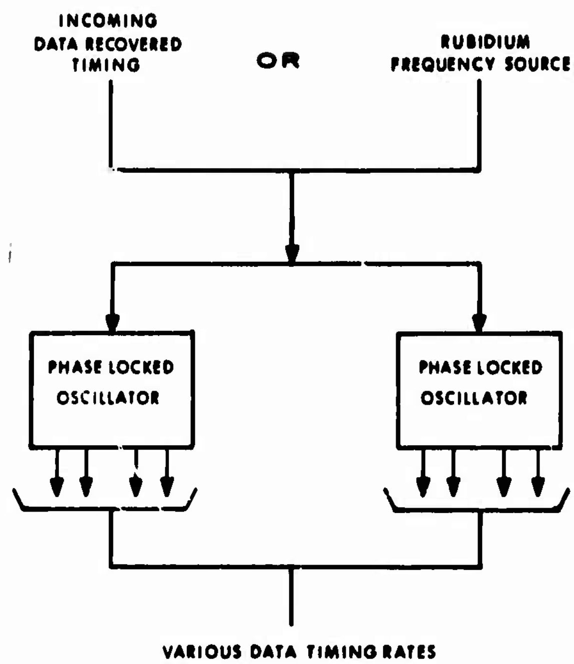

Figure 2. EXISTING TIME RECOVERY PHASE LOCKED SCHEME

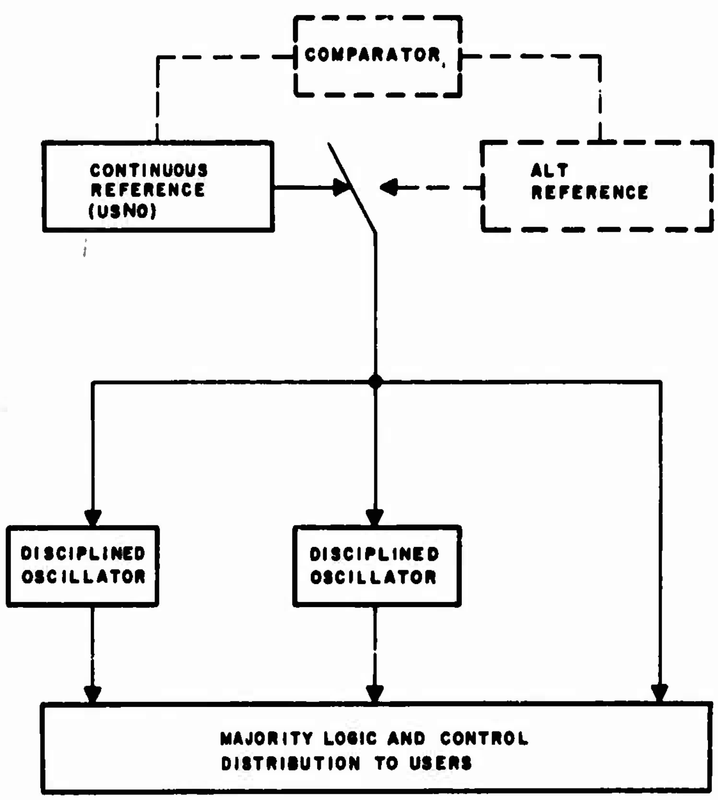

Figure 3. TYPICAL NODAL TIMING FACILITY

This system is triplicated to ensure a continuous uninterrupted precise source and identification of any frequency change that may occur in one of the sources. Standard outputs of 1 MHz are then distributed for user application. By further employing a time tic or code with the frequency reference, the facility will be able to provide precise time as well as time interval.

To satisfy immediate requirements, the AN/GSQ-174 Loran-C/disciplined oscillator scheme is currently being implemented for a number of nodal points in the DCS. This system provides a precise facility in consonance with the concept presented.

The application of the AN/GSQ-174 scheme provides an initial step in the establishment of a worldwide DCS PTTI subsystem. A system hierarchy as shown in Figure 4 must be developed from the Naval Observatory master reference, down through precise primary and secondary nodal point facilities, then distributed through various levels of precision as necessary to meet user requirements. Diversification of primary reference routes to the Naval Observatory will be essential to ensure survivability. At primary PTTI nodes, the reference should be obtained from combinations of two sources such as the Defense Satellite Communications System (DSCS), Loran-C, on-site cesium standard and other reliable methods as they are developed. Further distribution can be accomplished with NRL's Mini Modem over microwave links, UHF, balanced digital transmission devices (BDTD) on metallic cable pairs, optical fiber cables and local portable standards. End user facilities can then employ electronic servo controlled crystal oscillators updating against a continuously or periodically received reference.

The Music Man Committee is presently identifying user requirements in both the DCS and DOD that may be served by a DCS PTTI subsystem. The various identifiable PTTI techniques and applications may then be combined with the requirements in order to develop the concept and policy

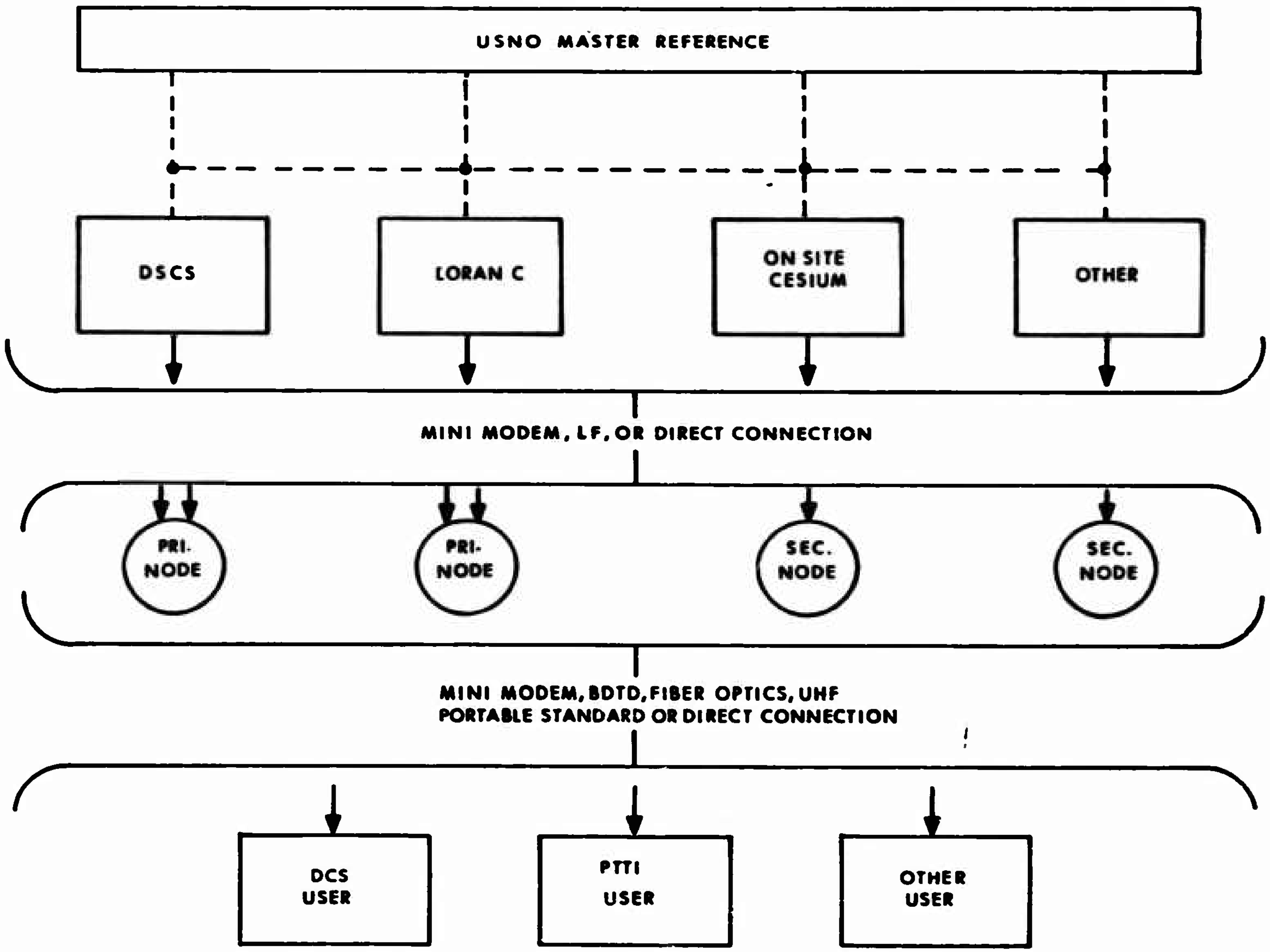

Figure 4. BASIC SUBSYSTEM HIERARCHY CONCEPT

guidelines for a DCS PTTI worldwide subsystem. The order accruing from a unified systems approach will lead to effective satisfaction of advancing communication requirements and will allow the extension of service to many other DOD PTTI users.

As this effort progresses, many additional benefits are expected to be realized from the evolution of a dynamic PTTI subsystem. The reliable and economical availability of PTTI to the user in the field should now stimulate new considerations throughout the spectrum of time and frequency applications to determine the potential benefits of reduced costs, simplified designs, and improved operational performance.

DISCUSSION

DR. REDER: I'm a little bit concerned about an implication in your paper: That if you go cesium in these stations as a replacement of VLF, for instance, this will solve all your problems. I don't think that it will.

MR. FOLTS: No sir, definitely not.

DR. REDER: Okay, because there are also possibilities that you have had a failure in the cesium standard without knowing it, if you mistakenly consider a straight line on the recorder of VLF as the natural thing. There is no substitute, I think, for proper education and proper training if you want this kind of a position.

MR. FOLTS: Yes sir, I think you are absolutely right, and we are quite well aware of this. If a cesium was used as an alternate source, it would be under continual monitoring status, and this would be done in the case where we couldn't get any other alternate source for the precise facility. There are a tremendous number of problems in the field with cesium standards. I know that in our Ground Satellite stations, we have had many problems where the troops have opened them up to show a new toy to everybody that visits and, of course, then they do not perform very well. A great deal of effort will have to be put into education in use of these facilities. This is one area that we found is very weak and will have to pursue very strongly.

MR. GATTERER: Continuing along the line of that same question, I think that you said, I believe the attitude manifested at the military communications sites is that people are not only encouraged to keep their hands off but are deliberately not trained in the fundamentals of standards. I wonder if that approach itself has created some problems. I am thinking of one case where people who were trying hard to educate themselves were greatly discouraged because of the policy that they should not be taught anything about the standard because if they were, they might touch it. This leads to the circumstances that were mentioned where a VLF receiver may be running for months not locked up without it being known. Would you comment on that please?

MR. FOLTS: I suppose it is a case of one extreme or the other, but I don't think there is any substitute for good education. Lots of times with any new thing that comes out, people that do not understand it want to ignore it and become afraid of it; this happens all too often. It's the overkill --if it's delicate, don't touch it, forget it and leave it alone. Now, we will really have to look at it in terms of turning out proper education overall in the PTTI area. This is the whole lack of understanding in PTTI which prevails not just in the maintenance and the field, but the whole area. This has been one of our biggest difficulties in getting this effort going and developing our committee. I think in the actual output, PTTI education is going to be an area that will be addressed and put into effect before we can effectively implement PTTI techniques in the field.

DR. WINKLER: I would like to comment on Mr. Gatterer's comment. I think he refers to a situation where at certain ground terminals, we are between two phases: one is the completed feasibility study or feasibility experiment to transfer time and the second is a complete operational condition with all training materials available, manuals distributed, a support service established for the cesium standards, and so on. I think we will hear more about that in Capt. Enright's talk. But at this moment, there are procurement actions under way, the manuals which have been printed are on the way to the stations, and there is no question, of course, that the personnel must be trained. I don't believe that there is anyone who would advise against training ground station personnel. I think the main point of Mr. Folts' papers is that as much as you can, you should go automatic and not rely on daily frequency adjustments to be done manually with some interpretation of the operator on what he has to see. I think that in the face of increasing operator problems and qualification problems, we should try to do as many things automatically as we can. However, this does not mean that the people will not have manuals or some training on what they are supposed to do. This has to be distinguished, and you should not base your judgment on one station which you have visited which has just been caught in between these two phases. Where one initial experiment was performed, equipment has been removed because there is no cesium standard in that station which I mentioned; it will, of course, have it again and then operations will begin. It's a different thing.

MR. GATTERER: I know to what you are referring, Dr. Winkler, but I'm not discussing that. I'm thinking of a particular Autodin communication terminal where there was a specific policy that the people were to stay as far away from the standards as they could other than the daily adjustment in the FSQ44. The reason I think it is important to respond is that it is my belief that there is a distinct policy that people shall stay away from the standards . I have not formed my own judgment as to whether or not that's good, but I do know it leads to the situations like the ones Mr. Folts mentioned.

MR. FOLTS: So this is the case of Autodin! I'm glad you identified that, because it clears up your question a little bit more. Autodin itself is not dependent upon highly accurate timing. As a matter of fact, in the tests we found that one Autodin center was off one part in 10^6, and still running very well with their traffic. Autodin is not a network situation; it is a point-to-point operation. In the Autodin school they teach: "this is a VLF receiver, now that you know what it looks like, forget about it," and so on. That is an entirely different situation and environment than we are now developing through Music Man.

LCDR POTTS: I would like to make a small comment regarding maintenance of standards. I am sure that there are differing philosophies, especially whether one considers crystal standards, rubidium standards or cesium standards. Fortunately or unfortunately we fell into the category of owning a lot of cesium standards; we have 86 now, we will have more in the future. In the early days we were on the learning curve and the curve was rather bumpy; we had problems with cesiums, we had problems with people. But to make the story short, our maintenance philosophy is paying off in terms of the performance we are getting from the standards now. We have experimented with training people to do maintenance in the field; we have trained them rather well. It just has not worked out in the case of the cesium standards so our philosophy now is hands off and it's paying off.

DR. REDER: I think the philosophy should be hands off the standards, hands off the equipment but stay close to the recorders.

THE EFFECT OF CHANGES IN ABSOLUTE PATH DELAY IN DIGITAL TRANSMISSION SYSTEMS

by

R. A. Day, Jr.

Mr. Day is Chief, Engineering Staff, Office of Telecommunications, National Security Agency, Washington, D.C.

One useful aspect of synchronous digital transmission is that we are not limited by noise in any given link when connecting in tandem a number of links. In the FDM world, the noise products are of critical importance in determining the number of tandem links permissible. A digital link operating without error for relatively long periods of time results in an operational performance that typically equates to the error burst distribution of the individual links. Over the years we have observed a large number of digital links and many of these are very long and made up of numerous tandem links. We noted, for example, that the error burst distribution on a 3600-baud, transatlantic data circuit between Frankfurt, Germany and the Washington, D.C. area was typically subjected to a short burst of errors approximately once every 20 minutes.

We also noted that the modulation rate up to the circuit maximum rate made no difference with regard to the number of error bursts. Changes in modulation rate from 600 to 3600 baud only changed the number of errored bits in any given burst.

Figure 1 shows a worldwide digital network now operating in a full synchronous environment. The individual links are operated from 2400 to 7200 BPS. The links are typically subdivided as shown and the channels are connected in tandem without buffering between each other. For example,

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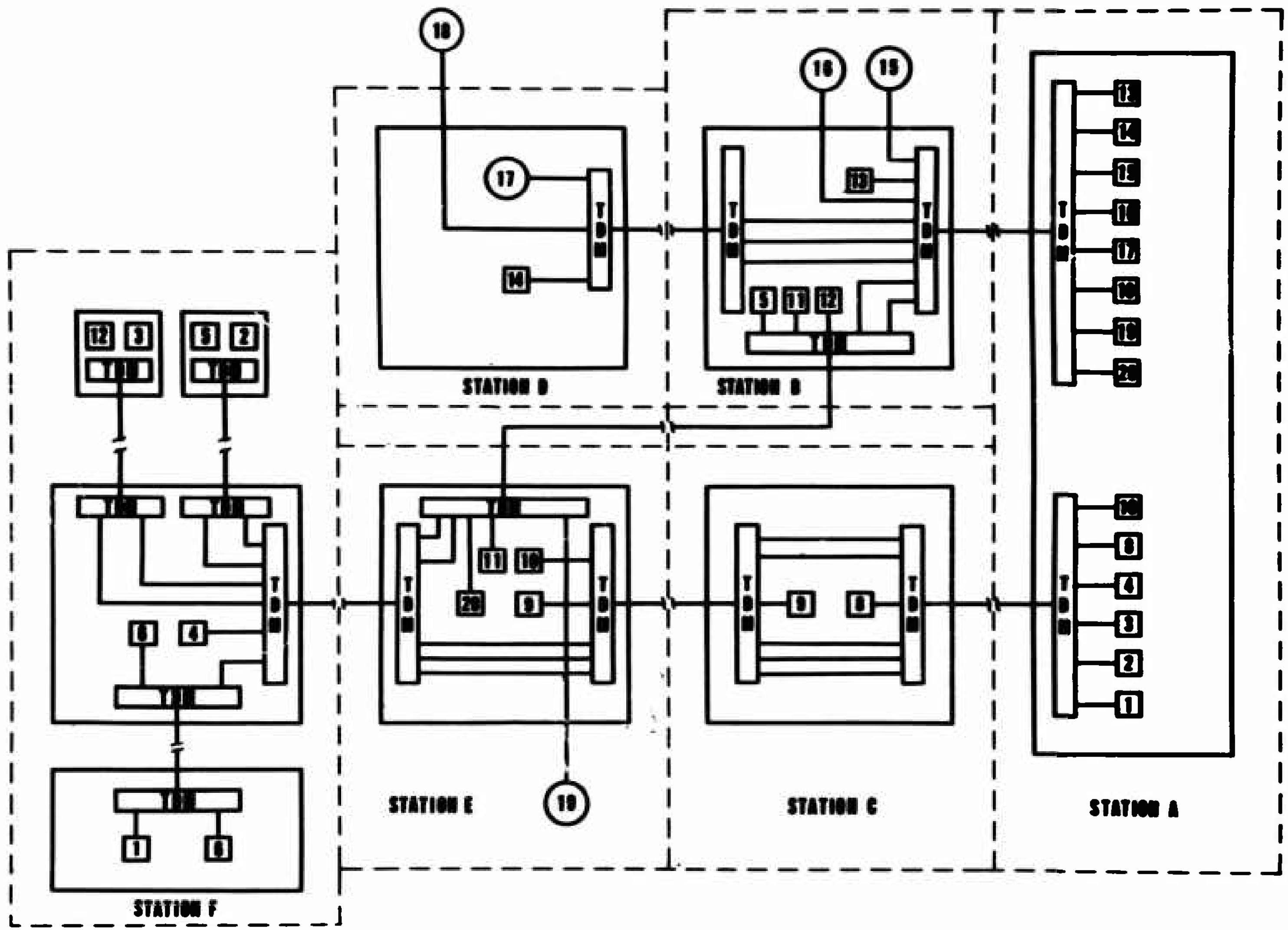


Figure 1. WORLDWIDE DIGITAL NETWORK

one can trace from Station F on the left a link from a time division MUX (TDM) port 2 through Station E to C to A.

In the early fifties, it was learned that the typical 50-baud telegraph channel did not behave quite as a lot of us assumed. HF radio paths were recognized to change in path absolute delay as one shifted from night or day frequencies or when the paths, due to propagation, etc., tended to switch between single and multiple hops.

In Europe "Multipath," for example, was most often on 600- to 1000-mile links, a matter of a few milliseconds and at most confined to one or two bits at 50 baud.

A most disturbing problem was that a telegraph channel operating on leased cable or microwave would abruptly change absolute delay by several hundred milliseconds. One had learned to expect a few milliseconds' shift for HF radio multipath but multipath also had habits which helped to spot it, in that it was not a stable shift and there would be seconds, minutes, or even hours when the path delay changes were not shifting fortuitously. It was noted that a path might suddenly, that is, essentially instantaneously grow shorter or longer by perhaps 5 bits at 20 milliseconds a bit. The path might remain at this absolute delay for a period of several hours to as much as a day or more.

It was also noted that some paths seemed to grow longer or shorter on a predictable basis. A path that changed in delay in this fashion immediately warned that the synchronous terminal equipment was not being properly clocked. As a result of the discovery that a telegraph channel could abruptly change absolute delay by many milliseconds, a device was developed for use with synchronous transmission systems. Records kept from 1958 through 1964 on 25 long-haul cable, microwave and HF radio, 61.1-baud telegraph channels showed typical abrupt delay changes of 30 to 125 milliseconds.

The device was a simple shift register that inserted 21 bits of additional delay between the incoming line and the synchronous receiver input.

(Twenty-one bits at 61.1 baud is approximately 1300 milliseconds.) A front panel control calibrated in terms of plus 10 to minus 10 bits delay was provided. The operational procedure is for the operator to set the delay to zero (bit position number of 11). The synchronous system was then started and, if the path delay then changed, the operator simply advanced or retarded the delay control until he regained synchrony (approximately 85 percent of the attempts did recover synchrony). If he did not regain synchrony, the device was either zeroed or returned to the last delay setting and the cause of the problem sought elsewhere.

Now we come to the heart of the matter: How did the crypto operator, in effect, measure changes in the path absolute delay? Perhaps the following explanation will help those not familiar with synchronous cryptographic devices.

One can think of a synchronous cryptographic device as having a memory that is arranged such that each bit that is to be transmitted from the crypto is programmed into it by the key setting. The mating receive crypto has a similar memory that performs in precisely the same manner. There is one and only one point at which the transmit and receive key will precisely mate and, therefore, if the relative phases of the transmitter and receiver crypto are not precisely maintained, the data will not be decrypted.

If the two devices are started they will run predictably and typically without error for as long as they are supplied timing, etc. If the timing is slewed at transmit and receive cryptos identically, they will also follow in synchrony and in the same predictable fashion. In typical operation the transmit and receive devices are provided a given key setting. The transmitter emits a precise starting sequence that propagates over the comm link with an absolute delay that is determined by the given link; the receiver is in effect "unlocked" by the "start" sequence which means that, if a successful start occurs and the timing is correct and the path delay does not shift, the receiver will continue to run in synchrony with the transmitter offset in phase by the absolute path delay. If the path fails the receiver will continue to run in synchrony with the transmitter for a period determined by the relative drift between the transmit and receive crypto timing. With a good timing scheme, if the path is restored normally, the crypto will be found to be "in set" and the data can pass without restarting the crypto system.

If the path absolute delay changes one can advance or retard the receive key in the receive crypto until the "set" is picked up or one can use the device mentioned earlier to cope with delay changes. Having operated both schemes, it is suggested that the artificial delay approach is more realistic in a large TDM network. The reasons for this will be explained shortly.

In the fifties and early sixties most low-speed synchronous cryptographic systems were operated on their own internal timing. The receivers recovered phase correction data from the incoming line transitions and corrected their internal timing accordingly.

This system suffers from the fact that channel perturbations, FOX TEST, intermod from adjacent channels, cyclic distortion, etc., too often modify the receive timing to the point that synchrony is lost and the entire system must be restarted.

Recognizing this fact, and knowing that, contrary to popular thought, telegraph channels did not always remain at a given absolute delay, a program was initiated to place station timing sources at a large number of sites throughout the world. The initial objective was to obtain a relative coherence among these timing sources such that a drift not greater than plus/minus 25 percent of the duration of the unit interval at the applicable modulation rate for 100,000 consecutive seconds would be obtained. In most cases in 1960 this was 6-2/3 milliseconds for a 75-baud circuit (approximately 140 microsecond per hour worst case drift). It was quickly proved, for example, that the channel suppliers could not drive the receive crypto out of synchrony by inadvertently placing FOX TEST on the circuits or by patching a 50-baud terminal to a 75-baud terminal, etc. The 100,000 seconds were a little over 24 hours, or one radio day. It was found that dramatic circuit improvements were obtained from operating on station rather than recovered clock. On one circuit operated on recovered clock the typical availability for traffic was less than two hours per 24 hours. After converting to station clock the circuit availability was typically better than 22 hours a day.

Over the years the station clocks have been brought closer and closer into coherence. At first one did not need to worry about the coherence since the basic timing sources were close enough even at their worst relative drift to run for 100,000 consecutive seconds at 75 baud without drifting outside of one bit.

The relative coherence of the station timing has improved network-wide to approximately 3 to 15 microseconds per hour relative drift. In a few stations with Loran-C the stations are now able to hold within approximately 100 nanoseconds relative drift. Those stations with VLF tracking and manual updating do well to meet the 3 to 15 microseconds per hour relative drift.

Experience has shown that the satellite paths tend to be better in all aspects save one than the transoceanic cable channels. Satellites have one technical parameter that must be dealt with if tandem operation of synchronous time division multiplexed links are to be successfully employed. That technical parameter is the change in absolute path delay over a 12-hour period. This change is caused by the suborbital movement of the satellite on a north/south path with relationship to the equator. The relative change is as predictable as the rise and fall of the tides and it can therefore easily be dealt with.

Figure 2 shows Intelsat III, Flight 7 on 28 July 1971. Reading left to right we see a change in path absolute delay between midnight and noon on the 28th of approximately 1390 microseconds, and from noon to midnight

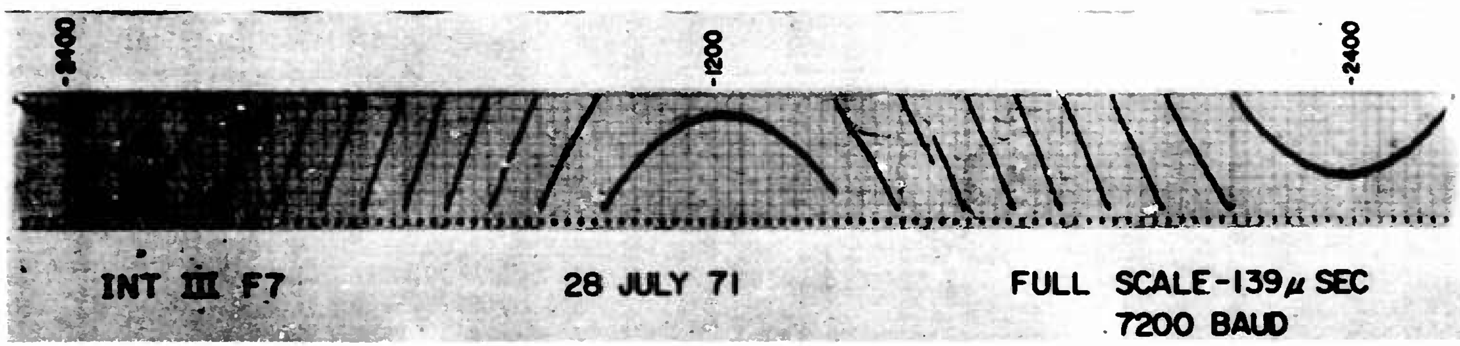


Figure 2. INTELSAT III, FLIGHT 7 ON 28 JULY 1971

a change in path absolute delay of approximately 1180 microseconds. The difference of approximately 210 microseconds between the first 12 hours and the second 12 hours is an indication of the relative drift of the station timing between the two multiplex terminals. This equates to approximately 8.75 microseconds per hour relative difference between the two stations.

At 7200 baud the duration of the unit interval is approximately 140 microseconds. Assuming no change in path delay an 8.75 microseconds/hour relative drift will cause synchrony to be lost in approximately 8 hours, if no phase correction is accomplished. The change in path absolute delay cannot be ignored however, and synchrony will be lost depending on the relative position of the satellite in its orbit anywhere from once in four hours when the satellite is slowing down and reversing its direction relative to the equator to once every half hour during the remainder of its orbit. This can quite easily be seen by referring to the trace displayed in Figure 2. The steeper the slope on the graph, the faster the rate of change. It might also be noted that each time the trace completes a transit from one edge of the chart to the other, this is comparable in time to one unit interval at the data modulation rate. It is quite easy therefore to estimate by observation of the chart how often and when synchrony will be lost. This display is not only a useful engineering tool but also a very useful tech control and maintenance technician guide. The recording is a comparison between modem recovered timing and the local station clock. Figure 3 has been prepared to bring out other important aspects of this phenomenon: One, the rate and amount of change is determined by a given satellite and its effect on the digital signal is proportional to the modulation rate. Doubling the signalling speed halves the time to loss of synchrony. Two, the sub-orbital movements of satellites change, as shown in Figure 3. On 29 May Intelsat IV, Flight 2 the change in path absolute delay was approximately 361 microseconds in 12 hours whereas the same satellite on 15 August 1971 had slowed down to approximately 70 microseconds per 12 hours. Seventy microseconds is approximately one-half the duration of the unit interval

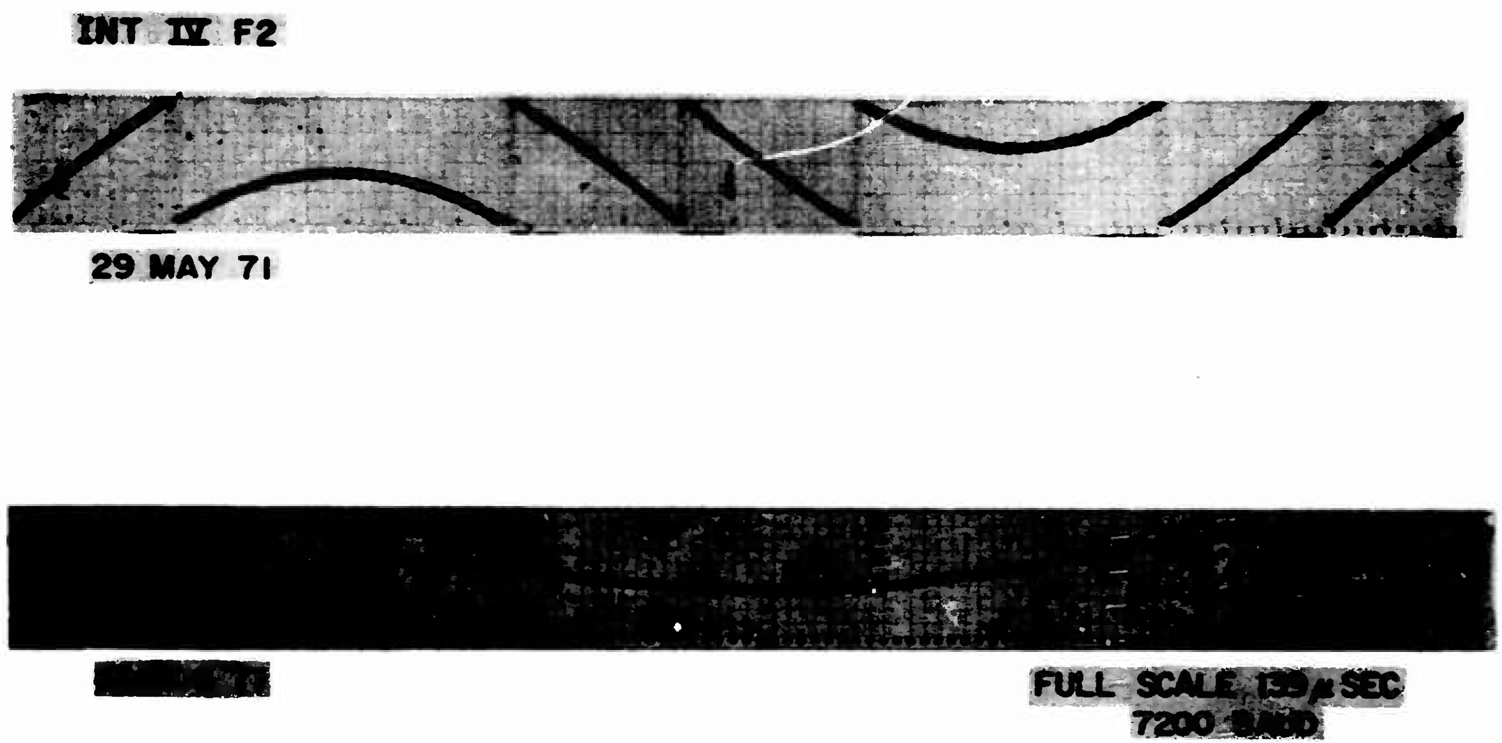


Figure 3. INTELSAT IV, FLIGHT 2 ON 29 MAY 1971

at 7200 baud; therefore, synchrony would not be just on a 7200-baud circuit over a 24-hour period on this path.

Figure 4 shows the typical Defense Communications System point-to-point configuration wherein recovered clock from the modem is utilized to time the crypto and data terminal equipment.

In this configuration any perturbation or phase shift in the recovered timing is passed to the crypto and to the data terminal devices(s), etc.

Figure 4 also indicates the difference in phase between station timing and recovered timing.

Figure 5 shows the method wherein the incoming data is retimed to station clock time such that shifts in phase in the recovered clock do not appear at the crypto or data terminal. Note that in Figure 5 data are retimed to clock, whereas in Figure 4 clock was retimed to data.
Figure 6 shows the addition of storage that permits one to deal with path absolute delay changes greater than one bit.

Figure 7 is intended to remind us that when path absolute delay changes it affects not only the crypto but all the associated devices. In other words, if the shift in absolute delay is permitted to propagate through the input device then all the equipment can also lose synchrony with their mating terminals.

In conclusion, Figures 8 and 9 are intended to indicate a path can get longer or shorter. In Figure 10 the relationship of station timing in a worldwide network must be made independent of the changes in absolute delay. The dotted lines in Figure 10 are intended to indicate how the timing sources may be directly related in a large network. Figure 11 is intended to indicate the path absolute delay changes in a large network that must be dealt with if tandem digital link operation is to be effective. An effective way of dealing with this problem can be the insertion of additional absolute delay between the nodes of the network. The objective

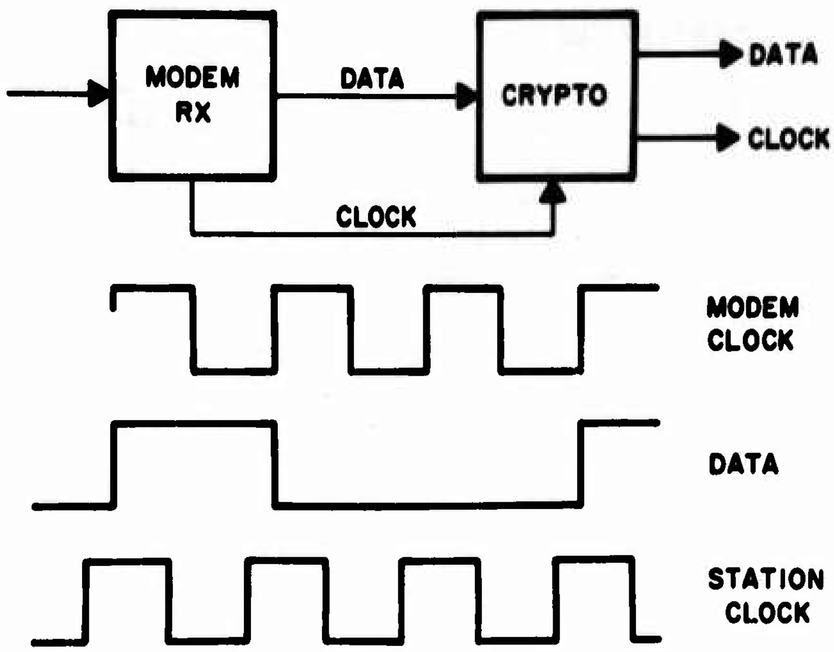


Figure 4. DEFENSE COMMUNICATIONS SYSTEM POINT-TO-POINT CONFIGURATION

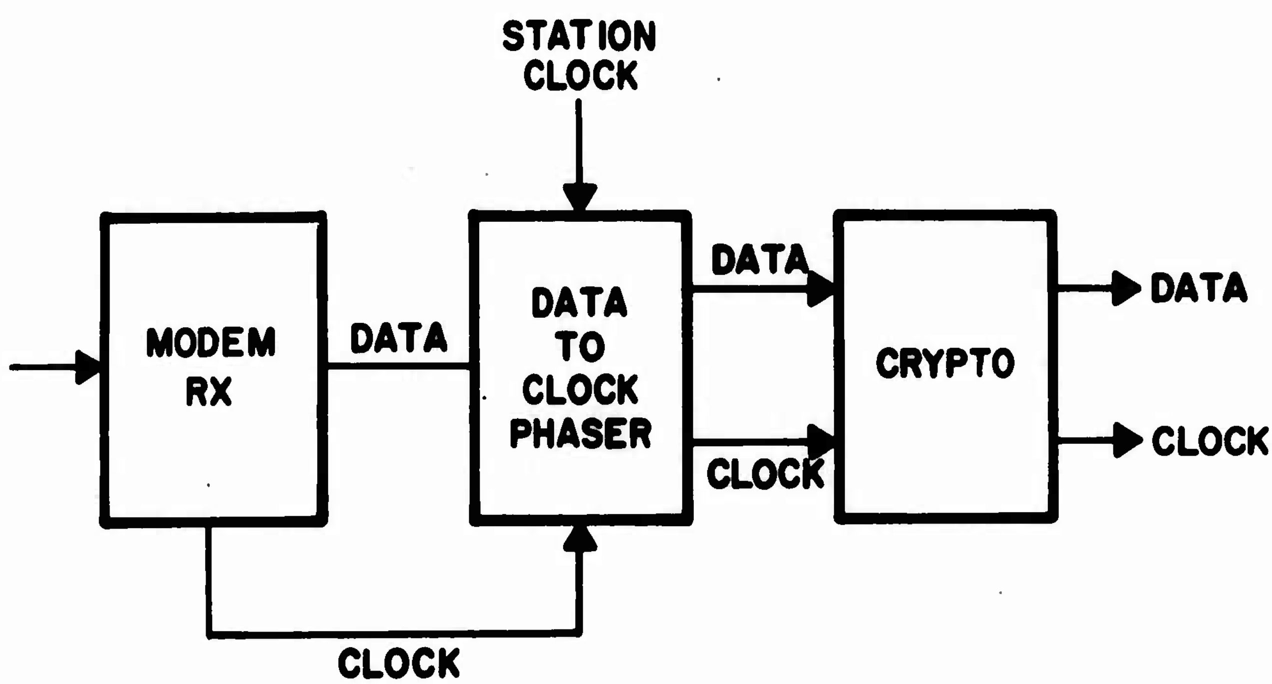


Figure 5. METHOD OF INCOMING DATA RETIMED TO STATION CLOCK TIME

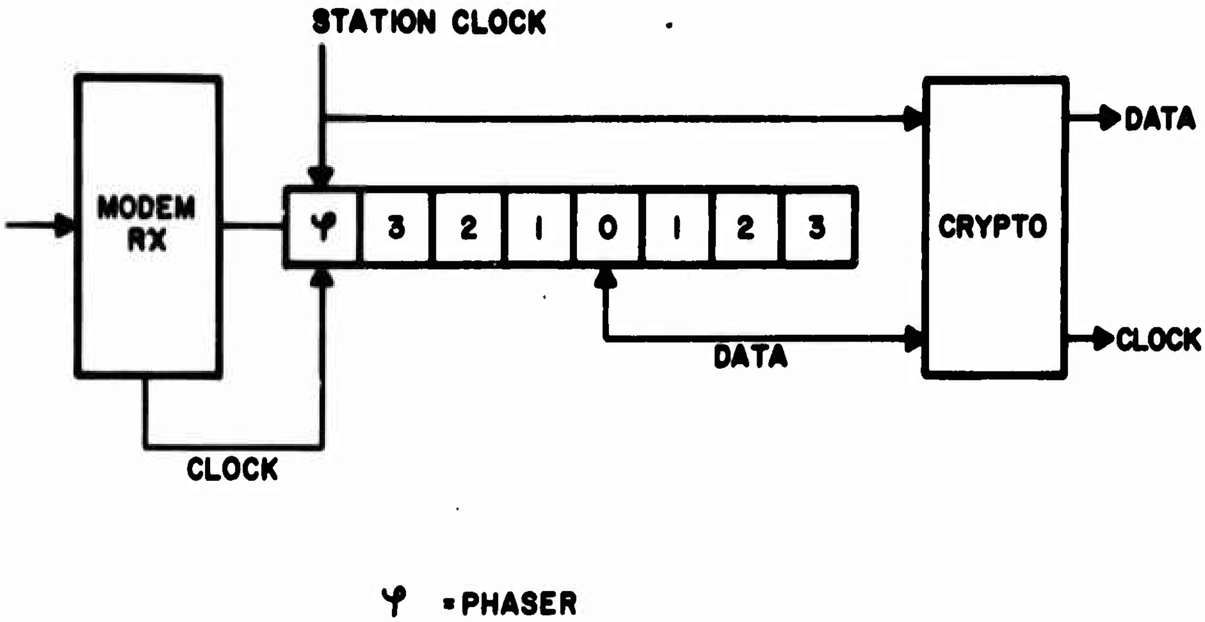


Figure 6. ADDITIONAL STORAGE FOR PATH ABSOLUTE DELAY CHANGES GREATER THAN ONE BIT

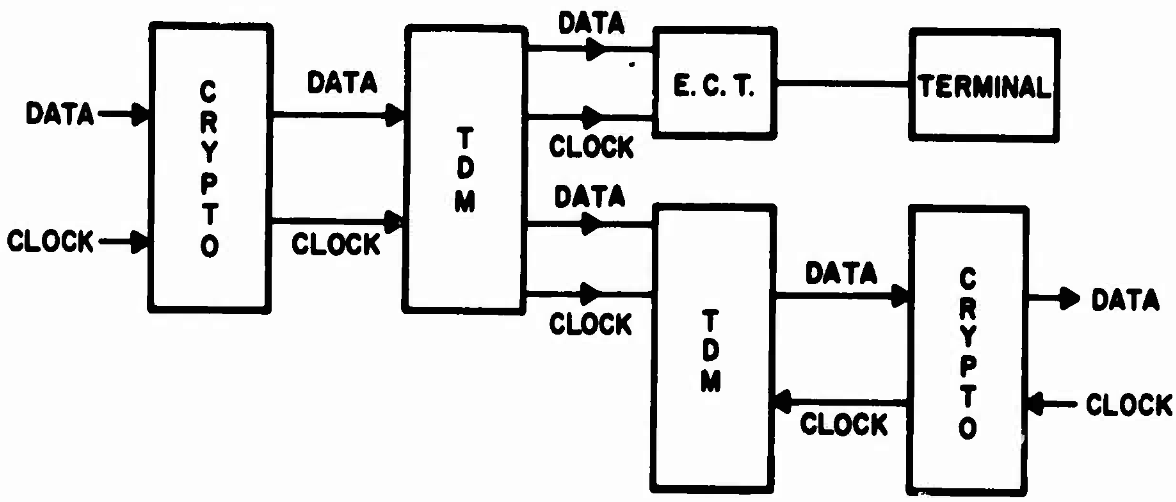


Figure 7. CRYPTO AND ASSOCIATED DEVICES AFFECTED WHEN PATH ABSOLUTE DELAY CHANGES

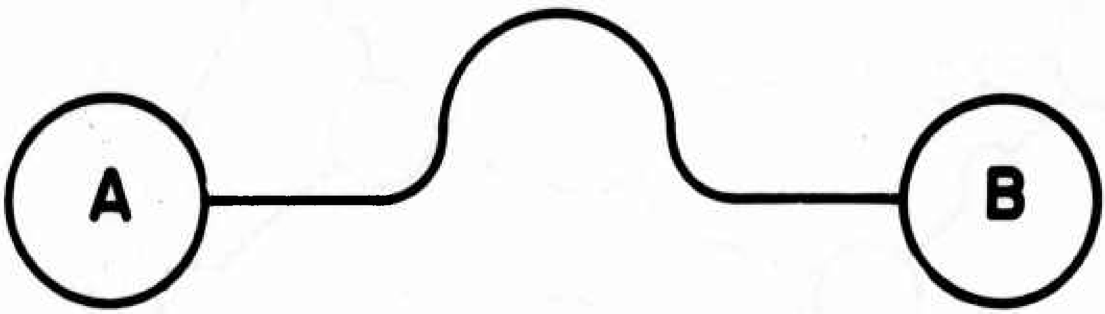


Figure 8. LONGER PATH ABSOLUTE DELAY

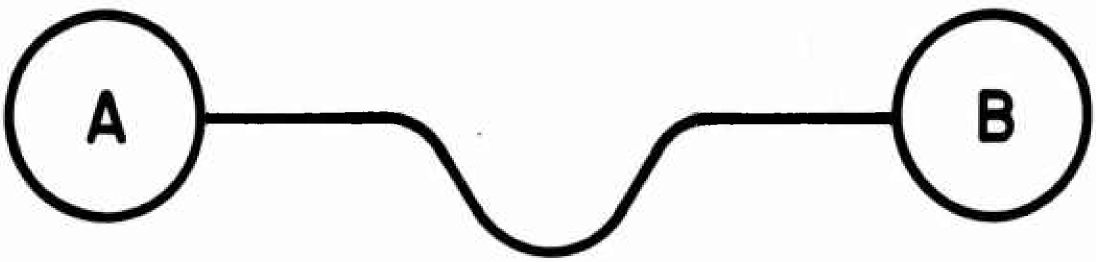


Figure 9. SHORTER PATH ABSOLUTE DELAY

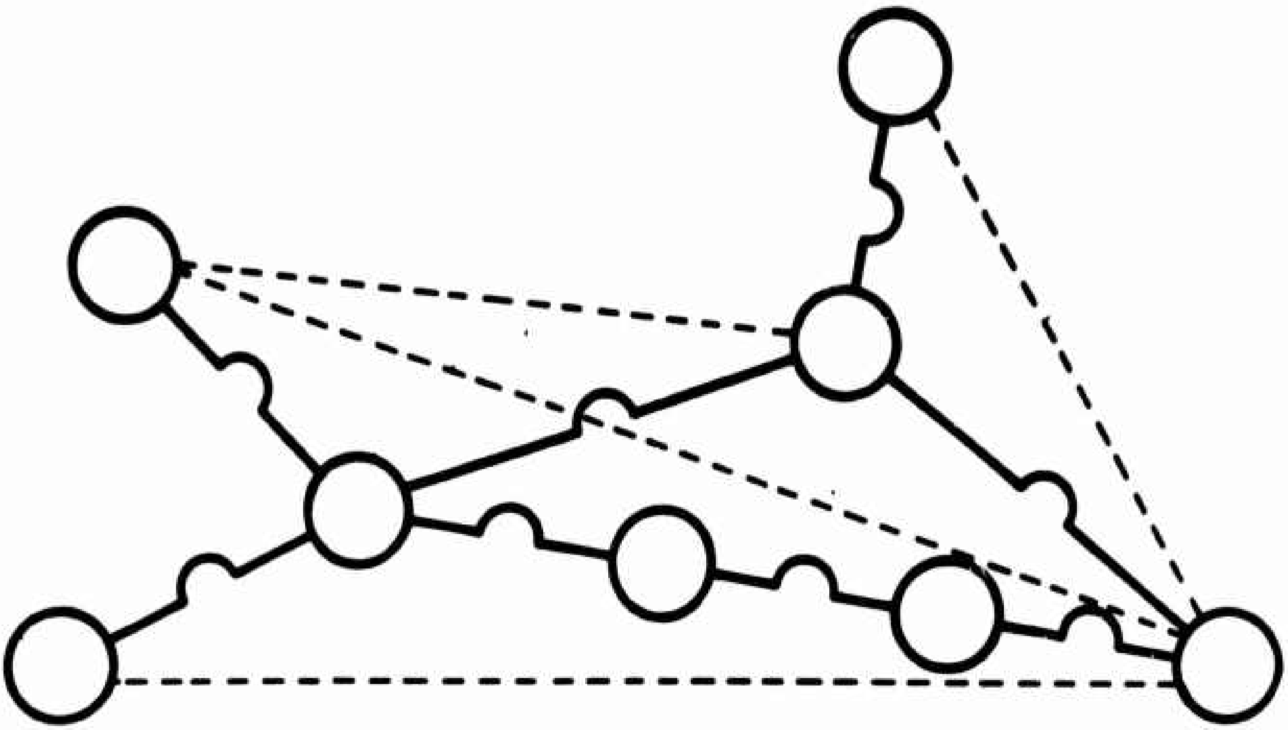


Figure 10. RELATIONSHIP OF STATION TIMING IN A WORLDWIDE NETWORK VS CHANGES IN ABSOLUTE DELAY

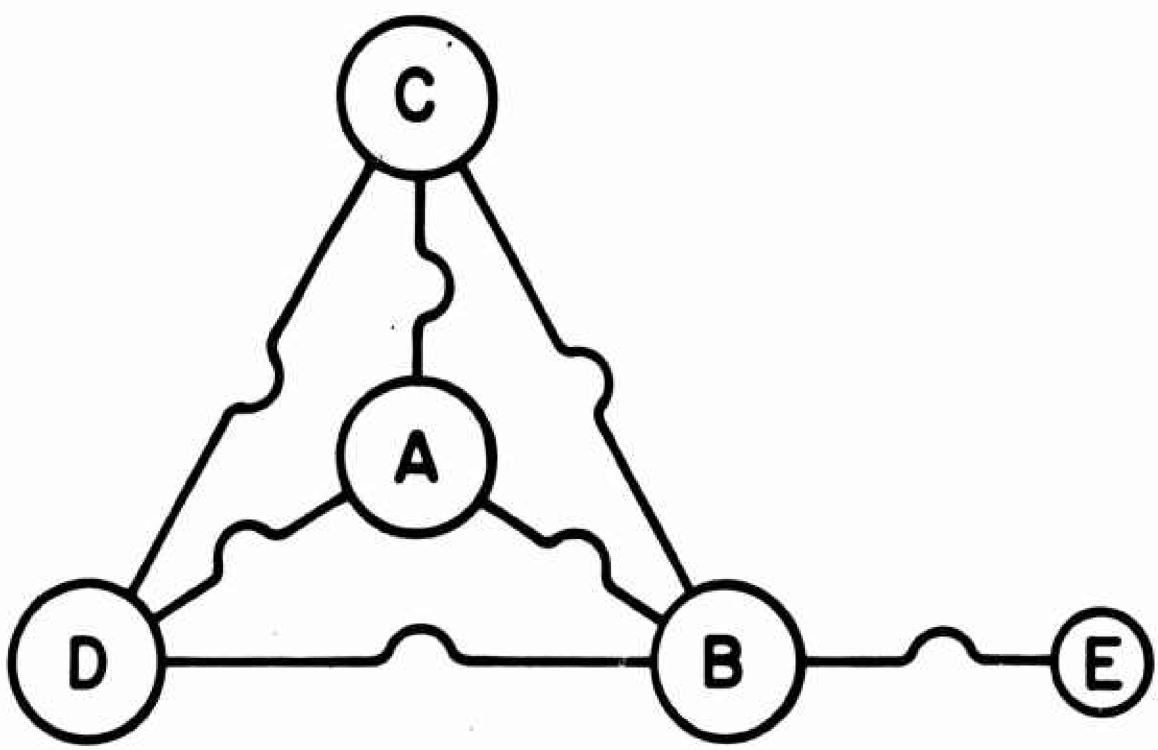


Figure 11. PATH ABSOLUTE DELAY CHANGES IN A LARGE NETWORK

would be to make each link appear to the terminal equipment as having a fixed delay. One might call this the "brick wall" approach. What is meant is that by providing excellent station timing and isolating path delays one can stop the propagation of the path delay changes through the network. Once one has the path delays under control one can then patch incoming links to outgoing links without the need for complicated and expensive buffering equipment on each link. One is also then able to avoid sequential resynchronization of each terminal equipment every time a path delay shifts.

DISCUSSION

DR. REDER: Do you have any idea what causes the large delays or delay changes in cables?

MR. DAY: We guess, we believe, we think--let's put it that way here--the channel supplier reroutes channels for routine maintenance checks, service restoration, and so on. That seems to be the real cause of it. We don't see any likelihood of it being stopped, or any advantage in having the channel supplier always reroute a certain facility in a certain way to control it. If you were to put that kind of limitation on the channel supplier, and if his first alternate failed, you'd be dead. So we feel that we just have to live with it, and the way to live with it is by putting delay external to the link.

DR. WINKLER: Regarding variations in cable, postulating cables has been interesting to telecommunications engineers since, I think, at least 1925 or 1930. There are many causes. A submarine cable, for instance, is subject to varying pressure depending on the tidal loading. If you figure out the length of that cable you get, very easily, variations of 1 part in 10^5, of the length, or 1 part in 10^4. A land line would be subject to atmospheric influences and temperature changes. But there is one more thing that we have observed in a relatively short link between NRL and the Observatory, which was used for several years to make use of the hydrogen masers which were at NRL. We had a dedicated line provided by the telephone company and we used a tuned 10-kilocycle channel. And we noticed sudden changes in phase delay, most likely caused by differences in capacity of loading. Also the channel did not go through switching centers. But apparently the condition in these switching centers changes abruptly from time to time, and I can imagine that, if you have a very long complicated system going through many of these centers, this can accumulate in a random fashion. It's clear, of course, that microwave links also are not perfectly stable. I will come to that fact a little bit later.

MR. DAY: I would like to make one additional comment on this. The abrupt changes of significant shift in milliseconds are very different than the breathing effects from temperature, atmospheric changes, and so on. We also know that the propagation velocity through a narrow band channel, for example in 75-baud telegraph channels, is around 18,000 kilometers a second. So a round trip between Tokyo and Washington is around 900 milliseconds, whereas I recall that some years ago we made some measurements on a voice band, Tokyo to Washington on a 3-kilohertz slot. It was 165 milliseconds around the loop, yet they were both essentially the same distance. So the bandwidth of the channel at the very narrow band does have some effect. But the thing that puzzles us is this abrupt, very large delay. We think it's probably maintenance-related,

DISCIPLINED TIME AND FREQUENCY OSCILLATOR

by

ROBERT STONE

Mr. Stone is the Head of the Time and Frequency Section of the Naval Research Laboratory, Washington, D.C.

The aim of the PTTI Program is to provide to the user a coordinated time system that can be referenced to the Naval Observatory. Long-range transfers will be accomplished via the Defense Satellite Communications System satellite link, and short-range transfers will be accomplished by microwave links, UHF links, or any other suitable system.

In concept, a centralized area (in a ship or a shore station) will contain the reference atomic standards (see Figure 1). Cables throughout the station will connect the reference standard to units called Disciplined Time Frequency Oscillators (DTFO). The DTFO is an important part of the concept; it separates the timekeeping function from the user-operator function and eliminates the necessity for frequent calibration, which aids considerab' in maintenance. It is also much less expensive to use the DTFO than to employ atomic standards in each of the user spaces.

The initial development of the DTFO is shown in Figure 2. It consists of a servo control, a crystal and oven, and a divider, clock or baud rate generator. Both frequency and time are controlled across the cable. The crystal is a high bake-out, minimum gravity effect, maximum short-term stability, fifth overtone AT cut. (Higher-frequency crystals are under investigation.) The unit will continue to operate at the rate of the crystal whenever the cable is disconnected or, for any reason, control is lost.

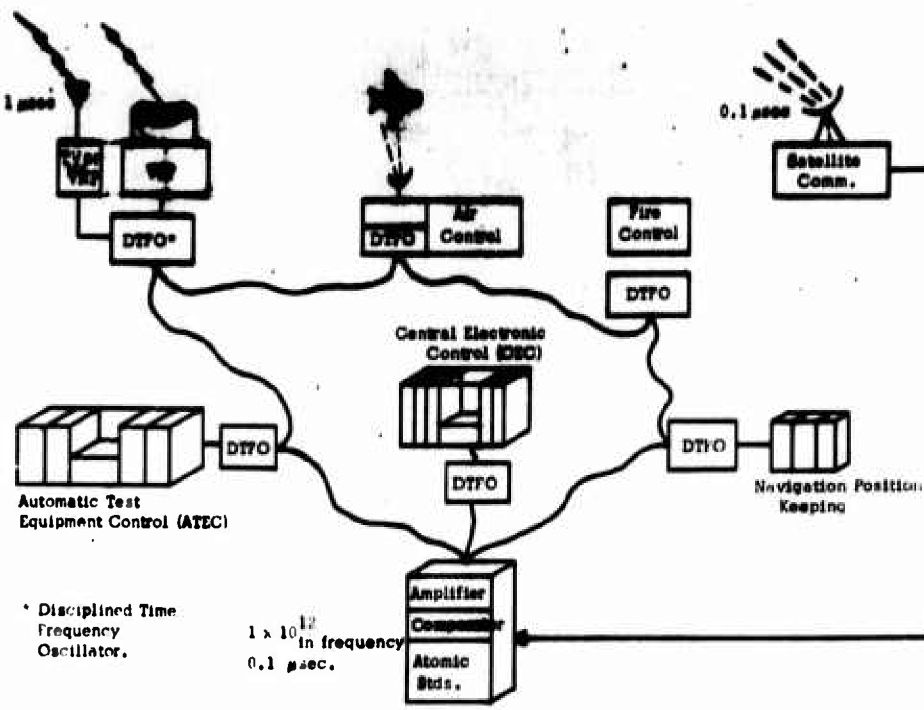
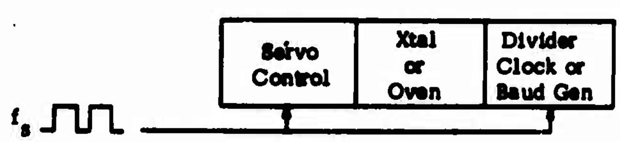


Figure 1. CONCEPT OF LOCAL DISTRIBUTION AND CONTROL FOR DISSEMINATION OF TIME AND FREQUENCY



SERVO

- Correct Xtal frequency to correspond with f_s.
- Capable of retaining last corrected frequency when f_s is removed.
- Input low frequency rectangular wave; leading edge frequency trailing edge time.

XTAL

- High bake out.
- Minimum gravity effect.
- Maximum short term stability.
- Maximum stability on eight-hour basis.
- Fast Warm Up

  Special oven
Special Xtal mount
Special Xtal heater — From cold start after 5-minute warm-up will not vary more than 5 μsec in next 4 hours.
- Room temperature turn over.
- 10 MHz.

Figure 2. DISCIPLINED TIME/FREQUENCY OSCILLATOR

After the unit is disconnected from the line, no more than 5 microseconds' drift in the next four to five hours is expected.

The unit shown in Figure 3 was produced under contract with the Frequency Electronics Incorporated. It is exactly the same size as the AN/URQ-10 and was designed to replace it. It weighs about 20 pounds.

The battery charger (see Figure 4) has one automatic and several manual positions for charging the battery. There are two time constants. When the system is initially set up, a manual slew adjust helps bring it into "lock." The coarse adjust is about a part in 10^7, the fine adjust is a part in 10^{11}. The meter circuitry has 12 positions; it indicates the 5-megahertz or the 1-megahertz reference input, the battery charging current, battery voltage, power supply lines, oven, output voltages, etc. Normally the operator will monitor the VCO voltage and the sync lights. The sync light flashes at 1 pulse/sec; short flashes indicate the unit is operative, but running on the internal oscillator alone; longer flashes indicate the unit is being synchronized by the external standard. The "unlock" light refers to the frequency only. If something happens to the control line, this light will turn on.

There are several ways of using the device. It can be locked from 5 megahertz or 1 megahertz (in the back of the unit). Separate references can be used for frequency and time, or the 1 pulse/sec can be imposed on the 1-megahertz input at the back of the unit, which locks time and frequency over the same cable. The continuous condition is used for synchronizing if a continuous stream of time pulses is available. If synchronization is required according to some time-event pulse that is sent down a line or derived from another system, the intermittent condition is used. The switch is slipped to the left to arm, then slipped back to the right. The next pulse to come through will synchronize the system and it will ignore all other pulses until the arming is repeated.

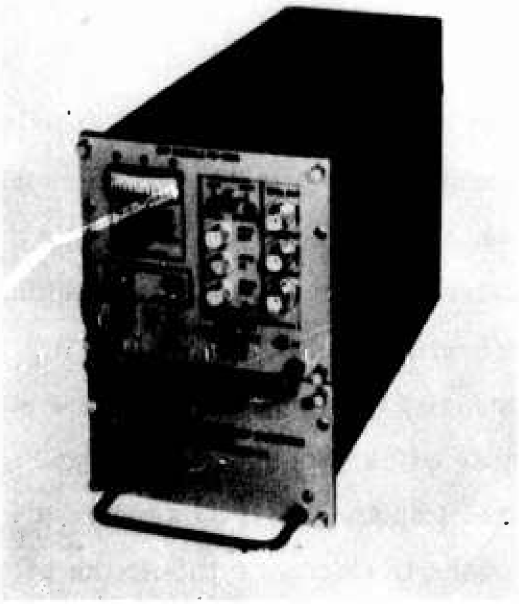


Figure 3. DISCIPLINED TIME/FREQUENCY STANDARD

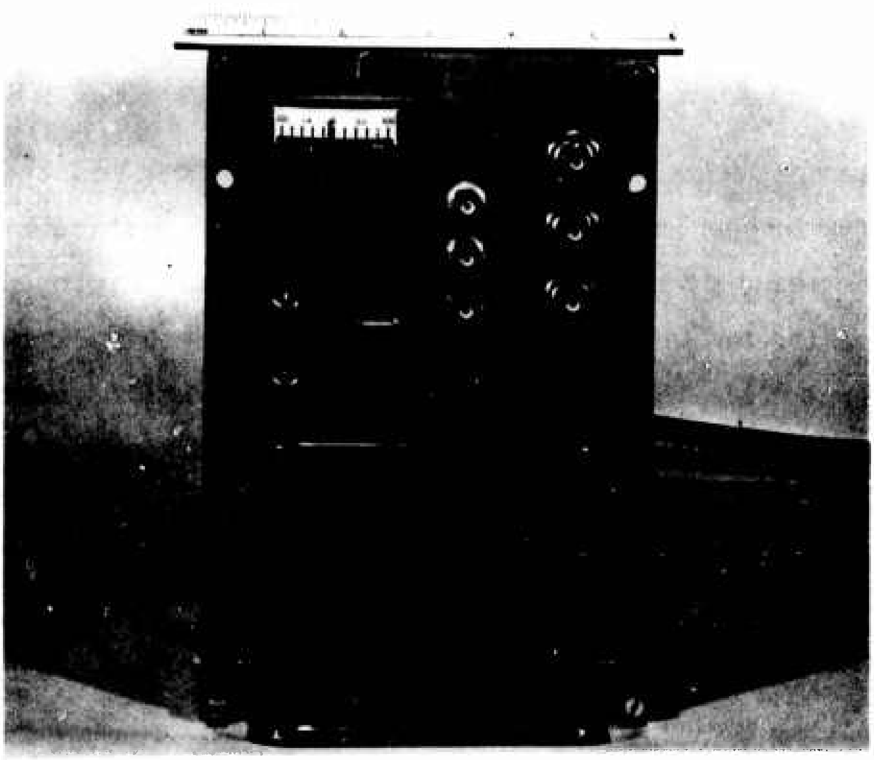


Figure 4. DISCIPLINED TIME/FREQUENCY STANDARD

At the back of the unit (see Figure 5) are the various outputs, sine wave and square wave. It is questionable whether one should ever revert to sine wave once a square wave or a pulse is produced. The 100 kilohertz is a square wave and interfaces well with digital systems. The unit will operate from an external DC supply.

The completely modularized unit is shown disassembled in Figure 6. The front panel, which contains the switches, is separate. The first module contains the crystal and oven assembly, itself modularized. The unit shown below the crystal is the control circuit for the crystal. The memory with its input and output control sections is also shown. Connectors on the front and the back of the module make it quite easy to change the functions of the module without disrupting the system. As the unit is developed and more is learned about how it should really be made, it will be possible to change individual modules without disrupting the entire system.

Figure 7 shows technical specifications of the disciplined time/frequency standard. The outputs of the system are sine wave: 5 megahertz, 1 megahertz; square wave: 100 kilohertz; pulse: 1 pulse/sec, 1 million pulses/sec. The levels are sine waves, 1 volt; square waves, 5 volts; pulses, 5 volts into 50 ohms. These pulses are exactly 20 microseconds wide. Since they are picked from the divider chain, they are controlled on both ends; this was done to be TTL-compatible. The cable jacks are so isolated that if something happens on one of the lines, it does not disrupt the system. A short on one of the cables will not affect the others.

Inputs are high impedance; harmonics, -40 db; spurious, -110 db below the signal level. The first unit, now being subjected to a complete checkout at NRL, is stable and performs very well. Initial test show it to be the quietest unit at NRL.

As previously stated, coarse range adjustment (see Figure 7) is a part in 10^7, and fine adjustment is a part in 10^{11}. Input frequencies are 5 megahertz and 1 megahertz. To provide a special clock frequency or timing

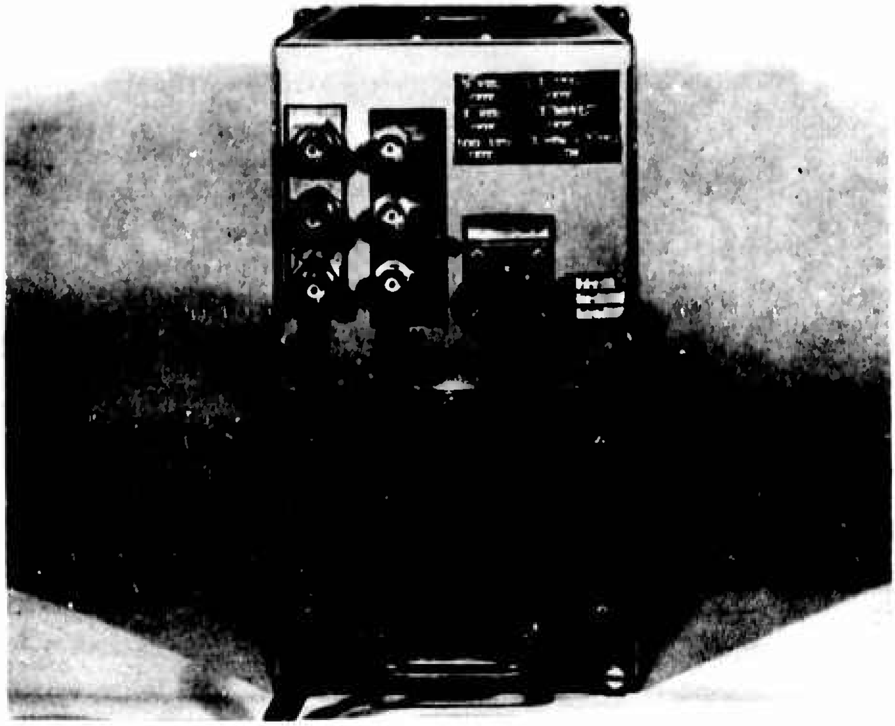


Figure 5. POWER SUPPLY MODULE FE-250A

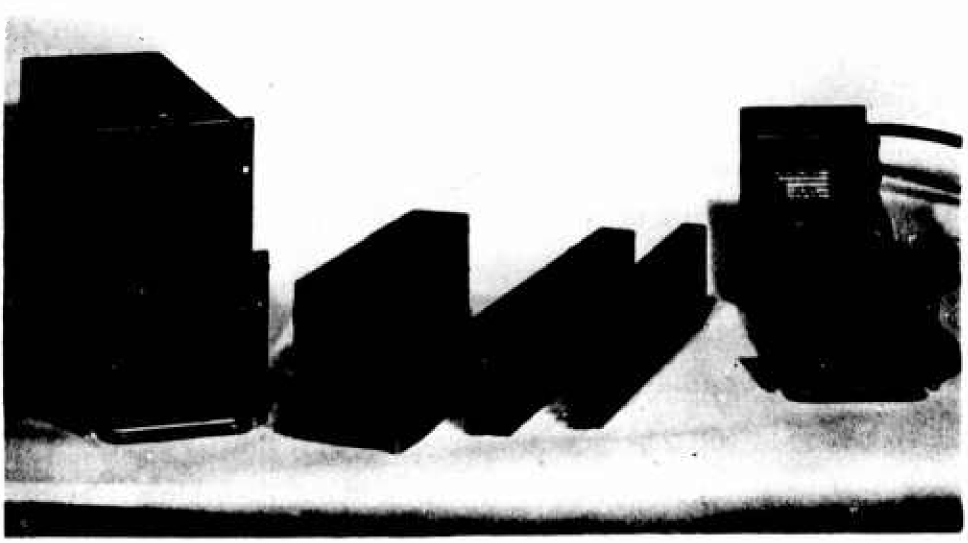


Figure 6. DISASSEMBLED DISCIPLINED TIME/FREQUENCY STANDARD

TECHNICAL SPECIFICATIONS

DISCIPLINED TIME FREQUENCY STANDARD

A. SIGNAL

OUTPUT SIGNAL FREQUENCIES:	
SINE WAVE:	5 MHz, 1 MHz
SQUARE WAVE:	100 kHz
PULSE:	1 PPS, 1 MPPS
OUTPUT SIGNAL LEVELS:	
SINE WAVE:	1.0 VRMS ± 20% INTO 50 OHMS
SQUARE WAVE:	5.0 VPP INTO 1K OHMS
PULSE:	
1 PPS	+5.0V INTO 50 OHMS, 20.0 USEC. WIDE, RISE TIME < 20NS.
1 MPPS	0.1 USEC. WIDE, TTL COMPATIBLE
STABILITY (5 MHz):	
100 USEC. AVG. TIME:	< 3 PP10^9
1 MSEC. AVG. TIME:	< 4 PP10^10
10 MSEC. AVG. TIME:	< 6 PP10^11
100 MSEC. AVG. TIME:	< 7 PP10^12
1 SEC. AVG. TIME:	< 3 PP10^12
10 SEC. AVG. TIME:	< 3 PP10^12
100 SEC. AVG. TIME:	< 3 PP10^12
24 HOURS:	< 5 PP10^11
ISOLATION:	ALL OUTPUTS SHORT CIRCUIT PROOF.
SIGNAL INPUT IMPEDANCE:	HIGH IMPEDANCE.
SPECTRAL PURITY:	
HARMONICS:	< -40 dB
SPURIOUS 5 MHz, 1 MHz:	< -110 dB

NOISE:

FREQUENCY FROM CARRIER	SINGLE SIDEBAND NOISE (dB/Hz) REFERENCED TO CARRIER 5 MHz	1 MHz
10 Hz	-130	-135
100 Hz	-140	-140
1 kHz	-160	-145
10 kHz	-165	-150

OSCILLATOR COARSE ADJ RANGE:	1 PP10^7
OSCILLATOR FINE ADJ RANGE:	DIGITAL INDICATOR 0 TO 999 IN PP10^11

B. PHASE LOCK FUNCTIONS

INPUT FREQUENCIES:	
5 MHz:	1 TO 10 VPP
1 MHz:	1 TO 4 VPP
RESOLUTION (WITH MEMORY):	2.5 x 10-12
PHASE LOCK LOOP FILTER:	HERMETICALLY SEALED
TIME CONSTANT:	100 SEC. OR 1 SEC., SWITCH SELECTABLE
CONTROL RANGE:	1 PP10^8
UNLOCK DETECTOR:	RESPONDS TO LOSS OF INPUT SIGNAL LEVEL OR PHASE DETECTOR SLIPPAGE
LOCK ACQUISITION:	MANUAL CONTROL

C. 1 PPS GENERATOR

SYNCHRONIZATION:	
EXTERNAL:	A) 1 PPS, 1-10 VPP WIDTH >5 USEC. B) 1 PPS + 1 MHz (ALGEBRAICALLY ADDED) EQUAL AMPLITUDES OF 1-5 VPP PULSE WIDTH >5 USEC.
SYNC PULSE RISE TIME:	0.1 USEC. MAXIMUM
SYNCHRONIZATION DELAY:	0.1 TO 0.2 USEC.
SYNCHRONIZATION MODE:	A) CONTINUOUS (SYNCS TO EVERY INPUT PULSE) B) INTERMITTENT (SYNCS TO FIRST PULSE AFTER SWITCH IS THROWN)
1 PPS JITTER (UNSYNCHRONIZED):	0.1 NANOSEC. RMS MAXIMUM

Figure 7. TECHNICAL SPECIFICATIONS DISCIPLINED TIME/FREQUENCY STANDARD

sequence, a small unit must be added or one of the internal modules must be changed. Phase lock of the system is very simple. All critical elements are hermetically sealed, and care has been taken to control parameters so that the unit will be very reliable in the field.

The time constant switch controls two time constants: 100 second and 1 second. The control range is a part in 10^8; i.e., when the system is being set up, the frequency is adjusted to within a part in 10^8, at which point it will pull in and hold. The synchronization signal is 1 pulse/sec, with amplitude of 1 to 10 volts and width of about 5 microseconds. When 1 pulse/sec is added to a 1-megahertz signal, both time and frequency will be locked. Note the data (Figure 7): 0.1 microsecond on the synchronization pulse rise time; if locking to a signal, the total delay through the unit is 0.1 to 0.2 microsecond. The unit at NRL has always been within 0.1 microsecond.

In Figure 8 the dotted lines represent the different modules in the oscillator. The modules are completely separated, thus well isolated. Because of problems with the memory, the unit will probably be constructed in two versions: one with a volatile memory that will hold only as long as power is supplied, and one with a nonvolatile silicon nitride memory that, if power is lost, will still remember where the oscillator was and that will come back to frequency more rapidly. Two versions may be required because the nonvolatile memory may be prohibitive in cost for those cases in which it is not really needed.

Figure 9 shows the expected stability by time rate measurement (Allan variance). Some points were checked and found to be valid; for instance, the 1-second point was 3 parts in 10^{12}. Some measurements made at the factory have not yet been repeated in the lab. The measurement method is a double chain multiplication system, in which the frequency of a very clean oscillator and the frequency of the oscillator under test are multiplied, then mixed. The difference between them is achieved by an

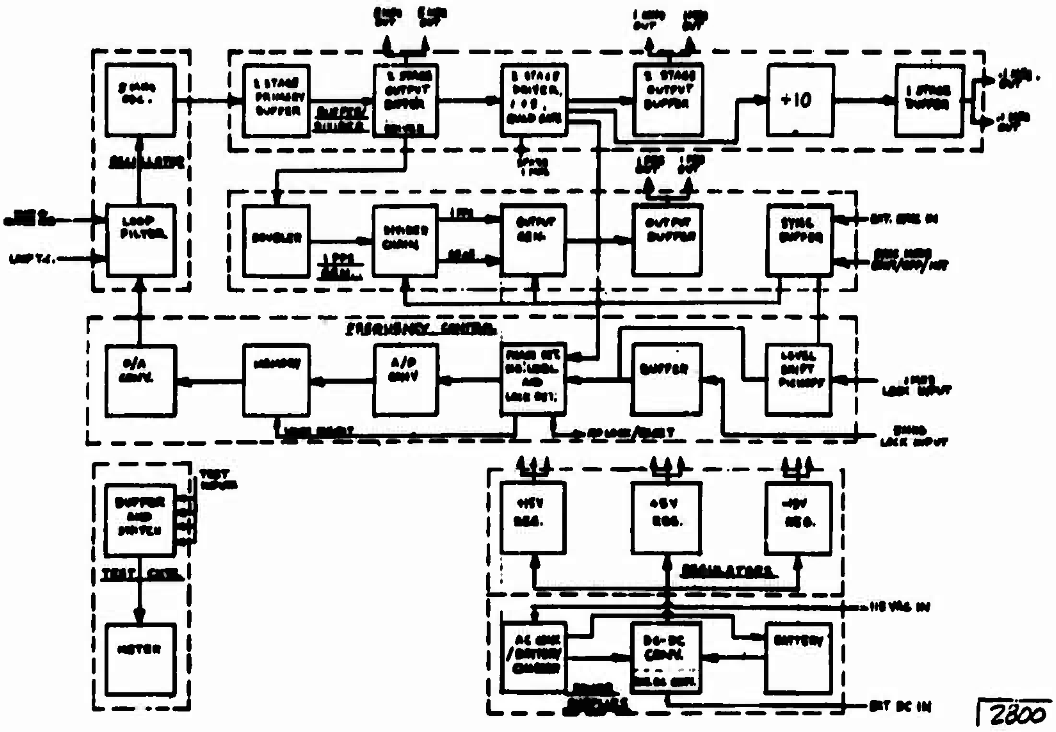


Figure 8. DISCIPLINED TIME/FREQUENCY STANDARD -- PRELIMINARY BLOCK DIAGRAM

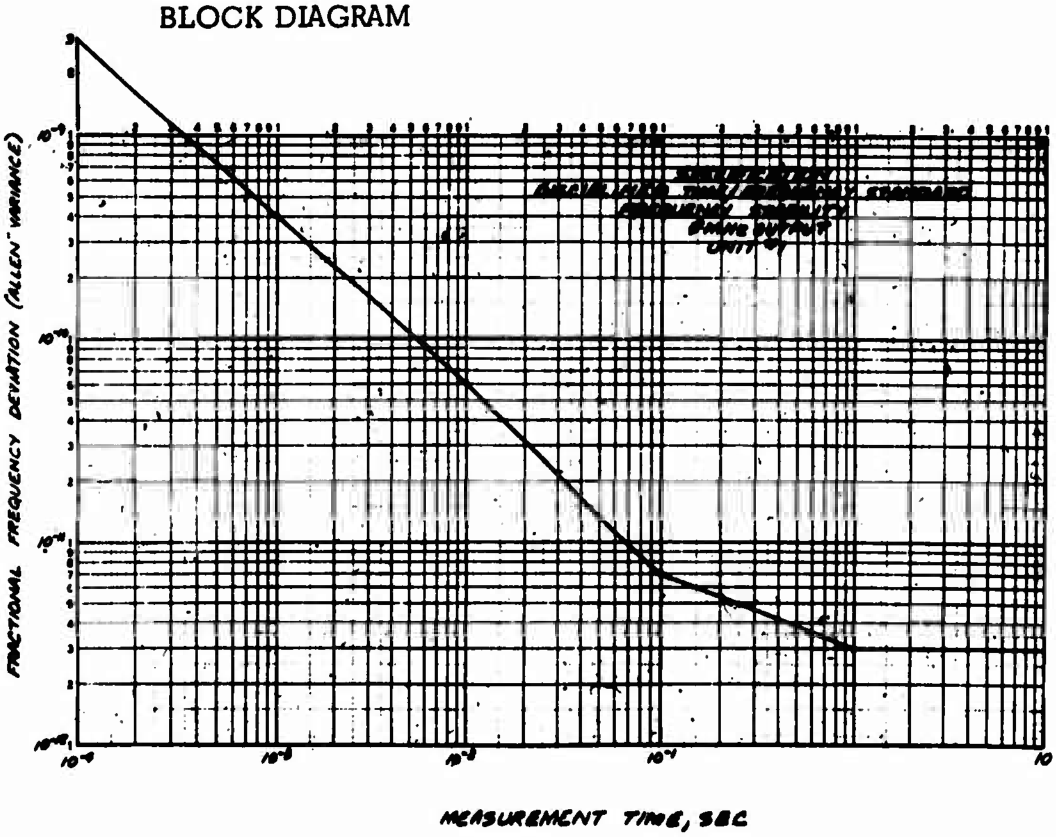


Figure 9. SPECIFICATION DISCIPLINED TIME/FREQUENCY STANDARD FREQUENCY STABILITY, 5 MEGAHERTZ OUTPUT -- UNIT #1

offset of the standard of about 5 kilohertz. This frequency difference is measured with a wave analyzer or a computing counter.

Figure 10 shows the spectral purity of the disciplined time frequency standard. The data were taken on a tracking analyzer. Figure 11, the house standard at Frequency Electronics Incorporated, has a 60-cycle sideband at 107 db and a 120-cycle sideband at 97 db. The disciplined oscillator was added to the system and the sidebands were remeasured. Ten cycles away is 129 db. These sidebands, as far as can be measured, have disappeared well into the noise. It is the cleanest oscillator demonstrated to date.

Figure 12 compares the DTFO locked to a cesium standard with a maser. The cesium beam tube is about five years old and is very noisy. On short time constant, the disciplined oscillator did not clean the signal very well; on long term, however, it did a very good cleaning job. These measurements, called phase recordings, were made on an error multiplier that multiplied the error by 1,000.

The question asked by all is: "If we're going to use this everywhere, what will the cost be?" At present, the one-time tooling cost is about $35,000. In lots of 100, the expected cost will be in the $2,000 category; In lots of 1,000, it will be from $1,380 to $1,495. However, the cost will range somewhat with different versions of the unit.

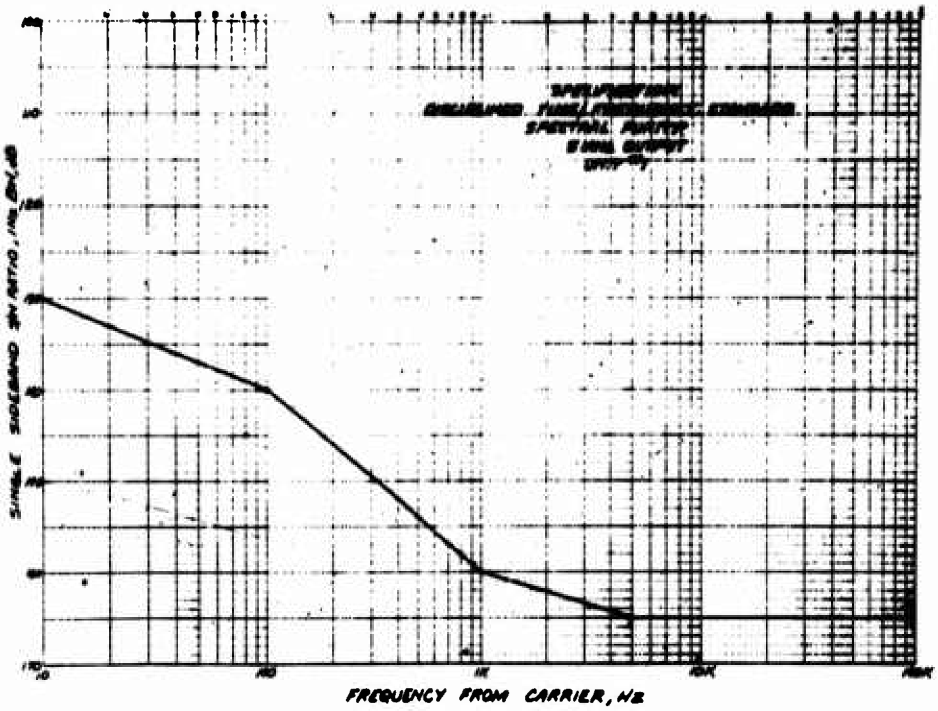


Figure 10. SPECIFICATION DISCIPLINED TIME/FREQUENCY STANDARD SPECTRAL PURITY - 5 MEGAHERTZ OUTPUT - UNIT #1

Figure 11. DTF STANDARD LOCKED TO HOUSE STANDARD

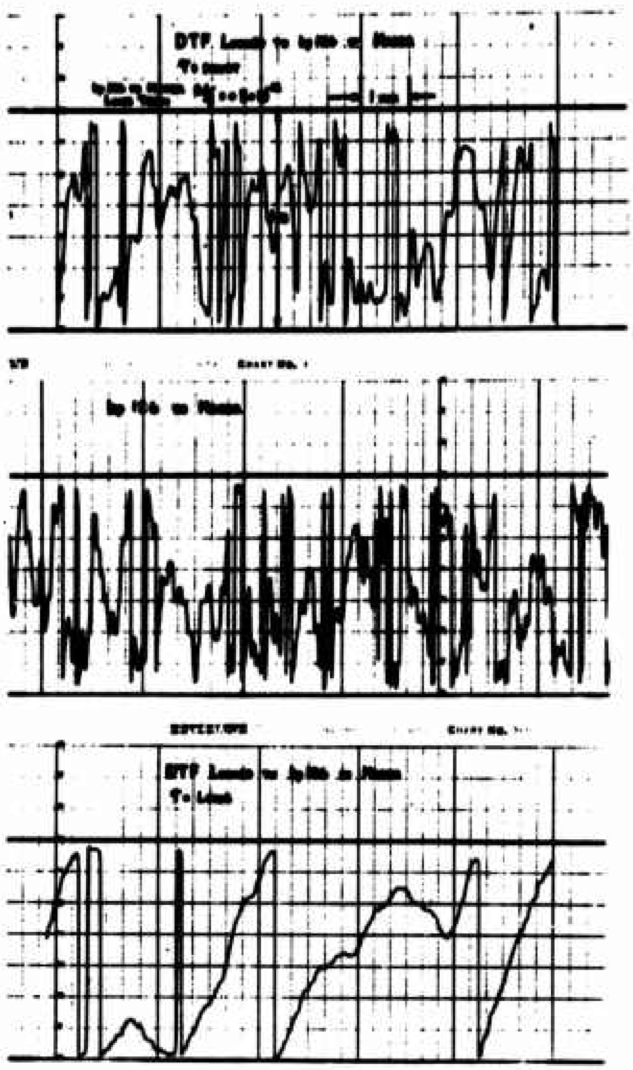


Figure 12. HP CESIUM BEAM STANDARD SER. NO. 126 VS NRL HYDROGEN MASER

DISCUSSION

DR. WINKLER: I have no questions, but I would like to comment on your presentation. I think the development of the disciplined oscillator is to be extremely useful.

For our timing application, it might be cheaper to make the unit not serviceable at all--to have no connectors or modules in it--but to case the whole unit in epoxy or concrete and have a unit that would work 10 years without any serviceman ever looking at it; after that time you would throw it away. Even if it is a $15,000 item it might be cheaper to do that in the face of ever-increasing costs of trained personnel and stockpiling replacement parts or modules, and of ever-increasing reliability problems with connectors, pilot lights, and other little things.

ATOMIC STANDARDS TEST AND EVALUATION

by

Dr. E. Hafner

Dr. Hafner is Leader, Frequency Control Devices Team, Electronics Technology and Devices Laboratory, U.S. Army Electronics Command, Fort Monmouth, New Jersey.

The U.S. Army Electronics Technology and Devices Laboratory, ECOM, Fort Monmouth, New Jersey, was asked at the end of 1969 by the then Naval Applied Sciences Laboratory to conduct an extensive series of evaluations of the performance of the Hewlett-Packard Model 5061A Cesium Beam Frequency Standard under a wide range of environmental conditions. The test conditions specified by the various Systems Management Groups were based on the anticipated environment in a nuclear submarine for use in a RHO-RHO navigation system. The test program took about 6 months. The paper presented here is essentially an excerpt of an R&D Technical Report prepared by ECOM describing the approach adopted for conducting the tests and the results obtained.

Only a brief summary will be given now. For more detailed information the reader is referred to R&D Technical Report, ECOM-3371, "Performance of Cesium Beam Frequency Standards and Clock Modelling," by Erich Hafner and Edward Simon, dated December 1970.

Three ruggedized HP5061A Cesium Atomic Frequency Standards were subjected to 2 Gauss ac and dc magnetic fields in three directions, supply voltages of 94 volts, 115 volts, and 126.5 volts; temperatures of 58°F, 75°F, and 92°F; vibrations of 0.120" DA at 4 to 15 hertz and 0.04" DA at 16 to 25 hertz; and 11 milliseconds shocks of 15 g, 40 g, and 60 g. Throughout these experiments the mean frequencies of the standards, averaged for the most part over three-

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day periods, remained within a 1σ limit of ± 1 x 10^{-12}, except during the ac magnetic field exposure. There, frequency deviations of up to 80 x 10^{-12} were observed. This ac magnetic field sensitivity was due primarily to field sensitive elements in the electronics and in the beam tube and is not an intrinsic property of Cesium Beam Frequency Standards.

The test results demonstrate that the ruggedized HP Model 5061A CS Atomic Beam Frequency Standard is capable of maintaining satisfactory operation under severe environmental conditions. No catastrophic failures were encountered at any time, and nearly all of the interruptions of normal service that did occur can be avoided if appropriate safety precautions are taken.

The Technical Report cited above provides a detailed description of the test procedures used and the results obtained, including an analysis of the various failure modes observed. Copies are available from Defense Documentation Center, Accession Nr. AD882827. A limited number of copies is still on hand at ECOM, Attn: AMSEL-TL-SF.

DISCUSSION

DR. HAFELE: It wasn't clear to me what clock you were comparing with what clock. You had two clocks and you were comparing the two clocks. What was the reference clock?

DR. HAFNER: We had three clocks. During all the tests except vibration and shock, one unit served as the reference. During the vibration and shock tests, two of the remaining units served as the reference. The comparison was made between the frequency difference between the two pairs.

MR. PITSENBERGER: What's the principle of the cesium oscillator? Secondly, are there any nuclear isotope decay processes involved?

DR. HAFNER: There are no decay processes involved. The cesium atom is stable. The cesium resonator serves as a passive device, effectively as a discriminator. It has a very high Q depending on such considerations as design and beam length. For this particular tube, the Q is in the order of 20 millions, so you have a very high Q discriminator. Its discriminating action is utilized to slave a crystal oscillator to it, to the center of the resonance.

DR. REDER: I have three questions. First, on this attitude test which caused the frequency change of two parts in 10^{12}, could that be measured fast enough to see whether there is a delay which would point towards temperature?

DR. HAFNER: I would think it would be rather difficult to detect the thermal transient there but we have observed rather large changes in the temperature. We had thermo couples distributed within the unit and outside the unit and the readings were substantially different in different attitudes. Correlation between temperature and frequency is a rather hairy problem and depends on many, many details.

DR. REDER: Second, when you made the vibrator test, did the vibrators cause any AC-magnetic fields which could possibly also have affected the cesium standards?

DR. HAFNER: This was a mechanical vibrator. We have searched for ambient AC-fields very carefully and within the resolution of our gaussmeter, which has a bandpass cutoff about 2000 Hz, we have never been able to detect any ambient AC-fields.

DR. REDER: Do you know what the source of the AC-magnetic field sensitivity is? Is it in the beam tube, in the electronics line, in transformer cores, or where?

DR. HAFNER: Dr. Cutler, would you care to answer that question?

DR. CUTLER: There are apparently several sources for the AC-magnetic field problem. There are some electronic effects and some effects in the beam tubes; generally the larger effects amount to a modulation in the electronics and then a demodulation by something vibrating inside the beam tube. Either something vibrating, or, in the case of the magnetic field, perhaps defection of ions, so we have taken steps both in the electronics to reduce the initial modulation effects and in the beam tubes to reduce the sensitivity to the magnetic field inside.

DR. REDER: On this magnetic field test is it possible that the harmonic of the AC frequency came close to the modulation frequency and caused havoc?

DR. CUTLER: That can happen, that's one of the things you have to watch out for.

DR. HAFNER: I think I can perhaps add something here. We had made the 3-day tests on the AC-magnetic field at 60 Hz. However, we have searched from 40 Hz to 400 Hz, that is, we applied AC-magnetic field over this frequency range to the coil, and when there was coincidence with the modulation frequency or harmonics, the unit would jump out of lock. This occurred at relatively small fields.

MR. CHI: In the beginning you mentioned you also tested a rubidium gas cell frequency standard. What is the result of that?

DR. HAFNER: We have not subjected rubidium gas cells to any similar tests. Not as extensively.

STABILITY CHARACTERISTICS AND APPLICATION TECHNIQUES FOR PRECISION FREQUENCY SOURCES

by

Dr. L.S. Cutler

Dr. Cutler is Director, Physical Research Laboratory, Hewlett-Packard Company, Palo Alto, California.

We would like to go back to some fundamentals and present some of the aspects of noise and fluctuation on signals which lead to the characteristics of various types of precision signal sources.

First we will discuss representations of signals and go into some of the simple noise relationships. We will talk about how signals can become contaminated and then consider some of the various stability measures that have been proposed and are in present use and then talk about the effects of frequency multiplication on precision sources and means for achieving low noise frequency multiplication. In addition, we will consider some of the techniques for measuring stability and getting some of the numbers involved in stability measures. Last of all, I will present some of the characteristics of available sources -- by no means an exhaustive list, just a few.

Figure 1 is a representation of a pure signal. We have a signal which is a sinusoidal function of time and is depicted as a rotating vector. The real signal is the projection on the horizontal axis of this vector as it rotates at the angular velocity of ω_0. Figure 1 is the vector as viewed in a coordinate system that rotates at the angular velocity ω_0. In this coordinate system, the vector is fixed. This is the phasor representation.

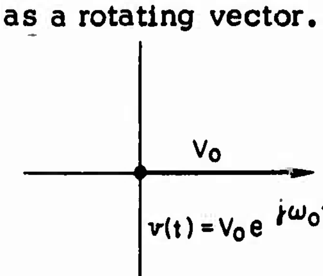


Figure 1. PURE SIGNAL

If we change the length of the vector (Figure 2) but do not rotate it about its position, then we get a representation of amplitude modulation. Again, remember that this total vector is rotating at the rate of ω_0, but its length is changing in time.

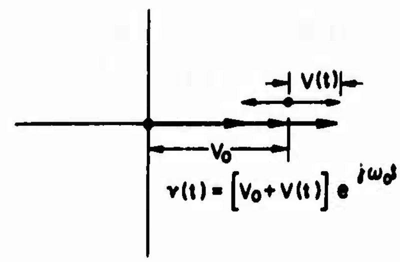


Figure 2. PURE AMPLITUDE MODULATED SIGNAL

If we take the vector, keep its length constant and swing it back and forth so that it advances and retards as it rotates at ω_0, we have pure phase modulation. This is directly related to frequency modulation and is shown in Figure 3. In this case the phase angle, $\phi(t)$ is a function of time and it appears in the argument of the exponential. If we do both things simultaneously, we obtain simultaneous amplitude and phase modulation as shown in Figure 4. There are cases where the amplitude--

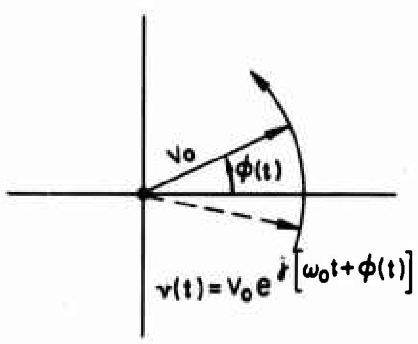


Figure 3. PURE PHASE MODULATED WAVE

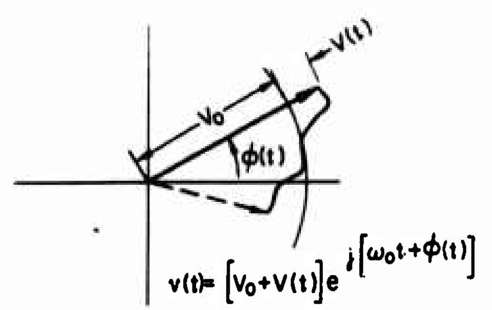


Figure 4. PHASE AND AMPLITUDE MODULATED SIGNAL

represented by $V(t)$ -- might be correlated with the phase angle $\phi(t)$, so one would have a correlation between the amplitude and phase modulation that is present. In some cases this can be very important.

We consider amplitude modulation first. There is the carrier V_0 and two sidebands (Figure 5) which rotate at rates ω_m with respect to this carrier vector, in opposite directions and are so phased that their maxima -- when they add up on the same direction -- lies along V_0. This gives us a representation in phasor language of pure sinusoidal amplitude modulation -- carrier plus two sidebands.

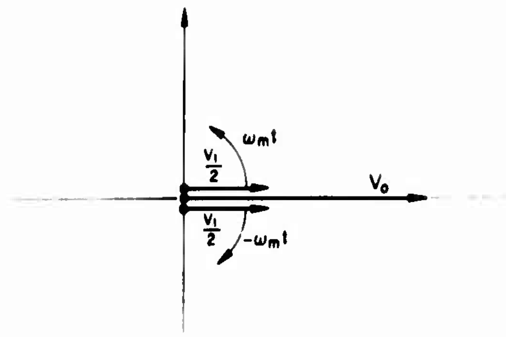


Figure 5. PURE SINUSOIDAL AMPLITUDE MODULATION-CARRIER PLUS TWO SIDEBANDS

You can picture these two sidebands as being added to the end of the vector and rotating in opposite directions so that the net resultant is just to change the lengh of this amplitude vector and not to change its phase angle.

If we go to a frequency domain representation (Figure 6) where we are talking about just the amplitudes of the carrier and sidebands, not the power, we represent the carrier at the center frequency ω_0 and the two sidebands equally spaced on either side of ω_0 by $\pm \omega_m$ where ω_m is the angular modulation frequency. The sidebands are shown as being in phase at the instant they lie along the carrier vector.

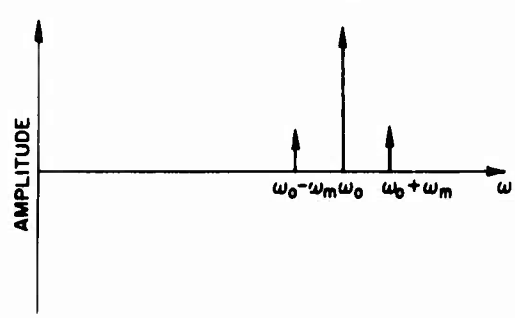


Figure 6. FREQUENCY DOMAIN REPRESENTATION FOR PURE SINUSOIDAL AMPLITUDE MODULATION

Now let us consider the case where we have two sidebands again, but phased differently from the case we had for amplitude modulation. This is shown in Figure 7. Here again the two sideband vectors rotate in opposite directions, but now when they point in the same direction the resultant would be to cause some phase shift and this is a representation of small index sinusoidal phase modulation. One can also see that if he added these vectors, the length of the total resultant vector would change slightly, and consequently a single pair of sidebands does produce some amplitude modulation in addition to phase modulation. Restraining the length of the vector to remain absolutely constant requires second-order and higher-order sidebands. One can go through and draw a diagram and see how all the Bessel function relations for the sideband amplitudes in phase modulation come about.

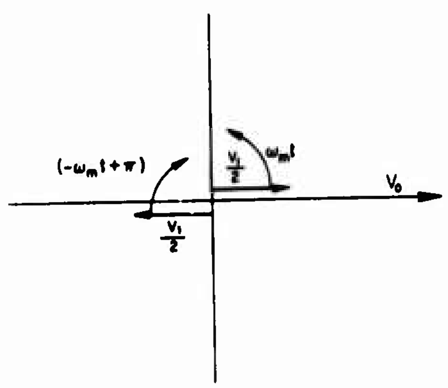


Figure 7. SMALL INDEX SINUSOIDAL PHASE MODULATION CARRIER PLUS TWO SIDEBANDS

Figure 8 is a frequency domain representation for pure sinusoidal phase modulation. This representation is to give the idea that the two sidebands are out of phase with respect to what they would be if it were amplitude modulation. Here again, if it were a power spectrum, one would have no indication of phase, but we have tried to preserve some phase here by having an amplitude spectrum rather than a power spectrum.

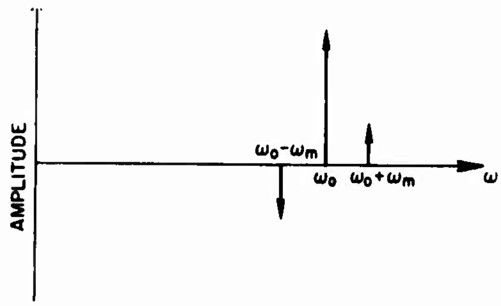


Figure 8. FREQUENCY DOMAIN REPRESENTATION FOR PURE SINUSOIDAL PHASE MODULATION (Small Index)

In Figure 9 we consider a pure signal and one sideband. This has been broken down, as the second line in Figure 9 shows, into a phase and amplitude modulated wave and the phase and amplitude modulations are correlated, so a carrier plus a single sideband does give correlated phase and amplitude modulation. The phase modulation is relatively pure if the sideband amplitude as compared to the carrier amplitude is fairly small. One can

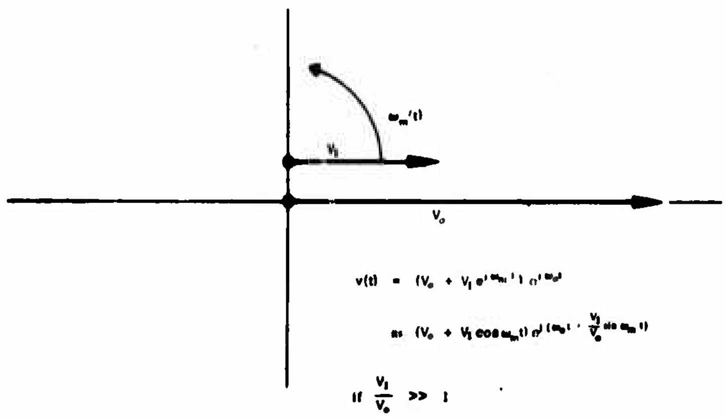


Figure 9. AMPLITUDE AND SMALL INDEX PHASE MODULATION -- CARRIER PLUS ONE SIDEBAND

picture this if he adds the sideband to the tip of the carrier vector and lets it rotate; it performs a circle out there, and the resultant vector then grows in length and shrinks in length at the same time it changes angle. It is apparent that the angle and length are correlated. This all leads to the point that any time there is an asymmetric power spectrum, there will be correlation between the amplitude and the phase modulation, even in the case of noise.

So far we have considered mainly pure sinusoidal modulations. Now let us look at random processes, including noise. Here one has to invoke such things as autocorrelation functions, probability densities, power spectral densities, and phase and frequency power spectral densities. Let us investigate some of these things.

Figure 10 shows some very basic definitions. If one can assume some things about the signal, he may say that the autocorrelation function is the average value of the product of a time function with itself at a time τ later as shown in the first part of the equation in Figure 10. v(t) is a real function and the average brackets mean either time or statistical average in the case where these two are equivalent. The spectral density $S(\omega)$ of this same function is the one-sided Fourier transform of the autocorrelation function R as shown in the second line. Conversely, there is the inverse Fourier transform relation between R and S shown in the third line. These relations are very useful; they come up time and time again in this sort of work. A lot of what we are covering is treated in fair detail in the National Bureau of Standards' Technical Memo 394, which was also published in the <u>IEEE Transactions on Instrumentation and Measurement</u> entitled, "Characterization of Frequency Stability."

$$R_v(\tau) = \langle v(t)\, v(t+\tau) \rangle \quad (v \text{ real})$$

$$S_v(\omega) = 4 \int_0^\infty R_v(\tau) \cos\omega\tau \, d\tau$$

$$R_v(\tau) = \frac{1}{2\pi} \int_0^\infty S_v(\omega) \cos\omega\tau \, d\omega$$

$\langle\ \rangle$ means time or statistical average

Figure 10. RELATIONS BETWEEN AUTOCORRELATION FUNCTION, $R_v(\tau)$, AND SPECTRAL DENSITY, $S_v(\tau)$

Now we would like to define a couple of useful quantities related to phase and frequency as shown in Figure 11. It is useful to normalize both phase and frequency by dividing by the angular frequency of the oscillator itself. We define a variable x which is equal to the phase divided by ω_0 and a variable y which is equal to the angular frequency (the time derivative of ϕ) divided by ω_0 so y is equal to $\dot{x}$.

$$x(t) = \frac{\varphi(t)}{\omega_0}$$

$$y(t) = \frac{\dot{\phi}(t)}{\omega_0} = \dot{x}(t)$$

Figure 11. DEFINITIONS OF x(t) AND y(t)

We have to work with spectral densities. Figure 12 shows some relationships between the spectral densities of x and y and ϕ. Inasmuch as frequency is essentially the time derivative of phase, the spectral density of frequency will be ω^2 times the spectral density of phase. $S_y(\omega)$, for example, is equal to $\omega^2 S_x(\omega)$. That is a very useful relationship.

$$S_x(\omega) = \frac{S_\varphi(\omega)}{\omega_o^2} = \frac{S_{\dot\varphi}(\omega)}{\omega^2 \omega_o^2} = \frac{S_y(\omega)}{\omega^2}$$

$$S_y(\omega) = \frac{S_{\dot\varphi}(\omega)}{\omega_o^2} = \frac{\omega^2 S_\varphi(\omega)}{\omega_o^2} = \omega^2 S_x(\omega)$$

Figure 12. RELATIONSHIPS BETWEEN $S_\varphi(\omega)$, $S_{\dot\varphi}(\omega)$, $S_x(\omega)$, AND $S_y(\omega)$

Let us talk now about contamination of signals. Signals can be contaminated through noise by two processes: (1) multiplication or modulation, and (2) additive noise. By multiplication, we mean multiplication by some time function rather than frequency multiplication, although contamination does occur in that process. Additive noise is added to a pure signal and contaminates it when it is localized in frequency around the signal. This effectively adds sidebands to the signal and can be construed as a mixture of amplitude and and phase noise sidebands.

We should look at various types of modulators. Figure 13 represents a simple amplitude modulator. The function A(t) is real, and consequently, one gets a signal which is not contaminated in phase. Its amplitude is now a function of time, therefore it is a pure amplitude modulator.

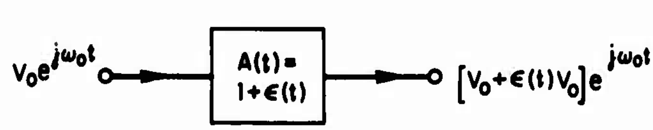


Figure 13. AMPLITUDE MODULATOR

Figure 14 shows a pure phase modulator. $V_0 e^{j\omega_0 t}$, a pure signal, is multiplied by a complex function with a constant magnitude, producing a signal with a constant amplitude, V_0, but a phase which is now a function of time.

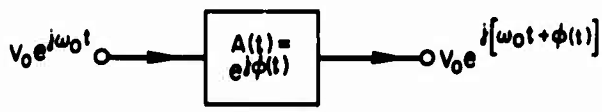


Figure 14. PHASE MODULATOR

Obviously, we can combine the two things and obtain simultaneous amplitude and phase modulation (Figure 15), and if one wants to make it correlated, he certainly can.

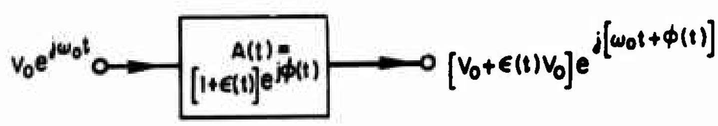


Figure 15. AMPLITUDE AND PHASE MODULATOR

Now let us look at additive noise -- the other contaminator of signals. Figure 16 is a representation of a narrow band random noise centered about the frequency ω_0 . It has a randomly varying amplitude and a randomly varying phase. The vector rotates around in some random fashion and changes its length in a random fashion. If the noise were not centered at the frequency ω_0, one would find there would be some net

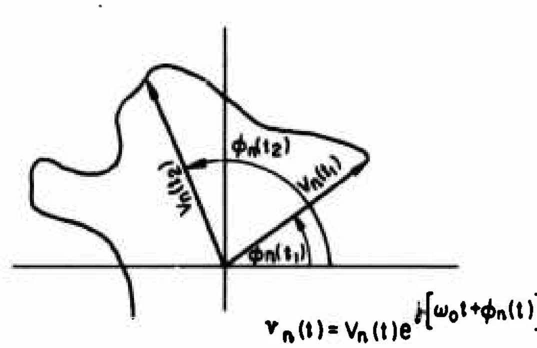
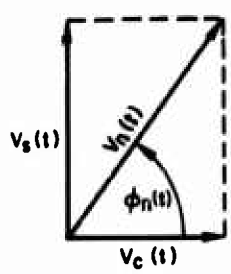


Figure 16. NARROW-BAND RANDOM NOISE CENTERED ABOUT ω_0

average rotation rates corresponding to the difference in frequency between the center of the spectrum and the frequency of reference, ω_0.

We can resolve this narrow-band noise as shown in Figure 17 into an in-phase part $V_c(t)$ and a quadrature part $V_s(t)$ both of which are random time functions. For most types of noise sources derived from a lot of statistically independent sources, one can prove that $V_c(t)$ and $V_s(t)$ will be gaussian random variables and will, in general, be independent processes provided we have chosen our center frequency properly. We can represent the instantaneous voltage, shown on the bottom line of Figure 17, as an in-phase and a quadrature part times our pure sinusoidal signal that is rotating at the frequency of ω_0. Now, if we add a pure signal to this, we get the pure signal modulated



$$V_c(t) = V_n(t) \cos \phi_n(t)$$

$$V_s(t) = V_n(t) \sin \phi_n(t)$$

$$v_n(t) = V_n(t)\, e^{j[\omega_o t + \phi_n(t)]}$$

$$= [V_c(t) + j V_s(t)]\, e^{j\omega_o t}$$

Figure 17. RESOLUTION OF NARROW-BAND RANDOM NOISE INTO AMPLITUDE (IN-PHASE) AND PHASE (QUADRATURE) COMPONENTS

as shown in Figure 18. The resultant signal can be resolved into an equivalent phase modulation and equivalent amplitude modulation.

Figure 19 represents the signal plus random additive noise in terms of $V_c(t)$ and $V_s(t)$. The relationships given hold true if the noise voltages are small compared with the signal voltage.

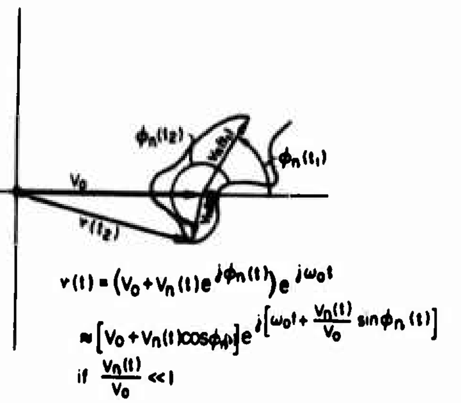


Figure 18. PURE SIGNAL AT ω_0 PLUS NARROW-BAND RANDOM NOISE

$$v(t) = \left[V_o + V_c(t) + jV_n(t)\right] e^{j\omega_0 t}$$

$$\approx \left[V_o + V_c(t)\right] e^{j\left[\omega_0 t + \frac{V_s(t)}{V_o}\right]}$$

$$\text{if} \quad \frac{V_c(t)}{V_o} \ll 1 \quad \text{and} \quad \frac{V_s(t)}{V_o} \ll 1$$

Figure 19. SIGNAL PLUS RANDOM ADDITIVE NOISE

Figure 20 is a representation of the RF power spectral density of a pure signal with added noise. The pure signal is an infinitely thin spectral line that is infinitely tall. Presumably, it has area P_0 under it and the additive noise has area P_n which is equal to the integral of the spectral density of the noise power over all frequencies. Here we are using one-sided spectral densities in terms of ω (rather than frequency f or ν).

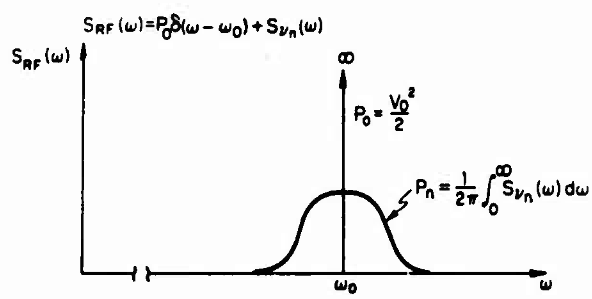


Figure 20. RF POWER SPECTRAL DENSITY OF PURE SIGNAL PLUS ADDED NARROW-BAND NOISE

If one has additive noise, how does he relate the effective phase modulation or the effective amplitude modulation of that noise back to things one can measure, such as spectral density of a noise itself, the signal power, etc.? Figure 21 shows some of the mathematics of how this is done. The spectral density, $S_\varphi(\omega)$, is given by the spectral density of the sine or quadrature part of the noise voltage divided by V_0^2 and that can be given in terms of the spectral density of the noise itself, as shown in the second line. We can say that the spectral density of phase is given by the bottom line, the spectral density of the noise voltage divided by the power in the signal. This is a very useful and important relation.

$$S_\varphi(\omega) \approx \frac{S_{V_s}(\omega)}{V_o^2} \quad \text{for } \frac{P_n}{P_o} \ll 1$$

$$\text{But } S_{V_s}(\omega) = S_{V_n}(\omega_0 + \omega) + S_{V_n}(\omega_0 - \omega)$$

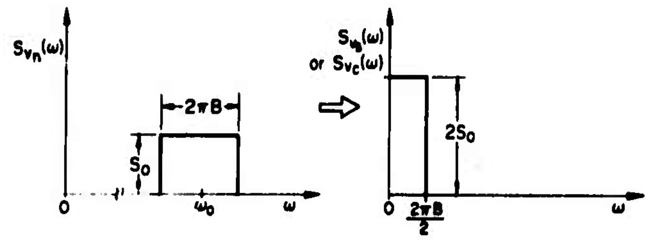
$$= 2\,S_{V_n}(\omega_0 + \omega) \quad \text{if } S_{V_n}(\omega)$$

is symmetric about ω_0

$$\text{Then } S_\varphi(\omega) \approx \frac{S_{V_n}(\omega_0 + \omega)}{P_o}$$

Figure 21

Figure 22 shows the effect of a spectrum of added noise that has even symmetry about ω_0. Suppose we have a rectangular band of added noise that is $2\pi B$ wide and S_0 tall. Therefore, the total noise power is $S_0 B$. This transforms to the effective modulation spectral density, either phase, $S_{V_s}(\omega)$, or amplitude, $S_{V_c}(\omega)$, as shown in the right half of Figure 22.



$$\sigma_v^2 = \sigma_{V_s}^2 = \sigma_{V_c}^2 = S_0 B$$

Spectrum symmetric about $\omega_0 \Rightarrow V_s$ & V_c uncorrelated

Figure 22

There one sees the spectral density is twice as high and it extends out to half the bandwidth, but the total area under it is the same, so that the total area under either the sine part or the cosine part is equal to the total area under the additive noise. This is a very important relationship. This is a case where we have a symmetric spectrum, and that implies immediately that the sine part and cosine part, or, equivalently, the phase and amplitude modulations produced by this additive noise, are uncorrelated.

Figure 23 is an example of an asymmetric power spectrum of the additive noise. This leads to the power spectral density for the sine or cosine part corresponding to the phase or amplitude modulation parts as shown on the right half of the figure. The spectral density is obtained essentially by taking the even part of the RF power spectral density of the added noise and translating it down to zero frequency. For the case of asymmetric spectral densities, one can show that the effective amplitude and phase modulations are correlated.

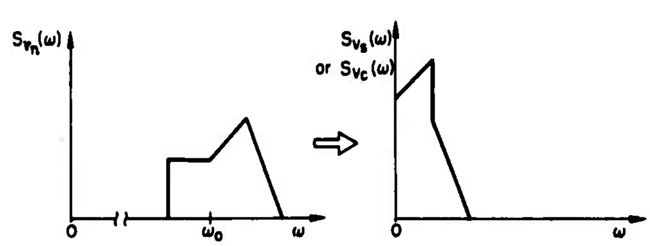


Figure 23. ADDITIVE RANDOM NOISE; SPECTRUM ASYMMETRIC ABOUT $\omega_0 \Rightarrow V_s$ AND V_c CORRELATED

If one has any kind of a signal with a zero mean, as in Figure 24, the variance of that signal is equal to the auto-correlation function at zero lag which is equal to the integral over the power spectral density. In other words, it is the total power in the signal. We are interested in the mean square value of the phase as given by the bottom line in Figure 24. If one has a signal that is quite pure but is contaminated with additive noise, then the total variance in phase produced by that additive noise is just equal to the noise-to-signal power ratio as shown in the bottom line.

For v with 0 mean,

$$\sigma_v^2 = R_v(0) = \frac{1}{2\pi}\int_0^{\infty} S_v(\omega)\,d\omega$$

so that

$$\sigma_\varphi^2 = \frac{\sigma_{v_n}^2}{P_o} = \frac{P_n}{P_o}$$

Figure 24

Obviously, one way to get a better signal or equivalently a smaller variance in phase, is to shrink the power spectrum of the additive noise by narrow-band filtering and, therefore, reduce the total noise power. This, of course, will reduce the total phase angle that the signal is swinging.

Let us look at Figure 25 which shows the spectral density of x for a typical signal that might be derived from a precision oscillator or a cesium standard, hydrogen maser, or something else. It has proven to be useful and accurate to represent this as a series in inverse powers of ω, and generally most sources will exhibit a number of these components. Remember $S_x(\omega)$ is essentially a measure of the spectral density phase -- not frequency.

Typical sources will have phase spectral densities that can be represented as

$$S_x(\omega) = h_{-4}\,\omega^{-4} + h_{-3}\,\omega^{-3} + h_{-2}\,\omega^{-2} + h_{-1}\,\omega^{-1} + h_0$$

- h_0 — white phase
- $h_{-1}\,\omega^{-1}$ — flicker phase
- $h_{-2}\,\omega^{-2}$ — random walk phase
- $h_{-3}\,\omega^{-3}$ — flicker frequency
- $h_{-4}\,\omega^{-4}$ — random walk frequency

Figure 25

Most signals can be broken down as shown in Figure 25, and one can assign values to the coefficients by making measurements. In the process of designing equipments, one can get some idea as to how to reduce some coefficients, perhaps at the expense of others.

In addition to spectral densities, there is another very useful measure, the Allan Variance shown mathematically in Figure 26. It is a measure of of frequency fluctuations for some averaging time τ. Figure 26 shows a special case of the more general Allan Variance which involves N samples with the time between samples of T and averaging time τ. There are also some cases involving high frequency divergences, so sometimes one must consider the high frequency cutoff either in the apparatus he is measuring or the apparatus with which he is making the measurement.

Another useful measure is the Allan Variance, $\sigma_y^2(\tau) = \langle \sigma_y^2(2, \tau, \tau) \rangle$ which is the rms fractional frequency fluctuation averaged over time τ for pairs of adjacent samples.

$$\sigma_y^2(\tau) = \frac{1}{\pi}\int_0^\infty d\omega\; S_y(\omega)\;\frac{\sin^4\left(\frac{\omega\tau}{2}\right)}{\left(\frac{\omega\tau}{2}\right)^2}$$

This is a special case of $\langle \sigma_y^2(N, T, \tau) \rangle$

Figure 26

Figure 27 shows some very simple relationships which have been derived for the power law spectra. These relationships are mentioned in detail in Technical Note 394 of the National Bureau of Standards. For a phase spectral density proportional to $\omega^{(\alpha - 2)}$, the Allan Variance is proportional to τ^{μ} where τ is the averaging time and the graph on the right of Figure 27 gives a relationship between μ and α. For example, for flicker-frequency noise, α would be -1 in which case μ is 0. That is, the Allan Variance is then proportional to τ^0; and so is a constant. Therefore, if one takes Allan Variances as a function of averaging time, and finds that they do not change, he knows that he is looking at a flicker frequency noise spectrum.

For $S_x(\omega) = h_{(\alpha - 2)}\,\omega^{(\alpha - 2)}$

$\sigma_y^2(\tau) = C_\alpha\,\tau^{\mu}$

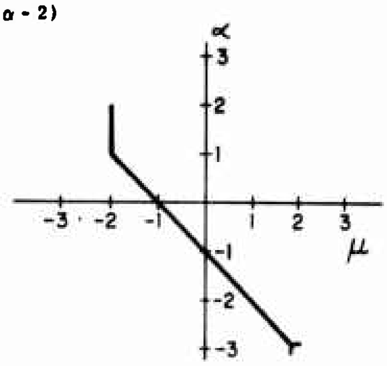


Figure 27. RELATIONSHIPS FOR POWER LAW SPECTRA

Another case that commonly occurs is white frequency noise. This is a commonly observed type of frequency fluctuation for moderate averaging time in cesium beam standards or rubidium standards. For this case, $\alpha = 0$ and $\mu = -1$.

Now let us talk about frequency multiplication. If a frequency multiplier multiplies by a number N, N does not necessarily have to be an integer. For example, in a well-designed frequency synthesizer, N can be some rational fraction. In any case, upon frequency multiplication by the factor N, the instantaneous phase angle is multiplied by N. Usually amplitude limiting occurs so that mose of the noise on the output is phase noise.

Let us now consider some of the techniques for frequency multiplication. Figure 28 shows one scheme for achieving a spectrally-pure signal after frequency multiplication. Of course, if one had a pure source and it was contaminated with some noise so that it represented a real physical source -- namely our precision frequency source -- then we would like to remove as much of the noise modulation as possible by using a narrow-band filter, which could be either a passive filter or active filter such as a high-level phase-locked oscillator. This filters the signal and improves the signal to phase noise ratio. The filtered signal can then be fed into a low-noise frequency multiplier. In order to have a decent RF power spectrum, the

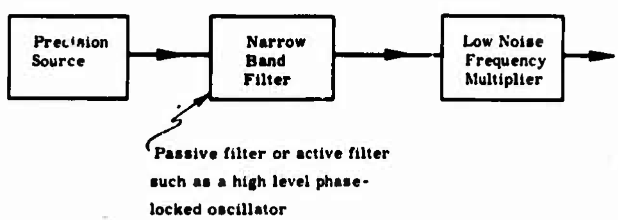


Figure 28. TECHNIQUE FOR ACHIEVING SPECTRALLY PURE SIGNALS

signal-to-noise power ratio after multiplication must be much greater than 1, so one must start out with a signal-to-noise ratio before multiplication which will satisfy this. For example, assume a 60-db signal-to-noise ratio prior to multiplication. Multiplying the frequency by 1,000 times corresponds to increasing the phase modulation by 60 db. The result would be a signal-to-noise ratio of 0 db after multiplication, and there would, consequently, be great spreading out of the noise, higher-order mixing products, etc. In addition, the power in the signal which we would have liked to preserve would have gone down and been smeared out into the sidebands. It is always necessary to look at what you wish to achieve; what frequency multiplication you want to do; and then satisfy the criterion that the signal-to-noise power ratio, after multiplication, be much less than 1. This places very stringent requirements on the signal-to-noise ratio prior to multiplication.

Figure 29 demonstrates one technique for achieving low noise frequency multiplication. An input signal is fed to a filter or a phase-locked oscillator to clean up the signal as much as possible before it goes into the first frequency multiplier. Somewhere along the chain is another phase-locked oscillator, which acts as an active filter, again cleans the noise off the sides of the signal with an optimum bandwidth such that the total spectral density of noise is minimized. This is again followed by frequency multiplication and filtering. The whole process is continued until the desired output frequency is achieved. This is probably one of the best techniques for achieving low noise frequency multiplication.

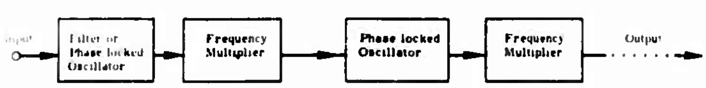


Figure 29. TECHNIQUE FOR LOW NOISE FREQUENCY MULTIPLICATION

A technique for achieving relatively low noise frequency multiplication if a fairly noise free signal is available is shown in Figure 30. It is essentially a phase-locked oscillator in which the phase comparison is done by sampling the output oscillator, the VCO, with a sampler run from the input signal. Loop bandwidth is determined by the sampling rate and the type of filter used. The loop bandwidth cannot be higher than one-half of the

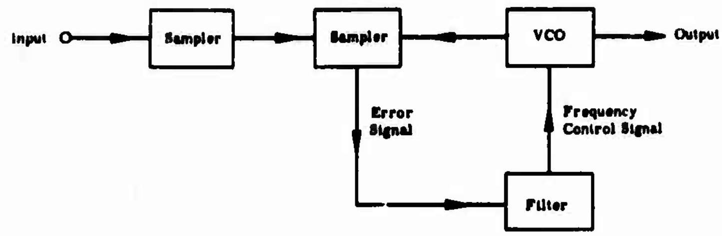


Figure 30. SAMPLED SIGNAL PHASE LOCK LOOP FOR FREQUENCY MULTIPLICATION

sampling rate. There are many samplers available now which will operate up into X-band regions and higher. This technique is useful for phase locking some of the very high frequency oscillators.

Now let us consider some methods of measuring the noise. Figure 31 shows a phase detector technique which is useful for measuring higher frequency noise. Two sources, presumed to be identical, and multiplied in frequency by optional frequency multipliers are fed into a phase detector. The output of the phase detector then can be fed back through a low-pass filter and thus make a very loose, narrow band phase-lock loop to keep the signals essentially in average phase quadrature for long periods of time.

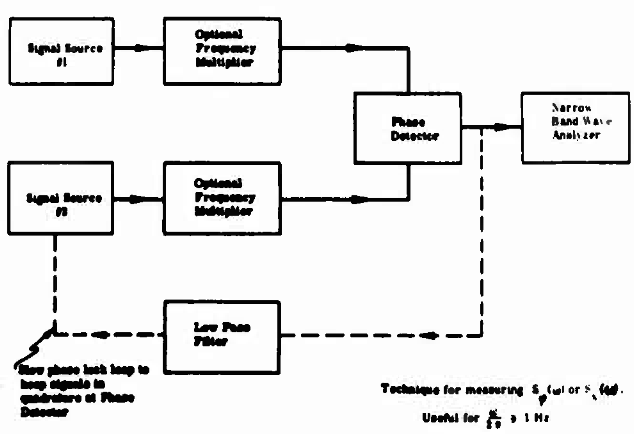


Figure 31. PHASE DETECTOR TECHNIQUE FOR MEASURING HIGH FREQUENCY NOISE

Operation is then on the linear slope portion of the phase detector. Its output can be spectrally analyzed by a narrow-band wave analyzer, and the output can be related back to $S_{\varphi}(\omega)$ or $S_x(\omega)$. This technique is well documented in the literature and very often used.

In Figure 32 is shown a technique for measuring $S_{\dot{\varphi}}(\omega)$ or $S_y(\omega)$. The signal source under test is passed through an optional frequency multiplier, then into a frequency discriminator. (One may use a cavity type discriminator or something similar.) The output will be a voltage that is proportional to the frequency swings on an instantaneous basis and may be analyzed with a narrow-band wave analyzer. It gives spectral information for the frequency components above about 1 hertz.

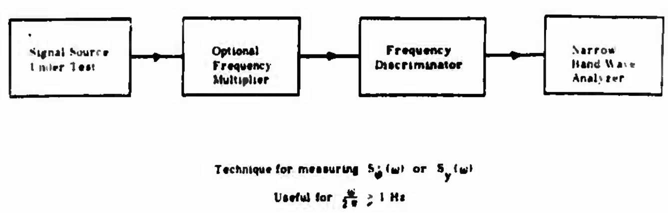
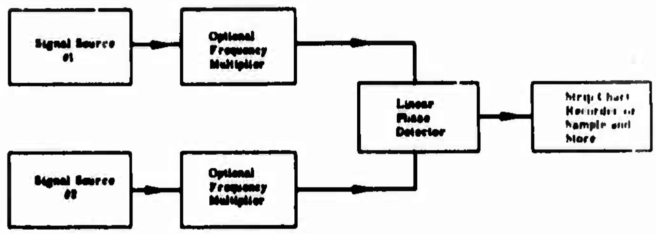


Figure 32. TECHNIQUE FOR MEASURING $S_{\dot{\varphi}}(\omega)$ or $S_y(\omega)$

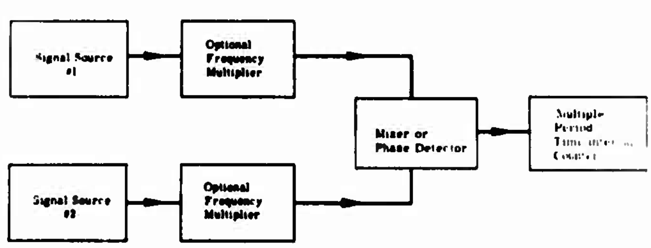
In the case of very low frequency noises where direct spectral analysis techniques cannot be used, one must actually record the phase (Figure 33). A plot should be made of the phase versus time. The autocorrelation function of the phase may then be obtained. $\sigma_y^2(\tau)$ can be obtained from the phase data by taking successive phase differences. Here again, we have two signal sources with optional frequency multipliers and linear phase detector. In this case it is desirable to have a linear phase detector because the phase will make very large excursions.



Direct Phase Recording - Suitable for getting $R_x(t)$ or $\sigma_y^2(t)$

Figure 33. DIRECT PHASE RECORDING

Another technique using two sources assumed to be identical is shown in Figure 34. The two sources are slightly offset in frequency to get a beat note for the counter measurement. This is called the "Beat Period Technique." The signals should be fed from the signal sources through the optional frequency multipliers into a mixer or phase detector followed by a counter. The period of beat note or its frequency is measured with an averaging time determined by the time interval counter. Applying the appropriate statistics to a number of such measurements gives $\sigma_y^2(\tau)$ directly.



Technique for measuring $\sigma_y(\tau)$. The two signal sources are offset in frequency to get a suitable beat note for he counter measurement.

Figure 34. TECHNIQUE FOR MEASURING $\sigma_y(\tau)$

Let us now look at a few of the actual characteristics of some of the sources. As mentioned previously, this is by no means an exhaustive list and there are probably great errors of omission.

Figure 35 shows σ versus τ for a number of sources. The 100-megahertz crystal oscillators have fairly low phase modulation in the high frequency range. Their σ is flat versus time for times much longer than about 10 milliseconds. This indicates that they suffer from flicker frequency noise. The higher the fundamental oscillation frequency, the worse the low frequency noise characteristic (or long-time performance) of an oscillator will be. Conversely, the higher the frequency of the oscillator, the better its

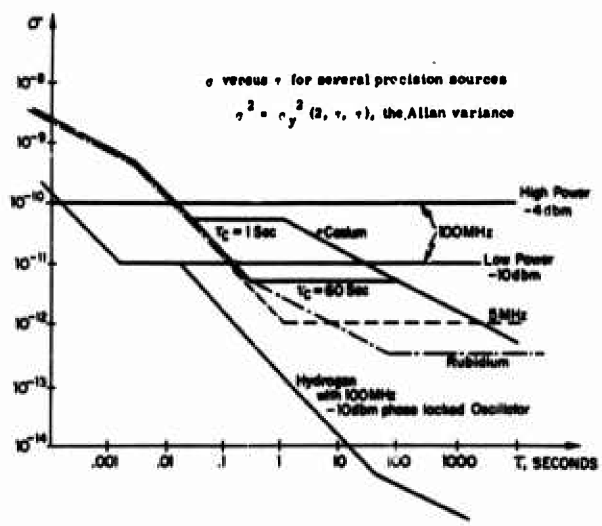


Figure 35. σ VERSUS τ FOR SEVERAL PRECISION SOURCES

high frequency noise characteristics (or its short-time performance) will be. Note the curves for cesium and rubidium. These are typical of the Hewlett-Packard rubidium and cesium standards. The short-time performance is dominated by the 5-megahertz crystal oscillator that is locked to the atomic resonance. The behavior for long times and intermediate times is determined by the atomic resonator. We have two time constants noted -- 1-second and

60-second time constants. One can get some control of the behavior by changing the loop time constant with which the oscillator is locked to the atomic resonator. We have shown rubidium flattening out into a flicker noise region, something below a part in 10^{12}.

The cesium curves on the right side of Figure 35 indicate the shot noise region. That is essentially the noise determined by the number of cesium atoms per unit time that one detects. Cesium performance has been greatly improved with the development of a new 16" tube that is about ten times better than that of the present 16" tube. The hydrogen maser is shown locked to a low-power, 100-megahertz oscillator. One can see where the loop crossover takes place.

The spectral density plots in Figure 36 are for some low-frequency oscillators. The solid curves are from the data sheet on the Hewlett-Packard 105 oscillator. The performance characteristics in the frequency range we measured were equivalent or better than our guarantee. The broken line represents the performance of a new low noise Ebauches oscillator which was recently reported by Brandenburger and Kartaschoff. The circled points are an experimental 10-megahertz Hewlett-Packard oscillator. The scale on the left is $S_x(\omega)$ in db and if one adds 216 db to the scale, it gives the performance

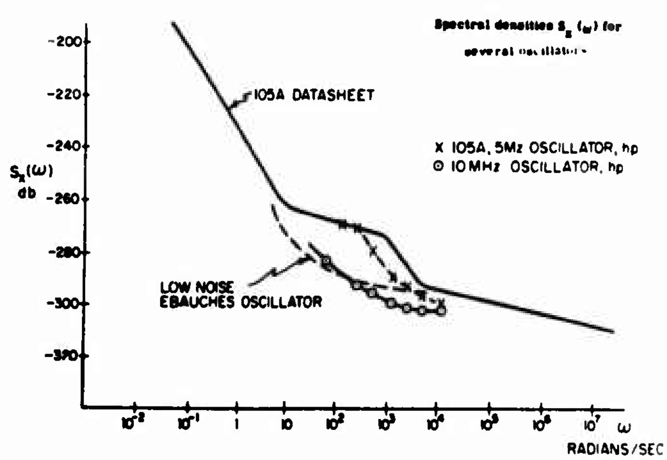


Figure 36. SPECTRAL DENSITIES $S_x(\omega)$ FOR SEVERAL OSCILLATORS

at X-band. Adding 206 db gives the performance at the S-band. Evidently one can scale the chart for any frequency that is of interest by adding the appropriate number of db to the ordinate.

Figure 37 gives spectral plots for other types of oscillators, including some microwave oscillators. The right-hand side of the figure represents high frequency behavior. Note that the two-cavity klystron, the UHF-cavity oscillator and X-band Gunn oscillator, and the UHF voltage controlled oscillator have very good performance for these short times. That bears out the earlier statement that if one wants very high spectral purity at high frequency for very short times, a high frequency oscillator should be used. Notice also

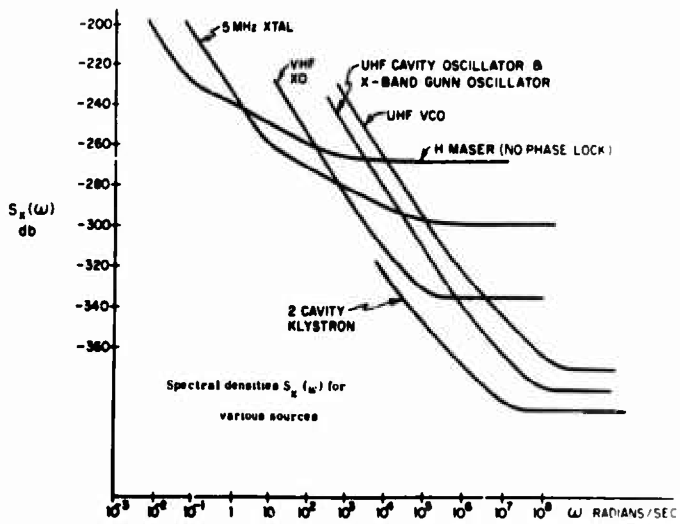


Figure 37. SPECTRAL DENSITIES FOR VARIOUS SOURCES

that these sources have spectral densities that go up quite steeply in the flicker noise region and the performance for low modulation frequencies with corresponding long averaging times is poor. We have plotted, for comparison, a 5-megahertz crystal which has rather intermediate performance high frequency wise, and considerably better performance low frequency wise. We have also plotted a hydrogen maser -- the purest oscillator. It has the best low frequency performance, but rather poor high frequency performance. This is because its power level is so low.

Figure 38 represents $S_x(\omega)$ for several precision sources. These sources are generally composite sources, such as two oscillators locked together to achieve the best results of both, a rubidium standard, a cesium standard, or a hydrogen maser with a phase lock. Again, if the output oscillator is a high frequency oscillator like the 100-megahertz oscillator, it has better high frequency performance than something that has a 5-megahertz oscillator tied to it. Over on the low frequency end, we see that hydrogen has the best performance.

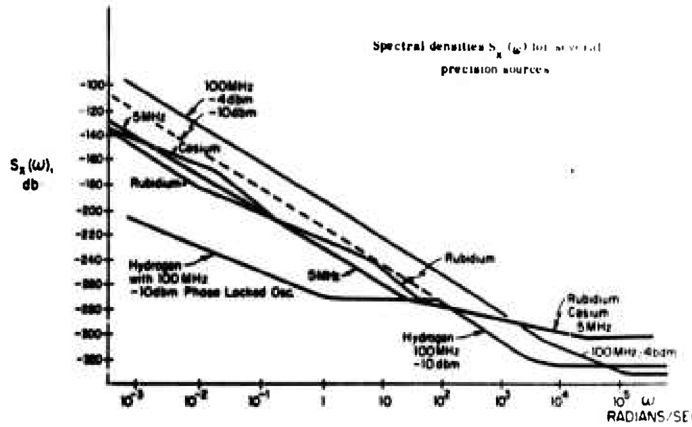


Figure 38. SPECTRAL DENSITIES FOR SEVERAL PRECISION SOURCES

Figure 39 shows spectral densities for two high-performance frequency synthesizers. One can see, here again, if we were to multiply these up to X-band, the 300 db point at the modulation frequency of 10^3 radians/second would be degraded to 84 db.

One word of caution on looking at frequency synthesizers: since they usually cover a very wide frequency range and the output frequency is very often achieved by mixing two high frequency signals, the spectral density does not improve as the frequency goes down. Therefore, $S_x(\omega)$ would get much, much worse at lower frequencies. The curves in Figure 39 are plotted for frequencies close to the top of the frequency range of each synthesizer, so they must be used with caution.

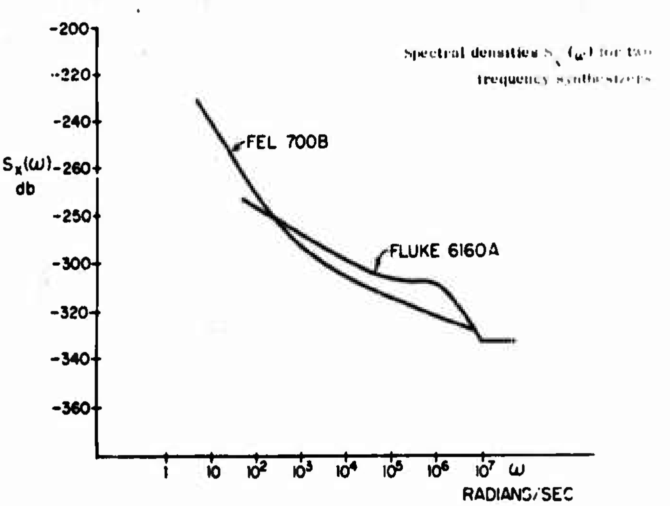


Figure 39. SPECTRAL DENSITIES FOR TWO FREQUENCY SYNTHESIZERS

We have tried to lead you very quickly through some of the basics that determine the characteristics of signal sources. We have also discussed some of the measuring techniques and some characteristics of various available precision sources.

DISCUSSION

DR. VESSOT: I think we can give you some fairly firm data on hydrogen masers beyond 100 seconds. The people at Jet Propulsion Labs have seen 7 parts in 10^{15} onward to 10^{6} seconds; and recently -- which is extraordinary since it shows flicker behavior that is flat over about four decades starting at 100 seconds going to 1,000,000 seconds -- we have seen 3 to 5 parts in 10^{15} at 1,000 seconds, in recent measurements with small masers and slightly different cavities.

DR. CUTLER: That is a very respectable performance.

PATH DELAY, ITS VARIATIONS, AND SOME IMPLICATIONS FOR THE FIELD USE OF PRECISE FREQUENCY STANDARDS

by

Dr. G.M.R. Winkler

Dr. Winkler is Director, Time Services Division, U.S. Naval Observatory, Washington, D.C. (202) 254-4546.

Abstract

In order to assess the practical utility of high preformance frequency standards in field applications, the effect of the propagation medium must be taken into account.

After a brief summary of noise processes, a discussion of the performance of current frequency standards is given, together with an estimate of the relative cost, reliability, and necessary system support for each type.

Literature references on atmospheric physics are given to allow determinations of those limitations which the earth's atmosphere and ionosphere impose on the transfer of precise frequency and time. Formulae are presented to estimate the effects of changes in temperature, pressure, humidity, and frequency on the propagation path of electromagnetic waves. Current methods used to compute the path delay for HF, VLF, Loran-C and other precise frequency transmissions are given. Based on this material, we outline needs for future frequency control capabilities.

The paper will be published in the Special Issue of the Proceedings of the IEEE, May 1972.

DISCUSSION

DR. VESSOT: First, I would like to commend your physical intuition, or your physics, in your statement concerning the white phase noise of atmospheric and ionospheric measurements. Recent measurements made using the hydrogen maser at two sites, namely Haystack and Greenbank, using VLBI techniques on water vapor line noise sources at 22 gigahertz show, very definitely, white phase noise down to about 3 parts in 10^{13} at 100 seconds. I share your intuition in wondering how one could expect the ionosphere to "go away" logarithmically. It's a bit like the old saying "the sky is falling in."

Those are the good comments; now for the bad ones. First of all, the data reported by JPL go up to a million seconds which is on the order of ten days. I admit that you have had very bad luck with your masers, and I should also say that the ones that have been operated at NRL are probably very old. The third and fourth instruments that I made might have been the seventh and eighth that were ever made, and I commend the people who have been running them and who have kept them alive for so long. I suggest that another part of my institution, which is the Smithsonian, might be very interested in those instruments. I also accept any challenge you might issue to improve your data by either the slight refinement or the updating of the instrument you have, or perhaps to bring one to you that may be of a little bit more modern construction.

DR. WINKLER: I think these are very interesting (and promising) comments. However, my main concern is that, for operational use, machines are needed which can be operated without a Ph.D. and which can be relied upon to work with an average mean-time-between-failures of <u>at least</u>, for a clock, 5,000 hours. In fact, to come back to my previous comments, I think we make a fundamental mistake if we confuse serviceability concepts --mean-time-between-failures and so on. What we need are instruments which can be turned on and will keep working for five years at least, hopefully for ten. By that time, they should be so surpassed by the new technology that they can be safely thrown away or given to the Smithsonian Institution.

MR. PETERS: On the question of field operability of hydrogen masers, although we have not published enough data on these facts, out of four years and two months of operation of experimental masers we've got about four years, one month and two weeks. Furthermore, the down-time was due to experiments we wanted to make. One of our masers (NPI) has been operating in the field continuously since 1968 and has been moved all over the face of the earth without any malfunctions. These have been operated by station personnel. In fact, in two of our field installations, no service calls by the manufacturers were necessary. We have an integrated operating time in the field of about ten or twelve years. We do not have any data to support the view that our lifetime will exceed five years, only because these masers have not been operating more than four years since they were built. Extrapolations of their present performances indicate that this type of device will operate up to the extent of the mean time before failure of the electronic components. This, in turn, depends upon how much effort is put into quality control when producing such a device.

DR. WINKLER: Mr. Peters, this is very fine and I am glad to hear it. Would you please care to comment on my last chart where you see the main benefit of the hydrogen maser?

MR. PETERS: The other thing is we are auto-tuned on our hydrogen masers, as other people have done. With auto-tuning, you would never make a parallel between the gaseous processes, which are probably the predominant drift mechanisms in rubidium cells and a hydrogen maser. Certainly the position of the curves for future hydrogen masers ought to lie on the same chart. We must assume parallel rates of development and judge whether one type of standard or the other might be the more useful one in the future.

Another reason, of course, is that the economics of hydrogen masers are going to go way down if they are used widely in the future.

I'm afraid I didn't answer your question. That was the last chart. I think that that curve does represent NRL3 and 4 and later H-10 designs with which you certainly have had unfortunate experiences.

DR. WINKLER: I would not completely accept that, because I think the lowest points on this curve and also the left branch of it, have been taken from your publication. The dotted line, again, is one of which we know only a few points. Consider the physics of a passive frequency standard like the cesium, which is not subject to cavity pulling, which has a magnetic field factor 42 times less than that of hydrogen, and which observes the atom completely isolated in space, as compared to the physics of a standard imprisoned in a buffer box, where it is subject to 10^4 collisions per second. Would you think that the physics are so similar as to expect that these lines would be parallel, as Mr. Peters has suggested? I cannot imagine that. I think that is where our lines part.

MR. PETERS: I would like to comment,at least, on two aspects of that. One is, of course, the magnetic field dependance. You operate at about 50 milligauss. The actual variation with the field is much lower for the hydrogen maser, due to the fact that we operate in the field at one milligauss. Our net magnetic correction in all our operating standards, which are not degaussed from year to year, is 2 parts in 10^{12}. This is a very small effect in hydrogen masers, so the magnetic field problem is not really part of the present discussion. It can be measured with the ultimate precision just as you can with cesiums.

DR. WINKLER: Please do not interpret my remarks as putting down the hydrogen maser as a beautiful scientific instrument. My remarks are entirely regarding the immediate usefulness of these devices for applications in systems as we have discussed them here. This is the background of my remarks. I am not, at the momemt, concerned with the widespread use of very long base line radio interferometers to bring time to a submarine, or to navigate, or for similar exotic applications. They may be possible; they should be looked into, but right now the question is what should be developed with DOD money? I think that's the background of my consideration here, and the purpose of my discussion.

MR. PETERS: Yes. I hope my comments were based on physical facts and not on duty, particularly in referring to the magnetic field dependance. I think, to fully answer all of these questions and problems at such a time, one would really need to prepare a paper on the subject, to present another point of view.

DR. WINKLER: I think my paper, up to now, has been eminently successful because we have had more questions and comments than on any other.

MR. LIEBERMAN: I wonder how your last chart and the weighted chart on standards would be revised if we add the disciplined oscillators--the new ones--into your calculations. Would it clean up short-term stability and be a general addition to what you had there?

DR. WINKLER: I think it would be a very good idea to add to it. I do not have enough information; I think we should do that however. It will require some test results.

DR. RUEGER: I was involved a little bit more in the earlier days of the cesium standards until Hewlett-Packard gave it the engineering I think it needed. We had a lot more unreliability problems than you've been able to tell me about in the hydrogen masers. I, personally, feel that the hydrogen maser problem, or feature, that is going to be predominant in the future has to do with its absolute stability and the fact that it has high spectral purity. With the applications in which I am concerned, the spectral purity is of great concern, and is not available with the others yet.

DR. WINKLER: That is very remarkable. Can't you get the spectral purity by locking or following Dr. Cutler's recipe either, for instance, by locking a klystron to a harmonic of one of the crystal standards? What you are saying here is that you need both spectral purity and a carrier of extreme long-term stability.

DR. ALLEY: There have been recent developments in optical pumping of cesium which may lead to a cesium maser. This may, in the long run, have the same kind of short-term spectral purity that the hydrogen masers exhibit. They could be readily combined with beam devices to provide the long-term stability as well. This is a long way from realization, but there seems to be considerable promise there.

MR. PETERS: I think it is probably appropriate to make another comment on the other hydrogen device with which I have been working; that is, a hydrogen beam device. We haven't locked it on at this time; yet, we do have resonances, so we may have, perhaps, cesium masers and cesium beams; we have hydrogen masers, perhaps hydrogen beams.

DR. WINKLER: Mr. Chi, please.

MR. CHI: I agree with your analysis, however, you do admit that the analysis is time dependent in short-term stability in the term of five years or so.

DR. WINKLER: Of course. Also, I repeat what I said before. My presentation has had two purposes. First, to bring up a subject for consideration, to start some thought processes among ourselves here, as a community; and second, to provide some references which I will give in the minutes of the proceedings. Otherwise I have said, and your comment forces me to emphasize it even more, that much of what I said about the contributions--the short-term contributions of the atmosphere--is really not too well documented, in fact, it is largely conjecture. My point has been to bring out the main ideas on how one can hope to deal with these things in the systems conceptual way.

MR. CHI: However, when you make a comparison of the behavior or performance of different types of standards (I think in the figure of merit) you should probably also include the total investment per type of standard. Obviously the performance is proportionate to the amount of time as well as funds put in.

DR. WINKLER: You mean development funds should also be reflected. If you refer to the U.S. Government development funds, the cesium standards would come out extremely well, at least in this particular example which we are using, because it was my understanding that it was not developed under U. S. Government funding.

MR. CHI: I mean the total funds.

DR. WINKLER: Yes, Dr. Reder, don't you have some figures of how much money was actually put into some of these standards?

MR. CHI: I'll give you a guess before he gives you the total amount. I think if you add up the total costs of R&D, the crystal will have the highest amount of time and money put in, and cesium's the next, and the rubidium and hydrogen maser, in that order.

DR. WINKLER: Well, I think that is probably true.

DR. REDER: If we forget about some very unfortunate development contracts after Hewlett-Packard got into the act, I would say about six million dollars altogether. However, this includes the work on rubidium and the work on some other schemes; it is actually very difficult to separate, since the rubidium people benefited very much from the development of cesium.

PERFORMANCE AND RESULTS OF PORTABLE CLOCKS IN AIRCRAFT

J. C. Hafele

PERFORMANCE AND RESULTS OF
PORTABLE CLOCKS IN AIRCRAFT

by

J.C. Hafele

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PERFORMANCE AND RESULTS OF PORTABLE CLOCKS IN AIRCRAFT

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J.C. Hafele

Professor Hafele is an Assistant Professor of Physics, Washington University, St. Louis, Missouri.

1.0 INTRODUCTION

During the first two weeks of October, 1971, R. E. Keating of the U.S. Naval Observatory and I flew twice around the world on regularly scheduled commercial flights, once eastward and once westward, with four Hewlett-Packard 5061A cesium beam clocks. For about a week before the first trip, between the trips, and for about a week after the second trip we recorded a continuous phase comparison between each clock and the MEAN (USNO) time scale. Time differences between the four clocks were also recorded with a time interval counter at regular intervals before, during, and after each trip, thereby permitting evaluation of the flying mean time scale. The experiment was conducted for two reasons: (1) to compare the known performance of similar clocks under fairly well controlled laboratory known performance of similar clocks under fairly well controlled laboratory conditions, and (2) to try to detect relativistic effects on the time recorded by clocks during terrestrial circumnavigations. It was performed with the interest and complete cooperation of Dr. G. M. R. Winkler and others of the Naval Observatory Time Service Division, and with financial support from the Office of Naval Research. A major portion of the credit for the experiment goes to Richard Keating, whose steadfast desire to perform such an experiment generated the necessary motivation. Although the performance of these clocks was found to be noticeably degraded during the trips, we also found that the ensemble of four flying clocks produces consistent time differences which are difficult to explain without invoking relativistic effects.

2.0 A PRECISION LONG-TERM TIME REFERENCE - MEAN (USNO)

When a reliable means of counting the accumulated number of periods of an oscillator is combined with a cesium beam frequency standard, the assembly approaches the realization of an ideal standard clock. In fact, a time interval of one second is now, by definition, exactly 9,192,631,770 accumulated periods of an "ideal" cesium beam frequency standard.[1] Experience shows, however, that the times recorded (periods accumulated from a common starting instant) by two "real" cesium beam clocks having no intentional frequency offset differ by as much as several parts in 10^{12}. Though this performance is truly remarkable, certainly beyond any expectations of a decade or so ago, for many purposes it is desirable to establish a stable, continuous atomic time scale which is independent of the characteristics of any particular cesium beam clock. It is not difficult to accept the premise that the long-term average or mean of the times indicated by two or more properly functioning cesium beam clocks is more reliable (or stable) than the individual times indicated. Ideally, the mean of a very large (infinite) number of clocks would provide a perfectly reliable time scale; however, budget limitations prevent realization of this goal. So we compromise by taking the mean of an ensemble of as many clocks as possible, or as is necessary to produce the desired reliability. The mean time scale at the U.S. Naval Observatory (MEAN(USNO)) represents a suitable average of the

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[1] Winkler, G.M.R., R.G. Hall, and D.B. Percival (1970), "The U.S. Naval Observatory Clock Time Reference and the Performance of a Sample of Atomic Clocks," Metrologia Vol. 6, p. 126.

of the time recorded by an ensemble of more than 15 cesium beam clocks.[2] As some of these clocks deteriorate or fail, they are replaced by standby clocks, thereby permitting an indefinite extension of the time scale into the future. The time indicated by MEAN(USNO) is believed by many to be the closest approximation we have today to an ideal long-term atomic time scale.

The basis for confidence in this time scale is the belief that both long- and short-term differences (or fluctuations) between the mean and each clock of the ensemble are random. If one clock of the ensemble increases its rate (relative to the mean), it will not be long before some other member on the average decreases. In this way, ultimately, the mean is correctly maintained. In fact, the stability of the mean is actually improved by taking into account rate changes for each member of the ensemble.[3]

The MEAN(USNO) time comes from a "paper" clock; that is, the mean is calculated after the fact and is not instantaneously available for time comparisons. This presents no real problem, however, because one of the members of the ensemble is chosen as the primary reference or "master" for the ensemble and all clocks are compared with this master. A secondary master is kept in reserve in case the primary master fails. This MASTER(USNO) time is tracked to follow the mean as closely as possible and is physically available for instantaneous time comparisons. Since the difference between MASTER(USNO) and MEAN(USNO) is calculated at regular intervals, it is an easy matter to convert to an equivalent comparison with MEAN(USNO) after the intercomparison measurements are completed.

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[2] Ibid.

[3] Ibid.

3.0 LABORATORY PERFORMANCE OF CESIUM BEAM CLOCKS

Now that we have a long-term reference time scale, it is straightforward to evaluate the performance of any particular clock simply by comparing the time it indicates with the time of the reference. There is extensive literature on evaluation of the performance of precision atomic oscillators, particularly on the subject of short-term time and frequency stability (see Barnes, J.A., et al and Allan, D.W., et al and bibliographies therein).[4] There seems to be a consensus in this literature that time domain stability is best described in terms of fractional frequency fluctuations, with the quantitative measure being the Allan variance $\sigma^2(\tau)$. Cesium beam clocks, like all clocks to a greater or lesser extent, are subject to short-term FM noise and this noise limits the precision with which the time or frequency can be determined during short averaging times (several days or less). In most cases, however, this type of noise is not the limiting factor for long-term stability. Long-term performance appears to be governed more or less by instantaneous and randomly occurring rate (or frequency) changes.

The characteristic long-term performance of cesium beam clocks can be described in terms of $\sigma(\tau)$, the square root of the Allan variance. As the averaging time τ increases from zero, $\sigma(\tau)$ characteristically decreases on a log-log plot with a slope of $-\frac{1}{2}$. However, beyond a certain τ, depending on the particular clock, the slope changes rather abruptly to zero, and for longer averaging times $\sigma(\tau)$ remains constant and in some cases eventually

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[4] Ibid.; Barnes, J.A., et al. (1971) "Characterization of Frequency Stability," IEEE Trans. Instr. Meas. IM-20 (May 1971), p. 105; Allan, D.W., B.E. Blair, D.D. Davis, and H.E. Machlan (1971) "Precision and Accuracy of Remote Synchronization via Portable Clocks, LORAN C, and Network Television Broadcasts," Proc. 25th Ann. Symp. Freq. Control, 26-28 April 1971 (Electronic Industries Assoc.) p. 195.; Martin, D. (1971) "Frequency Stability Measurements by Computing Counter System," Hewlett-Packard Journal Vol. 23 (November 1971) p. 9.

increases.[5] The averaging time for which $\sigma(\tau)$ decreases with slope $-\frac{1}{2}$ gives the time for which the frequency fluctuations are random about a constant mean. If the frequency fluctuations remained indefinitely random about a constant mean; that is, if $\sigma(\tau)$ continued to decrease indefinitely with slope $-\frac{1}{2}$, one could achieve indefinite long-term stability with a single clock simply by increasing the averaging time. In other words, if this were the case, once the average rate relative to MEAN(USNO) was established the average rate could be projected indefinitely into the future. This is not the case, however.

This change in the slope for $\sigma(\tau)$ indicates that "quasipermanent" changes in the average rate for the clock occur randomly with the average time interval between changes comparable to the averaging time for the slope change. By quasipermanent I want to suggest, or imply, that the clock changes (unpredictably) to a new average rate every so often. Uncertainty in the onset and magnitude for each new quasipermanent rate is related to the minimum value of the Allan variance.

Table I illustrates this long-term performance. The table lists quasipermanent rate changes for five cesium beam clocks over a 40-day period at the U.S. Naval Observatory. The data were taken from continuous phase comparison records with MEAN(USNO) as reference. Approximate rate changes are relative to MEAN(USNO). N is the number of changes during this period, the ΔR's are the signed magnitudes of the changes, $\overline{\Delta R}$ is the average rate change, and $\overline{T}$ is the approximate average duration between rate changes.

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[5] Winkler, G.M.R., R.G. Hall, and D.B. Percival; Winkler, G.M.R. (1970) "Requirements and Performance for Today's Atomic Standards," PTTI Strategic Planning Conference, Vol. 1, December 1970, p. 129.

TABLE I. QUASIPERMANENT RATE CHANGES FOR FIVE CESIUM BEAM CLOCKS

CLOCK (s. no.)	N (in 40 d)	ΔR (nsec/day)	$\overline{\Delta R}$ (nsec/day)	$\overline{T}$ (days)
140	3	-25; +28; -54	-17	10
3911	1	-17	-17	20
1471	2	+22; -19	+1	13
60	3	+17; -12; +17	+7	10
283	6	-33, +21; -50; +57; -41; +22	-4	7

The cause for these quasipermanent rate changes is not understood in detail.[6] Both the time of their occurrence and their direction appear to occur at random. Though they are quite unpredictable in nature and, of course, must average to zero over sufficiently long periods with properly functioning clocks (very many $\overline{T}$ periods) they limit the precision with which the rate of any particular clock can be projected into the future.

As can be seen in the table, the average time between changes and their magnitudes depends on the particular clock. $\overline{T}$ for clocks at USNO has been found to range between 1 and 40 days.[7] "Good" clocks are those which go longer than average between rate changes. One of the purposes of the experiment was to study deterioration, if any, in the performance of four good clocks under traveling conditions.

4.0 RELATIVISTIC EFFECTS DURING TERRESTRIAL CIRCUMNAVIGATION

In 1905 Einstein laid a radical new basis for the concepts of space and time. Though Newton's absolute time had proved adequate for most practical

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[6] Ibid.

[7] Winkler, G.M.R., R. G. Hall, and D.B. Percival (1970) "The U.S. Naval Observatory Clock Time Reference and the Performance of a Sample of Atomic Clocks," Metrologia, Vol. 6, p. 126.

purposes, Einstein produced convincing arguments against it. Absolute time contains an element of mystery which is incompatible with precisely defined scientific quantities. Consequently, Einstein defined a new empirical basis for time by accepting a definition which states, in effect, that "time is that which is indicated by a clock," and then proceeded to develop his relativity theories on that basis. Einstein's relativity has proved to be completely compatible with all relevant observations; in fact, no definitive test ever performed has disproved it. The results of our flying clock experiments, at least at the present state of analysis, offer no exceptions.

The special theory of relativity predicts that a moving clock will run slow compared with similar clocks distributed at rest and suitably synchronized in an inertial reference system. In addition, the general theory predicts that a clock in a stronger gravitational field will run slow compared with a similar clock in a weaker field. Most physicists believe these predictions have been verified through studies of lifetimes of elementary particles and studies employing the Mossbauer effect, but a small vociferous minority and indeed, I would say, most of the general public, are reluctant to accept the prediction that these effects also apply to ordinary time indicating clocks, particularly to biological clocks. For an excellent book devoted almost entirely to the "clock paradox," see L. Marder's "Time and the Space Traveler," printed by Allen and Univin, London, 1971.

Relativistic effects on times recorded by clocks are vanishingly small at ordinary speeds, certainly too small to detect with ordinary chronometers. However, the development of portable cesium beam clocks, with stabilities of better than 1 part in 10^{12} over a period of days, makes a direct test with time recording clocks feasible. I have shown that the predicted kinematic effects on the time recorded by clocks during equatorial circumnavigations at ordinary jet aircraft speeds and altitudes are enhanced by the Earth's rotation to a level which is probably above the threshold for detection with cesium beam clocks.[8] Although the assumption of an equatorial circumnavigation at constant ground speed and altitude is not essential, it does simplify somewhat the calculations for estimating the magnitude of expected relativistic effects. For an equatorial circumnavigation with constant ground speed v (m/sec) and altitude h(m), the predicted relativistic time gain for the flying clock over a similar reference clock kept at "rest" on the Earth's surface is given by[9]

$$\frac{\Delta\tau}{\tau_0} = \frac{\tau - \tau_0}{\tau_0} = \frac{gh}{c^2} - \frac{2R\Omega v + v^2}{2c^2}, \quad (1)$$

where τ and τ_0 are the respective times recorded by the flying and ground clocks; R(m) is the Earth's radius and Ω (rad/sec) its angular speed; g(m/sec^2) is the surface value of the acceleration of gravity; and c(m/sec) is the speed of light. In Equation 1, the ground speed is positive for eastward and negative for westward circumnavigations. At latitudes higher than the equatorial plane, the term in Equation 1, which depends linearly on the ground speed and gives an east-west directional asymmetry, becomes proportional to the cosine of the latitude,[10] so for latitudes as high as 60°, the directional dependence is reduced by less than one-half. Although Equation 1 is correct only to lowest order in the speed and altitude, it represents an extremely accurate approximation for jet speeds and altitudes because only these lowest order terms are detectable in this case.

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[8] Hafele, J.C. (1970), "Relativistic Behavior of Moving Terrestrial Clocks," Nature, Vol. 227, p. 270; Hafele, J.C. (1971), "Reply to Schlegel," Nature Phy. Sci. Vol. 229, p. 238; Hafele, J.C. (1971), "An Empirical Resolution of the Relativistic Clock Paradox," Bull. Am. Phys. Soc., Vol. 16, p. 611; Hafele, J.C., "Relativistic Time for Terrestrial Circumnavigations," Am. J. Phys. (in press, to appear January 1972).

[9] Ibid.

[10] Cutler, L.S. (1970), "Correction to 'Flying Clock' Comparisons Extended to East Europe, Africa and Australia," Hewlett-Packard Journal, Vol. 21 (March 1970), p. 10.

The actual time gain $\Delta\tau$ is a bit more instructive than the time ratio of Equation 1 and it follows from multiplication of Equation 1 by τ_0. Because standard clocks keep the same time while sitting on the ground anywhere on Earth (at average sea level and to this order of approximation),[11] only the actual time in flight during a trip contributes to relativistic effects. However, ground time does contribute to increasing the random, unpredictable time offset and therefore to the threshold for detection of relativistic effects. (Relativistic effects were not detected during previous flying clock trips because they accumulate only while the clocks are in flight, and for those trips most of the time was spent on the ground.) Suppose for the moment that ground time, for example, for refueling stops, is negligibly small compared with the time it takes to fly around the world. Then the time recorded by the ground clock during the circumnavigation is given by

$$\tau_0 = 2\pi R/|v| \quad .$$

Solving for $\Delta\tau$ and inserting this value for τ_0 in Equation 1 gives

$$\Delta\tau = \frac{2\pi Rgh}{c^2}\frac{1}{|v|} - \frac{2\pi R^2\Omega}{c^2}\frac{v}{|v|} - \frac{\pi R}{c^2}|v| \quad .$$

Figure 1 is a graph of this equation showing $\Delta\tau$ versus v for altitudes of 0, 10, and 20 kilometers. The dots in Figure 1 correspond to the cruising speed and altitude for a Boeing 707.[12]

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[11] Cocke, W. J. (1966), "Relativistic Corrections for Terrestrial Clock Synchronization," Phys. Rev. Letters, Vol. 16 (1966) p. 662.

[12] Schaefer, H. J. (1971), "Radiation Exposure in Air Travel," Science, Vol. 173 (1971), p.780.

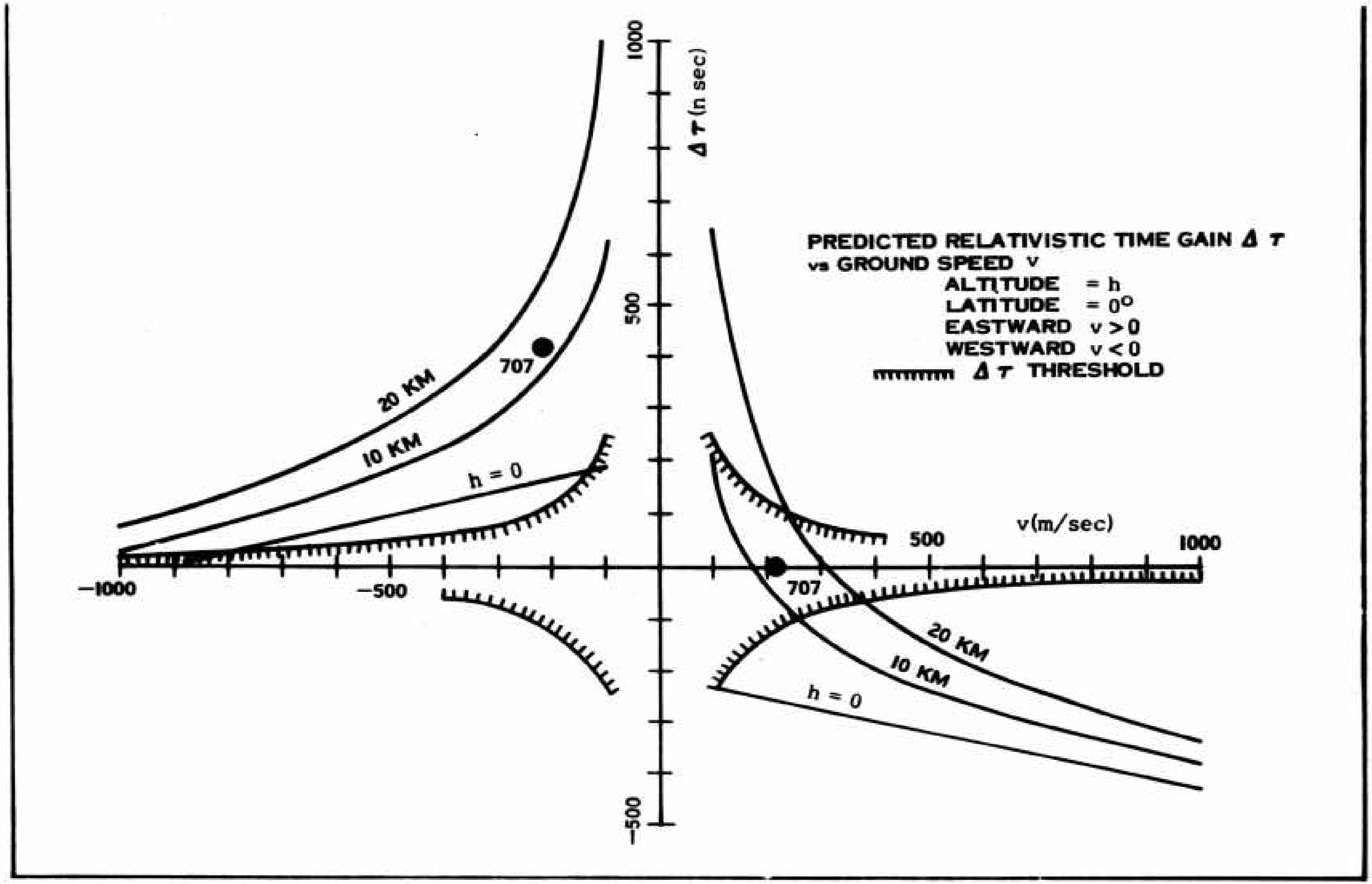

Figure 1. PREDICTED RELATIVISTIC TIME GAIN $\Delta\tau$ vs. GROUND SPEED v FOR EQUATORIAL CIRCUMNAVIGATIONS

Personnel of the Naval Observatory's Time Service Division have a considerable background of practical experience with cesium beam clocks, both in the laboratory and under traveling conditions. Their experience is that at the end of trips the time difference between the flying clocks and MEAN(USNO) is random with a zero center gaussian distribution having a spread of about 60 nanoseconds per day of trip.[13] Since this spread was for all portable clocks, "good" clocks may be expected to provide a somewhat lower threshold. A conservative estimate for the threshold of detection of relativistic effects with "good" clocks is given by

$$\Delta\tau_{threshold} = \frac{60\ \text{nsec}}{\text{day}} \times \tau_0\ (\text{days})\ .$$

The hatched lines in Figure 1 represent this threshold. Figure 1 shows there is a variety of available conditions with jet aircraft which predict relativistic time differences exceeding this threshold.

Commercial around-the-world flights do not, of course, maintain constant altitude, latitude, or ground speed. In this case, it is necessary to perform a numerical integration of the relativistic equations. The necessary calculation is given by

$$\Delta\tau = \int_{\substack{\text{flight}\\ \text{path}}} \left[\frac{gh(\tau)}{c^2} - \frac{1}{2c^2}\left(2R\Omega\cos\lambda(\tau)\cos\theta(\tau)\, v(\tau) + v^2(\tau) \right) \right] d\tau, \tag{2}$$

where, for each interval of the summation, λ is the latitude, θ is the azimuth or bearing of the plane's velocity relative to east, and the rest of the symbols have the same meaning as for Equation 1 (v is the unsigned magnitude of the ground speed in Equation 2; the azimuth θ accounts for the direction).

[13] Winkler, G.M.R., R.G. Hall, and D.B. Percival; Winkler, G.M.R. (1970) "Requirements and Performance for Today's Atomic Standards," PTTI Strategic Planning Conference, Vol. 1, December 1970, p. 129.

5.0 PREDICTED RELATIVISTIC TIME DIFFERENCES

Necessary data for each around-the-world flight were provided by the various flight crew captains. (We are greatly indebted to Pan Am, American Airlines, and TWA, and their flight captains, for this extraordinary service, and to Pan Am and TWA for sending a company official as escort.) In most cases the flight paths were traced on appropriate flight maps with the time (GMT), altitude, and ground speed recorded regularly at navigation check points. The least accurate quantities are probably the times over the check points, which appear to have been recorded to only the nearest three or four minutes in some cases. Our own records of liftoff and touchdown times, recorded to the nearest minute, are in good agreement with the corresponding times provided by the flight captains.

The information on the flight maps divided the eastward circumnavigation into 125 intervals and the westward circumnavigation into 108 intervals. The latitude and longitude with the corresponding time for each check point permit calculation of the average latitude, azimuth relative to east, and ground speed for each interval. The average altitude for each interval was estimated from the altitudes recorded at the end points. These calculations and the summation indicated in Equation 2 were carried out with the Washington University IBM 360/50 computer. Table II summarizes the data for each direction, and gives the predicted relativistic time gains based on Equation 2.

6.0 AMBIENT CONDITIONS

In addition to recording time differences between the four flying clocks at regular intervals during each trip, we recorded at irregular intervals the temperature, pressure, and relative humidity with a small aneroid desk-top weather station; the compass direction with a small pocket compass; and the ambient magnetic field with a small pocket magnetometer. Before and after each trip the clocks were kept in an unused darkroom at

TABLE II. SUMMARY OF AROUND-THE-WORLD FLIGHTS AND PREDICTED RELATIVISTIC TIME GAINS FOR FLYING CLOCKS

EASTWARD			WESTWARD		
Day	GMT	Location	Day	GMT	Location
04[1]	1930	USNO D[2]	13	1940	USNO D
05	0012	Dulles D (Pan Am 747)		2322	Dulles D (TWA 707)
	0656	London A[3] (*Pan Am 707)	14	0400	Los Angeles (*TWA 707)
	0814	D		0503	D
	0909	Frankfurt A		1014	Honolulu A
	1036	D		1313	D
	1248	Istanbul A		2015	Guam A
	1357	D		2113	D
	1513	Beirut A	15	0006	Okinawa A
	1619	D		0107	D
	1813	Tehran A		0209	Taipei A
	1940	D		0303	D
	2241	New Delhi A		0413	Hong Kong A
06	0000	D		1248	D
	0333	Bangkok A		1514	Bangkok A
	0513	D		1632	D
	0745	Hong Kong A		2006	Bombay A
	0855	D		2115	D
	1216	Tokyo A (*Pan Am 747)	16	0403	Tel Aviv A (*TWA 707)
	1432	D		0509	D
	2110	Honolulu A		0645	Athens A
	2314	D		0733	D
07	0350	Los Angeles A (*AA 707)		0903	Rome A
	0447	D		1001	D
	0713	Dallas A		1138	Paris A
	0753	D		1425	D
	0959	Dulles A		1557	Shannon A **
	1255	USNO return		1706	D
				2338	Boston A
			17	0118	D
				0226	Dulles A
				0400	USNO return

	Eastward	Westward
Trip time	65.42 hours	80.33 hours
Avg ground speed	243. meters/sec	218. meters/sec
Avg altitude	8.90 kilometers	9.36 kilometers
Avg latitude	34. degrees N	31. degrees N
Rel time gain	-40. nsec (loss)	+275. nsec

[1] October, 1971

[2] D - Depart

[3] A - Arrive

* Indicates clocks transferred to a different aircraft; 707 and 747 indicate Boeing aircraft type.

** Indicates an unscheduled fuel stop.

the Time Service Building where the temperature was held between 68 and 73°F. Temperatures during the trips averaged about 75°F with extremes between 70 and 85°F. During each flight between landing points, the cabin pressure dropped from 30 to 25 in Hg, except in one or two cases where it was not lowered that much. For each trip the relative humidity dropped from 60% to about 30%. Noticeably rough flying conditions occured only during the flight between Athens and Rome on the westward trip. At no time during either trip did any of the clocks lose regulation control; that is, the lights indicating momentary loss of feedback control did not light up.

The four clocks were carried as two assemblies, each assembly consisting of a bottom clock, a middle H-P K02-5060A battery pack and charging unit, and a top clock. To suppress any possible magnetic coupling between the clocks, additional magnetic shielding was placed between each clock and the battery pack of each assembly. Each assembly was rigidly bolted together.

For the eastward trip, the clocks were oriented in the airplane with the front of the clocks towards the front of the plane between Washington and London and between Tokyo and Washington, and with the front of the clocks towards the back of the plane from London to Tokyo. The clocks were oriented with the front of the clocks towards the front of the airplane during the entire westward trip. The clocks were strapped in seats in the passenger compartment.

When we discovered that one of the four batteries in one of the battery packs was dead, there was much concern on several occasions when electric power for charging the batteries was not available, because this abnormal situation caused the batteries to discharge rapidly. Fortunately, two of the clocks were never in jeopardy on this account, and our intercomparison data indicate no noticeable effect from low battery voltage for the clocks in question.

Near the end of the data period after the clocks were returned to the Naval Observatory, two environmental tests were performed. First, the clocks were reoriented to see if changes in the direction of the Earth's magnetic field caused noticeable changes in the clock rates; none were found. Secondly, line power charging the battery pack with the dead battery was interrupted for one hour to see if discharge of the remaining three batteries caused any noticeable change in the rates; again, none was observed.

Although environmental studies have shown that cesium beam clocks are susceptible to such effects as temperature changes and AC magnetic fields, it is important to note that no known effect consistently increases or decreases the rates for these clocks. That is, all known environmental effects cause rate changes that are random in direction. This observation gives additional confidence in the mean of an ensemble. (Strong DC magnetic fields cause predictable changes, but the clocks are triply shielded against the Earth's weak field.)

7.0 MEASURED TIME DIFFERENCES

A strip chart recorder with associated phase comparison electronics was used to record a continuous phase comparison between each of the four flying clocks and MASTER(USNO) before and after each of the trips. In addition, at periodic intervals before and after the trips, absolute time differences between the one second pulses or "ticks" were measured to the nearest nsec with a Hewlett-Packard computing counter.[14] The time differences between the ticks of each clock and MEAN(USNO) via MASTER(USNO) provide a calibration of the continuous phase graphs. Thus the rate of each clock relative to MEAN(USNO) before and after each trip is established.

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[14] Martin, D. (1971), "Frequency Stability Measurements by Computing System," Hewlett-Packard Journal, Vol. 23 (November 1971) p. 9.

Identically the same electronic arrangement was used for all time intercomparisons.

Six intercomparison times between the four clocks (three of them are redundant but serve as a check on the measurements) were recorded with the same computing counter at hourly intervals for a short period before, during, and for a short period after each trip, with additional readings taken shortly before and after each touchdown and liftoff. These intercomparison data permit evaluation of the mean of the flying ensemble (MEAN(FLYING)) in much the same way as MEAN(USNO) is determined. Although evaluation of MEAN(FLYING) is not yet completed, we expect this analysis of the data to produce the highest level of confidence in our results, and we hope to be able to report them soon.

The results reported here depend only on the intercomparison data with MEAN(USNO) before and after the trips. The final analysis is not expected to change these results significantly.

An early and very preliminary estimate of the results was based on extrapolation of the rate for each clock immediately before the trips. The difference between this extrapolated time (to the end of the trip) and the observed time was averaged among the four clocks for each trip. Even with this very simple approach, consistent time differences were found. But even a casual observer would be quick to criticize this approach by pointing out that it is necessary that the rate after each trip be the same as before the trip, because it assumes no quasipermanent changes occurred during the trip. This approach is difficult to defend because quasipermanent changes did occur for each clock during each trip; it represents the lowest level of analysis and produced the least confidence. I wish to present here a somewhat higher level of analysis.

Let τ_{mean} and τ_c be the respective times indicated by MEAN(USNO) and one of the clocks of the flying ensemble, and define the rate (difference) R as

$$R_c = \frac{\tau_c - \tau_{mean}}{\tau_{mean}} = \frac{\Delta\tau_c}{\tau_{mean}}$$

Figure 2 shows measured values of $\Delta\tau_c$ versus τ_{mean} for each clock taken before, between, and after the trips. (The curves in Figure 2 are displaced vertically from the original data to improve clarity; this displacement of course had no effect on the relative rates.) The vertical lines correspond to the times the clocks were removed from and returned to the Naval Observatory. Of course, no comparisons with MEAN(USNO) were possible during the trips. The slope of each trace in Figure 2 gives R_c. A slope of 30° for this graph corresponds to a rate of approximately 10 nsec/hour (2.8×10^{-12} sec/sec). It can be seen that all the clocks agree with MEAN(USNO) to within 3×10^{-12} sec/sec. Notice also that numerous quasipermanent rate changes occurred while the clocks were sitting in the laboratory. Moreover, rate changes that are noticeably larger than those typical in the laboratory occurred for each clock during at least one of the trips, except for clock 447. This result suggests that these clocks cannot be expected to perform under traveling conditions as well as they do in the laboratory; this is not particularly new information.

A careful study of the data shown in Figure 2 indicates that the rate for each clock immediately before and after each trip can be evaluated to perhaps better than 10% (except for the case of clock 361 after the eastward trip). The following is an attempt to justify the approach used to derive the results presented in this report.

During both trips each clock suffered one or more quasipermanent rate changes. On the basis of "the least number of assumptions, assume only one occurred. This change is then given by the difference in the rates

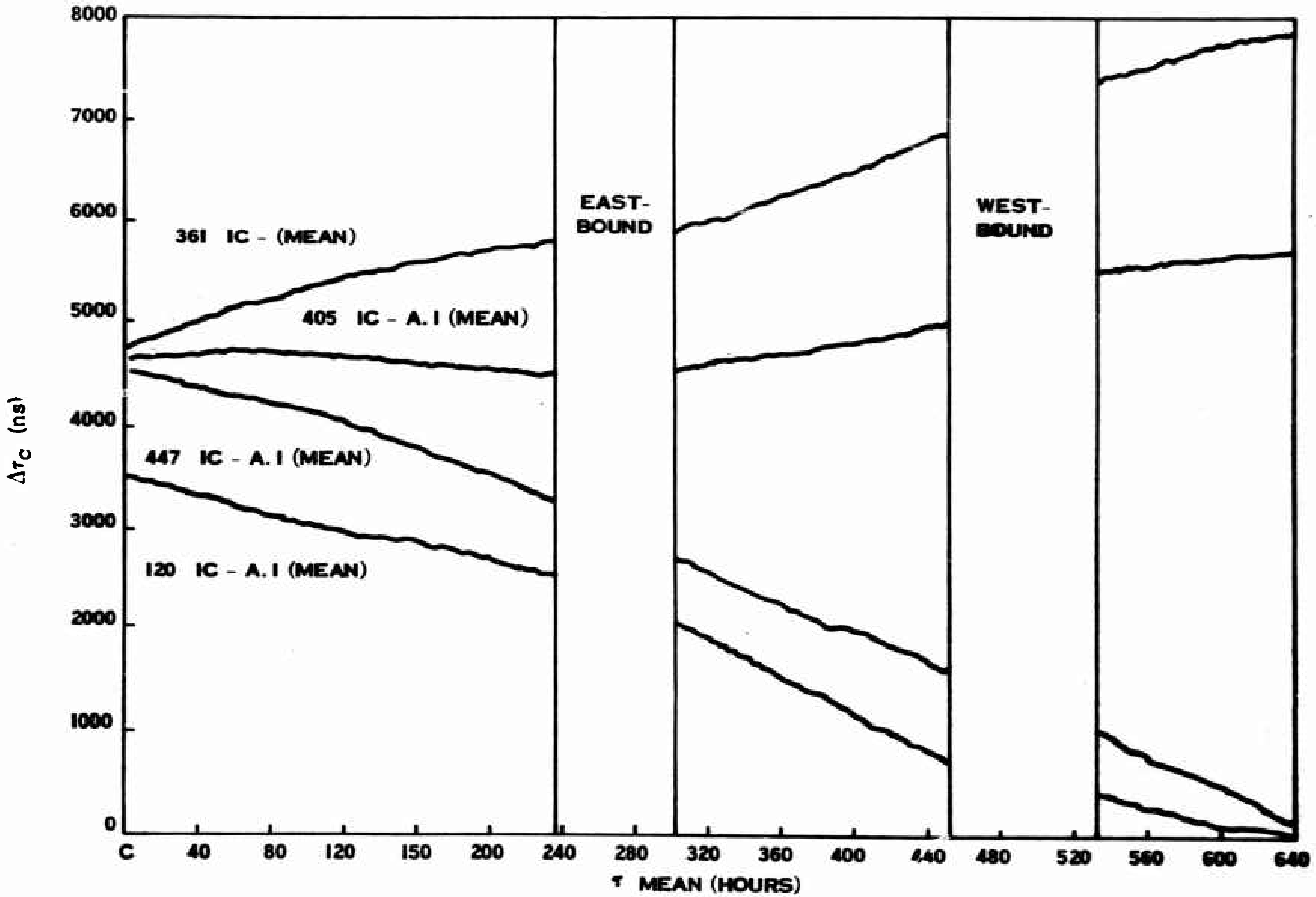

Figure 2. MEASURED VALUES OF $\Delta\tau_c$ VS τ MEAN FOR EACH CLOCK TAKEN BEFORE, BETWEEN, AND AFTER TRIPS

immediately before and after the trips. Without the inflight intercomparison data, we have no way of knowing at what time during the trip this rate change occurred. The least error accrues with the assumption that it occurred at the midpoint of the trip. Thus the average inflight rate (assuming no relativistic effects) is half the sum of the initial and final rates. Extrapolation with this average rate then gives the final times the clocks would have read if there were no relativistic effects. Figure 3 illustrates this approach and defines the symbols used.

Table III lists for each clock and each trip the initial and final rates, the average rate, the rate change, the observed initial and final time difference between each clock and MEAN(USNO), and the difference between the extrapolated time and the observed final time difference. Notice that the the average rate change for each trip is less than 1 nsec/hr (3×10^{-13} sec/sec). Hence MEAN(FLYING) can be expected to produce considerably more reliable results. Most people (myself included) would be reluctant to agree that the time gained by any one of these clocks is indicative of anything, but the rather striking consistency between all four clocks must be taken seriously. The averages of the four final time differences are consistently negative or near zero for the eastward trip and consistently positive for the westward trip. Corresponding standard deviations are also listed in Table III.

Figure 4 summarizes our results at this stage of the analysis. The numbers in the blocks indicate the serial numbers for the corresponding clocks. The average of the observed time gains, with corresponding standard deviations, and the predicted time gains are shown at the bottom of Figure 4. It is amusing to notice that the values for the eastward trip are in excellent agreement despite our expectation that we would not be able to detect a definite effect in this direction. On the other hand, the effect for the westward trip was predicted to be considerably larger and detectable, but the observed value is more than one standard deviation below the predicted value. Hopefully our final analysis will improve the situation.

TABLE III. FLYING CLOCK DATA - RATES RELATIVE TO U.S. NAVAL OBSERVATORY MEAN

CLOCK (ser. no.)	R_i (ns/hr)	R_f (ns/hr)	$\overline{R}$ (ns/hr)	ΔR (ns/hr)	$\Delta\tau_i$ (ns)	$\Delta\tau_f$ (ns)	$\Delta\tau$ (ns)
			Eastward flight				
			τ = 65.42 hr				
361	+2.66	+4.38	+3.52	+1.72	1790	1910	-110
408	-1.78	+3.22	+0.72	+5.00	-20	30	+3
120	-4.50	-8.89	-6.70	-4.39	-290	-780	-52
447	-7.16	-8.41	-7.78	-1.25	-1140	-1705	-56
				$\overline{\Delta R}$ = +0.27 ns/hr			$\overline{\Delta\tau}$ = -54 ns
				$\sigma_{\Delta R}$ = 3.8 ns/hr			$\sigma_{\Delta\tau}$ = 46 ns
			Westward flight				
			τ = 80.33 hr				
361	+6.89	+3.97	+5.43	-2.93	2880	3390	+74
408	+4.84	+2.16	+3.50	-2.68	490	980	+209
120	-8.88	-4.56	-6.72	+4.31	-2100	-2400	+240
447	-7.17	-9.42	-8.30	-2.25	-2840	-3390	+116
				$\overline{\Delta R}$ = -0.89 ns/hr			$\overline{\Delta\tau}$ = +160 ns
				$\sigma_{\Delta R}$ = 2.6 ns/hr			$\sigma_{\Delta\tau}$ = 78 ns

1 ns/hr = 2.78 x 10^{-13} sec/sec

$$\sigma = \left[\frac{\Sigma(\Delta\tau - \overline{\Delta\tau})^2}{3} \right]^{\frac{1}{2}}$$ (standard deviation)

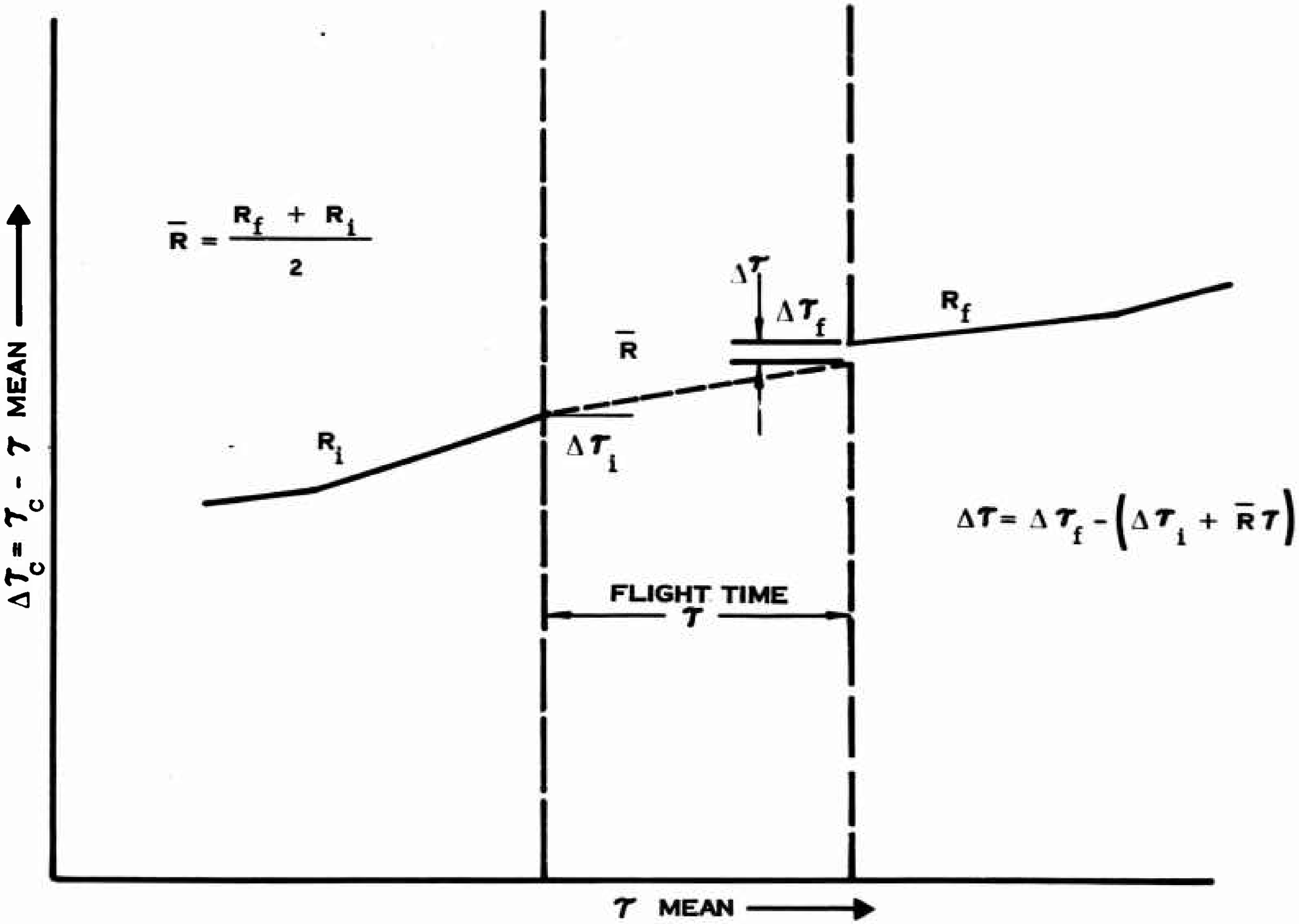

Figure 3. AVERAGE RATE METHOD FOR $\Delta\tau$

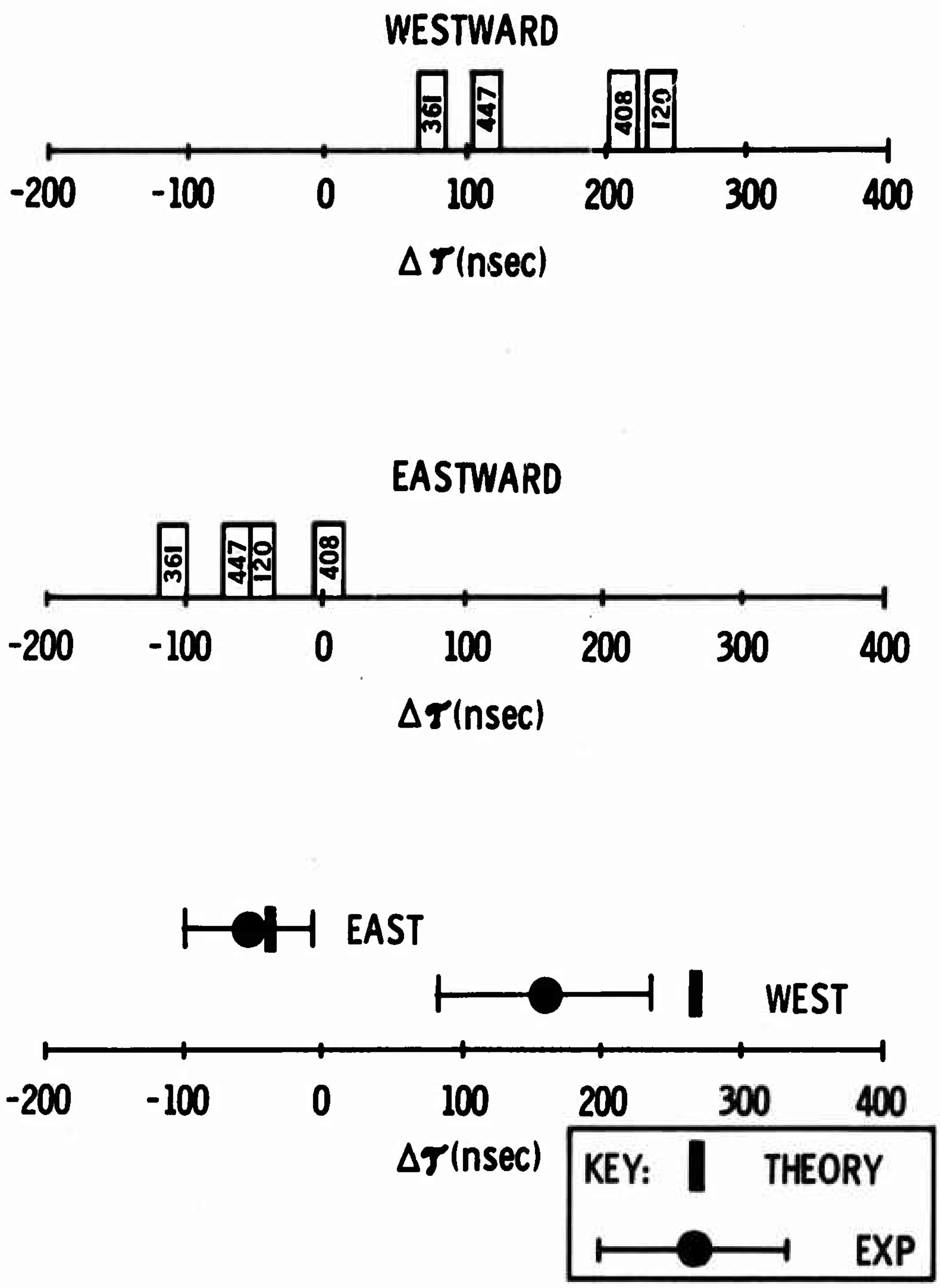

Figure 4. TIME GAINED BY FLYING CLOCKS

8.0 SUMMARY AND CONCLUSIONS

Portable cesium beam clocks (model 5061A) cannot be expected to perform as well under traveling conditions as they do in the laboratory. Our results show that quasipermanent rate changes as large as 5 nsec/hr (120 nsec/day) may occur during trips with clocks that have shown considerably better performance in the laboratory. Of course, such changes reduce the utility of these clocks. For example, if a flying clock changes rate by 5 nsec/hr shortly after the beginning of a two-week trip, and no other significant changes occur, synchronizations with this clock shortly before the end of the trip would be off by 1.6 μsec. However, our results also suggest that the average of four flying clocks permits synchronization with an uncertainty of less than 1 nsec/hr (24 nsec/day), assuming no intercomparison data are recorded. With intercomparison data, it should be possible to reduce the uncertainty even further.

Although the final analysis of our data is not yet completed, we have established, with an intermediate level of analysis, that portable cesium beam clocks are capable of showing relativistic effects with relatively inexpensive commercial jet flights. The results of this analysis are in reasonable agreement with theoretical predictions. However, those who doubt the validity of conventional relativity theory, and there are many people in this category, probably will not be converted by the results shown in Figure 4. Indeed, the difference between theory and measurement in Figure 4 is disturbing, and if our final analysis does not improve agreement, an improved version of this experiment should be given serious consideration. The standard deviation on the measurement could be reduced considerably, probably by a factor of ten, with such improvements as the use of dual beam clocks and circumnavigations with less ground time. In any event, this experiment verifies unequivocally the existence of the predicted east-west directional asymmetry; only more precise magnitudes remain to be established.

DISCUSSION

MR. CHI: Is your predicted time drift, or time change, nanoseconds per day, the initial and final? Are they about the same length of time to determine those values?

DR. HAFELE: What I did was to go from the time, either starting or stopping of the flight, to the first rate change that was obvious in the laboratory. Now all of these included at least twenty-four hours. Many of the clocks changed either a day before the flight (there was a rate change in the laboratory) or a day after the flight (there was a rate change in the laboratory) and that's why, particularly in the case of 361 after the eastbound flight, it is quite uncertain what the rate is after the flight. Hopefully, the intercomparison data will clear this question up a lot. What we'll have is a mean flying rate before the flight and a mean flying rate after the flight, which should be equal; if these four clocks are working randomly, if these effects are random, they will scatter about a constant mean. However, there will be an offset in the mean due to the relativistic effect. The theory of relativity cannot induce any permanent rate changes; it's only while the clock is moving that these changes occur.

DR. ALLEY: I think that Professor Hafele and Mr. Keating and Dr. Winkler and others are to be commended for carrying out, for the first time, an experiment in which a recording clock has actually been carried in a closed path in space-time and returned. I would, however, caution members of the audience, or remind them, that special relativity has been verified in many, many experiments, as has the frequency change of transmitters, like gamma ray emitting atoms and so on. I think the primary significance of this lies in the first time of returning a clock and comparing actual elapsed time.

DR. WINKLER: I would also like to make a comment here and attempt a clarification of the additional data processing which is still to be done, and why it hasn't been done yet. I feel very guilty about the fact that we haven't been able to provide better support to this case. What has happened is that the data set is available in digital form, but there are a couple of errors which are quite evident when you look at the chart. Charts are automatically produced from the data set, and Professor Hafele's assistant, Mr. Keating, had to be sent on temporary analysis duty immediately after their return. Therefore we felt it was wise to let the same people complete the analyses who have collected the data.

The analyses will be completed when the remaining 90 percent of the information is processed. I think what has been represented is not more than 10 percent of what is actually available by way of measurements. The basic idea is to keep account, by using the internal measurements, of the measured frequency variations of each standard and to be able to connect the average rate across a flight duration to what you find after you return. If the rate that you predict is altered by all corrections following from the hourly measurements made during the flight, and that result is very close to measurements after return, I think you will have a very great confidence in the result. So I am confident that data processing will produce a much more objective and much greater confidence in the final result, because we use an automatic procedure in which judgments are left to the computer.

DR. HAFELE: I wonder if I could respond to Professor Alley's comment. He said that the special theory had been thoroughly proved by all kinds of experiments. Well, I think that in the same respect there's never been an experiment done by anybody on either the special or the general theory of relativity which disproves either one. The general theory just makes some interesting predictions that you can't test. Does a clock on the ceiling run slower than a clock on the floor? We don't know for sure, but it looks as though when you send gamma rays up from a radioactive nucleus, they are absorbed only if you doppler shift the upper nucleus. Does that prove that a clock on the ceiling runs slower than a clock on the floor? Many people will say "yes, it has to, and there's no point in doing the experiment." But then there are a lot of people who don't buy that argument. So the special theory has been tested in the same way that the general theory has been tested so far.

DR. ALLEY: I just want to make clear that I do regard such experiments as worthwhile. In fact, there are people who have questioned the assumption that clocks actually run at different rates in different gravitational potentials. But that is an integral part of the structure of general relativity which has been tested to a certain extent. However, convincing demonstrations of this, I feel, are very much in order.

MR. GATTERER: For what it's worth department, I would not accuse Dr. Bonanomy of saying that this observation is worth very much. He may not even wish to be quoted in this gathering, but he's had recent experience in transporting portable clocks around in cars, and it is his opinion that, or at least it is his suspicion that, the environment in an aircraft is a little more devastating to a cesium standard than it is in a car. His experience indicates that his closing error is smaller than, for example, the Naval Observatory's portable clock trips. It is entirely possible that the environment that may be to blame is a relativistic change, although I think he thinks that the loading and the unloading process is damaging; therefore your data are varied, perhaps, in knocks and bumps.

DR. WINKLER: If you look at the differential phase plots available on the little paper and follow these differential phase plots which have been using the data throughout, the laboratory stay, the westward trip, the eastward trip and so on, you cannot discern any substantial change in the appearance of these phase plots. There are clock pairs--incidentally not in the same package--which have an extremely uniform performance, and there are instances in which you can identify very well the moment and the magnitude of the frequency change. I don't know if we have labeled them, but cesium 120 has suffered on the westward trip, a very definite and very accurately determined frequency shift. You question the effect of the environment. Well, that has been the main purpose of conducting the experiment; that is why we got the eight thousand dollars from ONR, to study that effect. I think we have plenty of information on it, some of it can be inspected visually, and I meant you to do that. I think the aircraft environment is somewhat better than in a car, it depends whose car. I think that is a very wise comment because Dr. Bonanomy's car may have been particularly bumpy.

DR. RUEGER: Were you instrumented in the three dimensions of the accelerational field during the flights?

DR. HAFELE: No, we don't know what the accelerational fields were, except for those that we felt. The plane jiggled a little bit between Athens and Rome, and there was some rough weather. When we were sitting in the seat we felt about as heavy as we always feel.

DR. RUEGER: But the circling of an aircraft over an airport would be an asymmetrical field you'd get on this instrument.

DR. HAFELE: Very slight. You mean that the force down would not be balanced by upward force; you mean that there would be a sidewise force on the clock. Very slight, I suppose that, yes, if you turned the clocks over it changes them. Well, I'm not the expert on how these clocks perform under various environmental conditions.

DR. RUEGER: Well, we knew that this was a very important parameter in the carrying of crystal clocks, and we've always been very careful to block them up square and do other things to keep them from being the least bit out of square.

DR. HAFELE: I see what you mean. Yes, the clocks sat in the seat and they weren't square in the seat, they were tilting back a bit in the seat, so they weren't sitting level in the plane. It was almost impossible to do that; we weren't rigged to do that. We just plopped them down on the seat and strapped them in.

MR. COCHRAN: Has anyone checked the gravitational effect of a high-altitude ground level against sea level? Or would that be within the accuracy of the clock?

DR. HAFELE: You can see from the plot (Figure 1) the difference between altitude zero and altitude 10 kilometers. With a high altitude balloon you can easily go to 100 kilometers. Nobody's ever done such an experiment.

DR. RUEGER: There was, I think, an experiment done with crystal clocks in eccentric orbits. If you massage the data rather exhaustively, they could show there was indeed an influence on what we call the gravitational redshift which at the surface of the earth is in the order of two parts in ten of the thirteen per kilometer. This is an effect of the difference of gravitational potential.

DR. HAFELE: You're talking about frequency now, though; I'm talking about time. That experiment was done with frequency on a crystal oscillator in a satellite.

DR. RUEGER: Frequency is synonymous with time for most people. Anyway, the experiment did show the periodic effect with the period of the orbit and I think there was a confirmation in that of, perhaps, 20 percent. Is that reasonable?

DR. HAFELE: I looked at those data and you believe what you wanted in there. If you don't want to believe it you don't need to. If you want to, you see it there.

DR. WINKLER: I would like to add an entirely different comment here. The experiments may have been more practical and may have more practical relevance than appears at this stage. Carrying clocks around the earth in a non-inertial frame of reference is essentially the same thing as sending an electromagnetic wave around the earth one way and the other way. If you remember the discussions about utilizing the Defense Communications Satellite System for high precision synchronization, if we have a network which depends on an internal high precision synchronization to within a few tenths of nanoseconds, then we will have to expect that the network will have some border difficulties. This depends on which way around we have propagated the precision timing, and this is a test which we have considered doing. We have discussed it with some people in DCA; there are some difficulties of an entirely practical nature. On the other hand, it has practical implications for the design of the systems and the operational routines to be employed.

DR. HAFELE: The magnitude of that effect is, I believe, about 250 nanoseconds difference in time. It's a big effect--a quarter of a microsecond.

MR. BARTKO: Why don't you take the predicted offset and get the clock out of synchronization and then try to bring it back in synchronization by going around the world, reversing the experiment so to speak?

DR. HAFELE: I'm not sure I understand. You want to predict where the plane's going to go so you can make a prediction of what the relativistic effect will be, and then you change the setting of the clock before you take off? And then come around and see if it reads zero? What is gained by that?

MR. BARTKO: Well, that's the reverse of what you did originally.

DR. HAFELE: I must admit I don't see the gain. I suppose that changing something in one of these clocks is one of the worst things you can do; just reaching in there and turning a knob, it takes it two weeks to settle down.

DR. KLEPCZYNSKI: I don't believe you could make a prediction in advance as to what the retardation or advance would be, because you wouldn't know what altitude or velocity you're flying at.

DR. HAFELE: That would be a problem.

LONG-RANGE POSITION DETERMINING SYSTEM (LRPDS)

by

Dr. F.W. Rohde

Dr. Rohde is with the Army Engineer Topographic Laboratories, Ft. Belvoir, Virginia.

The Long Range Position Determining System (LRPDS) is being developed by the Army Engineer Topographic Laboratories. The LRPDS is designed to provide a rapid survey and positioning capability for the Field Army. The basic design goals for LRPDS are :

- The system must be capable of determining 24 positions within one mission.
- The area of operation may be as wide as 200 km.
- The mission should be accomplished in less than one hour.
- The position accuracy may vary from 5 meters to 40 meters depending on where the position is located.
- The weight of one back-pack unit should not exceed 25 pounds.
- The communication links of the system should be jam resistant and difficult to detect.

Some of the significant design characteristics are as follows:

- All signals transmitted during the mission are transmitted on a single carrier frequency which makes simultaneous transmission and reception impractical.
- All data and messages for LRPDS operations are transmitted by the systems communication links.
- The aircraft carrying airborne LRPDS equipment shall not be dedicated only to LRPDS missions.

- The computer shall not be specifically designed for LRPDS.
- The system shall be operational in all weather.
- The system is only controlled by the user.

The range change measurement method has been primarily selected because of the single frequency constraint. The LRPDS hardware is being fabricated by Motorola in Scottsdale, Arizona. The delivery of the equipment is scheduled for December 1972. Although the design has been finalized and engineering prototype equipment has been built, some areas of LRPDS may still be subject to minor changes.

Figure 1 explains the range change measurement concept. The aircraft continuously transmits a coded signal which is received by the unknown station. The receiver compares the phase of the incoming signal with the phase of an identical signal generated by the receiver. As the aircraft moves, the phase of the received signal changes with respect to the phase of the signal generated by the receiver. These phase changes are proportional to range changes as shown in Figure 1. The code of the signal serves as a coarse yardstick with a resolution of 30 meters. The carrier serves as a fine yardstick with a resolution of 11.7 cm. Figure 2 shows a typical operational setup for LRPDS. The aircraft carrying the airborne equipment flies over an area where ground equipment has been deployed. The triangles represent base stations whose positions are known. The crosses represent ground stations whose positions are unknown and must be determined. A position computing center is located in the lower left of the picture. The airborne equipment generates ranging signals and read commands and serves as a relay in the communication, between ground stations and computer center.

There are five basic steps in an LRPDS operation. In the planning phase, all addresses, messages and commands necessary to execute the mission are put together in proper sequence and transmitted to the aircraft. The pilot is advised of the desired flight course. During the second phase,

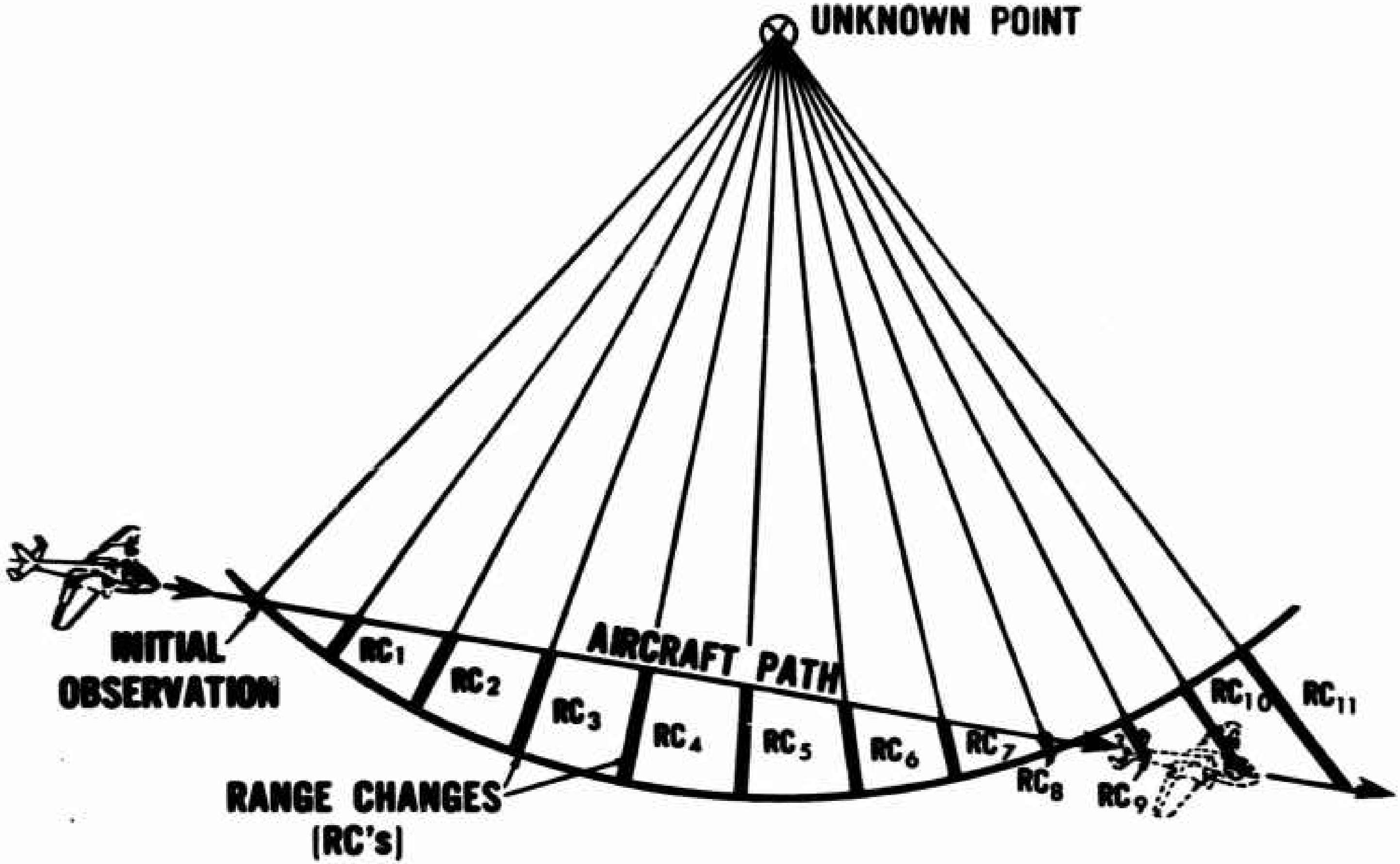

Figure 1. RANGE CHANGE GEOMETRY

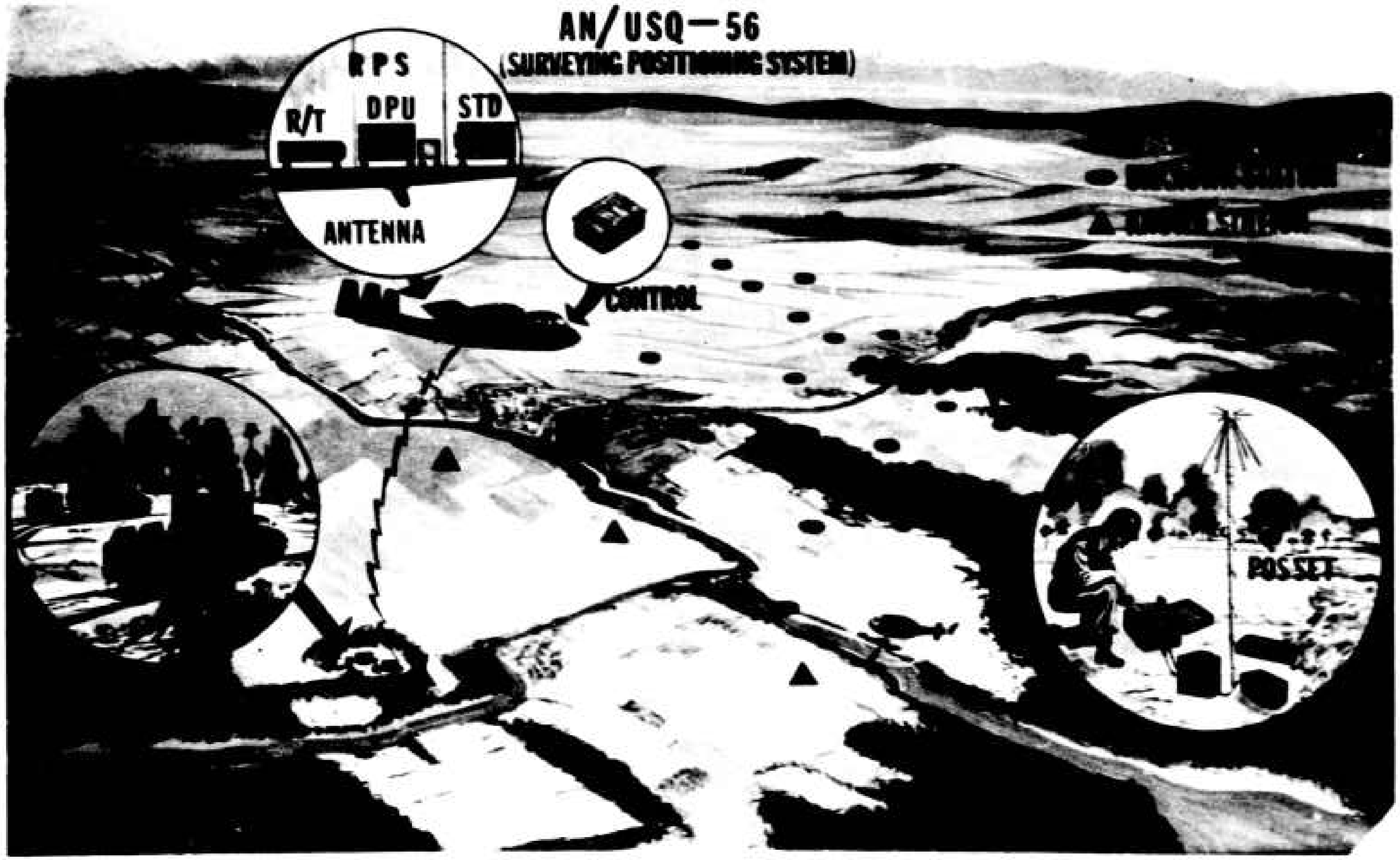

Figure 2. LRPDS CONCEPT

the aircraft transmits ranging signals, messages, and, at scheduled intervals, read commands to the ground stations. The ground stations receive the signals, measure the range changes at read commands, and store them in their memories. Message data are decoded and stored in the memory or displayed. During the third phase the ground stations transmit in sequence the stored range change data back to the aircraft which in turn stores and retransmits all data to the computing center. The positions of the ground stations are computed in phase four. During the last phase of the mission, all necessary information is transmitted to the ground stations via aircraft.

There are four LRPDS subsystems as shown in Figure 3. These are the positioning set, which is carried on two back-packs; the reference positioning set which consists of the LRPDS airborne equipment; the position computing central which contains the computer and serves as the mission control center; and the calibration and maintenance set. The latter two subsystems are housed each in a van and mounted on trucks.

The functional block diagram of the positioning set is shown in Figure 4. The receiver-transmitter unit and the data processing unit are housed in a single case, which is loaded on Packboard "A". Packboard "B" is used to transport the oscillator, battery, antenna, and cables. For certain missions, a digital display unit is included in this package. The receiver-transmitter unit is also a component of the reference position set and the position computing central. The receiver is capable of acquiring and tracking a RF-carrier that is bi-phase modulated with a predetermined pseudo-random code which has been modulo-two added with data symbol bits. The receiver output provides demodulated data and a phase coherent tracking signal representative of the reconstructed RF-carrier. The transmitter is used to transmit data and messages back to the aircraft. The data processing unit stores range change data, decodes messages, and establishes the format for data transmission to the aircraft. Figure 5 is a picture of the positioning set with receiver-transmitter unit and data processing unit in one box, the digital

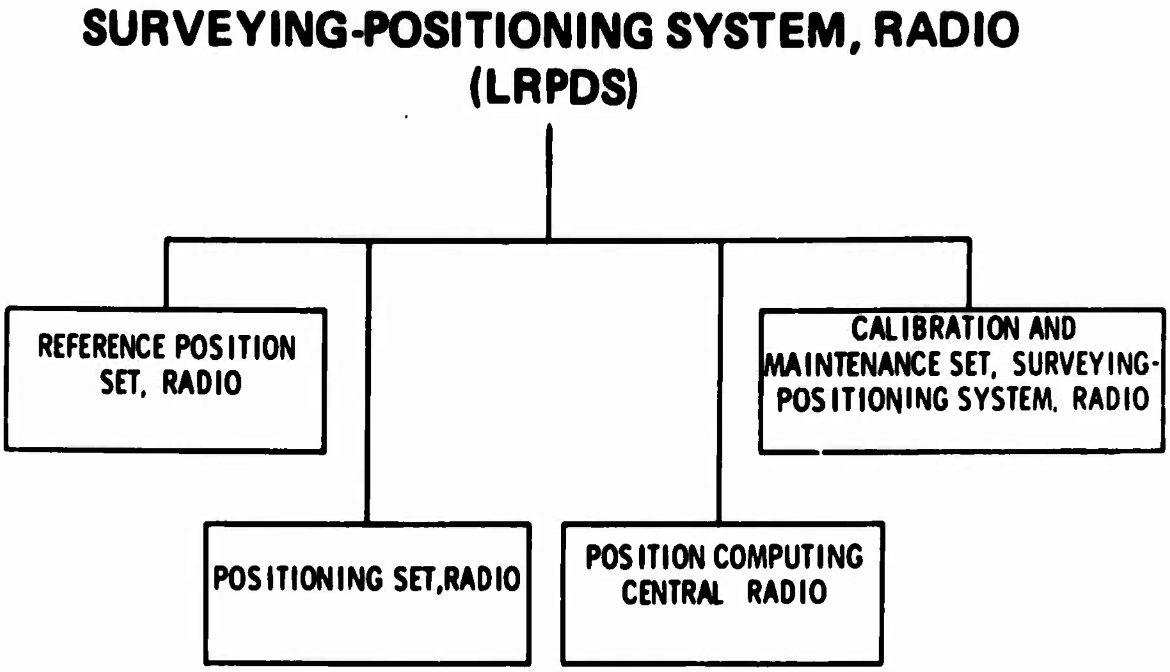

Figure 3. SURVEYING-POSITIONING SYSTEM, RADIO (LRPDS)

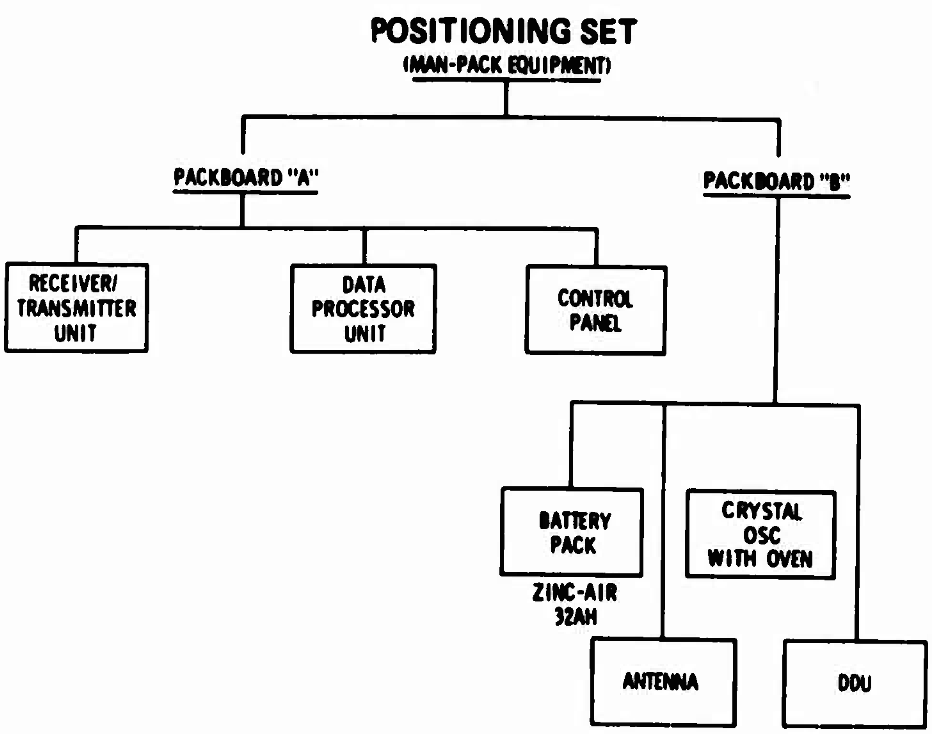

Figure 4. POSITIONING SET (Man-Pack Equipment)

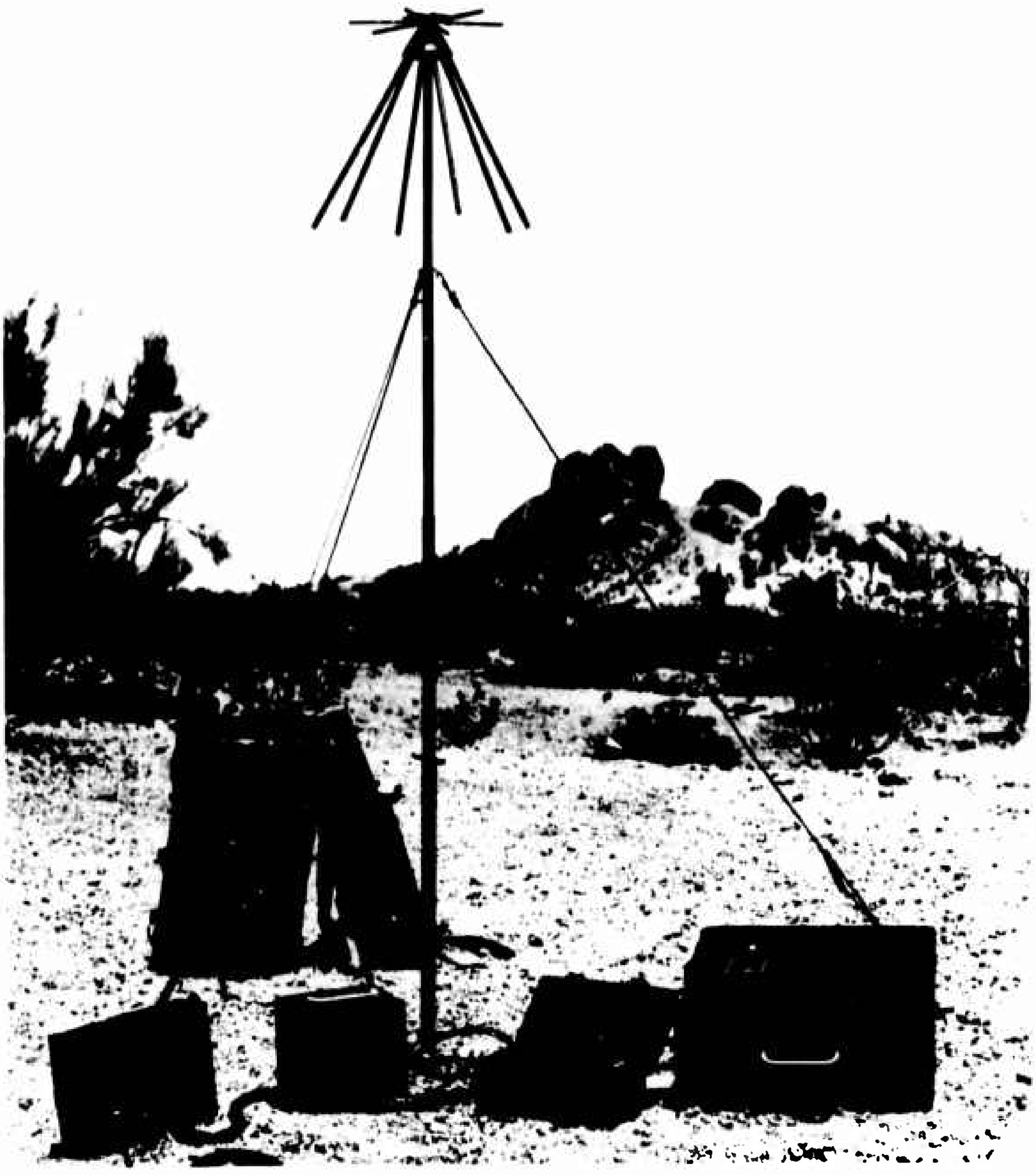

Figure 5. LRPDS POSITIONING SET

display unit, the oscillator package, battery, and antenna. The oscillator is an Austron double oven crystal oscillator which is shock mounted in the case. Figure 6 shows a close look at the unit which contains the transmitter-receiver and the data processor. The switches are used to generate a desired code and to enter data.

The LRPDS signed characteristics are as follows. The carrier is tunable between 260 and 440 megahertz in steps of 10 megahertz. The carrier is pseudo-noise modulated with a code consisting of 8.191 bits. The code is generated in a 13-stage linear feedback shift register. The duration of one bit is 100 nanoseconds. The data are synchronous with the code. One data bit consists of two code lengths and has a duration of about 1.62 milliseconds.

The acquisition of the signal is accomplished in sequential steps. During the first step, correlation between the incoming code and the receiver generated code is established, causing the carrier loop to close. After the carrier loop is closed, the loop will be phase locked. The bandwidth of the carrier loop is then narrowed to about 40 hertz. Finally, the receiver phase-corrected clock is adjusted to zero and the receiver is ready for full tracking. The reference input for the coarse-range measurements is the five megahertz sine wave generated by the Austron oscillator. This frequency is multiplied by two and shaped into a square wave which is counted by the coarse-range register. The coarse-range register is read at the coincidence of a range change measurement command and a unique state of the receiver code generator. The fine-range register is a nine-stage counter with a resolution of 60/512 meters (=11.7 cm). The fine-range measurement is made by measuring the relative phase between the reference wave from the crystal oscillator and the wave of the receiver phase-corrected clock. The receiver phase-corrected clock signal is a square wave at five megahertz ± doppler. The input to the phase-corrected clock is derived from the received RF-carrier. The relative phase measurement is made by counting cycles that occur

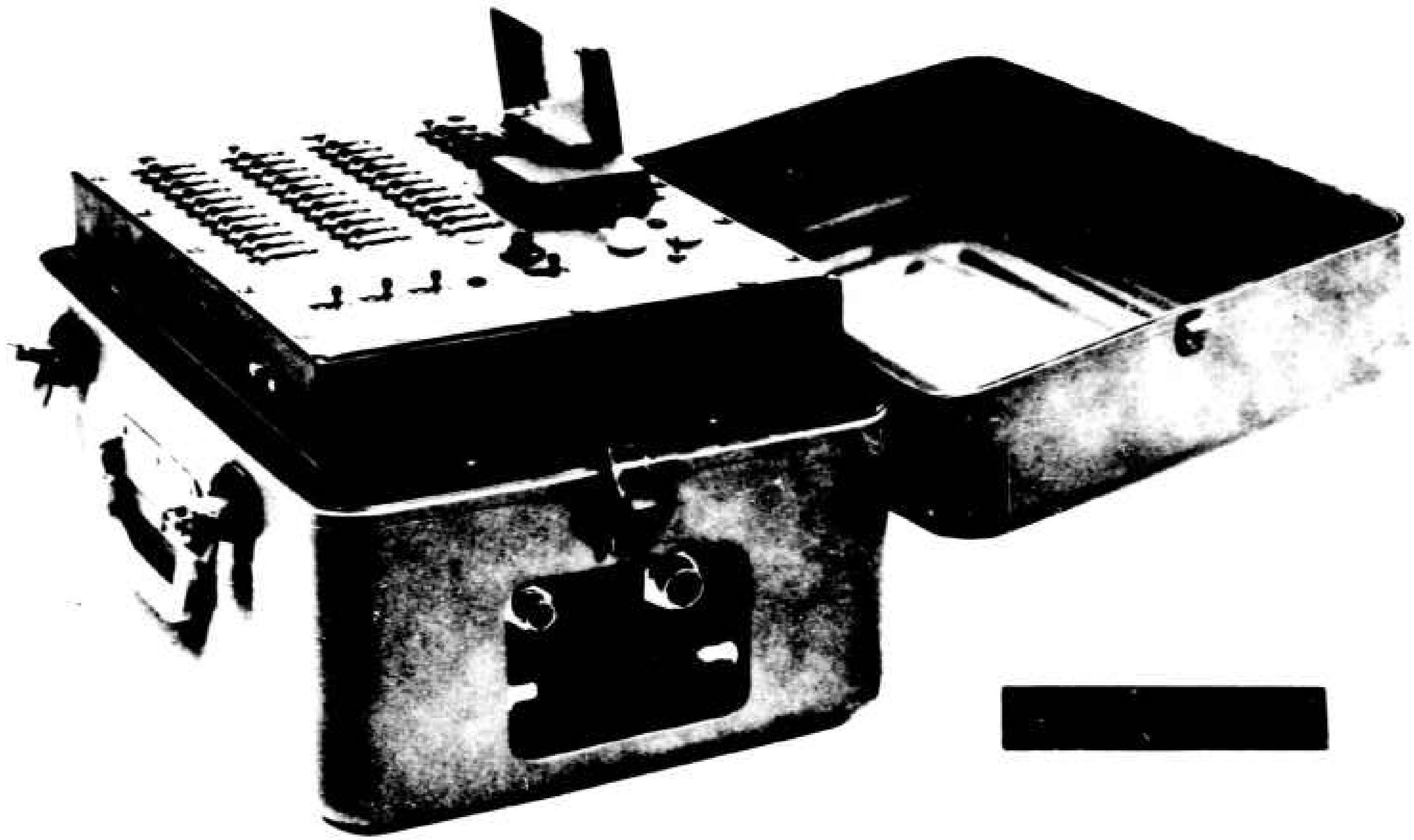

Figure 6. LRPDS POSITIONING SET

between the zero crossings of the reference wave and the translated carrier wave. One full 360° phase rotation at the translated frequency changes the fine range register by 512 counts.

The airborne reference positioning set is shown in Figure 7. The capacity of the data processing unit is considerably larger than that of the positioning set, because more data have to be stored and processed. The master clock is a Hewlett-Packard cesium beam clock which has been designed for airborne applications. This clock has been selected to provide the required stability under dynamic conditions such as aircraft maneuvers. The control and monitor unit provides the observer with control capability over the mission. The meterological data converter unit converts meterological data and altimeter readings in transmissible data.

The computer of the position computing central shown in Figure 8 will be a Datacraft Mod 5 computer with the following characteristics: 24-bit word with 8,192 words in the basic system. The computer capacity can be increased to 65,536 words in 8,192 word increments.

The internal stability of the receiver with respect to range change measurements was determined as a function of dynamic range, ambient temperature, warmup period, supply voltage variation, interference by jamming and adjacent users, shock, and vibration. The internal stability proved to be one to three bits of variation in most cases. Figure 9 shows the effect of a frequency offset and frequency drift of the oscillator on range change measurements. Because frequency effect and frequency drift are practically constant during the range change collecting period, these quantities can be treated as fixed unknowns and solved in the data reduction process. Figure 10 shows requirements and test results for the ground station crystal oscillators. The difference between airborne clock and ground station crystal oscillator is required to be not more than 1×10^{-7}. The drift should not be larger than 5×10^{-10} and phase noise should not exceed 2° RMS at five megahertz. Figure 11 shows the position accuracy which should be attained with LRPDS.

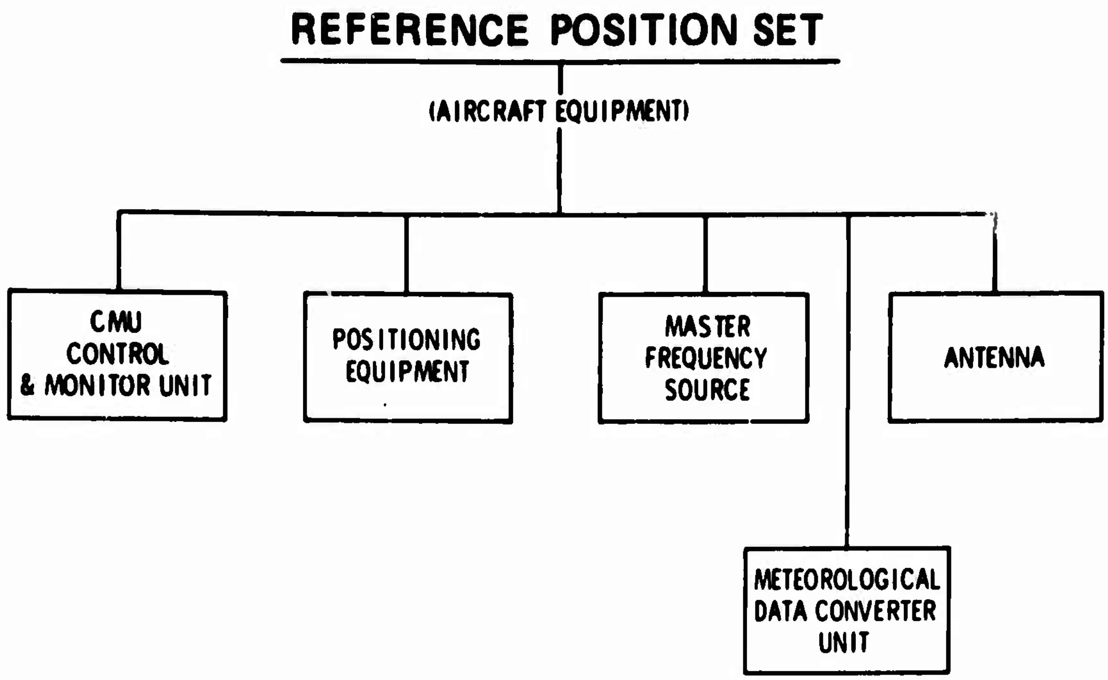

Figure 7. REFERENCE POSITION SET (Aircraft Equipment)

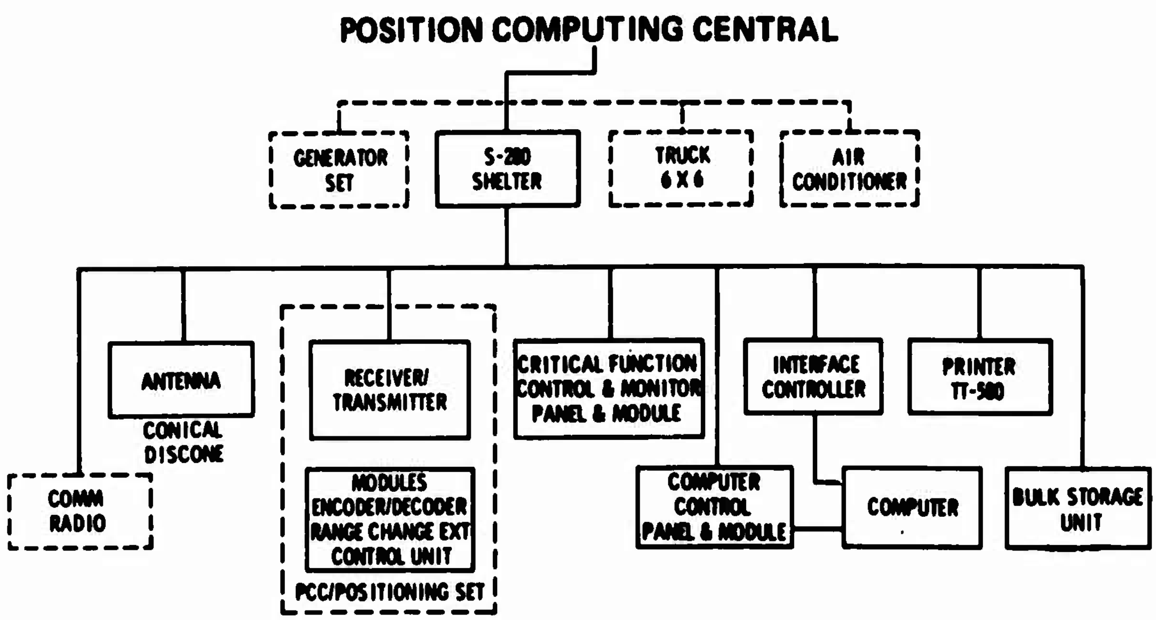

Figure 8. POSITION COMPUTING CENTRAL

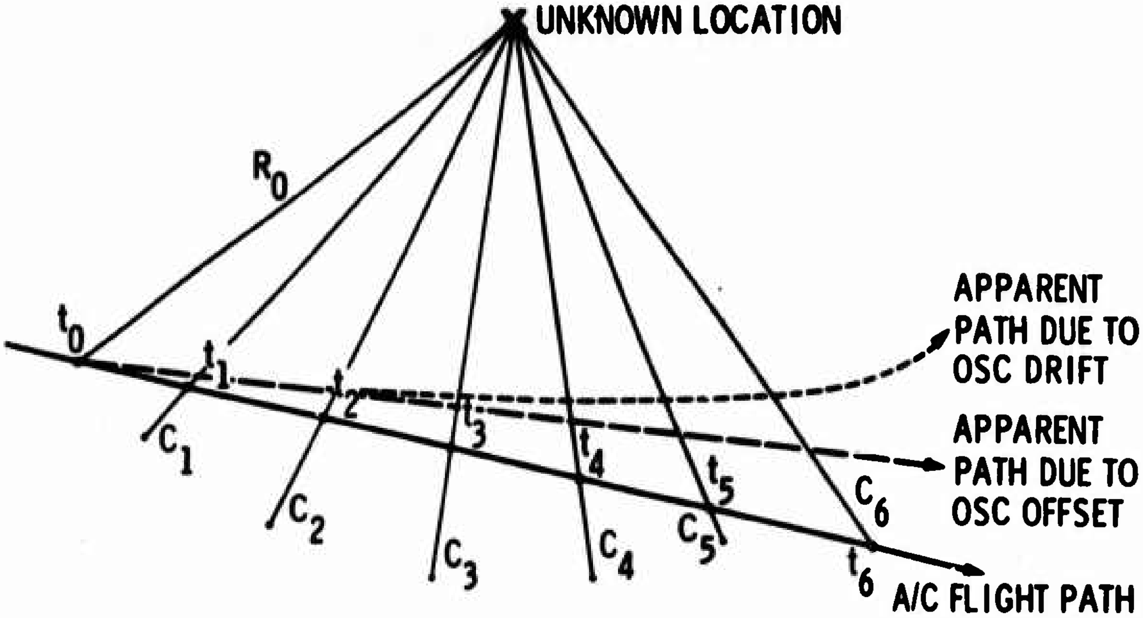

Figure 9. RANGE CHANGE PRINCIPLE AND OSCILLATOR EFFECTS

	REQUIREMENT	TEST RESULTS
OFFSET (f AIRCRAFT −f GND SET)	$< 1 \times 10^{-7}$	1×10^{-9}
DRIFT (PARTS/HR AFTER 4 HR WU)	$< 5 \times 10^{-10}$	1×10^{-10} WORST CASE
NOISE (TOTAL PHASE ERROR IN CYCLES AT 5 MHz)	< .005 RMS	.002 TO .005 RMS

Figure 10. LRPDS OSCILLATOR EFFECTS

SURVEY AREA	METERS RMS		
	X	Y	Z
30 × 30 KM	5	5	10
60 × 60 KM	8	8	30
LONG RANGE 200 KM	40	40	—

Figure 11. LRPDS ACCURACY

ROLE OF PRECISION CLOCKS IN FUTURE UNDERWATER TRACKING SYSTEMS

by

Albert Caron

Mr. Caron is Supervisory Electronic Engineer, Naval Underwater Systems Center, Rhode Island.

Abstract

The purpose of the paper is to provide information on Navy underwater three-dimensional tracking ranges, and to look at future ranges in terms of precise timing requirements.

The paper is divided into three sections. The first, entitled "Development of Three-Dimensional Underwater Ranges," historically brings the reader up to date on how the Navy tracking ranges, (of which there are five) evolved. It discusses the commonalities of these ranges and their differences. The subject of hydrophone configuration; e.g., short and long baseline systems, is discussed, as well as the rationale for selection of tracking frequencies. The timing requirements and error budgets are also explored. The second section, "AUTEC Weapons Range," describes in detail a modern underwater tracking range. Its capabilities, uses, and limitations are pointed out. The last section, "Future Underwater Tracking Systems," points out the need for much larger and deeper ranges. The cost for such future ranges is a problem and indicates that novel approaches and new concepts will be required. One particular concept which would be highly cost effective utilizes bottom-mounted beacons instead of hydrophones as in the conventional approach to tracking. The success of this concept is dependent upon obtaining

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clocks that are highly reliable, stable, and use little DC power. The concept and clock requirements are discussed in detail.

This complete report is classified SECRET and can be obtained only by written request to the U.S. Naval Observatory, Technical Officer, Washington, D.C. 20390.

TIME AND FREQUENCY RELATING TO COLLISION AVOIDANCE SYSTEM

by

J. L. Brennan

Mr. Brennan is Sub-Program Manager of Collision Avoidance Systems, Federal Aviation Administration, Washington, D.C.

This paper is a discussion of the history of the collision avoidance program and the current status of FAA plans and requirements. First, however, some basic definitions will be presented. A collision avoidance system (CAS) is an all-weather system which detects all potentially dangerous intruders, automatically evaluates the degree of the threat, and, if necessary, indicates a safe, evasive manuever to the pilot. A cooperative system is one which is only capable of detecting those aircraft which are equipped with the same cooperating system; that is, there is an active exchange of information between the aircraft. A non-cooperative system would protect against any other aircraft, equipped or not. While our objective is the development of non-cooperative systems, it is a fact today that the most promising CAS is a cooperative system.

The primary mission of the FAA is the safe and efficient movement of air traffic, with the emphasis on safety; as such the entire traffic control system can be thought of as a collision avoidance system. However, the philosophy behind our CAS program has been to search for a collision avoidance capability independent of the ground base air traffic control (ATC) system which could serve as a backup in the event of a failure in the ATC system and which could provide protection to aircraft in areas not serviced by an ATC system. In addition, our search has been directed primarily toward a collision avoidance capability utilizing an air-to-air data transfer. Again, it should be emphasized that the ATC system is, and will remain, the primary method of controlling air traffic; a CAS will simply serve as a back-up, not as a substitute for it. Much research on the CAS has been done in government and industry and quite a long time ago it was realized that a forum was needed for a continuing exchange of information on the subject. As a result, in 1959, the FAA formed the Collision Prevention Advisory Group, commonly known as COPAG. Membership is made up of representatives from government agencies and from selected civil aviation associations which best represent the majority of the airspace users; that is, those who have demonstrated both an interest and a competence in areas pertinent to mid-air collisions. The present members are from the FAA, NASA, the National Transportation Safety Board, the Army, the Navy, the Air Force, the Air Transport Association, the Aircraft Owners and Pilots Association, the Airlines Pilots Association, the National Business Aircraft Association, the National Pilots Association, and the National Air Transportation Conferences, Inc. The representative from the FAA serves as chairman. The group consists of organizations that are not involved in the manufacture or selling of commercial hardware, so there are no conflicts in this respect. Their primary function is to advise FAA regarding aspects of the mid-air collision problem, unique requirements, proposed solutions, etc. There is no voting in COPAG; it just provides an opportunity to consider everyone's needs and opinions. Since its inception, COPAG has kept abreast of FAA programs in these areas, has influenced them, and has assisted in carrying them out.

In order to provide some knowledge of the background of CAS, some of the completed projects should be mentioned. In 1958 we contracted with Bendix Corporation for a collision avoidance system which, since then, has come to be known as the ground bounce system. This system called for the transmission of a planes' altitude on a to-whom-it-may-concern basis.

Reception was both by the direct path and by the indirect, reflection path from the earth or the ground bounce. Thus, the receiving aircraft, knowing its own altitude and having been informed of the intruder's altitude and taking into consideration the time difference between direct and reflective pulses, could compute the range to the intruder. Successive computations of ranges were then made to determine range rate. Range divided by range rate, τ , was then computed. This contract with Bendix produced flyable hardware in 1961 and established the feasibility of the τ evaluator for the non-accelerating flight regime. However, the data exchange technique was not reliable and too much computation time was required. The obvious recommendations were to continue to search for a better data exchange technique and to reduce the threat evaluation time required.

Our next hardware contract was with the Sperry-Rand Corporation for a CAS which utilized an interrogate-transpond data exchange technique. This system utilized both an omnidirectional and a scanning antenna and exchanged altitude and velocity information. With this exchanged information and range and bearing measurements, an attempt was made to solve the collision triangle for the normal velocity component; i.e., that velocity component normal to the closing rate vector or line of sight. The threat evaluation criteria employed were relative altitude, range divided by range rate (τ), and normal velocity. If normal velocity is zero, and the range is closing, a collision course exists. The evaluation of this equipment was limited to bench tests only, due to the status of other contractual efforts at the time. These were a hardware contract with National Radio Company to investigate a time-frequency (TF) data exchange concept and an analysis computer simulation contract with Collins Radio Company. The TF concept involves synchronization in time and frequency of all cooperative aircraft so that range and closing velocity could be determined from the one-way propagation time and doppler frequency respectively. This effectively allowed the threat evaluation to be accomplished in a very short period of time and eliminated any mutual interference considerations, since time synchronization permitted one, and only one aircraft, to transmit at any one given time. We concluded from this hardware effort that the TF concept was indeed feasible and appeared very promising.

One task of the contract with Collins Radio Company was to consider all the promising CAS proposals and to recommend the most promising for concentrated effort. As a result of this analysis, the time-frequency concept was selected as the most promising. It still may be considered the best method, although several proponents of interrogated transpond techniques contend that the data processing state-of-the-art is now such that the inherent mutual interference problem of those techniques can now be overcome. Having decided that time-frequency was the best method, we prepared an engineering requirement for procurement of a time-frequency test bed whose initial primary purpose was the investigation of collision avoidance. This engineering requirement was reviewed by the members of COPAG and was supported by them. In late 1966, however, the Air Transport Association, a COPAG member, had second thoughts on the subject and in a letter to our administrator, requested cancellation of the planned procurement. As an alternate, they offered the following: the ATA would create the CAS Technical Working Group composed of representatives from the major avionic firms, interested government agencies, and industry experts in the TF technology. This group would convene and jointly prepare a CAS specification to which interested manufacturers would build equipment, at their own expense, for flight testing by the ATA. Because of certain obvious advantages in this arrangement, such as no government funding, we participated in the Technical Working Group. During the course of the Technical Working Group deliberations, it became apparent that a network of master time-disseminating ground stations would greatly simplify system operation. After discussion and analysis of the problem, it was determined that a synchronization requirement for these ground stations would be $\pm \frac{1}{2}$

microsecond between any ground station in the network and a master time. After considering this, the FAA went on record to the effect that, should the ATA system prove successful and become implemented, we would procure, install, and maintain the required ground stations.

It is now estimated that participating manufacturers have invested in excess of ten million dollars into the program. Equipment has been built by Bendix, McDonnell-Douglas, Sierra Research, and Wilcox to the specification prepared by the Technical Working Group. Flight test and evaluation of this equipment has been completed and no major technical problems appear to have been encountered. Based on the results of these flight tests, and on fast-time computer simulations by both FAA and the Technical Working Group, the CAS threat evaluation and manuever logics have been changed. However, operational questions which are impossible to evaluate with a limited number of equipments remained unanswered. For instance, what is the impact of the CAS on the ATC system in the area of false alarms? What is the effect on arrival and departure rates and what is the effect on the air traffic controller when aircraft make a sudden, perhaps unexpected, manuever? These questions and other questions are being investigated in a dynamic simulation, with controllers in the loop, at our Atlantic City Test Facility. The exploratory phase of this simulation was completed in late July, and the final report is due in February 1972. Tentative conclusions reached indicate that controllers can adapt to the effects of the CAS by modifying their control techniques. However, under certain configurations, this can result in a slight decrease in the rate of take-offs and landings per hour. While preliminary indications lead us to be optimistic, detailed analyses of the data and additional simulation are necessary before an optimum manuever logic for terminal area operations can be formulated. Follow-up simulation activity in this area is planned for the 1st or 2nd quarter of FY73. Hopefully, after follow-up simulation, our air traffic service will be in a position to state just what the significance of the CAS ATC interaction is and how a CAS can be used to supplement and assist the air traffic control system.

A Senate hearing on the subject of collision avoidance systems is scheduled for November 30. It was brought about by a bill, introduced for consideration by Senator Moss, to make collision avoidance systems and pilot warning instruments a requirement in aircraft in the very near future. However, Senator Moss, in an entry into the Congressional Records, indicated that one of the primary purposes of the introduction of the bill was simply to get expert testimony on the subject before Congress. The point is that the FAA and the Air Transport Association are doing quite a bit of work in preparation for that hearing.

Certain airlines have expressed a desire to proceed with fleet implementation of a collision avoidance system on a voluntary basis. In fact, Piedmont Airlines has already signed a letter of intent to procure collision avoidance system equipment from McDonnell-Douglas, and United Airlines is flying two sets of McDonnell-Douglas equipment in order to obtain maintenance and other associated data. In conformance with the desire of United Airlines, McDonnell-Douglas has petitioned the Federal Communications Commission for an operational frequency license in the provisional U.S. allocated CAS frequency band which is 1592.5 megahertz to 1622.5 megahertz, a total of 30 megahertz. While an experimental license already exists, the operational license will mean that a buyer of CAS equipment of the type specified by the Technical Working Group will be assured of receiving a regular FCC license to radiate and be protected against any harmful radio interference from other systems in accordance with the applicable FCC and Office of Telecommunication policy rules and regulations. The FAA's position on that frequency application is being reviewed.

The most promising systems proposed are cooperative in nature. Therefore, only one system is desired wherein all airplanes carrying collision avoidance equipment work with each other. However, there has been no decision reached in the agency on the matter of picking a system. The FAA does support the voluntary use of the equipment by the airlines, but it is felt that there are too many unanswered questions to predict if, or when, such a system would become a requirement.

Within the FAA, time-frequency is the main directed effort. However, the agency, in conjunction with other government agencies is monitoring other efforts in this field, one being a contract that the Navy has with RCA to test a portion of their collision avoidance system. Action is now underway to develop a time-frequency ground station. The FAA has a contract with Sierra Research Corporation to investigate the possibility of utilizing DME stations, suitably modified, to provide a ground-air synchronization capability. We are also about to request proposals for a more accurate and sophisticated form of ground station which, along with providing the ground-air synchronization function, will provide a performance check of the CAS equipment. Complementing these hardware efforts, the FAA is about to request proposals for a ground station network configuration study which will determine the optimum number, location, and type of ground station required, along with the best implementation priority. If the T/F system is approved, the schedule calls for the installation of the ground network between 1974 and 1978. This reasonably fits with the airline implementation schedule set up previously.

Another effort being made, which will be continued through FY72 is the investigation of techniques for the synchronization of a ground station network with master time. It is felt that the synchronization, at least of the developmental ground station network, will be accomplished by the fly-by technique; that is, synchronization with a standard carried by an aircraft specifically for that purpose. Ultimately, a more efficient method, such as satellite relay will be necessary. In relation to this, the FAA is in the preliminary discussion phase with NASA, Goddard to try to set up a joint program to investigate satellite usage for synchronization. The objective of the experiment is to evaluate a method of disseminating precise time and time interval from a master reference time station to a large number of ground stations. This would be done by time synchronizing the clocks at the ground station, via a communication relay satellite to the clocks at the master station. The operating data obtained from the experiment will be of value in designing the ground facilities for the T/F collision avoidance system, will augment radio astronomical studies, and will add to the data needed for the precise synchronization of national and international clocks. As stated before, the requirement for the time-frequency ground station synchronization network is to maintain time in all ground stations to within $\pm\frac{1}{2}$ microsecond, 3σ, of a master time reference. The rms value then is 167 nanoseconds and, if we permit a 100-nanosecond drift in each ground station between synchronization periods, we are looking for at least 60-nanosecond synchronization accuracy. There is the additional requirement that the synchronization be absolute, rather than relative, timing accuracy. It is hoped that the achievable level of synchronization accuracy will be shown for (1) laboratory conditions, (2) a situation where a satellite transponder with a common transmitter-receiver on the ground is used, and (3) a situation where two widely separated ground stations are used via the satellite transponder. As we said before, this is still in the preliminary discussion phases.

In summary, the FAA hopes to issue an RFP in the immediate future to determine the number, type, location, and implementation priority of the required synchronizing ground stations. An existing contract is for study of the possibility of providing a ground-air synchronization function via suitably modified distance measuring equipment (DME). The results of this study are expected in mid-1972. An RFP will be issued fairly soon for development of a more accurate and sophisticated ground station which will be capable of testing the operation of the airborne CAS equipment. The FAA is participating with other government agencies--the Navy in particular--in the testing and evaluation of the RCA correlator which is the data processing heart of their system.

Just recently an inter-departmental group on collision avoidance and pilot warning has been formed. Members are from the Department of Defense, FAA, and NASA. There has been one meeting which was primarily an introductory meeting. The purpose of the group is to accomplish more work in the collision avoidance area, in technologies other than TF, in an effort to determine the best system, and to make use of other government expertise, facilities, etc.

DISCUSSION

LCDR SEELEY: I wonder just what interface on an international nature might you have had in this area. I understood the French might be doing some work in this area.

MR. BRENNAN: We have heard the same thing. In fact several months ago, a telegram was sent to our representative in France in an attempt to determine exactly what they were doing and in a followup just recently, another telegram was sent, but just what the French are doing, what they're accomplishing, I don't know. However, this subject has been informally discussed in various ICAO conferences and it is an item for discussion at the Seventh ANC Conference in Montreal, which is next spring. So, there has been informal coordination on an international level.

LCDR SEELEY: The second question I had pertains to the candidate systems or references for this master time reference which you mentioned had not yet been chosen.

MR. BRENNAN: No decision has been made and on an informal basis the only two candidates I know of are the Naval Observatory and the National Bureau of Standards. We haven't thought about operational problems involved one way or the other, I think it's a little preliminary at this time in the program to discuss that.

LCDR SEELEY: My final question is in regard to the shift that is coming on January 1, 1972; how that might affect your plans?

MR. BRENNAN: I don't know any of the details but certainly the shift shouldn't affect us, because we have no ground stations to be affected.

MR. WATSON: The ATA specification is set up for A-1 frequency. This is a very good thing, in going to the A-1 frequency and the new UTC specification. Our interfaces are very smooth compared to what it would have been with the offset.

DR. HAFELE: You mentioned a network of coordinated time on the ground for synchronization. Are you thinking of stations every hundred miles on a grid work? How far, throughout the United States, throughout the world? I have some ideas on coordinating time on the ground like that and I wondered what extent you had in mind.

MR. BRENNAN: The RFP that I mentioned, will give the number, location, and implementation priority of ground stations, considering the system characteristics that have been described by the Technical Working Group. These considerations are the power, the time hierarchy system, and the altitude coverage that would be required or that we would want. It will be similar to a grid network, but not exactly located on a square grid or rectangular grid. It would be a function of coverage required and utility to be gained by certain locations; for instance, you will service more aircraft with a ground station at Idlewild than possibly another location. This study, we hope will come up with those answers.

DR. HAFELE: You said that these stations should be synchronized to within one-half millisecond.

MR. BRENNAN: Plus or minus $\frac{1}{2}$ microsecond of a master time. Such master time will be decided upon in the future.

MR. GATTERER: I would like to read again some comments I made in my talk the other day with regard to the Synchronous Meteorological Satellite (SMS), Geostationary Operational Environmental Satellite (GOES) which is a Department of Commerce (DOC) satellite to be operated by NOAA after a launch sometime in early 1973. It is still in the planning stage but we hope to provide one-tenth microsecond timing at 29 hertz.

MR. BRENNAN: While the frequency band for the collision avoidance system developed by the ATA is L band, 1592.5 to 1622.5 megahertz, the subject of synchronizing the ground stations is left open. The proposer that got this contract would analyze this a little further. In other words we're not saying you have to do it on that frequency and we're not saying you can't do it either, this will be one of the things to look into.

MR. FOSQUE: Some time ago, questions were raised regarding the CAS and how it might inter-act with the ordinary control procedures. I understood you to say that the FAA position was to encourage the ATA to implement some sort of system and to try this out. If so, how do you plan to take care of the possible interference with normal control procedures?

MR. BRENNAN: The agency position is that they are for the voluntary use of collision avoidance systems by anybody. However, that depends on the formulation of some rules, guidelines, and regulations, as to how a collision avoidance system would fit into the air traffic system with the least disruptive effect and the most beneficial effect. The simulation that we've been accomplishing at our Atlantic City facility is towards that end. However, as I understand the situation right now, there are still unanswered questions which we hope to answer with followup simulation early next year. Subsequent to that simulation we are hoping the air traffic service will be in a position to state just how a collision avoidance system utilizing range, range rate, altitude information, threat evaluation, and manuever logic of that type can fit into the air traffic system. You are quite right; that is the critical path item right now. On an operational basis, I don't think collision avoidance systems can be implemented until the air traffic service makes the decision.

FIBER OPTIC LINKS FOR PTTI DISSEMINATION

by

J. F. Bryant

Mr. Bryant is with the Naval Electronics Laboratory Center, San Diego, California.

This paper is about the fiber optic development work that has been going on at the Naval Electronics Laboratory Center, particularly an application for PTTI dissemination. I really don't know how old Fiber Optics happens to be, I think the Venetians probably started it in their glass work. I have been told that it is rediscovered every generation, and I think that it's about to be discovered again. One of the advantages of using fiber optic for transmitting data is that it is secure from radiation leakage. This is of benefit not only for secure systems for communications, but also for preventing cross-talk. Being glass, they provide no grounding problems, they are free of RF interference, and they are small and lightweight. To give an idea of the weight reduction, glass is about 150 to 208 pounds per cubic foot compared to copper which is approximately 544 pounds per cubic foot. Fiber optic lines are inexpensive, comparable with coaxial cable in cost, resistant to heat, and have high tensile strength. Of course there is no copper present, except as an impurity, hopefully there is none at all, and there are no ringing problems.

NELC was asked last spring to develop a repeater system that would receive the output from a clock or from an electronic system. The specifications that it was to meet were a one volt high and a one microsecond wide pulse. Also, it was to have as high a frequency response as possible.

Initially, a semiconductor laser system was considered, but there are restrictions in its repetition rate because of some of the components in the driving circuitry and in the laser itself. Various techniques for improving the repetition rate of pulses are being studied at our laboratory at this time. We are using an infrared emitting diode and a silicon detector.

Figure 1 is a diagram showing the mechanism of fiber optics. On the left is a schematic of a single fiber; the core is a high index refraction glass, the cladding material is a lower index refraction glass. The fibers to be used at the present time are commercially available. There are a number of companies in the United States and throughout the world that make fibers; NELC happens to be using Corning Glass Work fibers. The index of refraction of the core is 1.62 and the index of the cladding is 1.47. This gives us a numerical aperture which defines the acceptance angle of the fiber to about .6. On the right is the configuration that one might have in a fiber bundle with a large number of individual fibers and a protective covering. The protective covering that we are using at the present time is a polyvinyl chloride which seems to be able to survive extreme temperatures. At least,I know that it will go to 124° centigrade.

The diameter of the individual fibers that we are using, as shown in Figure 2,is 1.8 mils. More than 200 fibers are used in each bundle but the overall dimension of the fiber bundle is 63 mils.

Figure 3 is a representation of the transmission of the core material. As we said, we are using an infrared emitting diode so the peak radiation is about 9,000 angstroms or 0.9 micron.

Figure 4 is a schematic diagram of a light-emitting diode showing how the radiation is distributed from it. These are typical manufacturer's configurations. In Figure 5, the circuit on the left gives an indication of how one drives a diode. The graph shows the spectral response of the diode as a function of wave length which peaks at 0.9 micron. A typical mounting of a photodiode generator is shown in Figure 6. Figure 7 shows the response

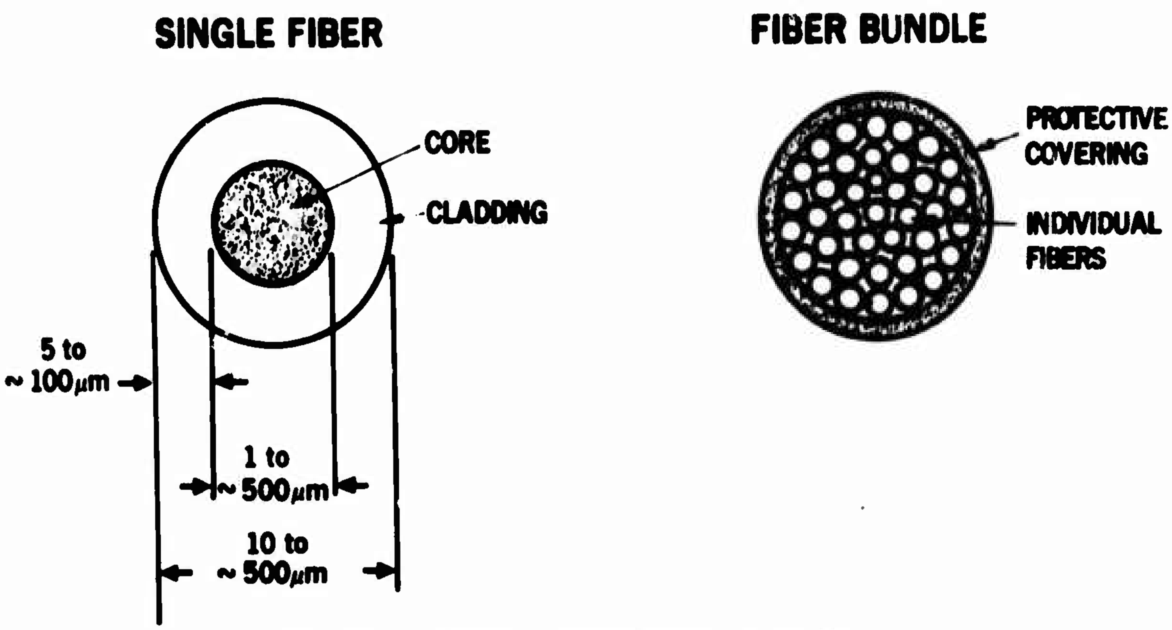

Figure 1. FIBER OPTICS MECHANISM

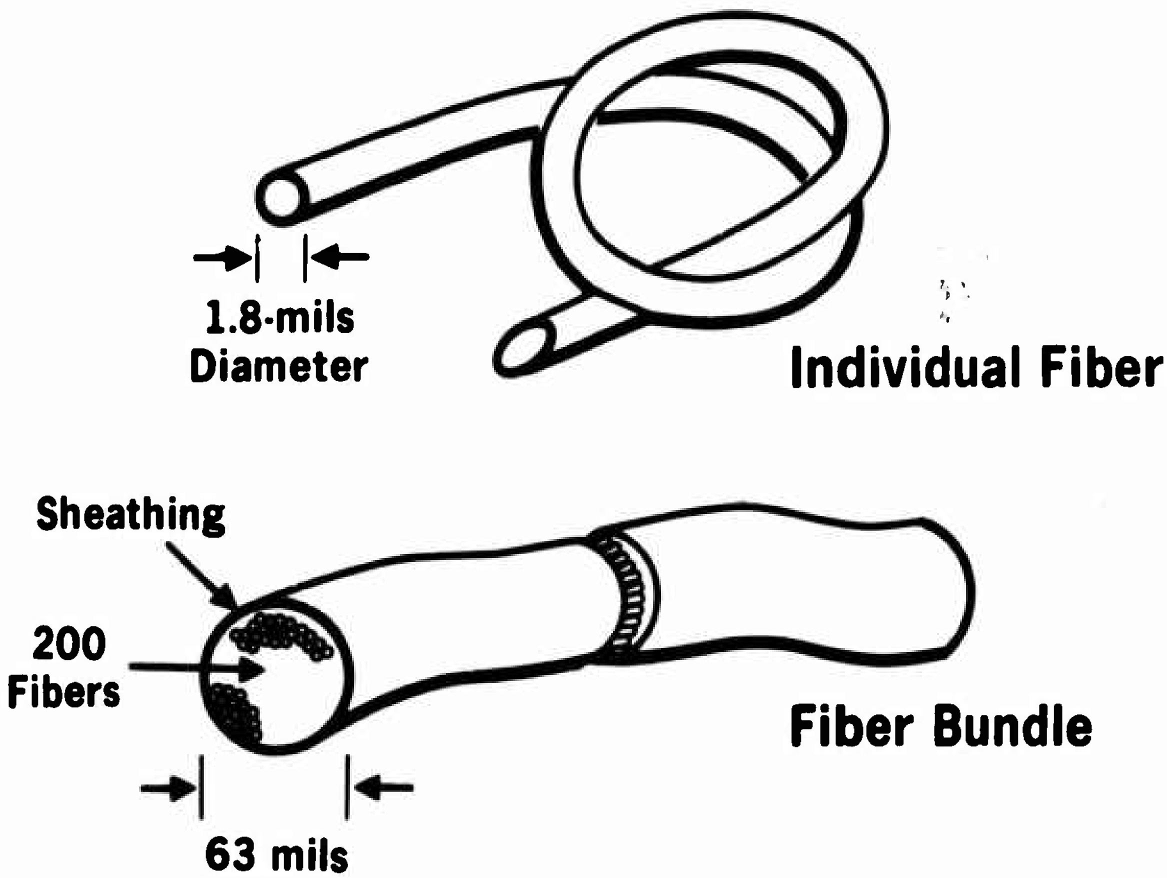

Figure 2. FIBER OPTIC DIMENSIONS

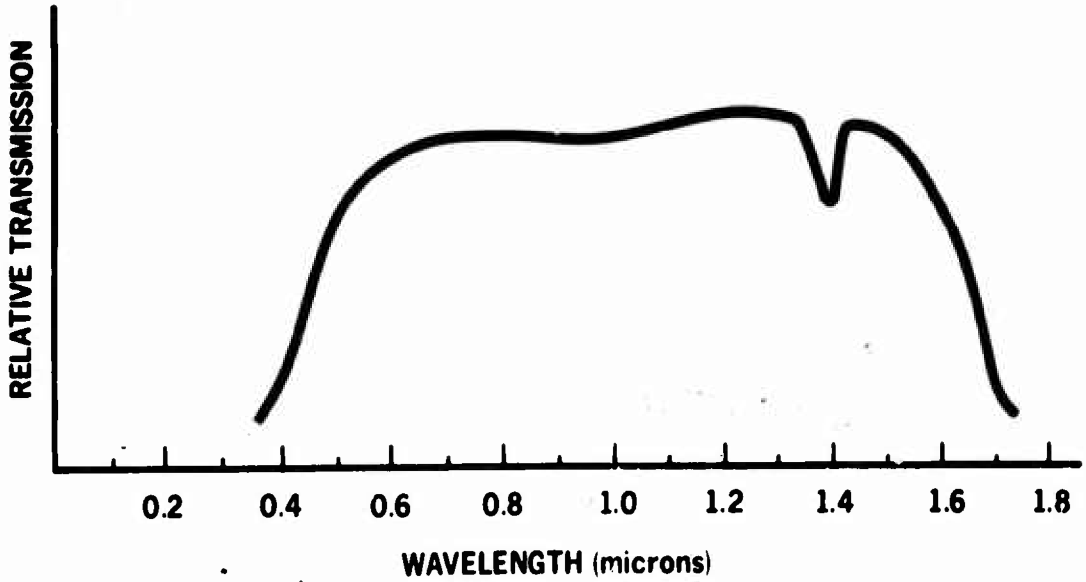

Figure 3. TRANSMISSION OF CORE MATERIAL

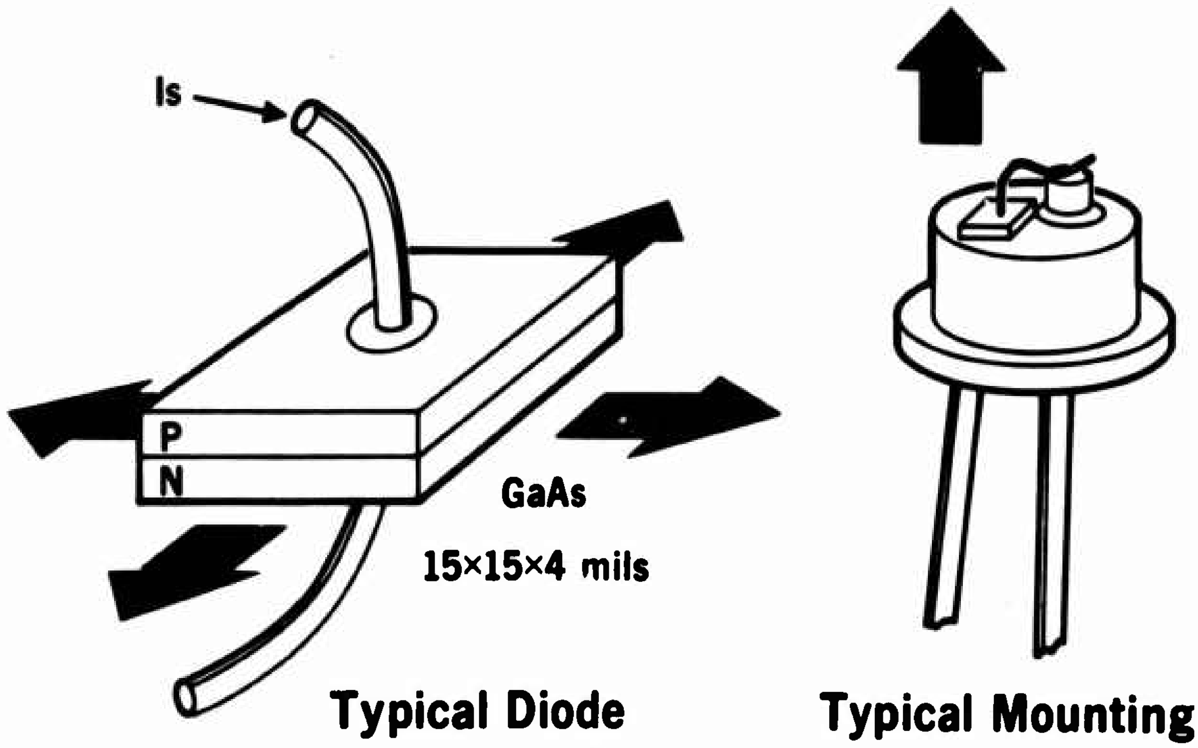

Figure 4. LIGHT-EMITTING DIODE

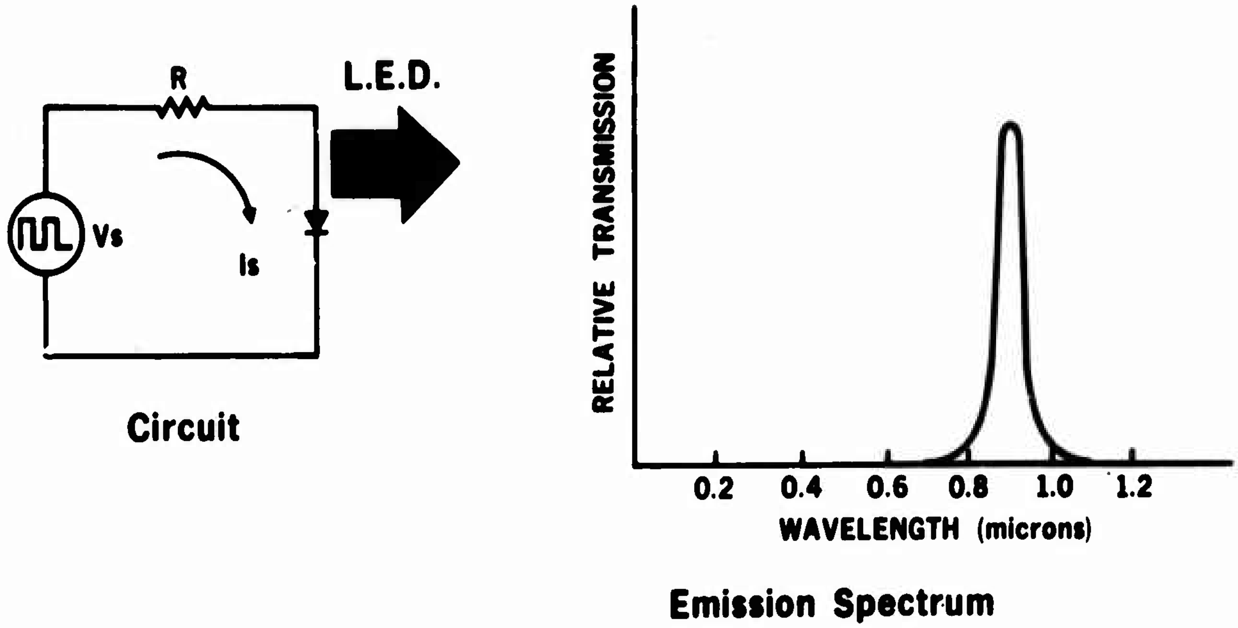

Figure 5. LIGHT-EMITTING DIODE (LED)

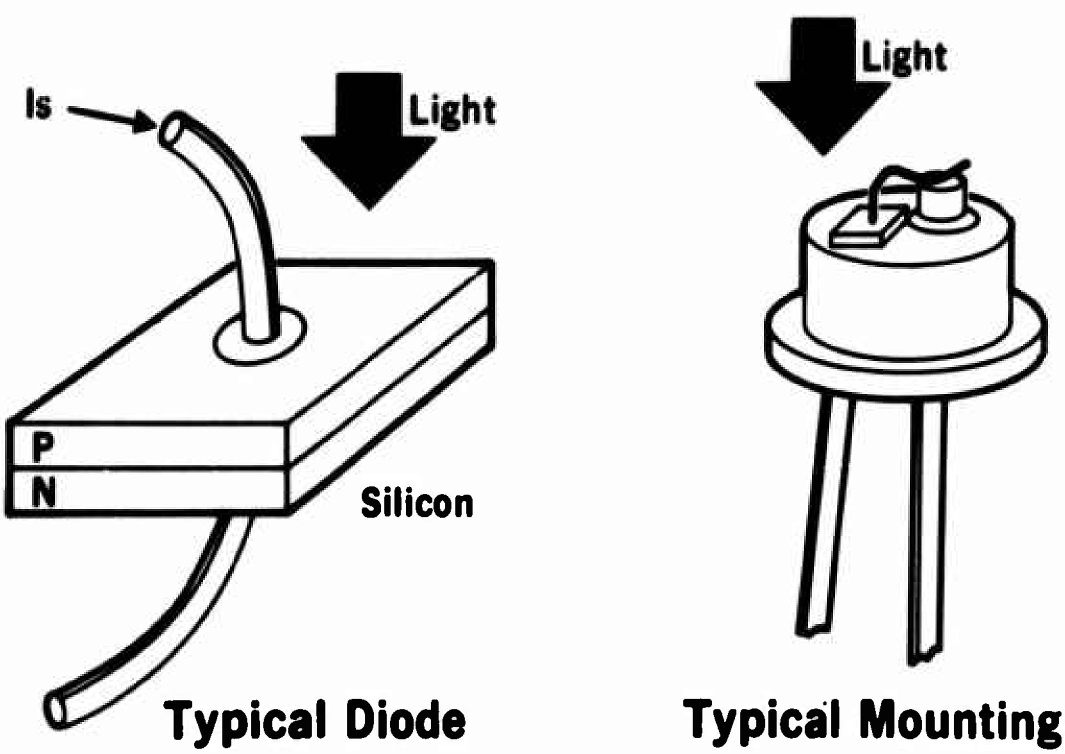

Figure 6. PHOTODIODE GENERATOR

curve of the photo detector that we are using: a silicone photo diode which peaks at the wave length of the light-emitting diode being used.

Figure 8 is a schematic representation of the system that we have developed, which is a repeating system. An input is received, fed into the driver amplifier to excite the diode, and transmitted to some remote point through the fiber optic bundle. It is then detected by a photo detector and the pulse is reconstructed. The small PC board with the BNC connector, on the left in Figure 9, is the emitting diode section. Reading left to right we have the photo detector and the associated amplifiers, the trigger circuitry, and the pulse shaping circuitry. Figure 10 shows an experimental device; the power supply is in the base and the emitting diode is in the little box on top. The receiver, which has its own power supply, is shown in Figure 11. The circuitry is in the receiver with the power supply underneath. The power supply can be detached and, with a short cable, can be placed wherever you might like to have it.

Figure 12 shows the configuration we used with the transmitter on the left connected by the fiber optic bundle to the receiver on the right. One of the characteristics of this system is that our signal-to-noise ratio prior to entering our Schmitt trigger circuitry is 14.6 db. The radiation power out of the light-emitting diode is 3.5 microwatts and we are detecting .119 microwatts at the detector. There is a 15 db loss in the fiber optics. The measured jitter at 10 kilohertz with a 10 kilohertz with a 1 microsecond pulse is approximately 6 nanoseconds. The power consumption is 88 milliamps at 12 volts DC which is 1.03 watts. The transmitter is consuming 150 milliwatts; we have a total line power of approximately 1 watt. This system has a propagation delay time of approximately 200 nanoseconds. I would like to call your attention to a report by Dr. Taylor from our laboratory on transfer of information on Naval vessels via fiber optic transmission lines. This is available on request from the Laboratory.

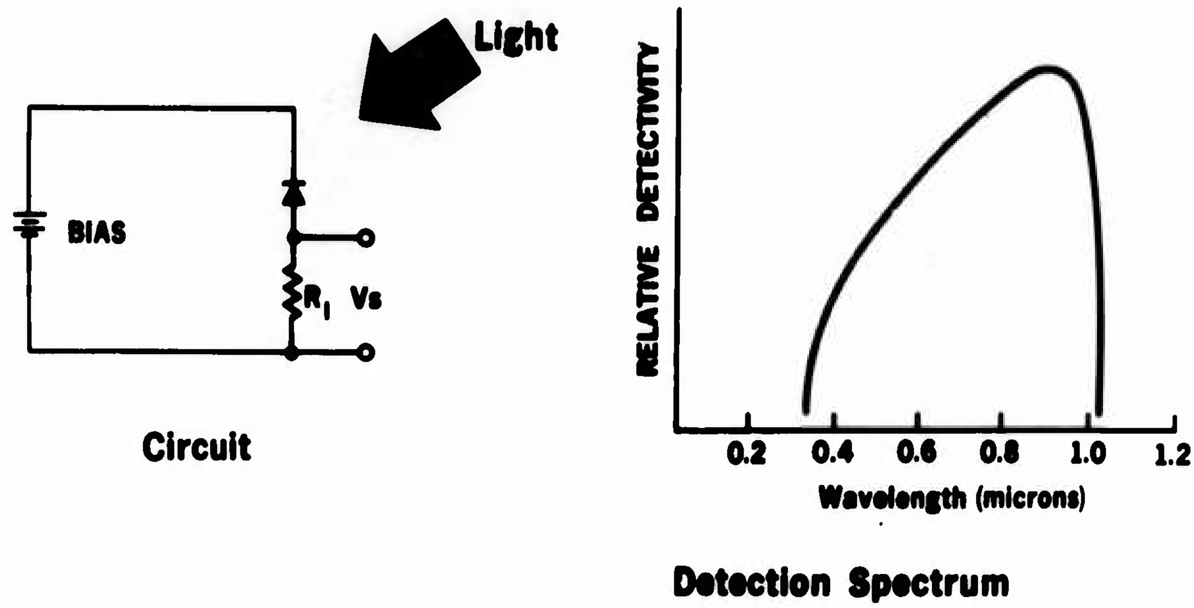

Figure 7. PHOTODIODE

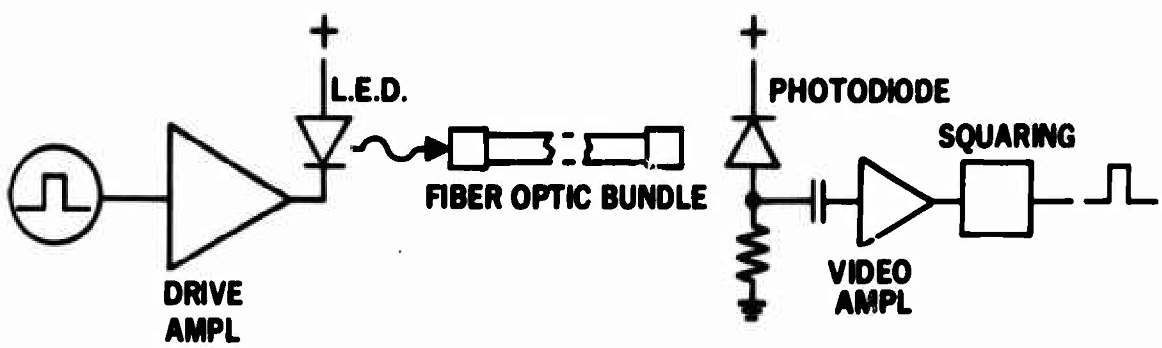

Figure 8. SCHEMATIC DIAGRAM OF A TYPICAL SYSTEM

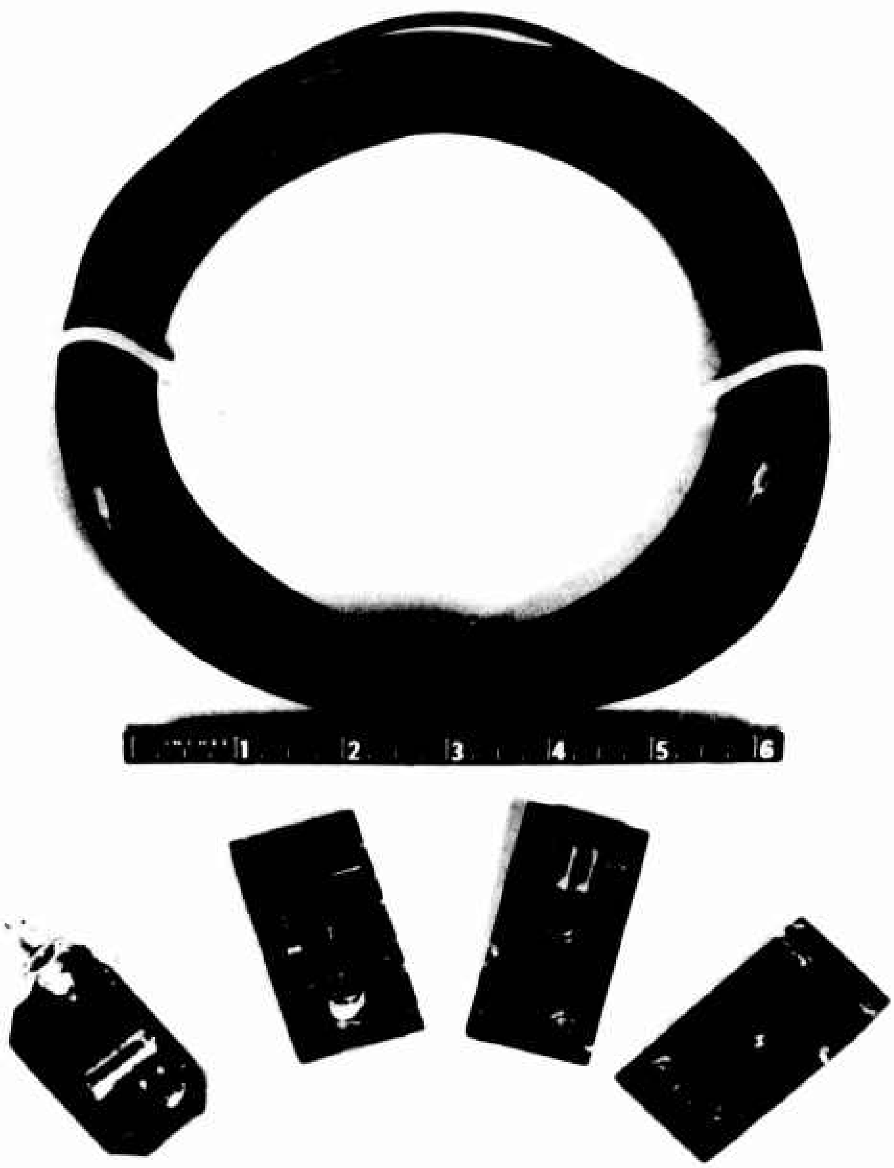

Figure 9. EMITTING DIODES

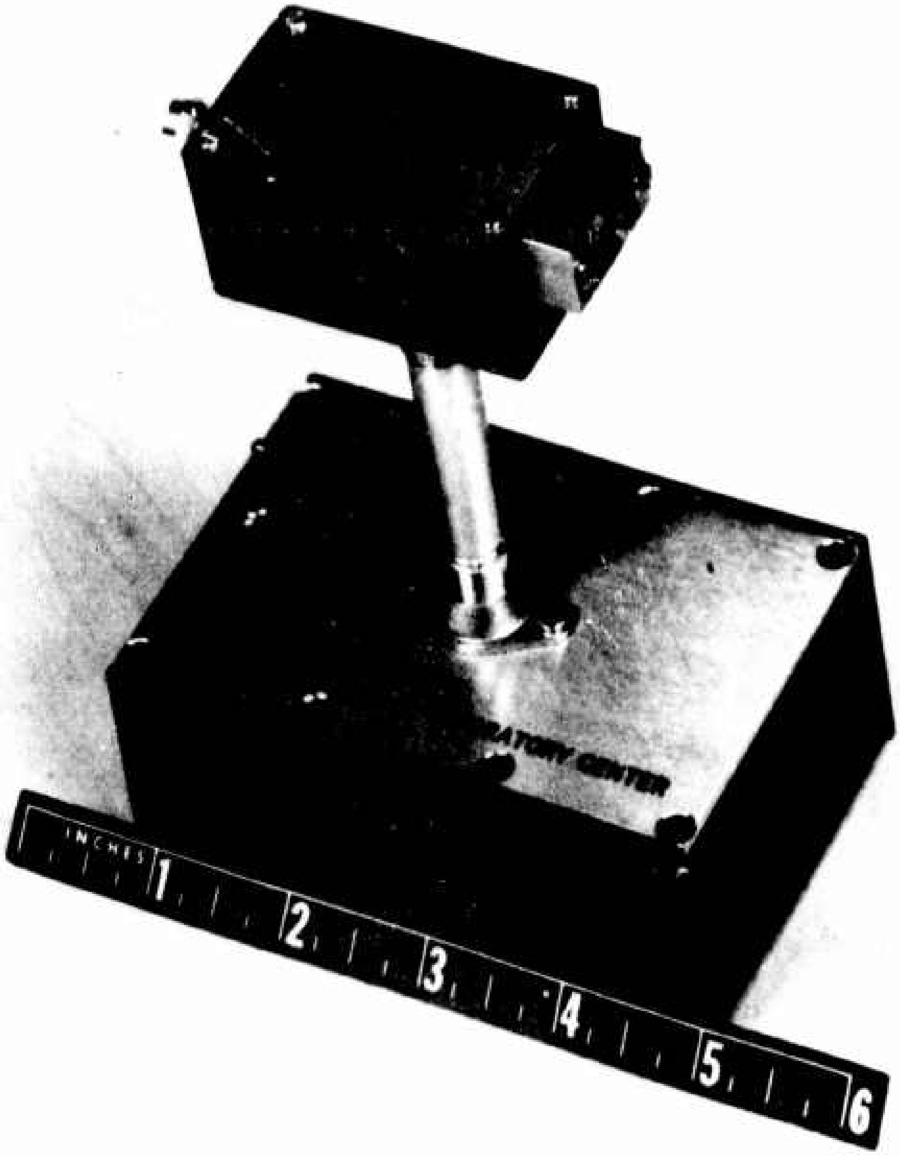

Figure 10. [illegible]

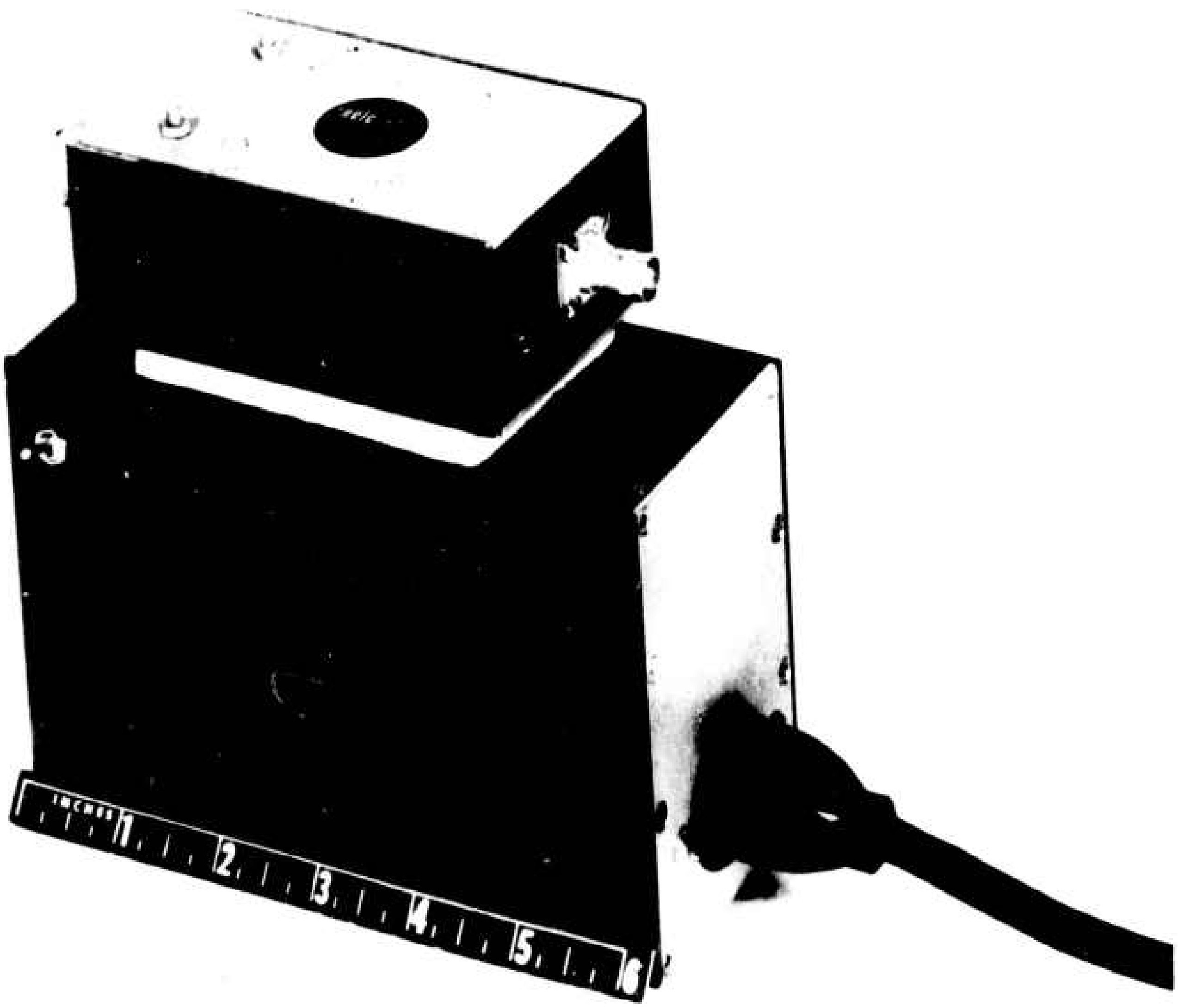

Figure 11. RECEIVER WITH POWER SUPPLY

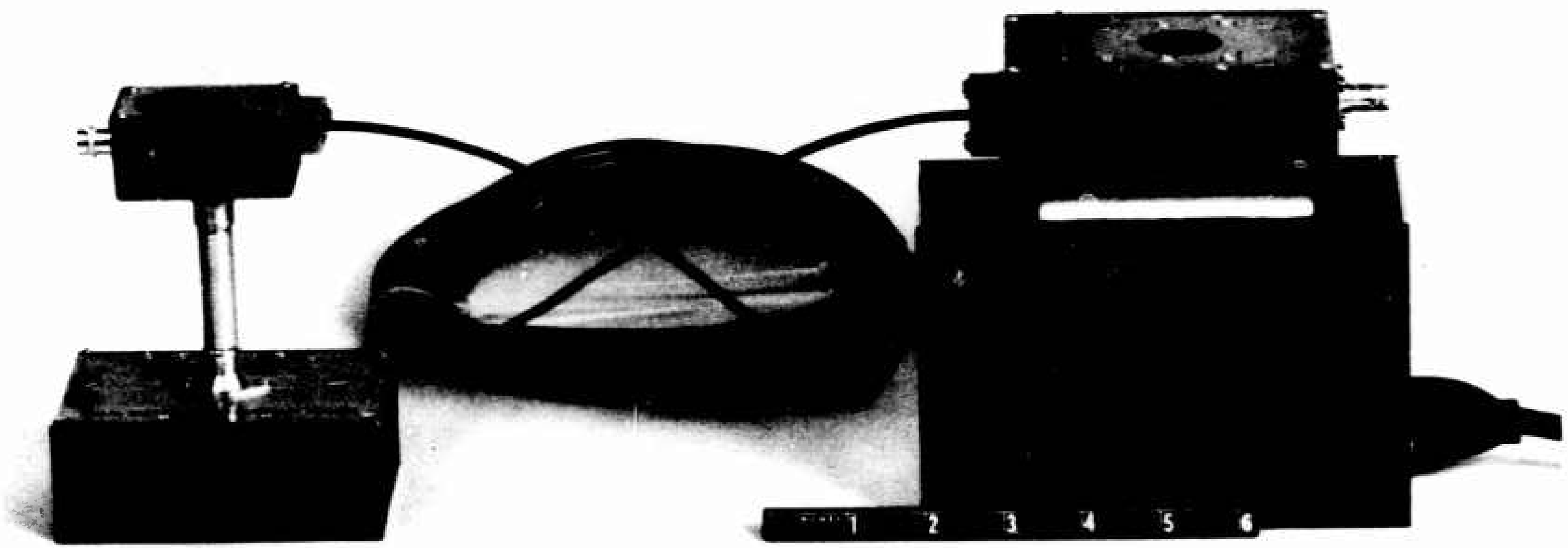

Figure 12. FIBER OPTIC CONFIGURATION

DISCUSSION

MR. FOLTS: At the Defense Communications Engineering Office we are very interested in some of these techniques both for digital transmission and, perhaps, timing transmission. What is the general modulation frequency response over length of transmission and so on?

MR. BRYANT: Do you mean the modulation transfer function? For instance, if I were transmitting data through this. would I be able to run several miles with this at some fairly high speeds, or what? Well, at the present time, the commercially available fibers have a very high attenuation loss of approximately 1 db/ft. We are expecting delivery, within the next two months, of some specially developed fibers that have 0.1 db/ft. Next year we're hoping to have fibers that have about 0.01 db/ft so they are a little bit lossy. The loss mechanisms that are involved are absorption in the fiber optic bundle itself and also Fresnel reflection. These are very thin glass fibers, so there is some breakage. We have not as yet established specifications as to the number of broken fibers per bundle, but these are things that are to be worked on. Right now the losses are high due to coupling losses, Fresnel reflection, the packing density of the fibers in the bundle, and the number of broken fibers. I should point out that these are incoherent fibers, in that there is no correlation from one end to the other as to their spacial orientation. If you wish to use them for transmitting visual information, greater care must be taken in putting them together.

MR. FOLTS: You use a bundle as a single circuit rather than using individual fibers in a bundle for separate circuits.

MR. BRYANT: Yes, hopefully each fiber is carrying the same information and, ideally, there would be no broken fibers.

MR. PITSENBERGER: We've looked, in the past, at laser-initiated ordnance systems and this might be a variation if the power could be raised. Could you send a joule in a microsecond or a millisecond? What would be your limit?

MR. BRYANT: I'm not sure whether a joule, incident on the end of the fiber, is going to do any damage or not. It might do some pitting, it might not.

DR. HAFNER: You mentioned 200 nanoseconds delay. Is this exclusive of the propagation time through the cable or is this just your trigger and receiving circuit?

MR. BRYANT: That is the total time from the transmitter, through the fiber bundle, and through the receiver.

DR. HAFNER: What is the rise time of your pulses? How much degradation do you get?

MR. BRYANT: The rise time on the pulses from the LED is less than 10 nanoseconds.

REAL TIME SYNCHRONIZATION VIA PASSIVE TELEVISION TRANSMISSION

Jean D. Lavanceau and Diane Carroll

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REAL TIME SYNCHRONIZATION VIA PASSIVE TELEVISION TRANSMISSION

by

Jean D. Lavanceau and Diane Carroll

Mr. Lavanceau and Mrs. Carroll are with the Time Service Division, U.S. Naval Observatory, Washington, D.C.

1.0 ABSTRACT/INTRODUCTION

A method to utilize television transmission in a passive mode for the real time synchronization of clocks has been developed and is presented herewith.

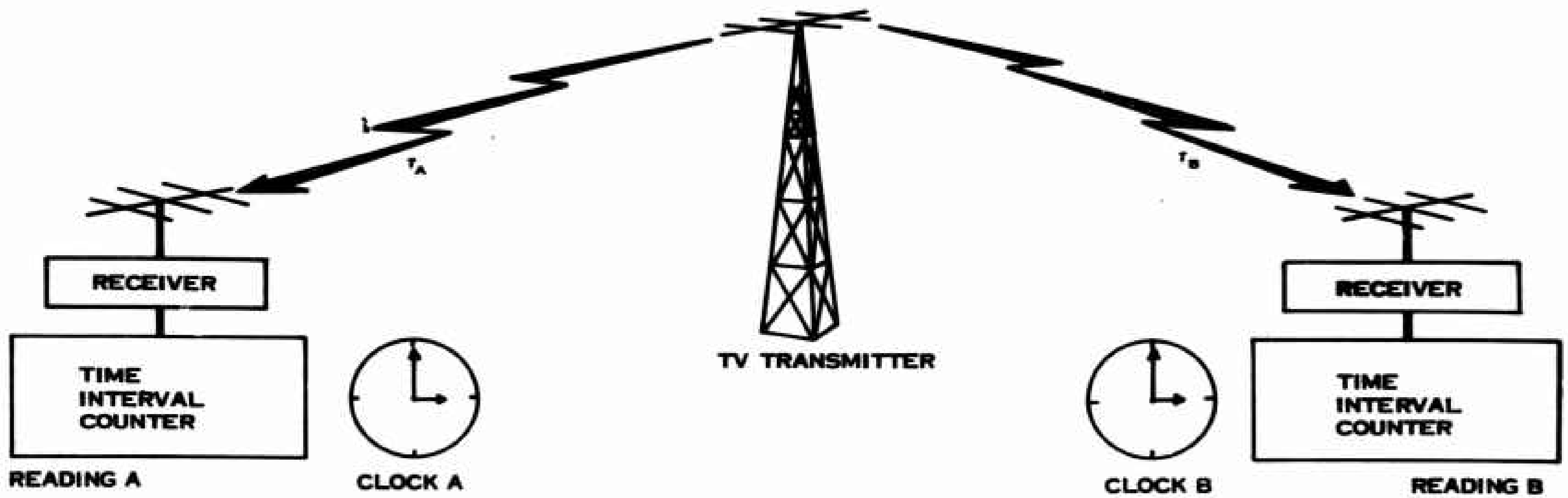
A demonstration is currently being conducted in Washington, D.C. to show that the time of day referenced to the U.S. Naval Observatory (USNO) Master Clock (MC) can be derived independently by timing stations monitoring the transmission from the local TV station WTTG (Channel 5). The accuracy and precision that can be achieved with this method is in the submicrosecond region.

2.0 BACKGROUND

2.1 Passive System for Differential Time Transfer

A passive method using television transmission for precise clock time comparisons was first conceived and demonstrated in Europe by an experiment conducted in November 1965.[1] Since then, this method

[1] Tolman, J., V. Ptacek, A. Soucek, and R. Stecher, (1967), "Microsecond Clock Comparison by Means of TV Synchronizing Pulses," IEEE Transactions on Instrumentation and Measurement, Volume IM-16, No.3, September 1967, pp. 247-254.



$$\left[\text{CLOCK A} - \text{CLOCK B}\right] = \left[\text{READING A} - \text{READING B}\right] - \left[\tau_A - \tau_B\right]$$

NOTE READING A AND READING B ARE THE TIMES OF ARRIVAL OF THE SAME RECEIVED VIDEO PORTION (LINE) READ SIMULTANEOUSLY AGAINST THE RESPECTIVE CLOCKS.

Figure 1. "PASSIVE" SYSTEM FOR DIFFERENTIAL TIME TRANSFER (EUROPEAN SYSTEM)

has been widely used in some European countries and with some success in the U.S.A. to monitor time differences between clocks located in various laboratories.[2,3,4]

The method consists of recognizing and identifying a portion of a video transmission as a time marker (line 10 is used in the U.S.) and of measuring its time of arrival simultaneously at remote locations using precise clocks. Successive differential measurements against the participating clocks will give a measure of the time divergence of the clocks.

The fact that the circuit and propagation delays have submicrosecond stability and that the TV time marker can be defined with nanosecond resolution permits relative time transfer measurements to be made with submicrosecond precision.

In this passive system, relative time transfers can be made provided that:

- Readings are taken simultaneously.
- Readings are exchanged after the fact between monitoring clocks.

2.2 Active System for Real Time Transfer

Another approach for precise time transfer via television transmissions was demonstrated in 1970 by the U.S. National Bureau of Standards.[5] This method consisted of actually transmitting time information

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[2] Parcelier, P., (1969), "Developpement des synchronisations de temps par la television," Proceedings Internat. Conf. Chrommetry (Paris), Series A-26, 16-20 September 1969, pp. 1-6.

[3] Parcelier, P. (1970), "Time Synchronization by Television," 1970 Conference on Precision Electromagnetic Measurement, IEEE Transactions on Instrumentation and Measurement, Volume IM-19, No. 4, November 1970, pp. 233-238.

[4] Davis, D.D., Bryon E. Blair, and James F. Barnaba, (1971), "Long-Term Continental U.S. Timing System via Television Networks," IEEE Spectrum, August 1971, pp. 41-52.

[5] Koide, F.K. and E.J. Vignone, (1971), "TV Time Synchronization in the Western U.S.," EID-Electronic Instrumentation, October 1971, pp. 26-31.

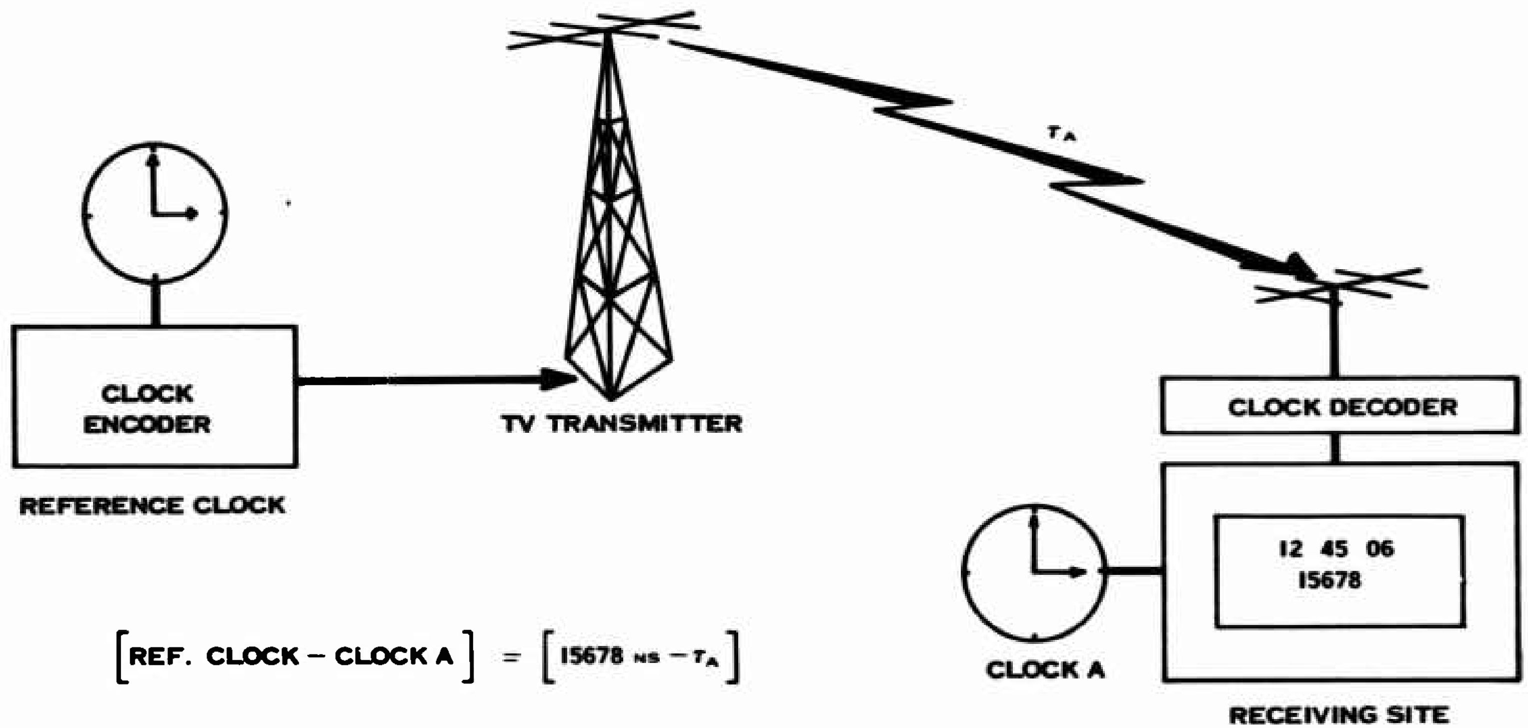

Figure 2. "ACTIVE" SYSTEM FOR REAL TIME TRANSFER (NBS LINE 16 AND 1 SYSTEM)

via the television media. For that purpose, a precise clock and clock encoder were located at the TV transmitter and clock decoders and television receivers were placed at remote locations where precise time transfers were to be made.

In this active system, real time transfers can be made provided that:

- Clock and clock encoder are available at the TV transmitter.
- Clock decoders are placed at time monitoring sites.
- Actual time transmissions are secured.
  - A "portion" of the video transmission must be available for insertion of the time information.
  - FCC authorization is required.

3.0 DESCRIPTION OF THE REAL TIME SYNCHRONIZATION TRANSFER METHOD

A passive method for real time transfer via television transmissions has been conceived and proposed by the USNO. This method can be used to set clocks at remote locations, independently, and in an absolute sense, to within a few nanoseconds of a reference clock.

The technique consists of time positioning the video transmissions from a TV station such that certain television horizontal pulses are transmitted in synchronization with particular seconds of a UTC scale referenced to the U.S. Naval Observatory Master Clock.

By stabilizing the 3.579545 megahertz TV color subcarrier frequency of a TV transmitter and by phase shifting it, it is possible to synchronize the TV transmissions by forcing a coincidence between an emitted horizontal line (line 10 odd was selected as a reference time marker to keep it compatible with existing receiving equipment) and a one-second pulse from a reference clock (the USNO MC itself was selected for this purpose). This subcarrier frequency is also used to maintain proper timing of the horizontal and vertical pulses.

Because of the unique TV frame repetition rate, this coincidence for the U.S. television system (33.36666666...ms), will occur every 1001 seconds exactly ($16^M\ 41^S$). By establishing an arbitrary time of coincidence, it is possible to calculate the dates (times) at which subsequent coincidences will occur between one pulse per second time marks from the USNO Master Clock and the emitted odd horizontal line 10. Such times of coincidence have been computed by assuming an initial coincidence at 0000 UT 1 January 1958 and are given for the second half of the year 1971 in the appendix as "Time of Coincidence (TOC) Ephemeris Reference Tables for Television Transmissions Synchronized to the USNO Master Clock." These tables have the same format as those presently used for Loran-C. Table 1* gives the first TV line 10 odd TOC for each day in hours, minutes, and seconds. Table 2 gives all relative TOC's in a day -- in hours, minutes, and seconds. By adding the relative TOC's (Table 2) to the first TOC of any day (Table 1), one obtains the absolute TOC's for that day. Table 3 gives the time differences for every second of the time interval between the relative TOC's of Table 2 (1001 seconds) and the subsequent TV odd line 10 pulse.

A clock located near a local television stations, whose transmissions are disciplined to the USNO Master Clock, can be set to or accurately measured against the reference clock by using the TOC tables. The procedure involved is similar to the one used for the synchronization of clocks via the Loran-C system.

- A knowledge of the geographical location of the clock relative to the TV transmitting antenna is necessary in order to compute the propagation time delay. This delay can also be determined initially by transport of clocks.

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* Tables 1, 2 and 3 are located in the appendix.

- The clock time must be set or known to within 16 milliseconds (half of the TV frame period). This can be done by using the HF standard time signal transmissions from CHU, WWV, NSS, etc.

Using the receiving system shown in Figure 3, the procedure listed below should be followed:

1. Take a series of measurements during a synchronized period of TV transmissions, recording:
   (a) The time differences between the one-second pulse from the local clock and the received horizontal line 10 odd pulse (output of the line 10 pulse discriminator).
   (b) The dates (times) at which those readings are taken.
2. Using the TOC tables (see appendix), reduce the data as shown in the example below:

   Example: Let the local clock be a clock (Clock A) located at a monitoring station A. Suppose measurements are taken on 21 October 1971.

   (a) From the measurements: (e.g., as printed by a line printer)

Hr.	Min.	Sec.	μs
16	51	17	9121.25
16	51	16	8121.24
16	51	15	7121.26
16	51	14	6121.25
16	51	13	5121.25

   (b) From the TOC Tables:

From Table 1		0^H	11^M	48^S
From Table 2	+	16^H	24^M	19^S
Time of last coincidence:		16^H	36^M	7^S

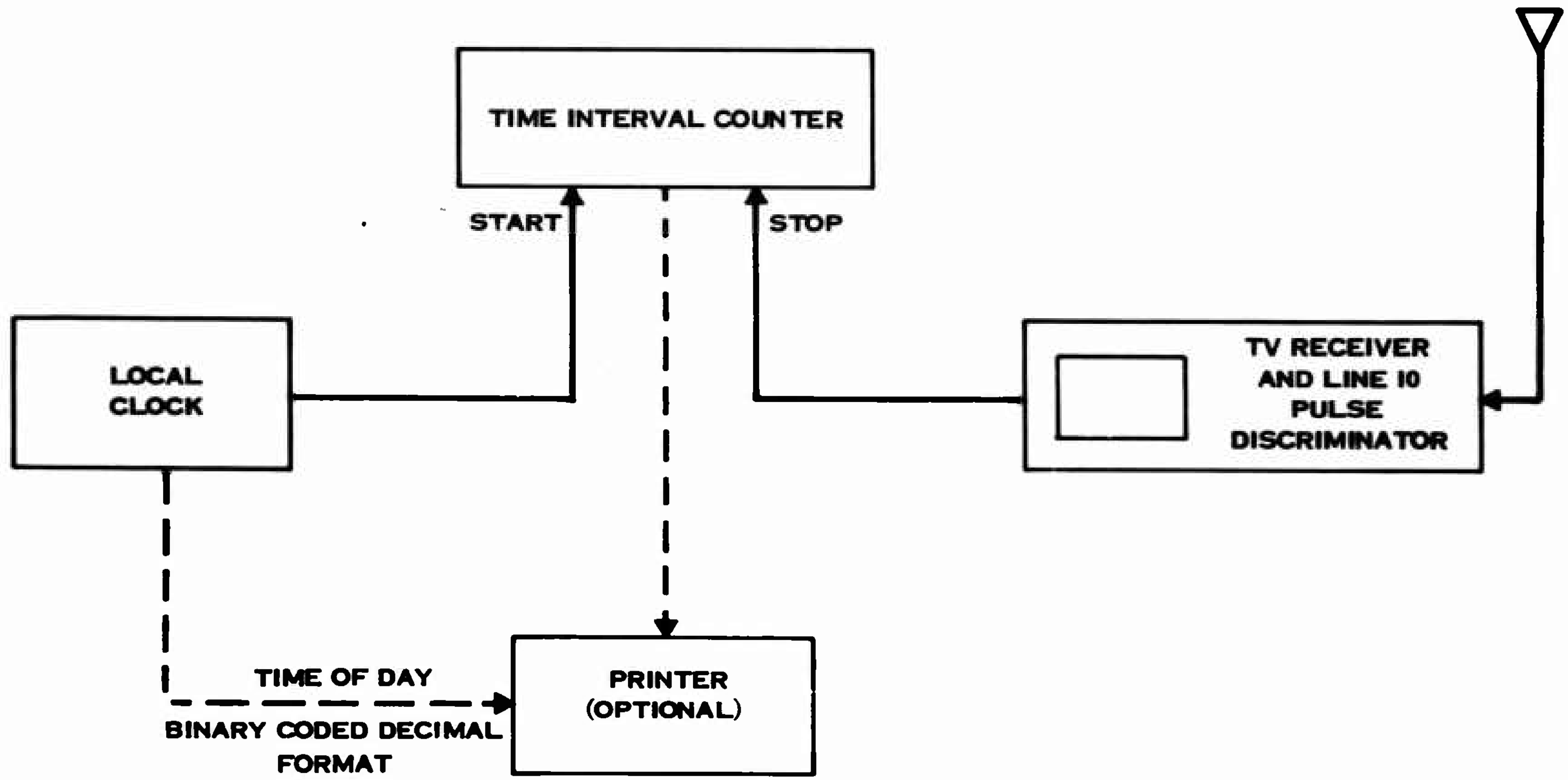

Figure 3. RECEIVING SYSTEM FOR TV TIME TRANSFER

Selecting arbitrarily the measurement taken at $16^H\ 51^M\ 14^S$, one calculates the time which has elapsed between that measurement and the last coincidence:

$$\begin{array}{rrrr} & 16^H & 51^M & 14^S \\ - & \underline{16^H} & \underline{36^M} & \underline{7^S} \\ & & 15^M & 7^S \end{array}$$

(c) From Table 3 one finds that $15^M\ 7^S$ corresponds to 6,100.000 μs.

This means that the first horizontal line 10 odd pulse following $16^H\ 51^M\ 14^S$ was transmitted on 21 October 1971 at $16^H\ 51^M\ 14^S.006100000$, (or 6,100.000 μs after the 14th second). That very same horizontal line was received at $16^H\ 51^M\ 14^S.00612125$ (or 6,121.25 μs after the 14th second).

Assume that the propagation time for the path between the transmitting antenna of the TV station and the TV receiving antenna at the Monitoring Station A is 18.00 μs. One finds, by subtraction, that Clock A was in error with respect to the TV transmissions by:

(6121.25 μs - 18.00 μs) - 6100.00 μs = 3.25 μs.

This can be expressed as follows:

At 1651 UT 21 October 1971, UTC (Clock A) - UTC (TV) = 3.25 s.

4.0 EXPERIMENT

On 23 September 1971, the U.S. Naval Observatory installed an instrumentation systems, which was conceived and assembled at the Observatory, in the master TV control room of the local Metromedia station WTTG (Channel 5). A cesium portable clock set to the USNO Master Clock was carried to the TV studio at this time.

This system was set up as shown in Figure 4. All instruments were connected to a 24-hour service power source. The digital clock was synchronized to the USNO MC via the cesium portable clock. The 3.579545 megahertz frequency output of the synthesizer was phase shifted so that the time difference between the 1 pps from the digital clock and the emitted horizontal line 10 odd pulse output of the TV discriminator agreed with the values listed in the TV TOC tables (see appendix).

The video transmissions, thus synchronized at the TV studio by using the TOC tables, were checked at the U.S. Naval Observatory by measuring the time of arrival of the same horizontal line. No attempt was made at that time to accurately set the video emissions from WTTG to the U.S. Naval Observatory Master Clock. This could have been done by applying necessary corrections for all instrumentation delays.

The daily time differences between the USNO Master Clock and the WTTG emitted horizontal line 10 (odd frame) are listed in Table I and plotted in Figure 5. Some daily measurements were made during live transmissions and others during film transmissions. Transmitter delays were measured to vary by about 0.5 microsecond when programs were switched between those two sources. This and the fact that daily measurements recorded were not from averaged readings, accounts for the large variations shown on the graph (Figure 5). Precautions can easily be taken during measurements to prevent this from happening. The path delay at the transmitter, between the oscillator and the transmitting antenna will be kept constant by using the automatic line of instrumentation proposed below.

Note: The oscillator was free running during the period of the experiment. No corrections were applied to the phase of the 3.57945 megahertz synthesized frequency nor were any corrections applied to the frequency or the phase of the oscillator.

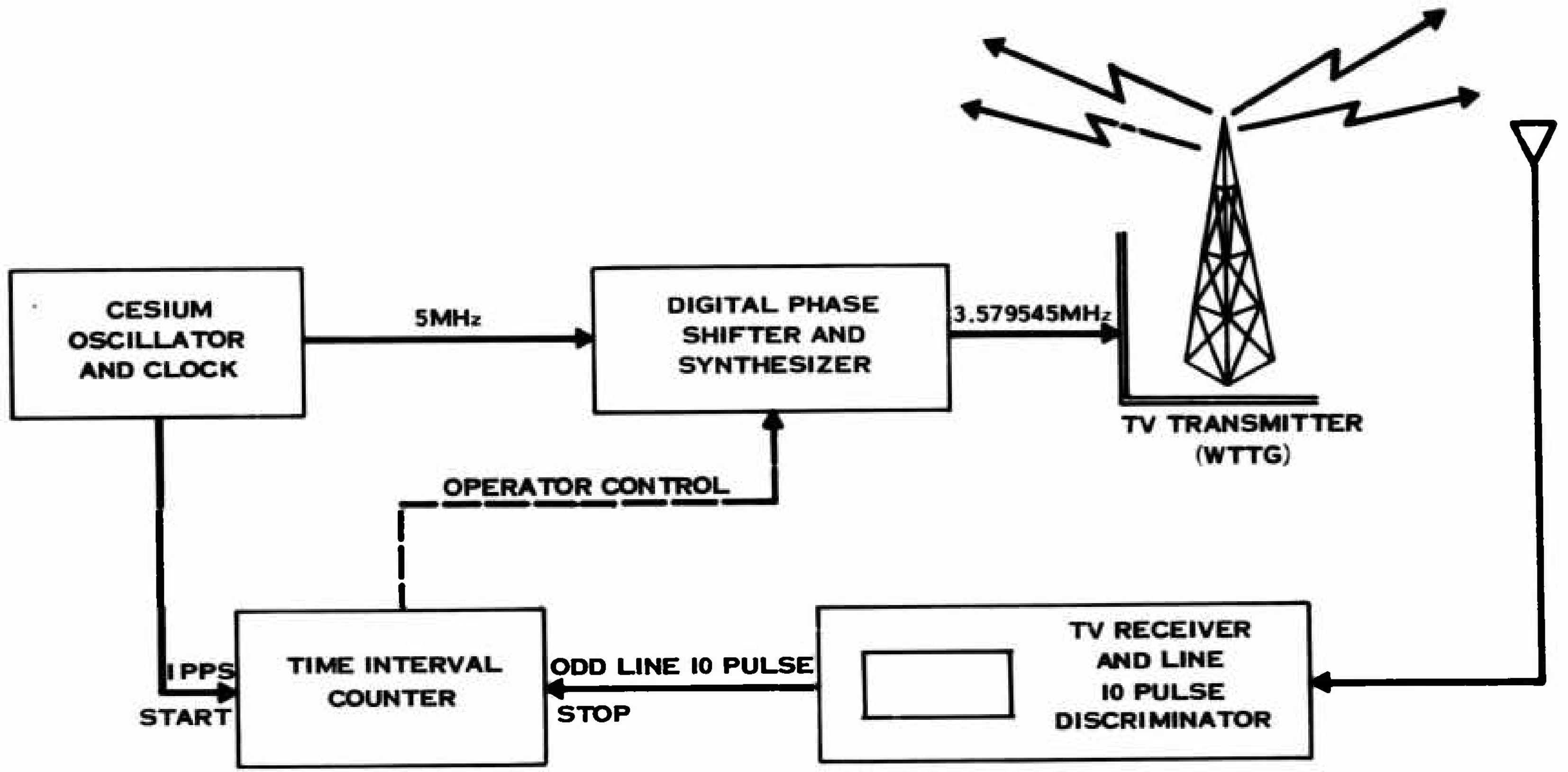

Figure 4. EQUIPMENT INSTALLED AT THE TV TRANSMITTER FOR THE EXPERIMENT

Table I. DAILY TIME DIFFERENCES
UTC (USNO MC) - UTC (WTTG)*

DATE 1971		UTC (USNO MC) - UTC (WTTG)*
SEPTEMBER	28	3.22 μs
	29	3.15
	30	3.18
OCTOBER	1	3.18
	2	
	3	
	4	3.80
	5	3.65
	6	3.24
	7	3.60
	8	3.13
	9	
	10	
	11	
	12	3.00
	13	2.86
	14	2.80
	15	2.82
	16	
	17	
	18	2.86
	19	2.84
	20	2.72
	21	2.71
	22	2.71
	23	
	24	
	25	
	26	2.69
	27	2.63
	28	2.10
	29	2.56
	30	
	31	
NOVEMBER	1	2.73
	2	2.63
	3	2.49
	4	2.48
	5	2.24
	6	
	7	

* UTC (WTTG) is the emitted odd horizontal line 10 of phase controlled transmissions from WTTG.

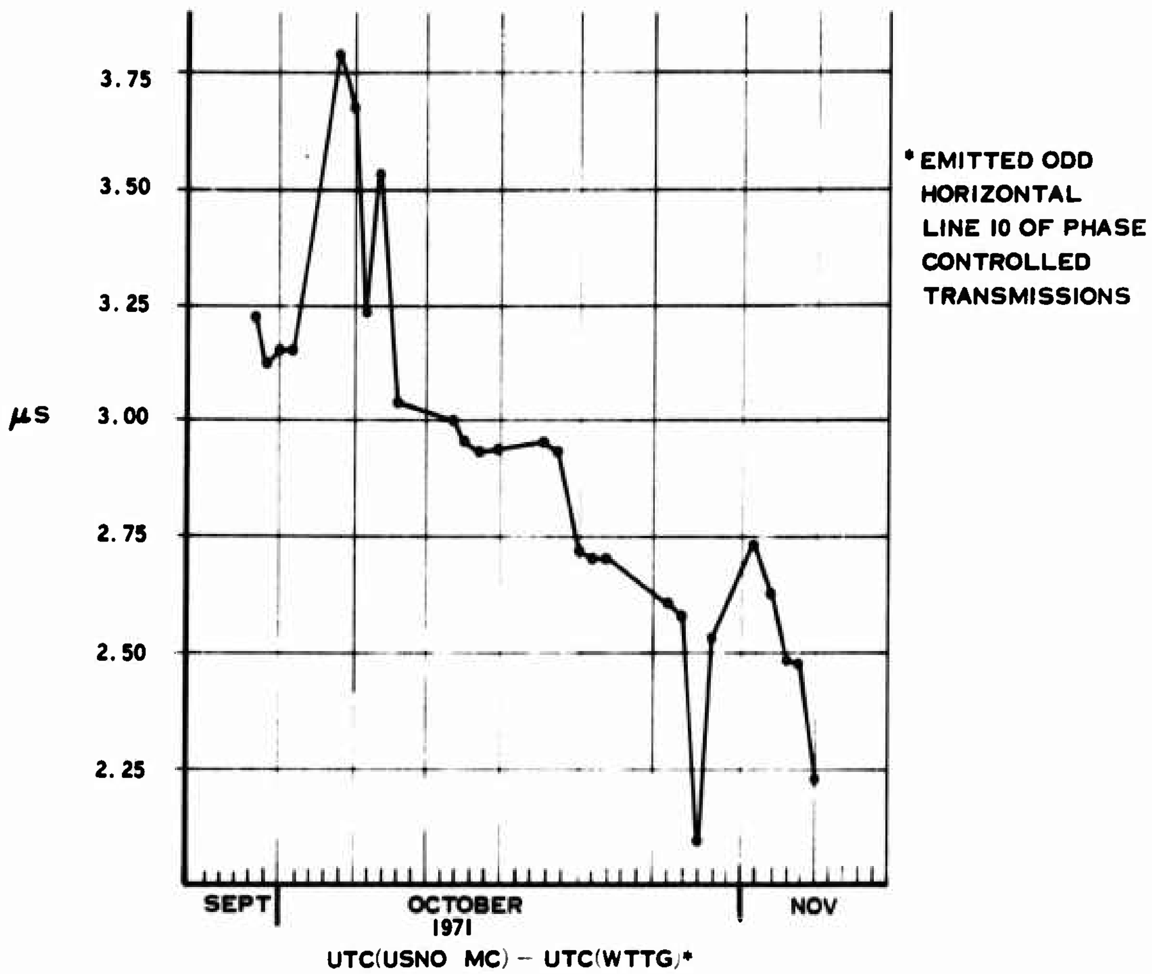

Figure 5. EMITTED ODD HORIZONTAL LINE 10 OF PHASE-CONTROLLED TRANSMISSIONS FROM WTTG VERSUS THE U.S. NAVAL OBSERVATORY MASTER CLOCK

5.0 EQUIPMENT USED FOR THE EXPERIMENT

5.1 TV Transmitter (WTTG)

The equipment installed by the USNO in the WTTG TV control room consists of a cesium oscillator and digital clock, a digital phase shifter and TV subcarrier frequency synthesizer, a time interval counter, and a TV receiver and line 10 pulse discriminator (see Figure 6).

The five megahertz output of the cesium oscillator is connected to the input of the synthesizer and digital phase shifter unit which generates the 3.579545 megahertz color subcarrier frequency for the TV transmitter. The TV receiver and line 10 pulse discriminator monitor the TV transmissions and generate a pulse every odd horizontal line 10 transmitted. This pulse is compared every second to the output of the clock on the time interval counter.

A completely automatic line of instrumentation could be developed for use at the TV transmitter. Presently, by using the system installed by the USNO, approximately 50 percent of all transmissions from WTTG are phase-controlled, such that the video is transmitted on time with respect to the USNO MC by positioning line 10 as explained above. That percentage could be increased substantially, however, by installing in the TV studio a phase shifter which could automatically correct the phase of the subcarrier frequency when video transmissions step away from the synchronized position. Certain sources of programs will generate this condition. A prototype for an automatic phase detector, phase shifter, and video positioner is presently being developed and should be evaluated in the next few months.

5.2 Monitoring Site (U.S. Naval Observatory)

The instrumentation system at the USNO consists of a TV receiver and line 10 pulse discriminator, a time interval counter, and a

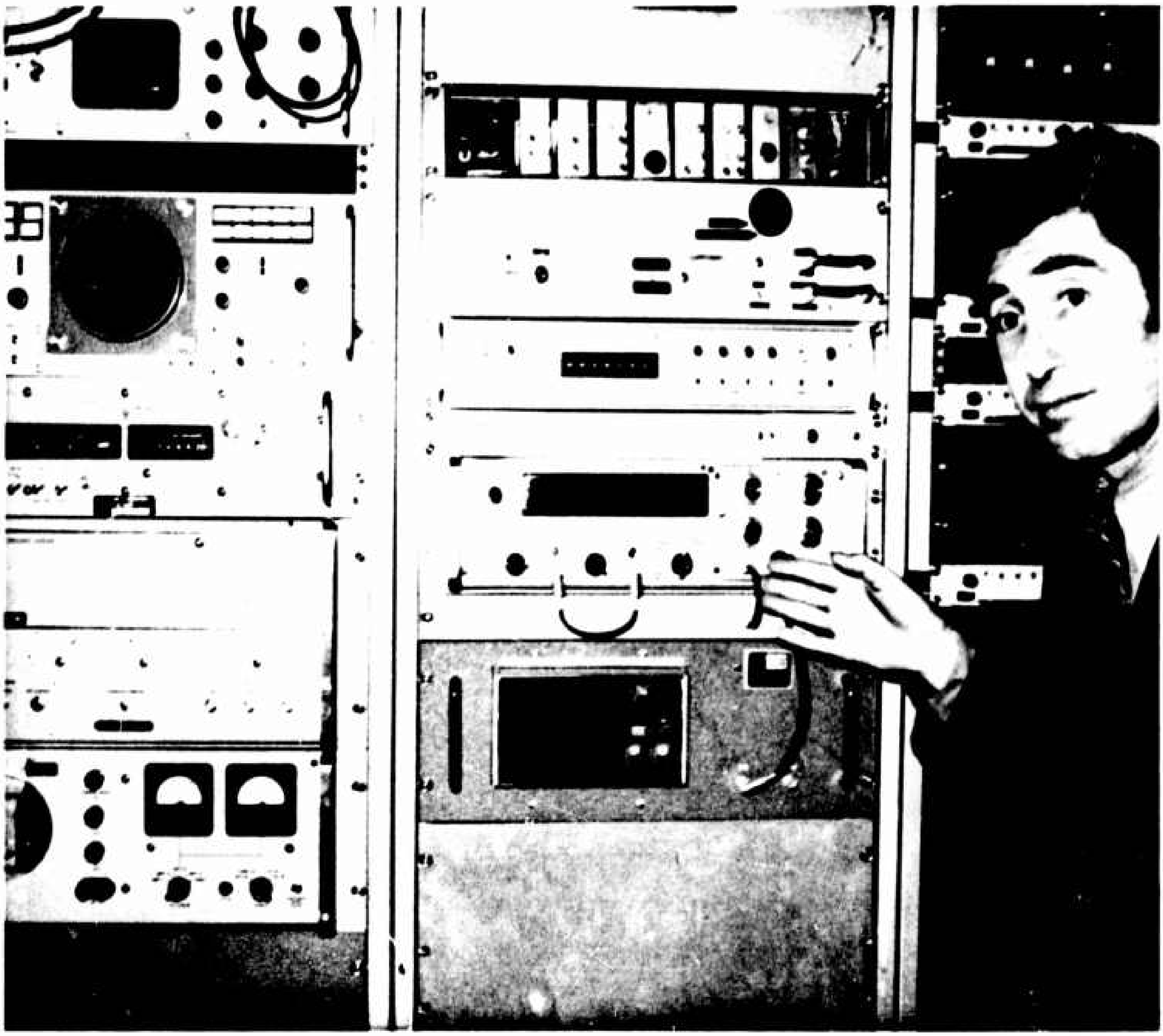

Figure 6. EQUIPMENT AT TELEVISION TRANSMITTING STUDIO

printer. The TV receiver and line 10 pulse discriminator monitors the TV transmissions and generates a pulse every odd horizontal line 10 received. This pulse can be compared at any second to the output of the USNO Master Clock and the time of arrival of this TV reference pulse is read on the time interval counter (see Figure 7).

Similarly, improved TV time receiving systems can be built to give a direct presentation of the time difference in microseconds between a local clock and a "TV transmitter clock." This can be done by compensating for the propagation delays and by normalizing one of the clocks to the other, such that their respective time marks can be compared on a time interval counter to give an actual display of the time difference between the two clocks. A prototype of such an apparatus is also being developed for evaluation.

6.0 CONTROL OF TRANSMISSIONS BY A REFERENCE CLOCK

The correct time position of the video transmissions can be secured by a monitor station having the reference clock for the system. In the Washington, D.C. area, the USNO is that control station and the reference clock to the TV transmitter is the USNO Master Clock (see Figure 8).

As long as the clock and phase control equipment installed at the TV station performs normally, the only parameter which may have to be adjusted is the frequency of the oscillator located at the TV studio. The effective frequency of this oscillator must be the same as the frequency of the reference clock (USNO MC). Any frequency offset of the TV oscillator from this clock will cause the position of the video transmissions to shift slowly away from it. A time agreement between the TV and USNO clocks can be secured by issuing to the station minute periodic phase step corrections which will be computed at the USNO. This could be accomplished automatically by installing at the TV studio a programmable microphase stepper, the rate of which will be controlled by the USNO (see

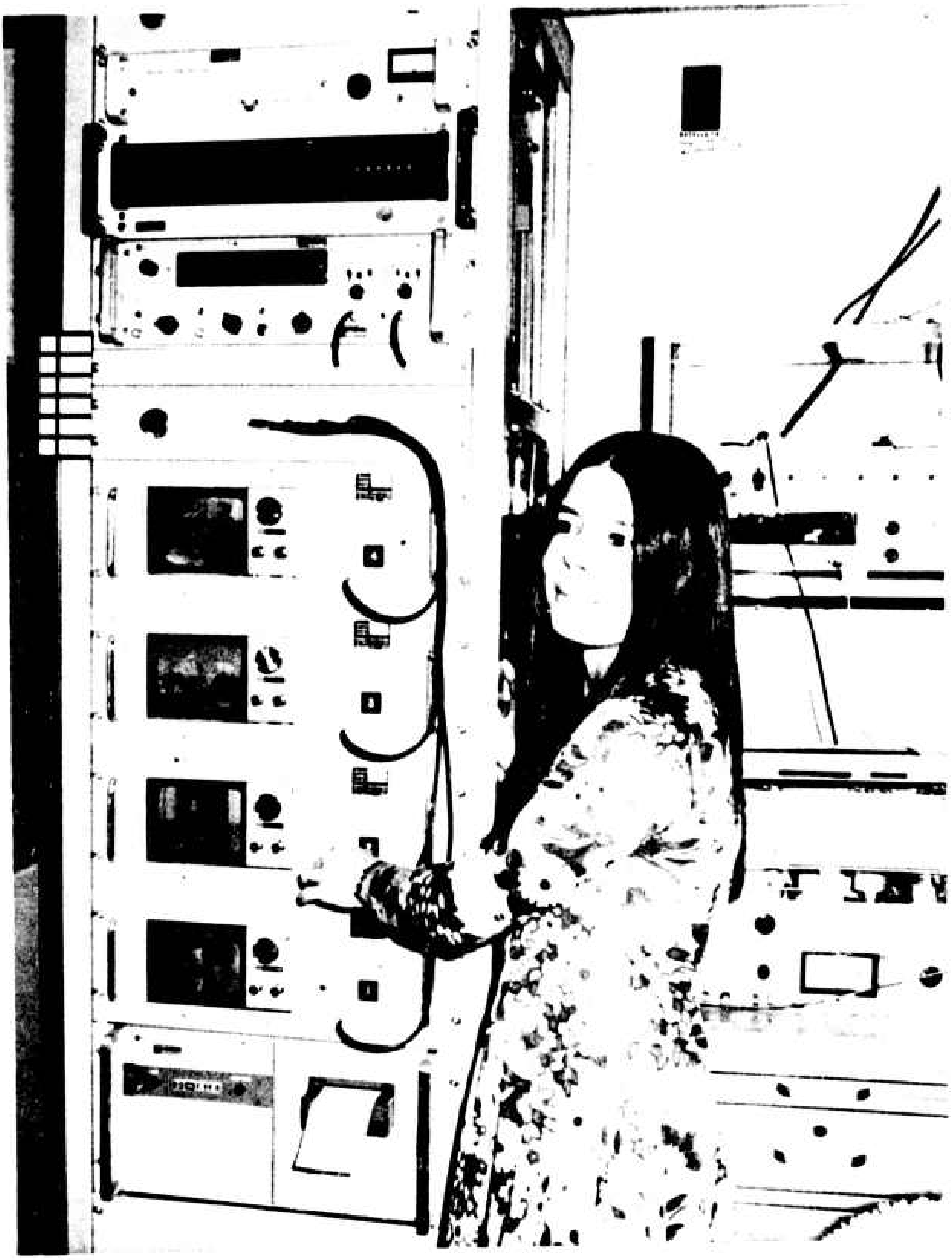

Figure 7. TIME MONITORING RECEIVING SYSTEM

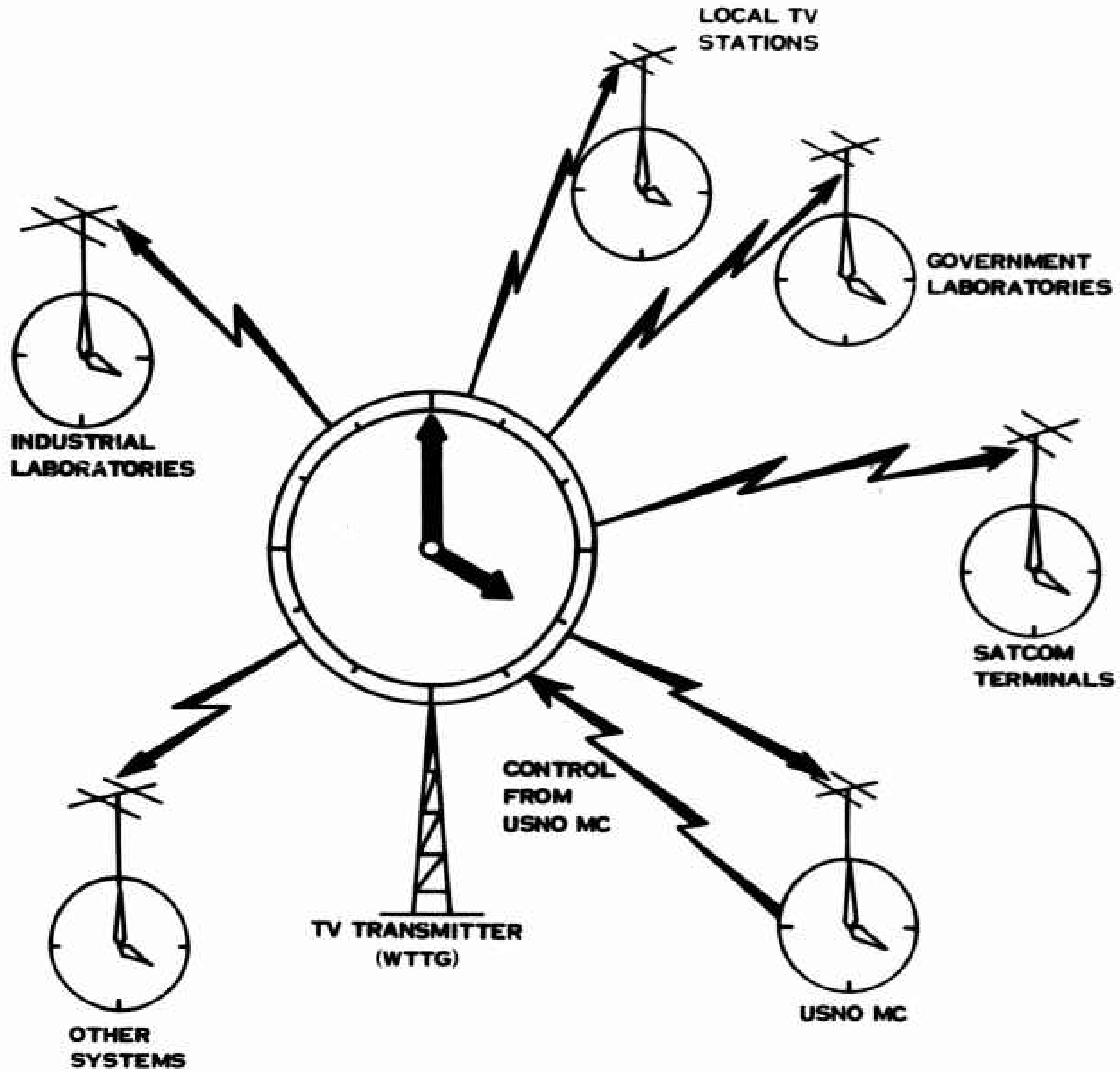

Figure 8. DISTRIBUTION SYSTEM AND CONTROL

Figure 9). Incidentally, such an apparatus is commercially available to give programmable phase corrections at an average rate as small as ten femtoseconds/sec (0.000000010 microseconds/sec). Also, a "disciplined oscillator" could replace the cesium oscillator installed at the TV studio, thus effecting a consequent cost reduction.

7.0 EXTENDED COVERAGE

Any timing system located within the reception area of time-controlled TV transmissions emitted from a local TV station can, of course, be synchronized using the method described above.

A large number of time-controlled TV transmissions could be set up over the continental United States simply by installing at the TV transmitter similar types of equipment as shown in Figure 9. The major problem would be to keep all clock systems installed at the TV studios on time and on frequency with the reference clock. However, this could be implemented in many cases by the stations linking together (line-of-sight or microwave link) to keep their local oscillator and clock synchronized to each other, or by installing precise time standards which could be "visited" periodically to keep the offset (time and frequency) within acceptable limits. These "visits" could be done by portable clocks, fly-over techniques, satellite time transfers, Loran-C, and others.

It is possible and could be proposed to link the East Coast and West Coast U.S. TV stations to the USNO Master Clock via the SATCOM system. Time transfer with submicrosecond accuracy is presently and routinely being done between the SATCOM terminals located in Brandywine, Maryland; Camp Roberts, California; and others. Since the USNO has access to this SATCOM network through the Brandywine terminal, the system could be configured as shown in Figure 10. Selected TV stations located in Guam, Hawaii, the Philippines, Alaska, etc. could be linked to the USNO Master Clock simply and economically by using the same approach.

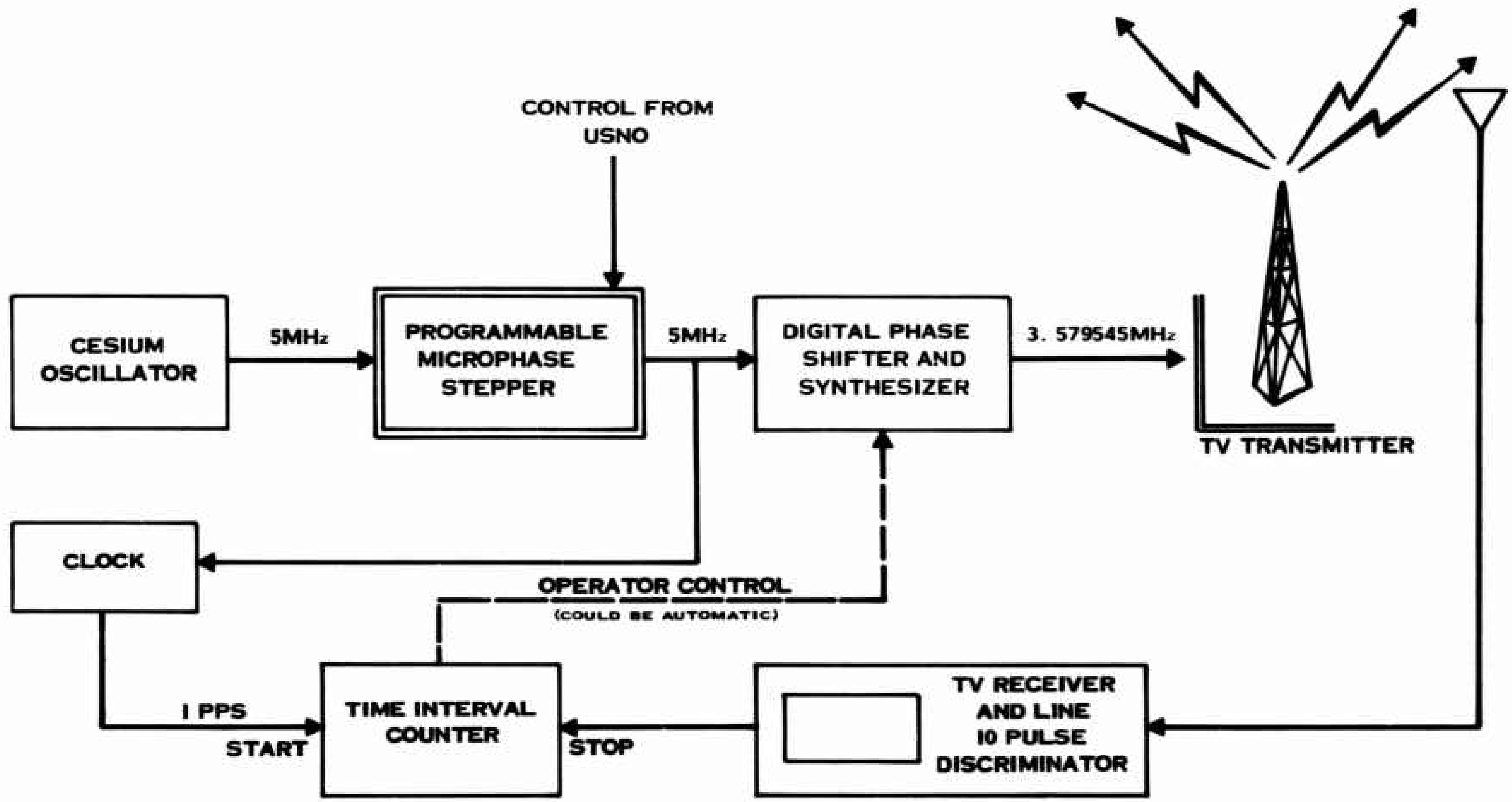

Figure 9. PROGRAMMABLE MICROPHASE STEPPER AT TV STUDIO

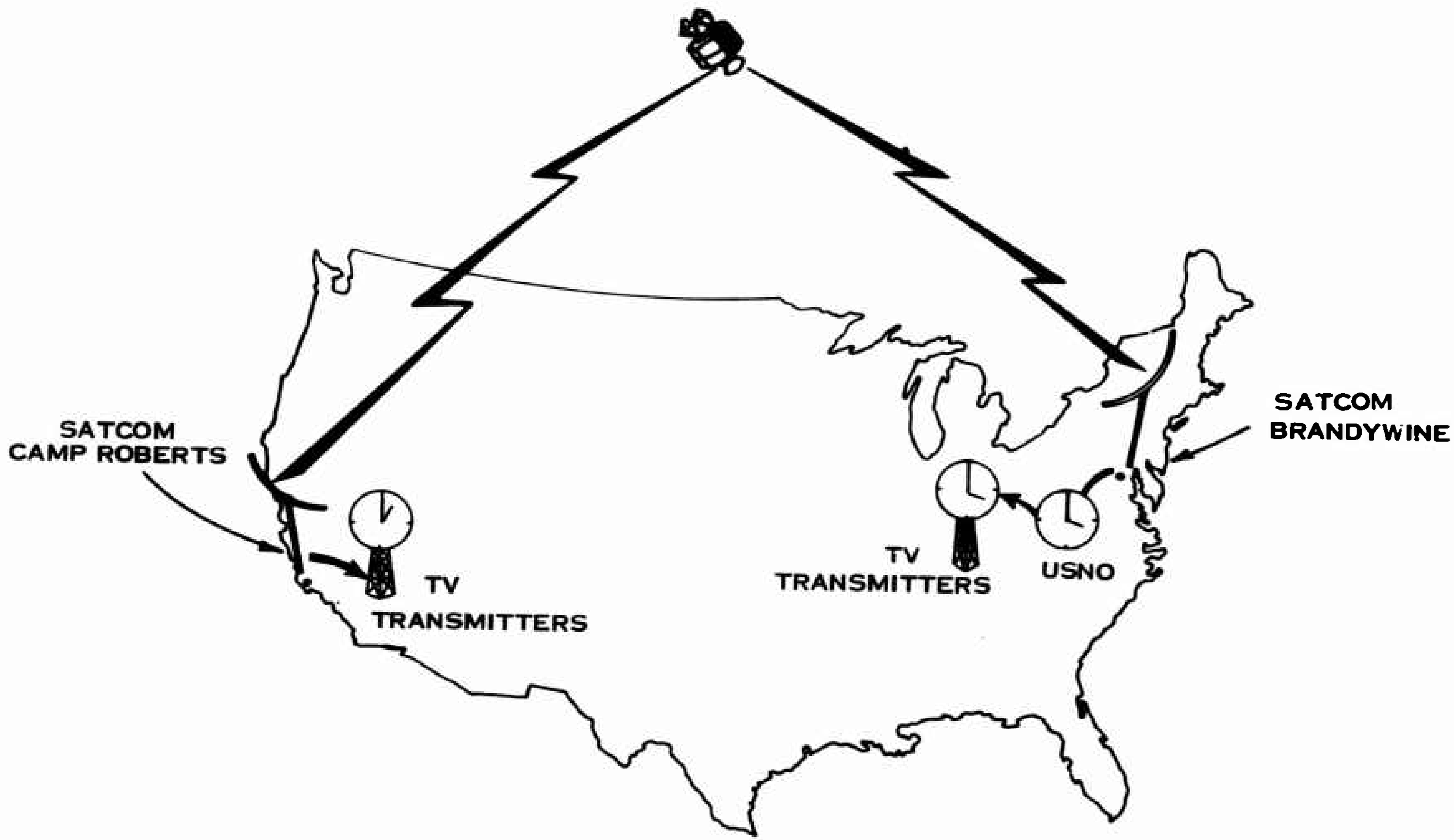

Figure 10. EXTENDED COVERAGE - LINKING EAST AND WEST COAST BY SATCOM SYSTEM

8.0 APPLICATIONS

Numerous applications could be found and implemented if accurate time and frequency could be obtained easily and inexpensively from the transmissions of existing TV stations. This could be the case, if the method of video phase-control described were to be used to discipline key TV transmissions.

Some of these applications could certainly be found in the fields of precise navigation, traffic control and transportation, collision avoidance systems, real time computer systems, geodesy, the TV industry, and high speed communications, just to name a few.

9.0 CONCLUSION

The method presented herein introduces a new approach to the use of existing television transmissions for PTTI applications. It is a system which:

- Permits real time transfer to be made independently to sub-microsecond accuracy
- Does not require any special TV transmissions (channel capacity)
- Improves stability of TV emissions
- Does not require special licensing
- Is simple to use
- Could be developed into the most economical system available for real time applications
- Is compatible with existing receiving equipment

A summary of the characteristics of the three TV transfer methods is discussed in Figure 11.

10.0 ACKNOWLEDGMENT

The authors wish to express their gratitude to the personnel of the WTTG Metromedia television station and, in particular, to Albert Harmon

"PASSIVE" SYSTEM FOR DIFFERENTIAL TIME TRANSFER

(EUROPEAN SYSTEM)
IN USE IN EUROPE AND IN THE USA

REQUIREMENTS:

- READINGS MUST BE TAKEN SIMULTANEOUSLY BY THE TIMING STATIONS TO BE SYNCHRONIZED.
- DATA MUST BE EXCHANGED AFTER THE FACT BETWEEN THE MONITORING STATIONS.
- LINE 10 PULSE DISCRIMINATOR MUST BE INSTALLED AT TIME MONITORING STATIONS.
- PROPAGATION AND EQUIPMENT DELAYS MUST BE KNOWN FOR ALL COOPERATING STATIONS.

CAPABILITIES:

- PERMITS DIFFERENTIAL TIME SYNCHRONIZATION TO SUBMICROSECOND PRECISION.

"ACTIVE" SYSTEM FOR REAL TIME TRANSFER

(NBS LINE 16 OR 1)
PROPOSED AND TESTED

REQUIREMENTS:

- CLOCK AND CLOCK ENCODER MUST BE INSTALLED AT TV TRANSMITTER.
- FCC AUTHORIZATION TO TRANSMIT IS REQUIRED.
- ACTUAL TIME INFORMATION MUST BE TRANSMITTED.
- TV RECEIVER MUST BE INSTALLED AT TIME MONITOR STATION.
- CLOCK DECODER MUST BE INSTALLED AT TIME MONITOR STATION.

CAPABILITIES:

- PERMITS REAL TIME TRANSFER TO SUBMICROSECOND ACCURACY.
- GIVES HOURS, MINUTES AND SECONDS IN ADDITION TO SYNCHRONIZATION.

"PASSIVE" SYSTEM FOR REAL TIME TRANSFER

(USNO SYSTEM)
PROPOSED AND TESTED

REQUIREMENTS:

- CLOCK AND PHASE SHIFTING SYNTHESIZER MUST BE INSTALLED AT TV TRANSMITTER.
- LINE 10 PULSE DISCRIMINATOR MUST BE INSTALLED AT TIME MONITOR STATION.

CAPABILITIES:

- PERMITS REAL TIME TRANSFER TO SUBMICROSECOND ACCURACY.
- PERMITS USE OF EXISTING "LINE 10" RECEIVERS.
- CAN BE IMPLEMENTED ANYWHERE WITHOUT SPECIAL LICENSING.

Figure 11. COMPARISON OF TV TIME TRANSFER METHODS

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APPENDIX

26 August 1971

Time of Coincidence (TOC) ephemeris Reference tables for Television Transmissions synchronized to the USNO Master Clock.

1. INTRODUCTION:

Some Video transmissions are time positioned such that certain Television horizontal pulses - identified as line 10 odd - are transmitted in synchronization with particular seconds of a UTC scale referenced to the U. S. Naval Observatory Master Clock.

2. DISCUSSION:

The times of coincidence of TV line 10 odd pulses with second pulses of the U. S. Naval Observatory Master Clock are found for each day by adding the values given in Table 2 to the values given in Table 1.

Table 1 gives the first TV line 10 odd TOC for each day in hours, minutes and seconds.

Table 2 gives all relative TOC's in a day in hours, minutes and seconds.

By adding the relative TOC's (Table 2) to the first TOC of any selected day (Table 1) one obtains the absolute TOC's for the day.

Example 1:

Assume that an operator monitoring a Television transmission desires to make a synchronization check between the station clock and the TV synchronized transmissions at about 1930 UT 19 September 1971.

From Table 2, the values near 1930 UT are:

H	M	S
19	11	09
19	27	50
19	44	31

These values added to the value from Table 1 listed for the 19 September 1971:

H	M	S
00	12	26

give the times of coincidence between the beginning of TV line 10 odd pulses and U. S. Naval Observatory Master Clock one-pulse-per-second, namely:

H	M	S
19	23	35
19	40	16
19	56	57

Table 3 gives the time differences between every second of the time interval between the relative TOC's of Table 2 (1001 seconds) and the subsequent TV line 10 odd pulse.

Between the times of coincidence as given by Tables 1 and 2, the time difference between any one-pulse-per-second of the U. S. Naval Observatory Master Clock and the immediately following line 10 odd pulse of a synchronized TV transmission can be determined by using Table 3.

Example 2:

Assume that such a time difference is required at $19^h\ 30^m\ 00^s$ UT on 19 September 1971. For Tables 1 and 2 we found that the last TOC occurred at $19^h\ 23^m\ 35^s$ (see example 1). Therefore, the time at which the time measurement is required occurs 6M 25 sec after that last TOC.

From Table 3 we note that the value corresponding to 6 minutes 25 seconds is 17966.667 microseconds. Therefore, the TV line 10 odd pulse immediately following the $19^h\ 30^m\ 00^s$ UT one-pulse-per-second of the U. S. Naval Observatory Master Clock on 19 September 1971 will be transmitted at $19^h\ 30^m$ 0.017966667 sec.

TABLE 1

FIRST TOC FOR EACH DAY

TIMES OF COINCIDENCE (NULL) EPHEMERIS
TELEVISION LINE 10 ODD SYNC
33,366.666 MICROSECONDS/PERIOD

DATE 1971	TIME H	M	S	DATE 1971	TIME H	M	S	DATE 1971	TIME H	M	S
OCT 1	0	16	22	NOV 1	0	4	17	DEC 1	0	14	7
2	0	11	8	2	0	15	44	2	0	8	53
3	0	5	54	3	0	10	30	3	0	3	39
4	0	0	40	4	0	5	16	4	0	15	6
5	0	12	7	5	0	0	2	5	0	9	52
6	0	6	53	6	0	11	29	6	0	4	38
7	0	1	39	7	0	6	15	7	0	16	5
8	0	13	6	8	0	1	1	8	0	10	51
9	0	7	52	9	0	12	28	9	0	5	37
10	0	2	38	10	0	7	14	10	0	0	23
11	0	14	5	11	0	2	0	11	0	11	50
12	0	8	51	12	0	13	27	12	0	6	36
13	0	3	37	13	0	8	13	13	0	1	22
14	0	15	4	14	0	2	59	14	0	12	49
15	0	9	50	15	0	14	26	15	0	7	35
16	0	4	36	16	0	9	12	16	0	2	21
17	0	16	3	17	0	3	58	17	0	13	48
18	0	10	49	18	0	15	25	18	0	8	34
19	0	5	35	19	0	10	11	19	0	3	20
20	0	0	21	20	0	4	57	20	0	14	47
21	0	11	48	21	0	16	24	21	0	9	33
22	0	6	34	22	0	11	10	22	0	4	19
23	0	1	20	23	0	5	56	23	0	15	46
24	0	12	47	24	0	0	42	24	0	10	32
25	0	7	33	25	0	12	9	25	0	5	18
26	0	2	19	26	0	6	55	26	0	0	4
27	0	13	46	27	0	1	41	27	0	11	31
28	0	8	32	28	0	13	8	28	0	6	17
29	0	3	18	29	0	7	54	29	0	1	3
30	0	14	45	30	0	2	40	30	0	12	30
31	0	9	31					31	0	7	16

TABLE 1

FIRST TOC FOR EACH DAY

TIMES OF COINCIDENCE (NULL) EPHEMERIS
TELEVISION LINE 10 ODD SYNC
33,666.666 MICROSECONDS/PERIOD

DATE 1972	TIME H	M	S	DATE 1972	TIME H	M	S	DATE 1972	TIME H	M	S
JAN 1	0	2	2	FEB 1	0	6	38	MAR 1	0	5	1
2	0	13	29	2	0	1	24	2	0	16	28
3	0	8	15	3	0	12	51	3	0	11	14
4	0	3	1	4	0	7	37	4	0	6	0
5	0	14	28	5	0	2	23	5	0	0	46
6	0	9	14	6	0	13	50	6	0	12	13
7	0	4	0	7	0	8	36	7	0	6	59
8	0	15	27	8	0	3	22	8	0	1	45
9	0	10	13	9	0	14	49	9	0	13	12
10	0	4	59	10	0	9	35	10	0	7	58
11	0	16	26	11	0	4	21	11	0	2	44
12	0	11	12	12	0	15	48	12	0	14	11
13	0	5	58	13	0	10	34	13	0	8	57
14	0	0	44	14	0	5	20	14	0	3	43
15	0	12	11	15	0	0	6	15	0	15	10
16	0	6	57	16	0	11	33	16	0	9	56
17	0	1	43	17	0	6	19	17	0	4	42
18	0	13	10	18	0	1	5	18	0	16	9
19	0	7	56	19	0	12	32	19	0	10	55
20	0	2	42	20	0	7	18	20	0	5	41
21	0	14	9	21	0	2	4	21	0	0	27
22	0	8	55	22	0	13	31	22	0	11	54
23	0	3	41	23	0	8	17	23	0	6	40
24	0	15	8	24	0	3	3	24	0	1	26
25	0	9	54	25	0	14	30	25	0	12	53
26	0	4	40	26	0	9	16	26	0	7	39
27	0	16	7	27	0	4	2	27	0	2	25
28	0	10	53	28	0	15	29	28	0	13	52
29	0	5	39	29	0	10	15	29	0	8	38
30	0	0	25					30	0	3	24
31	0	11	52					31	0	14	51

TABLE 1

FIRST TOC FOR EACH DAY

TIMES OF COINCIDENCE (NULL) EPHEMERIS
TELEVISION LINE 10 ODD SYNC
33,666.666 MICROSECONDS/PERIOD

DATE 1972	TIME H	M	S	DATE 1972	TIME H	M	S	DATE 1972	TIME H	M	S
APR 1	0	9	37	MAY 1	0	2	46	JUN 1	0	7	22
2	0	4	23	2	0	14	13	2	0	2	8
3	0	15	50	3	0	8	59	3	0	13	35
4	0	10	36	4	0	3	45	4	0	8	21
5	0	5	22	5	0	15	12	5	0	3	7
6	0	0	8	6	0	9	58	6	0	14	34
7	0	11	35	7	0	4	44	7	0	9	20
8	0	6	21	8	0	16	11	8	0	4	6
9	0	1	7	9	0	10	57	9	0	15	33
10	0	12	34	10	0	5	43	10	0	10	19
11	0	7	20	11	0	0	29	11	0	5	5
12	0	2	6	12	0	11	56	12	0	16	32
13	0	13	33	13	0	6	42	13	0	11	18
14	0	8	19	14	0	1	28	14	0	6	4
15	0	3	5	15	0	12	55	15	0	0	50
16	0	14	32	16	0	7	41	16	0	12	17
17	0	9	18	17	0	2	27	17	0	7	3
18	0	4	4	18	0	13	54	18	0	1	49
19	0	15	31	19	0	8	40	19	0	13	16
20	0	10	17	20	0	3	26	20	0	8	2
21	0	5	3	21	0	14	53	21	0	2	48
22	0	16	30	22	0	9	39	22	0	14	15
23	0	11	16	23	0	4	25	23	0	9	1
24	0	6	2	24	0	15	52	24	0	3	47
25	0	0	48	25	0	10	38	25	0	15	14
26	0	12	15	26	0	5	24	26	0	10	0
27	0	7	1	27	0	0	10	27	0	4	46
28	0	1	47	28	0	11	37	28	0	16	13
29	0	13	14	29	0	6	23	29	0	10	59
30	0	8	0	30	0	1	9	30	0	5	45
				31	0	12	36				

TABLE 2

ALL TOC'S IN A DAY

TIMES OF COINCIDENCE (NULL) EPHEMERIS

TELEVISION LINE 10 ODD SYNC
33,366.666 MICROSECONDS/PERIOD

H	M	S	H	M	S	H	M	S
0	0	0	11	7	20	22	14	40
0	16	41	11	24	1	22	31	21
0	33	22	11	40	42	22	48	2
0	50	3	11	57	23	23	4	43
1	6	44	12	14	4	23	21	24
1	23	25	12	30	45	23	38	5
1	40	6	12	47	26	23	54	46
1	56	47	13	4	7			
2	13	28	13	20	48			
2	30	9	13	37	29			
2	46	50	13	54	10			
3	3	31	14	10	51			
3	20	12	14	27	32			
3	36	53	14	44	13			
3	53	34	15	0	54			
4	10	15	15	17	35			
4	26	56	15	34	16			
4	43	37	15	50	57			
5	0	18	16	7	38			
5	16	59	16	24	19			
5	33	40	16	41	0			
5	50	21	16	57	41			
6	7	2	17	14	22			
6	23	43	17	31	3			
6	40	24	17	47	44			
6	57	5	18	4	25			
7	13	46	18	21	6			
7	30	27	18	37	47			
7	47	8	18	54	28			
8	3	49	19	11	9			
8	20	30	19	27	50			
8	37	11	19	44	31			
8	53	52	20	1	12			
9	10	33	20	17	53			
9	27	14	20	34	34			
9	43	55	20	51	15			
10	0	36	21	7	56			
10	17	17	21	24	37			
10	33	58	21	41	18			
10	50	39	21	57	59			

TABLE 3

INTERPOLATIONS FOR ALL SECONDS BETWEEN TOC'S

TELEVISION LINE 10 ODD SYNC

33,366.666 MICROSECONDS/PERIOD

M	S	(µS)	M	S	(µS)	M	S	(µS)	M	S	(µS)
0	1	1000.000	0	51	17633.333	1	41	900.000	2	31	17533.333
0	2	2000.000	0	52	18633.333	1	42	1900.000	2	32	18533.333
0	3	3000.000	0	53	19633.333	1	43	2900.000	2	33	19533.333
0	4	4000.000	0	54	20633.333	1	44	3900.000	2	34	20533.333
0	5	5000.000	0	55	21633.333	1	45	4900.000	2	35	21533.333
0	6	6000.000	0	56	22633.333	1	46	5900.000	2	36	22533.333
0	7	7000.000	0	57	23633.333	1	47	6900.000	2	37	23533.333
0	8	8000.000	0	58	24633.333	1	48	7900.000	2	38	24533.333
0	9	9000.000	0	59	25633.333	1	49	8900.000	2	39	25533.333
0	10	10000.000	1	0	26633.333	1	50	9900.000	2	40	26533.333
0	11	11000.000	1	1	27633.333	1	51	10900.000	2	41	27533.333
0	12	12000.000	1	2	28633.333	1	52	11900.000	2	42	28533.333
0	13	13000.000	1	3	29633.333	1	53	12900.000	2	43	29533.333
0	14	14000.000	1	4	30633.333	1	54	13900.000	2	44	30533.333
0	15	15000.000	1	5	31633.333	1	55	14900.000	2	45	31533.333
0	16	16000.000	1	6	32633.333	1	56	15900.000	2	46	32533.333
0	17	17000.000	1	7	266.667	1	57	16900.000	2	47	166.667
0	18	18000.000	1	8	1266.667	1	58	17900.000	2	48	1166.667
0	19	19000.000	1	9	2266.667	1	59	18900.000	2	49	2166.667
0	20	20000.000	1	10	3266.667	2	0	19900.000	2	50	3166.667
0	21	21000.000	1	11	4266.667	2	1	20900.000	2	51	4166.667
0	22	22000.000	1	12	5266.667	2	2	21900.000	2	52	5166.667
0	23	23000.000	1	13	6266.667	2	3	22900.000	2	53	6166.667
0	24	24000.000	1	14	7266.667	2	4	23900.000	2	54	7166.667
0	25	25000.000	1	15	8266.667	2	5	24900.000	2	55	8166.667
0	26	26000.000	1	16	9266.667	2	6	25900.000	2	56	9166.667
0	27	27000.000	1	17	10266.667	2	7	26900.000	2	57	10166.667
0	28	28000.000	1	18	11266.667	2	8	27900.000	2	58	11166.667
0	29	29000.000	1	19	12266.667	2	9	28900.000	2	59	12166.667
0	30	30000.000	1	20	13266.667	2	10	29900.000	3	0	13166.667
0	31	31000.000	1	21	14266.667	2	11	30900.000	3	1	14166.667
0	32	32000.000	1	22	15266.667	2	12	31900.000	3	2	15166.667
0	33	33000.000	1	23	16266.667	2	13	32900.000	3	3	16166.667
0	34	633.333	1	24	17266.667	2	14	533.333	3	4	17166.667
0	35	1633.333	1	25	18266.667	2	15	1533.333	3	5	18166.667
0	36	2633.333	1	26	19266.667	2	16	2533.333	3	6	19166.667
0	37	3633.333	1	27	20266.667	2	17	3533.333	3	7	20166.667
0	38	4633.333	1	28	21266.667	2	18	4533.333	3	8	21166.667
0	39	5633.333	1	29	22266.667	2	19	5533.333	3	9	22166.667
0	40	6633.333	1	30	23266.667	2	20	6533.333	3	10	23166.667
0	41	7633.333	1	31	24266.667	2	21	7533.333	3	11	24166.667
0	42	8633.333	1	32	25266.667	2	22	8533.333	3	12	25166.667
0	43	9633.333	1	33	26266.667	2	23	9533.333	3	13	26166.667
0	44	10633.333	1	34	27266.667	2	24	10533.333	3	14	27166.667
0	45	11633.333	1	35	28266.667	2	25	11533.333	3	15	28166.667
0	46	12633.333	1	36	29266.667	2	26	12533.333	3	16	29166.667
0	47	13633.333	1	37	30266.667	2	27	13533.333	3	17	30166.667
0	48	14633.333	1	38	31266.667	2	28	14533.333	3	18	31166.667
0	49	15633.333	1	39	32266.667	2	29	15533.333	3	19	32166.667
0	50	16633.333	1	40	33266.667	2	30	16533.333	3	20	33166.667

TABLE 3

INTERPOLATIONS FOR ALL SECONDS BETWEEN TOC'S

TELEVISION LINE 10 ODD SYNC
33,366.666 MICROSECONDS/PERIOD

M	S	(µS)	M	S	(µS)	M	S	(µS)	M	S	(µS)
3	21	800.000	4	11	17433.333	5	1	700.000	5	51	17333.333
3	22	1800.000	4	12	18433.333	5	2	1700.000	5	52	18333.333
3	23	2800.000	4	13	19433.333	5	3	2700.000	5	53	19333.333
3	24	3800.000	4	14	20433.333	5	4	3700.000	5	54	20333.333
3	25	4800.000	4	15	21433.333	5	5	4700.000	5	55	21333.333
3	26	5800.000	4	16	22433.333	5	6	5700.000	5	56	22333.333
3	27	6800.000	4	17	23433.333	5	7	6700.000	5	57	23333.333
3	28	7800.000	4	18	24433.333	5	8	7700.000	5	58	24333.333
3	29	8800.000	4	19	25433.333	5	9	8700.000	5	59	25333.333
3	30	9800.000	4	20	26433.333	5	10	9700.000	6	0	26333.333
3	31	10800.000	4	21	27433.333	5	11	10700.000	6	1	27333.333
3	32	11800.000	4	22	28433.333	5	12	11700.000	6	2	28333.333
3	33	12800.000	4	23	29433.333	5	13	12700.000	6	3	29333.333
3	34	13800.000	4	24	30433.333	5	14	13700.000	6	4	30333.333
3	35	14800.000	4	25	31433.333	5	15	14700.000	6	5	31333.333
3	36	15800.000	4	26	32433.333	5	16	15700.000	6	6	32333.333
3	37	16800.000	4	27	66.667	5	17	16700.000	6	7	33333.333
3	38	17800.000	4	28	1066.667	5	18	17700.000	6	8	966.667
3	39	18800.000	4	29	2066.667	5	19	18700.000	6	9	1966.667
3	40	19800.000	4	30	3066.667	5	20	19700.000	6	10	2966.667
3	41	20800.000	4	31	4066.667	5	21	20700.000	6	11	3966.667
3	42	21800.000	4	32	5066.667	5	22	21700.000	6	12	4966.667
3	43	22800.000	4	33	6066.667	5	23	22700.000	6	13	5966.667
3	44	23800.000	4	34	7066.667	5	24	23700.000	6	14	6966.667
3	45	24800.000	4	35	8066.667	5	25	24700.000	6	15	7966.667
3	46	25800.000	4	36	9066.667	5	26	25700.000	6	16	8966.667
3	47	26800.000	4	37	10066.667	5	27	26700.000	6	17	9966.667
3	48	27800.000	4	38	11066.667	5	28	27700.000	6	18	10966.667
3	49	28800.000	4	39	12066.667	5	29	28700.000	6	19	11966.667
3	50	29800.000	4	40	13066.667	5	30	29700.000	6	20	12966.667
3	51	30800.000	4	41	14066.667	5	31	30700.000	6	21	13966.667
3	52	31800.000	4	42	15066.667	5	32	31700.000	6	22	14966.667
3	53	32800.000	4	43	16066.667	5	33	32700.000	6	23	15966.667
3	54	433.333	4	44	17066.667	5	34	333.333	6	24	16966.667
3	55	1433.333	4	45	18066.667	5	35	1333.333	6	25	17966.667
3	56	2433.333	4	46	19066.667	5	36	2333.333	6	26	18966.667
3	57	3433.333	4	47	20066.667	5	37	3333.333	6	27	19966.667
3	58	4433.333	4	48	21066.667	5	38	4333.333	6	28	20966.667
3	59	5433.333	4	49	22066.667	5	39	5333.333	6	29	21966.667
4	0	6433.333	4	50	23066.667	5	40	6333.333	6	30	22966.667
4	1	7433.333	4	51	24066.667	5	41	7333.333	6	31	23966.667
4	2	8433.333	4	52	25066.667	5	42	8333.333	6	32	24966.667
4	3	9433.333	4	53	26066.667	5	43	9333.333	6	33	25966.667
4	4	10433.333	4	54	27066.667	5	44	10333.333	6	34	26966.667
4	5	11433.333	4	55	28066.667	5	45	11333.333	6	35	27966.667
4	6	12433.333	4	56	29066.667	5	46	12333.333	6	36	28966.667
4	7	13433.333	4	57	30066.667	5	47	13333.333	6	37	29966.667
4	8	14433.333	4	58	31066.667	5	48	14333.333	6	38	30966.667
4	9	15433.333	4	59	32066.667	5	49	15333.333	6	39	31966.667
4	10	16433.333	5	0	33066.667	5	50	16333.333	6	40	32966.667

TABLE 3

INTERPOLATIONS FOR ALL SECONDS BETWEEN TOC'S

TELEVISION LINE 10 ODD SYNC
33,366.666 MICROSECONDS/PERIOD

M	S	(µS)	M	S	(µS)	M	S	(µS)	M	S	(µS)
6	41	600.000	7	31	17233.333	8	21	500.000	9	11	17133.333
6	42	1600.000	7	32	18233.333	8	22	1500.000	9	12	18133.333
6	43	2600.000	7	33	19233.333	8	23	2500.000	9	13	19133.333
6	44	3600.000	7	34	20233.333	8	24	3500.000	9	14	20133.333
6	45	4600.000	7	35	21233.333	8	25	4500.000	9	15	21133.333
6	46	5600.000	7	36	22233.333	8	26	5500.000	9	16	22133.333
6	47	6600.000	7	37	23233.333	8	27	6500.000	9	17	23133.333
6	48	7600.000	7	38	24233.333	8	28	7500.000	9	18	24133.333
6	49	8600.000	7	39	25233.333	8	29	8500.000	9	19	25133.333
6	50	9600.000	7	40	26233.333	8	30	9500.000	9	20	26133.333
6	51	10600.000	7	41	27233.333	8	31	10500.000	9	21	27133.333
6	52	11600.000	7	42	28233.333	8	32	11500.000	9	22	28133.333
6	53	12600.000	7	43	29233.333	8	33	12500.000	9	23	29133.333
6	54	13600.000	7	44	30233.333	8	34	13500.000	9	24	30133.333
6	55	14600.000	7	45	31233.333	8	35	14500.000	9	25	31133.333
6	56	15600.000	7	46	32233.333	8	36	15500.000	9	26	32133.333
6	57	16600.000	7	47	33233.333	8	37	16500.000	9	27	33133.333
6	58	17600.000	7	48	866.667	8	38	17500.000	9	28	766.667
6	59	18600.000	7	49	1866.667	8	39	18500.000	9	29	1766.667
7	0	19600.000	7	50	2866.667	8	40	19500.000	9	30	2766.667
7	1	20600.000	7	51	3866.667	8	41	20500.000	9	31	3766.667
7	2	21600.000	7	52	4866.667	8	42	21500.000	9	32	4766.667
7	3	22600.000	7	53	5866.667	8	43	22500.000	9	33	5766.667
7	4	23600.000	7	54	6866.667	8	44	23500.000	9	34	6766.667
7	5	24600.000	7	55	7866.667	8	45	24500.000	9	35	7766.667
7	6	25600.000	7	56	8866.667	8	46	25500.000	9	36	8766.667
7	7	26600.000	7	57	9866.667	8	47	26500.000	9	37	9766.667
7	8	27600.000	7	58	10866.667	8	48	27500.000	9	38	10766.667
7	9	28600.000	7	59	11866.667	8	49	28500.000	9	39	11766.667
7	10	29600.000	8	0	12866.667	8	50	29500.000	9	40	12766.667
7	11	30600.000	8	1	13866.667	8	51	30500.000	9	41	13766.667
7	12	31600.000	8	2	14866.667	8	52	31500.000	9	42	14766.667
7	13	32600.000	8	3	15866.667	8	53	32500.000	9	43	15766.667
7	14	233.333	8	4	16866.667	8	54	133.333	9	44	16766.667
7	15	1233.333	8	5	17866.667	8	55	1133.333	9	45	17766.667
7	16	2233.333	8	6	18866.667	8	56	2133.333	9	46	18766.667
7	17	3233.333	8	7	19866.667	8	57	3133.333	9	47	19766.667
7	18	4233.333	8	8	20866.667	8	58	4133.333	9	48	20766.667
7	19	5233.333	8	9	21866.667	8	59	5133.333	9	49	21766.667
7	20	6233.333	8	10	22866.667	9	0	6133.333	9	50	22766.667
7	21	7233.333	8	11	23866.667	9	1	7133.333	9	51	23766.667
7	22	8233.333	8	12	24866.667	9	2	8133.333	9	52	24766.667
7	23	9233.333	8	13	25866.667	9	3	9133.333	9	53	25766.667
7	24	10233.333	8	14	26866.667	9	4	10133.333	9	54	26766.667
7	25	11233.333	8	15	27866.667	9	5	11133.333	9	55	27766.667
7	26	12233.333	8	16	28866.667	9	6	12133.333	9	56	28766.667
7	27	13233.333	8	17	29866.667	9	7	13133.333	9	57	29766.667
7	28	14233.333	8	18	30866.667	9	8	14133.333	9	58	30766.667
7	29	15233.333	8	19	31866.667	9	9	15133.333	9	59	31766.667
7	30	16233.333	8	20	32866.667	9	10	16133.333	10	0	32766.667

TABLE 3

INTERPOLATIONS FOR ALL SECONDS BETWEEN TOC'S

TELEVISION LINE 10 ODD SYNC

33,366.666 MICROSECONDS/PERIOD

M	S	(µS)	M	S	(µS)	M	S	(µS)	M	S	(µS)
10	1	400.000	10	51	17033.333	11	41	300.000	12	31	16933.333
10	2	1400.000	10	52	18033.333	11	42	1300.000	12	32	17933.333
10	3	2400.000	10	53	19033.333	11	43	2300.000	12	33	18933.333
10	4	3400.000	10	54	20033.333	11	44	3300.000	12	34	19933.333
10	5	4400.000	10	55	21033.333	11	45	4300.000	12	35	20933.333
10	6	5400.000	10	56	22033.333	11	46	5300.000	12	36	21933.333
10	7	6400.000	10	57	23033.333	11	47	6300.000	12	37	22933.333
10	8	7400.000	10	58	24033.333	11	48	7300.000	12	38	23933.333
10	9	8400.000	10	59	25033.333	11	49	8300.000	12	39	24933.333
10	10	9400.000	11	0	26033.333	11	50	9300.000	12	40	25933.333
10	11	10400.000	11	1	27033.333	11	51	10300.000	12	41	26933.333
10	12	11400.000	11	2	28033.333	11	52	11300.000	12	42	27933.333
10	13	12400.000	11	3	29033.333	11	53	12300.000	12	43	28933.333
10	14	13400.000	11	4	30033.333	11	54	13300.000	12	44	29933.333
10	15	14400.000	11	5	31033.333	11	55	14300.000	12	45	30933.333
10	16	15400.000	11	6	32033.333	11	56	15300.000	12	46	31933.333
10	17	16400.000	11	7	33033.333	11	57	16300.000	12	47	32933.333
10	18	17400.000	11	8	666.667	11	58	17300.000	12	48	566.667
10	19	18400.000	11	9	1666.667	11	59	18300.000	12	49	1566.667
10	20	19400.000	11	10	2666.667	12	0	19300.000	12	50	2566.667
10	21	20400.000	11	11	3666.667	12	1	20300.000	12	51	3566.667
10	22	21400.000	11	12	4666.667	12	2	21300.000	12	52	4566.667
10	23	22400.000	11	13	5666.667	12	3	22300.000	12	53	5566.667
10	24	23400.000	11	14	6666.667	12	4	23300.000	12	54	6566.667
10	25	24400.000	11	15	7666.667	12	5	24300.000	12	55	7566.667
10	26	25400.000	11	16	8666.667	12	6	25300.000	12	56	8566.667
10	27	26400.000	11	17	9666.667	12	7	26300.000	12	57	9566.667
10	28	27400.000	11	18	10666.667	12	8	27300.000	12	58	10566.667
10	29	28400.000	11	19	11666.667	12	9	28300.000	12	59	11566.667
10	30	29400.000	11	20	12666.667	12	10	29300.000	13	0	12566.667
10	31	30400.000	11	21	13666.667	12	11	30300.000	13	1	13566.667
10	32	31400.000	11	22	14666.667	12	12	31300.000	13	2	14566.667
10	33	32400.000	11	23	15666.667	12	13	32300.000	13	3	15566.667
10	34	33.333	11	24	16666.667	12	14	33300.000	13	4	16566.667
10	35	1033.333	11	25	17666.667	12	15	933.333	13	5	17566.667
10	36	2033.333	11	26	18666.667	12	16	1933.333	13	6	18566.667
10	37	3033.333	11	27	19666.667	12	17	2933.333	13	7	19566.667
10	38	4033.333	11	28	20666.667	12	18	3933.333	13	8	20566.667
10	39	5033.333	11	29	21666.667	12	19	4933.333	13	9	21566.667
10	40	6033.333	11	30	22666.667	12	20	5933.333	13	10	22566.667
10	41	7033.333	11	31	23666.667	12	21	6933.333	13	11	23566.667
10	42	8033.333	11	32	24666.667	12	22	7933.333	13	12	24566.667
10	43	9033.333	11	33	25666.667	12	23	8933.333	13	13	25566.667
10	44	10033.333	11	34	26666.667	12	24	9933.333	13	14	26566.667
10	45	11033.333	11	35	27666.667	12	25	10933.333	13	15	27566.667
10	46	12033.333	11	36	28666.667	12	26	11933.333	13	16	28566.667
10	47	13033.333	11	37	29666.667	12	27	12933.333	13	17	29566.667
10	48	14033.333	11	38	30666.667	12	28	13933.333	13	18	30566.667
10	49	15033.333	11	39	31666.667	12	29	14933.333	13	19	31566.667
10	50	16033.333	11	40	32666.667	12	30	15933.333	13	20	32566.667

TABLE 3

INTERPOLATIONS FOR ALL SECONDS BETWEEN TOC'S

TELEVISION LINE 10 ODD SYNC
33,366.666 MICROSECONDS/PERIOD

M	S	(μS)	M	S	(μS)	M	S	(μS)	M	S	(μS)
13	21	200.000	14	11	16833.333	15	1	100.000	15	51	16733.333
13	22	1200.000	14	12	17833.333	15	2	1100.000	15	52	17733.333
13	23	2200.000	14	13	18833.333	15	3	2100.000	15	53	18733.333
13	24	3200.000	14	14	19833.333	15	4	3100.000	15	54	19733.333
13	25	4200.000	14	15	20833.333	15	5	4100.000	15	55	20733.333
13	26	5200.000	14	16	21833.333	15	6	5100.000	15	56	21733.333
13	27	6200.000	14	17	22833.333	15	7	6100.000	15	57	22733.333
13	28	7200.000	14	18	23833.333	15	8	7100.000	15	58	23733.333
13	29	8200.000	14	19	24833.333	15	9	8100.000	15	59	24733.333
13	30	9200.000	14	20	25833.333	15	10	9100.000	16	0	25733.333
13	31	10200.000	14	21	26833.333	15	11	10100.000	16	1	26733.333
13	32	11200.000	14	22	27833.333	15	12	11100.000	16	2	27733.333
13	33	12200.000	14	23	28833.333	15	13	12100.000	16	3	28733.333
13	34	13200.000	14	24	29833.333	15	14	13100.000	16	4	29733.333
13	35	14200.000	14	25	30833.333	15	15	14100.000	16	5	30733.333
13	36	15200.000	14	26	31833.333	15	16	15100.000	16	6	31733.333
13	37	16200.000	14	27	32833.333	15	17	16100.000	16	7	32733.333
13	38	17200.000	14	28	466.667	15	18	17100.000	16	8	366.667
13	39	18200.000	14	29	1466.667	15	19	18100.000	16	9	1366.667
13	40	19200.000	14	30	2466.667	15	20	19100.000	16	10	2366.667
13	41	20200.000	14	31	3466.667	15	21	20100.000	16	11	3366.667
13	42	21200.000	14	32	4466.667	15	22	21100.000	16	12	4366.667
13	43	22200.000	14	33	5466.667	15	23	22100.000	16	13	5366.667
13	44	23200.000	14	34	6466.667	15	24	23100.000	16	14	6366.667
13	45	24200.000	14	35	7466.667	15	25	24100.000	16	15	7366.667
13	46	25200.000	14	36	8466.667	15	26	25100.000	16	16	8366.667
13	47	26200.000	14	37	9466.667	15	27	26100.000	16	17	9366.667
13	48	27200.000	14	38	10466.667	15	28	27100.000	16	18	10366.667
13	49	28200.000	14	39	11466.667	15	29	28100.000	16	19	11366.667
13	50	29200.000	14	40	12466.667	15	30	29100.000	16	20	12366.667
13	51	30200.000	14	41	13466.667	15	31	30100.000	16	21	13366.667
13	52	31200.000	14	42	14466.667	15	32	31100.000	16	22	14366.667
13	53	32200.000	14	43	15466.667	15	33	32100.000	16	23	15366.667
13	54	33200.000	14	44	16466.667	15	34	33100.000	16	24	16366.667
13	55	833.333	14	45	17466.667	15	35	733.333	16	25	17366.667
13	56	1833.333	14	46	18466.667	15	36	1733.333	16	26	18366.667
13	57	2833.333	14	47	19466.667	15	37	2733.333	16	27	19366.667
13	58	3833.333	14	48	20466.667	15	38	3733.333	16	28	20366.667
13	59	4833.333	14	49	21466.667	15	39	4733.333	16	29	21366.667
14	0	5833.333	14	50	22466.667	15	40	5733.333	16	30	22366.667
14	1	6833.333	14	51	23466.667	15	41	6733.333	16	31	23366.667
14	2	7833.333	14	52	24466.667	15	42	7733.333	16	32	24366.667
14	3	8833.333	14	53	25466.667	15	43	8733.333	16	33	25366.667
14	4	9833.333	14	54	26466.667	15	44	9733.333	16	34	26366.667
14	5	10833.333	14	55	27466.667	15	45	10733.333	16	35	27366.667
14	6	11833.333	14	56	28466.667	15	46	11733.333	16	36	28366.667
14	7	12833.333	14	57	29466.667	15	47	12733.333	16	37	29366.667
14	8	13833.333	14	58	30466.667	15	48	13733.333	16	38	30366.667
14	9	14833.333	14	59	31466.667	15	49	14733.333	16	39	31366.667
14	10	15833.333	15	0	32466.667	15	50	15733.333	16	40	32366.667

DISCUSSION

MRS. CARROLL: Are there any questions?

LCDR POTTS: It's not clear to me why, on your last figure, in the proposed USNO system, there is no requirement to know the equipment delays and propagation delays.

MRS. CARROLL: That would be necessary; it is in all the systems.

LCDR POTTS: I didn't see it listed under that proposed system. Thank you.

MRS. CARROLL: Any other questions?

MR. GATTERER: I'd like to make a couple of comments and ask you a question. I think this stabilizing of line 10 and putting line 10 on time is a very valuable contribution. I would like to point out that NBS did stabilize the color sub-carrier frequency in our early line 10 systems. Is the pulse discriminator circuit in your present equipment different than in the equipment we originally supplied to you? Is there an improvement, is it cheaper, and that sort of thing?

MRS. CARROLL: The specifications of that piece of equipment have been shown. I think it is different, because, as I mentioned before, this piece of equipment counts lines, and I believe the piece of equipment that you are referring to recognizes the line 10 because of the particular unique pulse that is located on line 10. All this discriminator does is count the lines until it gets to 10, and then it uses that line. In other words, this piece of equipment could be made to count to any number of lines, whereas yours requires a particular uniqueness about a line, in particular line 10.

MODERATOR: Thank you, Mrs. Carroll.

HYDROGEN MASERS AND OTHER STANDARDS

by

H. E. Peters

Mr. Peters is with the Goddard Space Flight Center, National Aeronautics and Space Administration, Greenbelt, Maryland.

This paper is concerned with some of the standards which were discussed in previous papers.

The first picture, Figure 1, is a source of what I really consider to be beauty. It is a hydrogen maser source which is operating and is giving out the Balmer alpha spectrum of hydrogen. This indicates a high percentage of hydrogen atoms in the source. Figure 2 is a photograph of an experimental hydrogen maser which was designed and put together in late 1966 or early 1967. This particular maser has had over four years of continuous operation and has operated most of that time as a basic frequency standard.

Figure 3 shows NP-1, which is a NASA prototype atomic hydrogen standard. It was the first of four models which we built, and was completed in late 1968. It has been oscillating continuously since then, when it was not in shipment, and had required no maintenance other than normal efforts required in transportation and shipping. The hydrogen masers are portable. Our hydrogen masers, to date, have about 100 hours of flight time on them. They can operate in transit; they operate continuously in trucks. It is not absolutely necessary to degauss them when they are put in a station. They seem to continue to function without magnetic field problems as a matter of general operation.

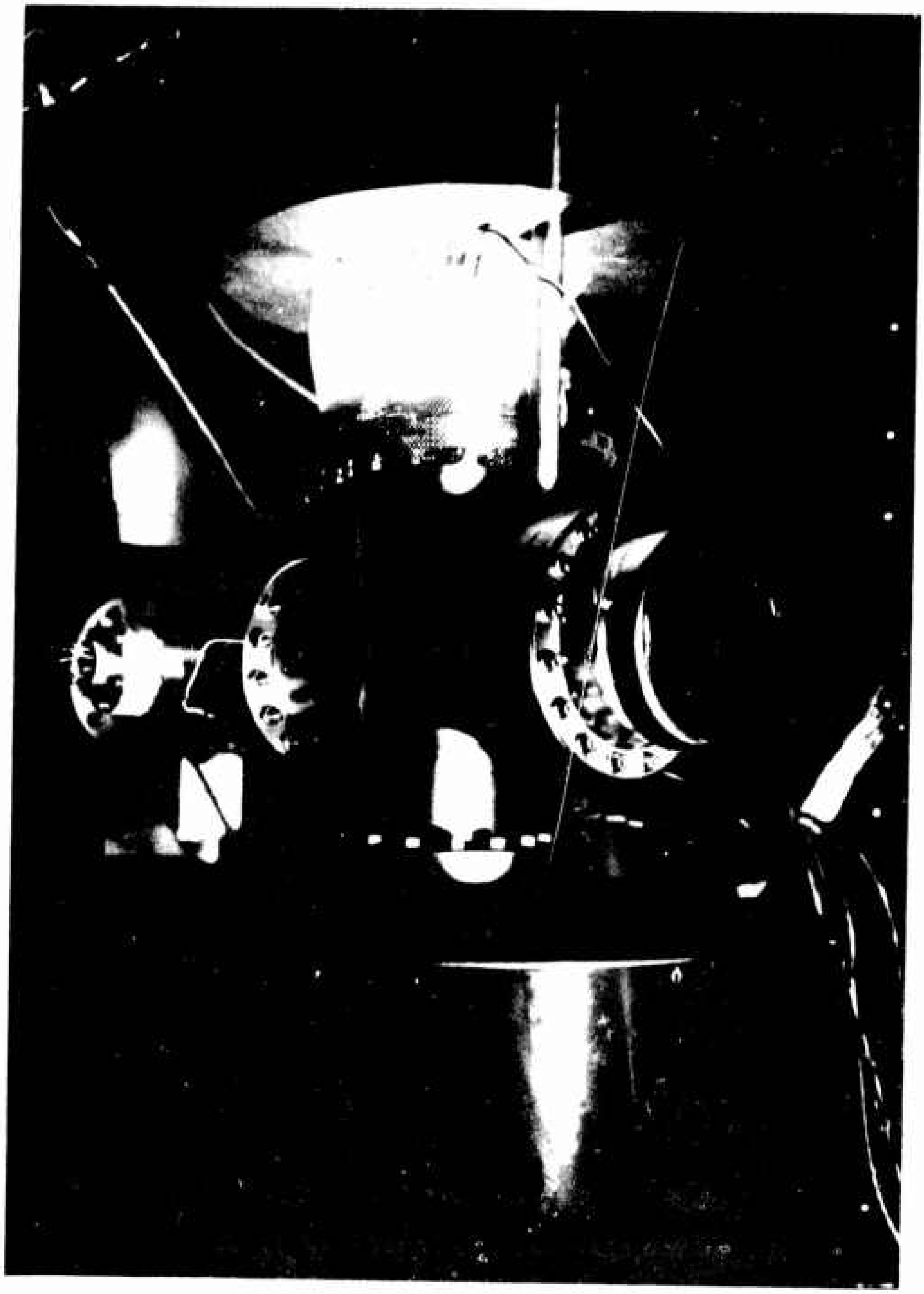

Figure 1. HYDROGEN MASER SOURCE

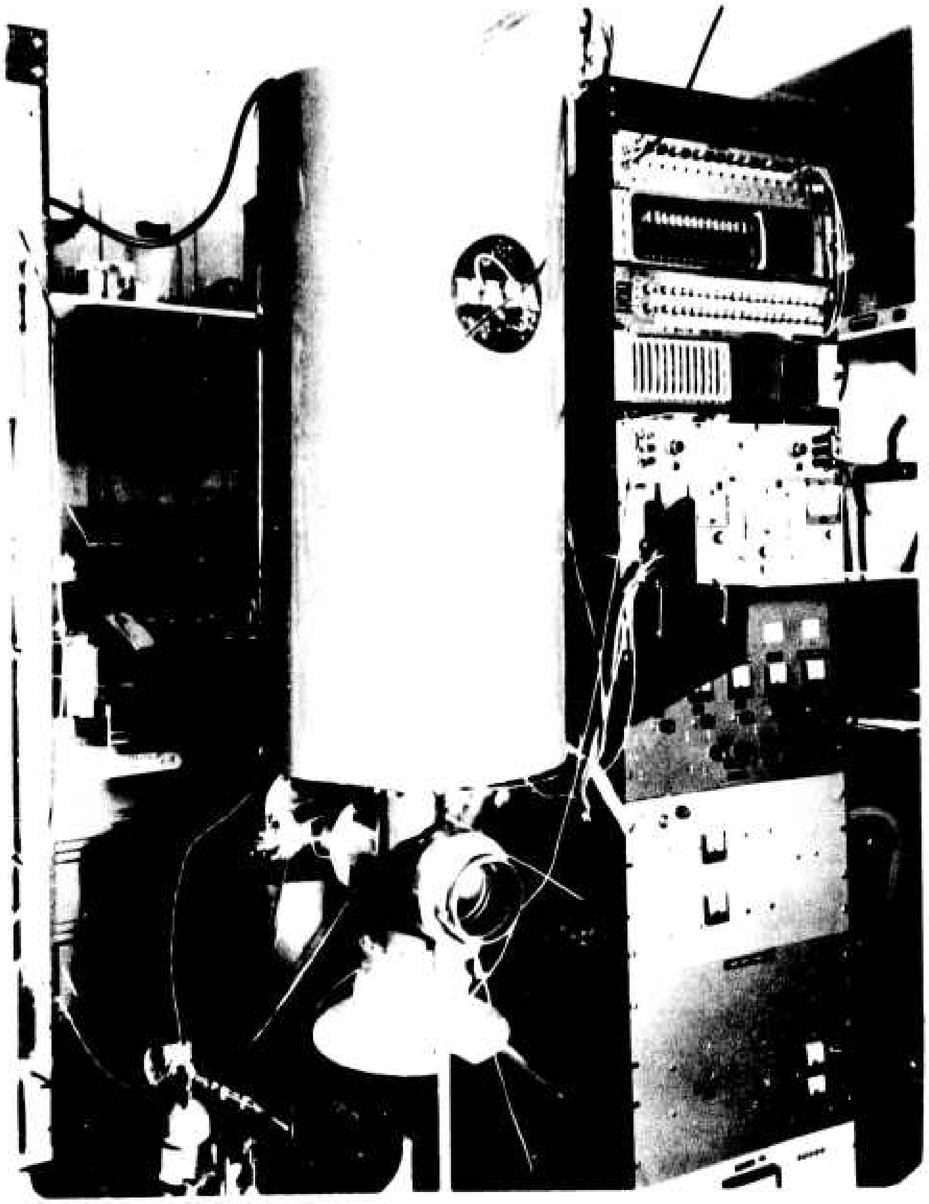

Figure 2. EXPERIMENTAL HYDROGEN MASER

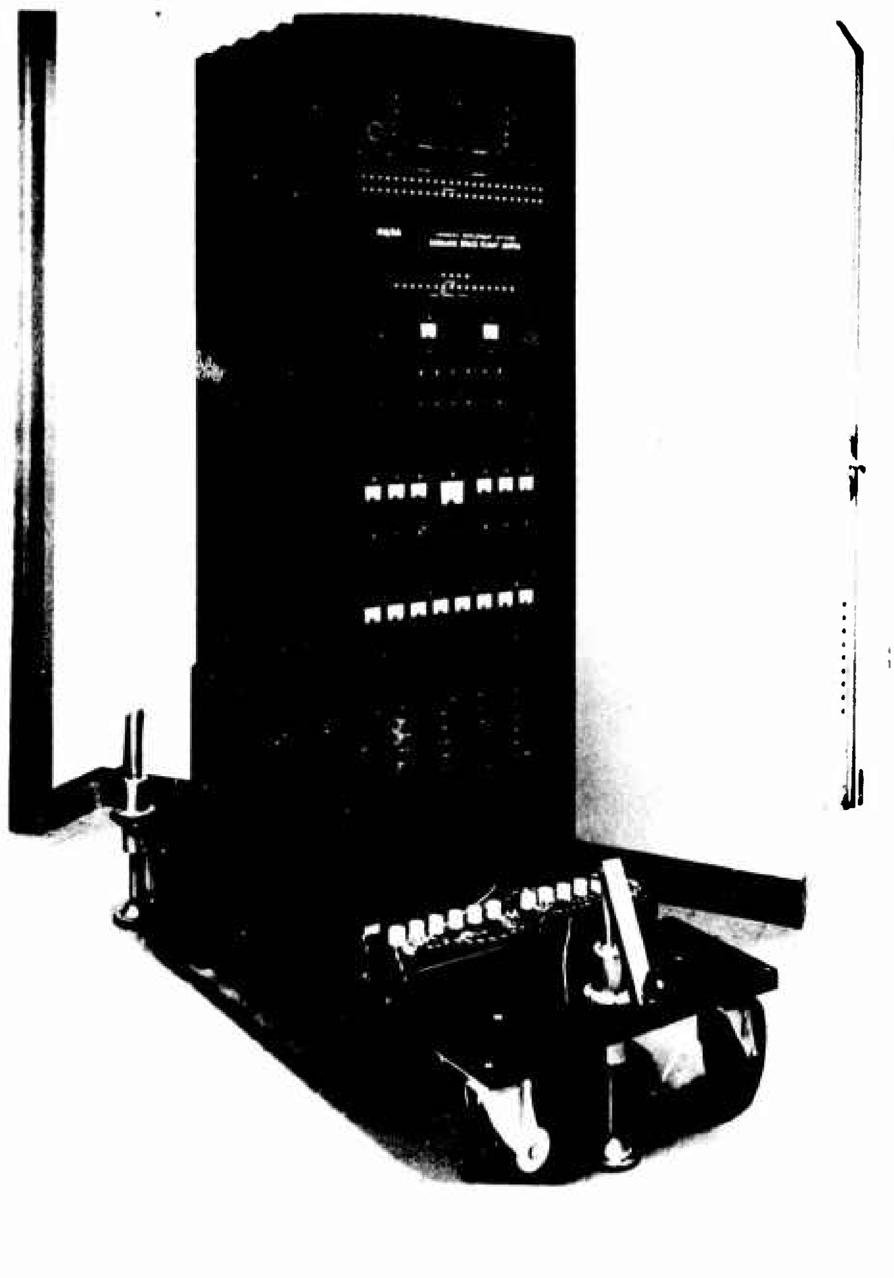

Figure 3. NP-1 -- A NASA PROTOTYPE ATOMIC HYDROGEN STANDARD

Figure 4 gives an idea of the overall Goddard hydrogen maser operation. It gives the continuous operation and experimental use times for NX. In 1969, NP-1 was at Goddard until August and was at MIT Haystack with some VLBI experiments for the rest of that year. It was at MSFN, Bermuda during the Apollo 13 and 14 flights and operated continuously during this period. It is now on-line as the prime frequency standard at the DSN in Johannesburg, South Africa, and it has been there for the past few months looking at Mariner Mars.

NP-2 was a little longer in coming out of the cocoon. It was at our network test and training center for some period of time as well as under test at our Goddard Labs. It was at MSFN in Madrid, Spain during the Apollo 14 flight and is now on-line at DSN Woomera, Australia. These masers are not just being used for Mariner Mars. Several VLBI intercontinental base line experiments have been based upon their use and other experiments in tracking, geodesy and so forth are anticipated.

The NP-3 was at Cal Tech for VLBI experiments in August and September, 1969. It then went to the NBS in Boulder, Colorado. We had some very nice stability curves from it at that time, which indicates that at least for three months operation we were well below 1 part in 10^{13} in comparison with their cesium ensemble. It was at MSFN Goldstone during the Apollo shots. It is still at the DSN Goldstone Pioneer Station on-line for Mariner.

Our experience has not been as good with NP-4; however, it has been used for over a year and a half. It was at MSFN in Madrid during Apollo 13. We replaced it with NP-2 in September of that year. It has been undergoing repair and modification since then. Some new and improved parts have also been put into this hydrogen maser. As you realize, these represent a state-of-the-art circa 1968. We know quite a few things now which can improve our stability curves but, unfortunately, we do not have any data. We have not put any of these changes in these masers but we will work more on NP-4 and I think it will represent, if future masers don't, some of the improved stability characteristics.

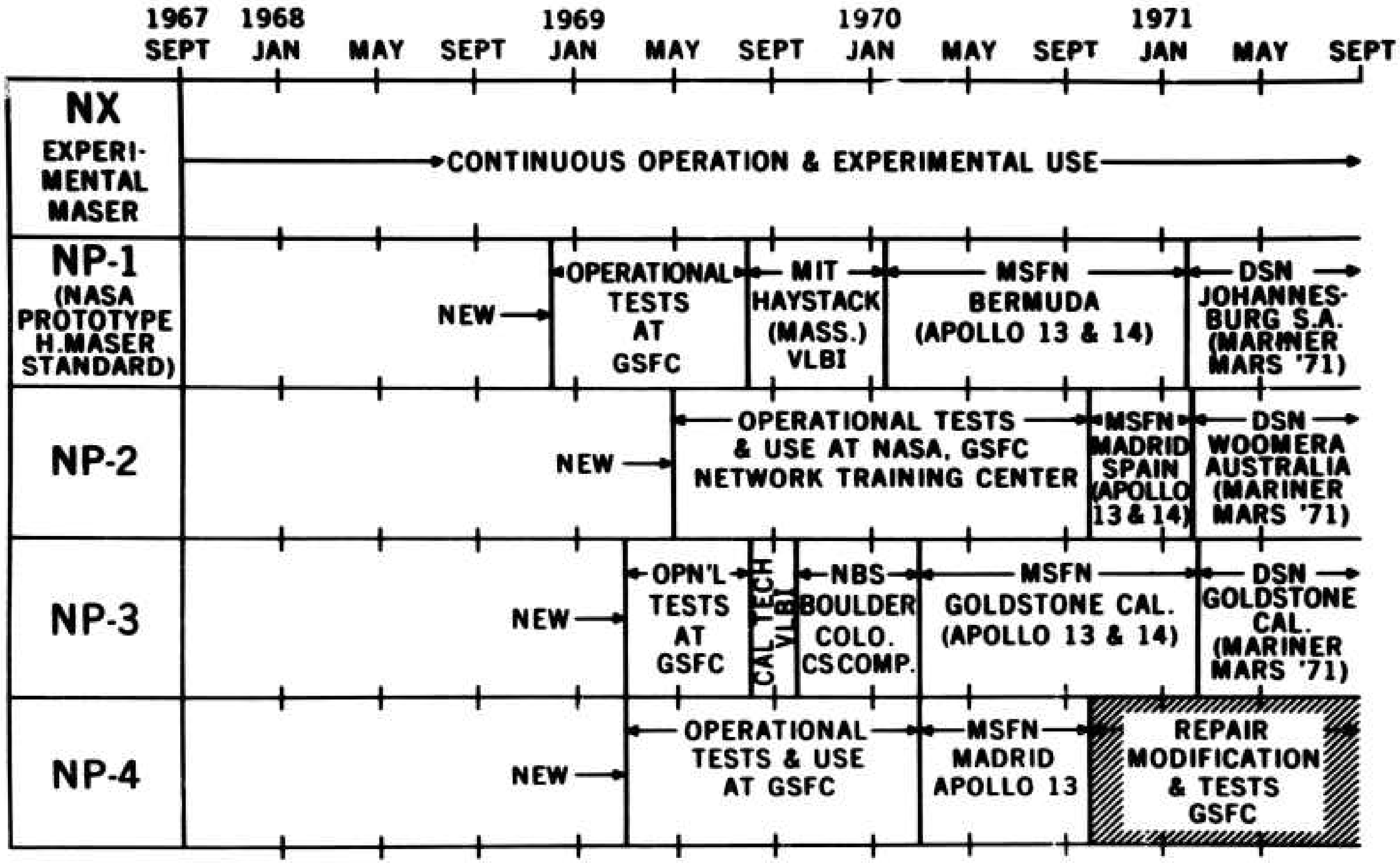

Figure 4. GSFC HYDROGEN MASER OPERATION

Figure 5 shows the stability comparison of instability contributions involved with the USB system at some of the NASA tracking stations and illustrates the effect of the delay in light transmission times. This is a very important parameter when using a standard at the stations. As you can see, this figure relates very much to the useful stability characteristics, not only of the cesium standards and the exciter synthesizers, buffers, etc., but also to the hydrogen masers.

One of the more important points brought up in previous papers was the sensitivity of a hydrogen maser or of similar devices to magnetic field perturbations. Figure 6 illustrates the homogeneity that can be achieved in magnetic fields. In this case, we are not using a hydrogen maser, we are looking at the magnetic field using a beam. Although this resembles cesium beam resonance it is atomic hydrogen beam resonance and it is rather unique. The top curve is a single state transition in hydrogen and is occurring at 8.8 milligauss; the next one is 0.88 milligauss; and the lower one is "0" milligauss. This is with an error of approximately 30 microgauss. If there were a cesium atom going through these shields, the upper curve would show other resonances which would try to crowd into this picture. The nearby transitions would be only seven divisions away. In the lower curves, however, the pattern would be completely washed out by overlapping transitions. This is one of the most fundamental limitations in accuracy and stability with the cesium atom.

Figure 7 shows the transitions in hydrogen and cesium energy levels, with hydrogen shown on the left and cesium on the right. With cesium, there is a total of 35 transitions and there are 7 sigma transitions; with hydrogen, there is a total of 5 transitions with only 1 sigma transition and things can be arranged so that only this 1 hydrogen transition is seen.

Two important points which have not been adequately discussed at this meeting are accuracy and reproducibility. As everyone who has used standards realizes these are very important factors in the capabilities of the standards. Figure 8 illustrates the accuracy capability of the various standards. It also shows our potential stability for hydrogen beams. It is unfair, of course,

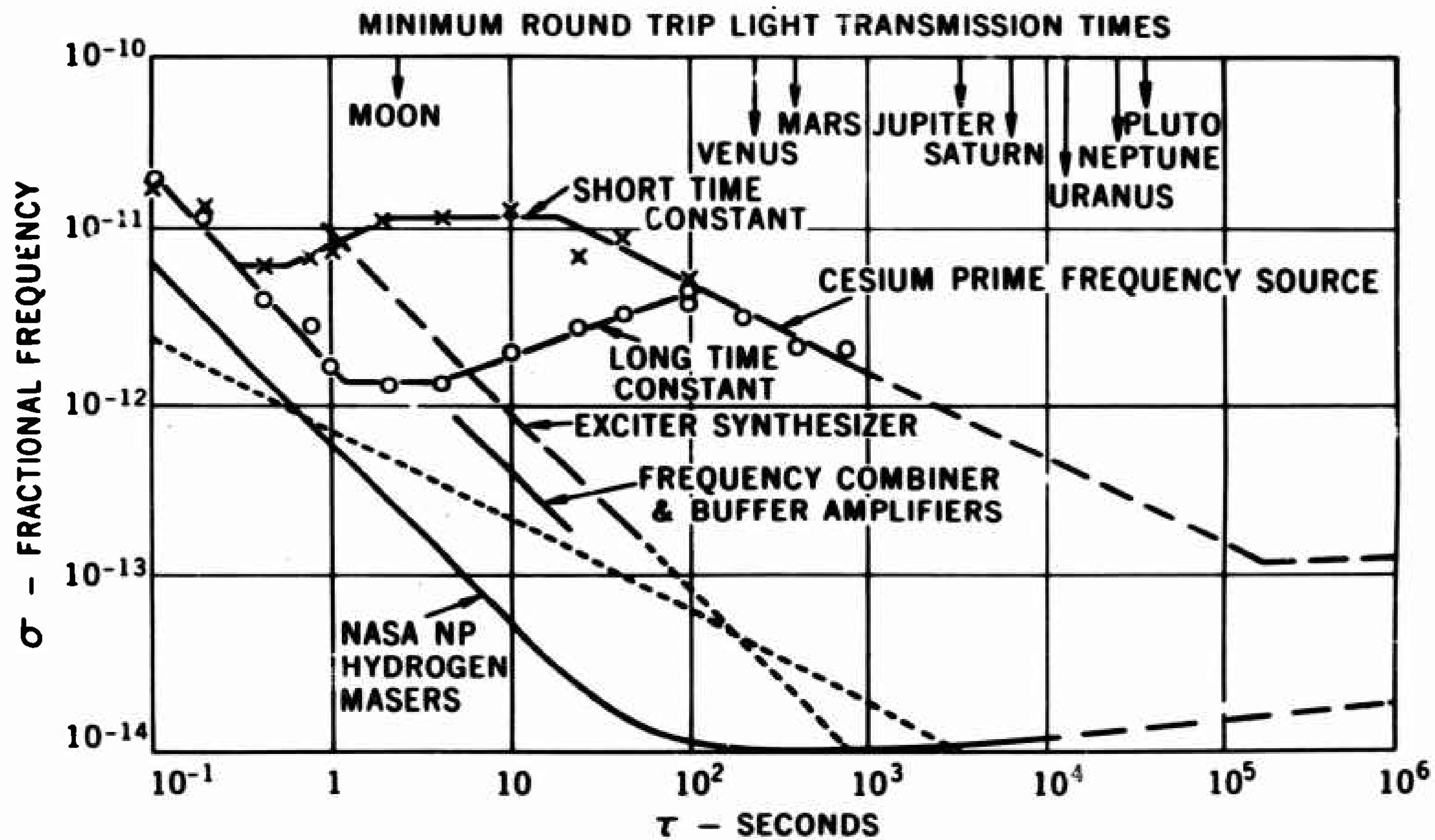

Figure 5. NASA USB SYSTEM INSTABILITY CONTRIBUTIONS

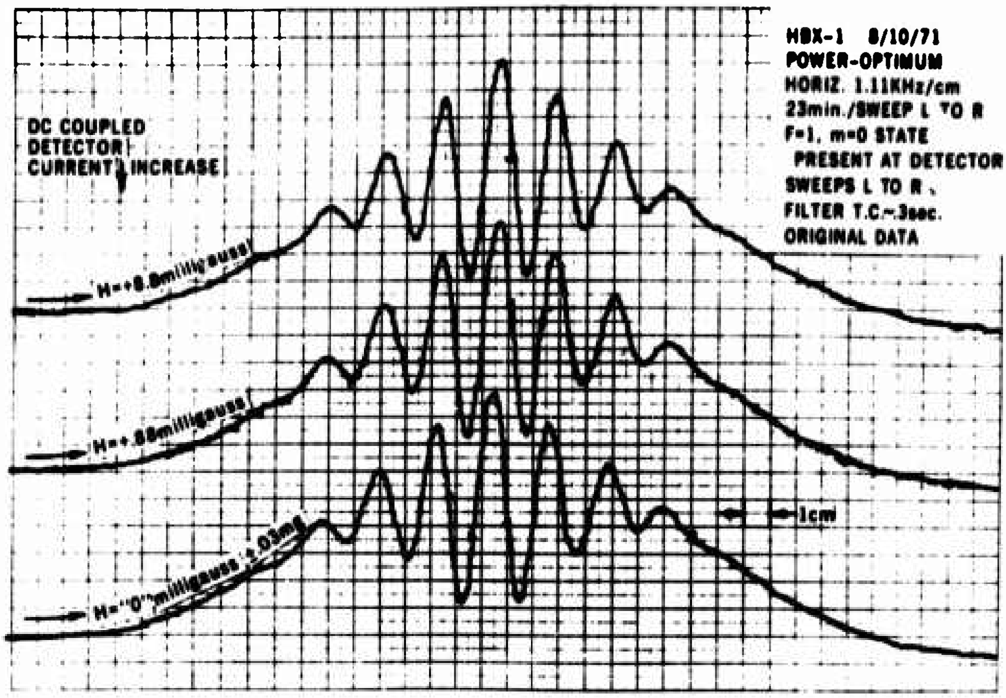

Figure 6. HYDROGEN TRANSITION (F=1, m=0) → (F=0, m=0) at VARIOUS MAGNETIC FIELDS

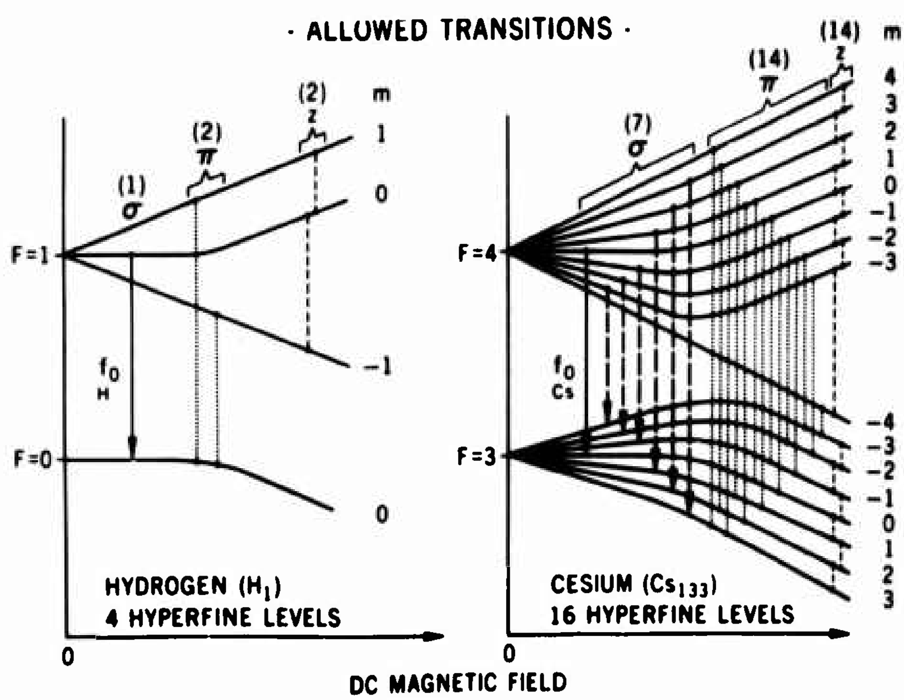

Figure 7. HYDROGEN AND CESIUM HYPERFINE ENERGY LEVELS (Allowed Transitions)

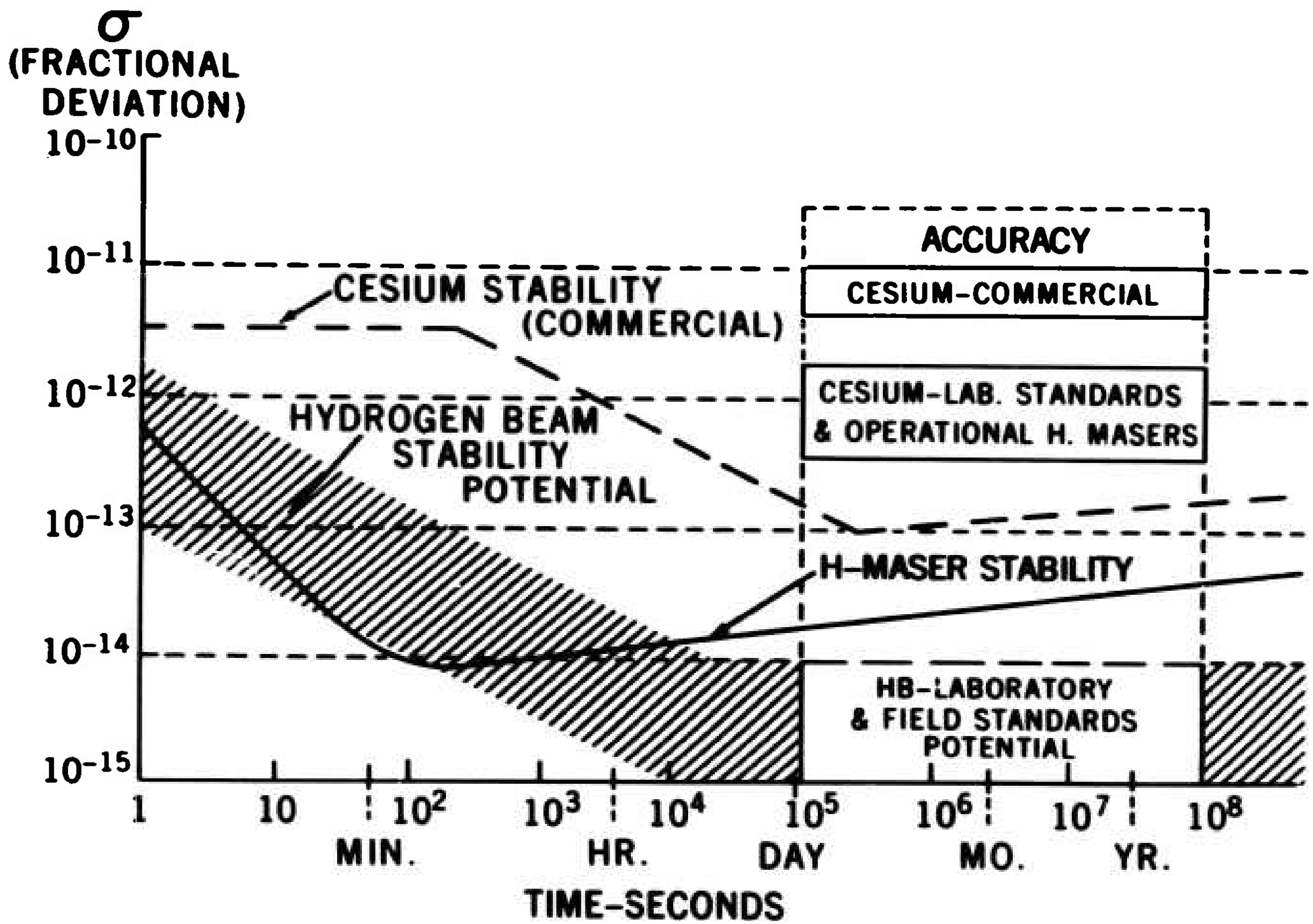

Figure 8. STABILITY AND ACCURACY (Hydrogen Beam Standard vs Hydrogen Maser and Cesium Beam)

to compare a potential stability of a hydrogen beam, an experimental possibility, with state-of-the-art of other equipment. The hydrogen maser, we expect, will be improved. We expect cesium will be improved, too.

A hydrogen beam device is shown in Figure 9. It is primarily designed to test velocity distribution, detectors, and various other problems that used to be considered a real problem with hydrogen beams. Figure 10 is a diagram of this device. We have a source of atoms, transition field region, a detector, and resonances in the laboratory at this time. It is not necessary to have such a large hydrogen beam device. However, it will not be as small as a hydrogen maser and it will not replace commercial standards, such as rubidiums or cesiums, which are much more portable. These will be important in the future, if we can achieve the stability and the accuracy illustrated on Figure 8. We have one operating experimental beam apparatus and have parts for another in the lab. We have just completed, on the drawing boards, a unit which is much smaller, has a higher velocity atomic beam than the one I illustrated, and could be something for the future which is field operable and has all of the advantages of the beam technique. If we are successful with this, we will have two good ways of looking at the hyperfine transition of atomic hydrogen. I have very great hope for it in all of the applications which are coming up in the future.

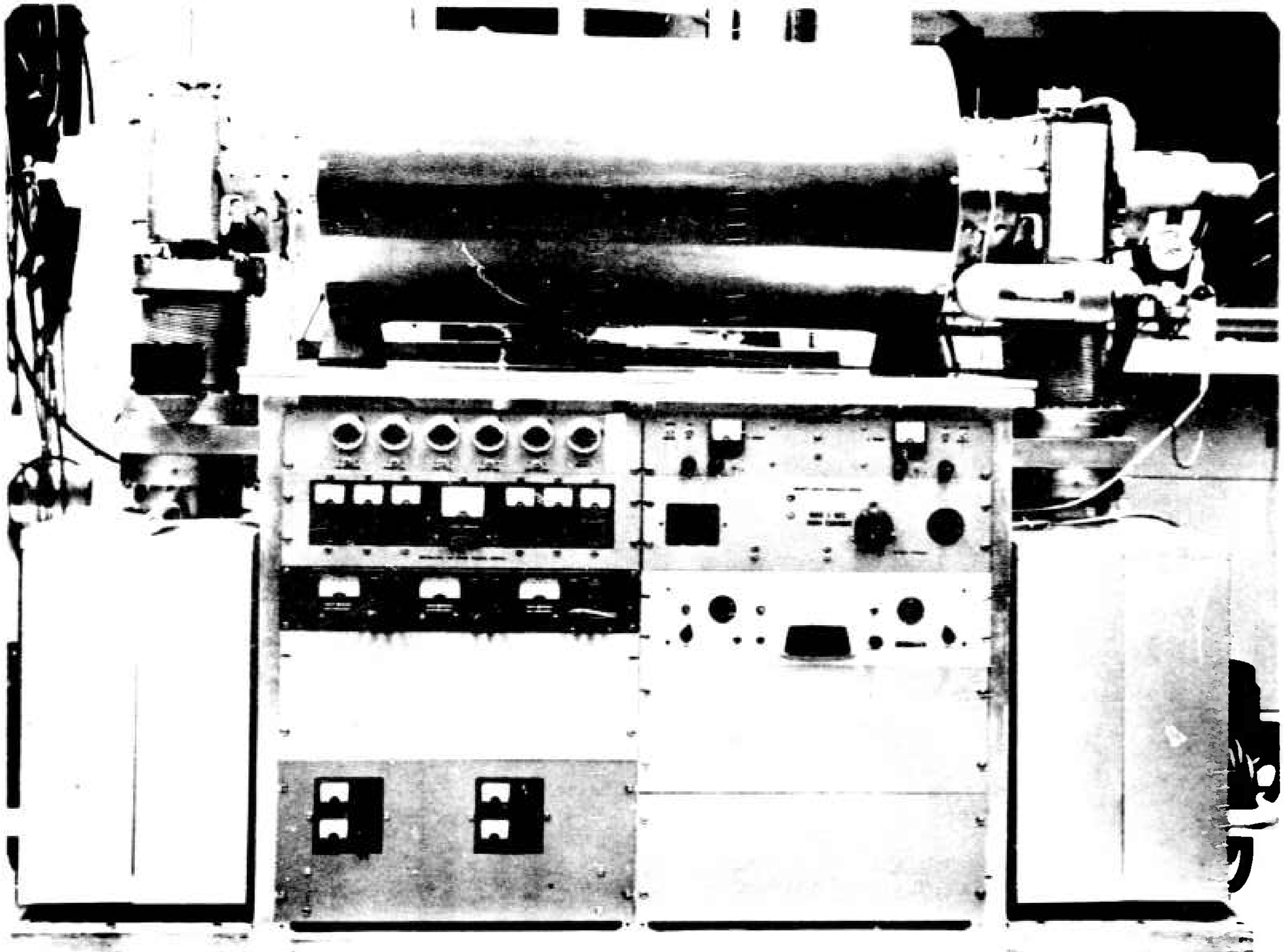

Figure 9. HYDROGEN BEAM DEVICE

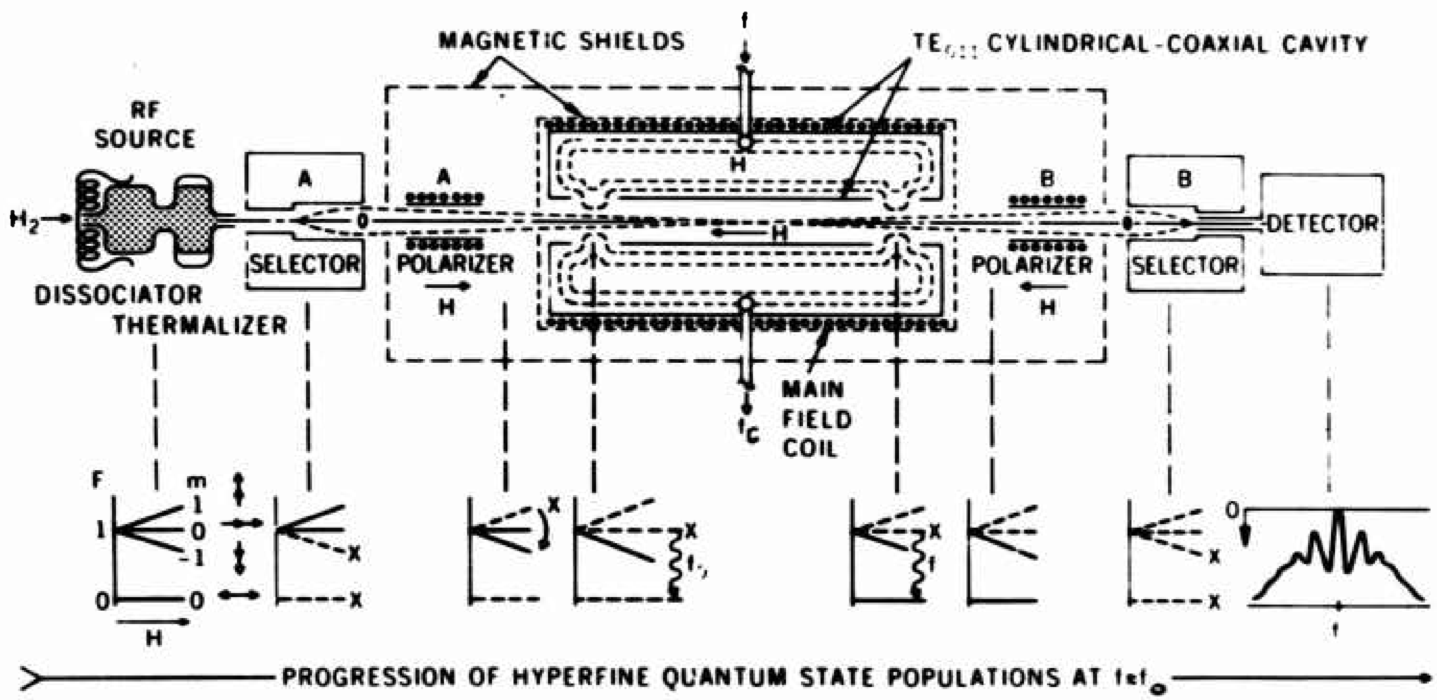

Figure 10. HYDROGEN ATOMIC BEAM STANDARD SCHEMATIC

DISCUSSION

DR. WINKLER: Mr. Peters, I am delighted to see your illustrations and performances, but there are two items to which I would have to take exception. First, is your statement that the first machine is portable. I don't think it is portable in the Navy sense, because I didn't see the crane hook. The second item to which I would like to take exception is your claim on accuracy. It has been the unanimous opinion of the members of the consortitive committee, which was formed to provide recommendations to the International Conference of Weights and Measures that it would be premature to even consider changing the definition of the second from the present reference (the cesium atom) to anything else, including hydrogen. This is because there is no clear understanding as to what way any frequency extracted from the hydrogen atom will be directly traceable, by means of a theory, to a fundamental natural constant. Therefore, I would think that the claim of accuracy is confusing. If you would restrict yourself to precision, I would be in complete agreement.

MR. PETERS: Again, I think that accuracy analysis of the hydrogen beam shows some rather startling results. There is not a unanimity of opinion throughout the scientific community on what we might have in the future, although I certainly am in agreement with the committee, of which I am not a member, that for practical reasons they have the best choice at the moment. Returning to your first question, we have never used a hook for moving masers. However, we have used airplanes and they are easy to transport. We use elevators, we don't carry them on first class, I'm afraid.

DR. VESSOT: I thought I'd add that we are building four small standards at a comparatively modest cost. These are being built for radio astronomers; in particular for NRL (Mr. Easton and Dr. Meyer each will be using one), for the Haystack Observatory, and for the NRAO Observatory. We have an inquiry, I think a serious one, from the Swedish National Science Foundation for the observatory at Onsula, also. These masers are substantially smaller and weigh between 500 to 600 pounds, depending on how many pounds of batteries you try to jam into them. They travel very nicely in the belly of the 747 and we have found that four able-bodied technicians with good stomach muscles can indeed lift them, although they have no handles or hooks on them. Generally, we slide a pallet underneath them. They will travel in the back of a station wagon. So, although it isn't going to be a small rack-mounted item as we've seen for some other standards, there is hope one can wander around the country at modest speeds and with some degree of flexibility with the hydrogen maser, as long as you have four strong people who are willing to lift it.

MR. PETERS: Thank you. Could I comment on portability, and operation in transit? This is interesting in regard to the special relativity experiment. It is known to be possible to make time and frequency comparisons between aircraft flying overhead and ground stations which have very excellent standards. This can be done by looking at a plane going overhead; first in one direction and then in the other, and integrating it over many, many samples with only one moving standard involved. It is also possible that a hydrogen maser could contribute to this experiment, since they can operate under these environments very well. They are not subject to vibration or acceleration to an undue degree. Their mass helps stabilize them a bit. They will operate in an aircraft and supposedly there aren't many magnetic field variations, not many cars going by up there, so that we might get extremely good accuracy on such an experiment. I think that portability is illustrated in these possibilities.

MR. FOSQUE: I would like to ask Dr. Winkler a question regarding the comments he made. Dr. Winkler, you made the point that the Committee for the Definition of the Second, had concluded that the adoption of a hydrogen standard was inappropriate at this time. I wish to make sure that I understand completely your comments regarding the accuracy concerned that the oscillators would not oscillate repeatedly on the same frequency or just that not enough evidence had been accumulated over a period of time.

DR. WINKLER: The principle involved is that you would need to be able to relate the output frequency from the device to an inner atomic condition under conditions of controlled environmental influences. For instance, if you take a cesium atom in an atomic beam, the only force which acts on it while it is in a transition region is a magnetic field, which can be controlled. There exists a formula to give the effect of the magnetic field. It is true as Harry Peters said, in a case of cesium, one cannot reduce that field to the same lower levels as you operate in hydrogen, but at the same time, I would point out, that even in hydrogen, you don't go to 0 field. So, the idea is to require that a clear connection, by means of a physical theory, exists between what you measure at the output and between what goes on inside the atom. An atom, which during the observation is bounced around, is perturbed mechanically by a close contact or proximity to other atom's teflon. For instance, teflon which is bouncing with other hydrogen atoms, is not conducive to a clear understanding and that is the reason why the cesium atom has been recommended, and of course, there are other reasons. It is very easy to detect in a beam apparatus. The accuracy requirements, although not the very highest of all possible atoms, are certainly sufficient for all present practical applications and for these reasons it is extremely unlikely that any change in the definition will be considered for the next couple of years, possibly ten years or so. A fundamental change in the situation would have to exist. But let me clear up another misconception once and for all. Relativity experiments are not proving a special theory of relativity. They are trying to prove, or to be in conformance, with the consequences of the general theory of relativity, because the clock effects are due to the distortion of the matrix of space and time. In the case of the special theory of relativity, you have no such distortion. You have transformation formulae which bring you from one system to the other, but there is no absolute frame of reference. In the case of the general theory of relativity and the application which Professors Hafele and Keating have made of the clocks, you do have absolute frames of reference; any inertial frame of reference can be used for that. Space exhibits a frame of reference, when you talk about accelerations, but it does not exhibit any absolute reference when you talk about uniform motion. So, a clock effect exists only in the concept of the general theory of relativity, because it is a consequence of the distortion of the space time matrix.

MR. FOSQUE: Excuse me, Dr. Winkler, I'd like to again make sure I understood the impact of your comment. My own limited knowledge would lead me to conclude that if a sufficient number of these hydrogen oscillators were constructed and if it was found that over a wide variety of circumstances they oscillated on pretty much the same frequency, although it might take five years for the CCDS to change the definition, it is not fair to say that these won't prove to be a better standard than the cesium could.

DR. WINKLER: That is not what I wanted to say. There may be a better frequency standard, but the question is, do we understand the disturbances. If you build a hydrogen maser without looking at any other standard, where will that output frequency be in reference to one which you have built according to different principles. There is a tremendous amount of detailed information. I think that one of the prime concerns of the Standard Laboratories is to investigate the effects of the observation of these standards. In the case of cesium, you have a more transparent situation than in the case of any confined observation space where you bounce atoms around and expose them to additional perturbations. It is not a question of better or worse, it is a question of theoretical understanding and transparency in that process of explaining an output frequency in terms of an inner atomic situation or constant.

MR. FOSQUE: Could we perhaps have your opinion as to what might happen if we had a well proven, more stable, center frequency for the oscillations without suitable theory for this explanation. Would you care to comment on what the CCDS might do under those circumstances?

DR. WINKLER: I don't think that would, at least under the present philosophies of operations, be considered a possible candidate.

MR. CHI: Dr. Winkler, would you wish to distinguish the difference between the hydrogen maser and the hydrogen beam? For instance, if you're discussing in terms of hydrogen beam, it would not be the same as cesium beam; rather than trying to consider hydrogen maser.

DR. WINKLER: I agree.

DR. VESSOT: I cannot resist. There is a light at the end of this tunnel of accuracy consideration on the hydrogen maser. Dr. Winkler is certainly very correct that there has been a great deal of controversy and some very substantial differences of opinion on how one should represent the hydrogen frequency in relation to the cesium frequency. Not long ago this was done with a set of measurements between Harvard, the observatory at the Smithsonian, and the National Bureau of Standards. The agreement there was within two millicycles at L Band. In regard to the wall shift, this is the effect of confining the atom and having it relatively pounded by the walls as it collides many, many times. The situation is indeed more complex than that for cesium, but it is not without a solution and I think that we are beginning to understand it well and that there are means now to eliminate it. I'd like to point out to this group something that they may not realize and that is the resonance transitions which you've seen in Mr. Peter's illustrations are the very first of their kind in the world. Secondly, they are of a resonance which is in the same nature as Dr. Winkler has described as applying to cesium, namely, that of a beam, where a particle flies and doesn't hit anything. It's in completely free fall. Those resonances, when they are properly explored, will provide us with a very good basis for comparing the corrections that we must apply in the maser to obtain the right frequency. We have both an experimental weapon and a beginning of an understanding of how to correct. I won't go into the details of how it's done, but, believe me, it's beginning to look a lot better.

DR. REDER: I wonder why no one mentioned that there are also some possibilities of improving the cesium standard.

MR. PETERS: Dr. Cutler would be best qualified to discuss that at the moment, I think.

DR. CUTLER: One comment I'd like to make concerning the magnetic field in either hydrogen masers or hydrogen beam devices, is that there are the $\Delta M = 1$ transitions, which will be excited unless the RF magnetic field and the static fields are absolutely parallel. So these do represent some source of pulling that must be taken into account and may prevent, in the last word, the reduction of the magnetic field to the really small values that you would like to use. Concerning cesium, there are indeed improvements possible there. We've been doing some work in our laboratories and will have available shortly, an improved 16-inch tube to replace, in a retrofitable manner, tubes that are in existing H.P. cesium standards. This tube has a cesium flux considerably larger than the previous tubes; hence, has considerably greater short-term stability. In addition, it has greatly improved magnetic shielding and magnetic shield structures to improve the immunity to external magnetic fields and changes in external magnetic fields and has improved the homogeneity of the field inside the interaction regions, so that the accuracy should be improved. In addition, we have included a new cavity structure that is very precisely machined and can be tested for symmetry to very good precision, so that we expect the reproducibility of the intrinsic cesium frequency with regard to its perturbation by phase shift effects, to be considerably reduced. We might expect reproducibility to be better than 1 part in 10^{12}. It's not a guarantee, but that's the sort of thing that we expect. I think that covers my comments.

DR. REDER: One more question for Dr. Cutler. Is there any possibility or has any thought been given to the possibility of eliminating states which contribute to the $\Delta M = 1$ transitions before the beam enters the cavity so that you could then use a smaller C-field in cesium?

DR. CUTLER: You would still have the possibility of $\Delta M = 1$ transitions, even if you had atoms in an absolutely pure state going in. The atoms still have the possibility of making a transition to that state while they're in the transition region due to small inhomogeneities in the magnetic field and just the latent potentiality of making such transitions. So I don't think you can do very much there.

DR. REDER: But, wouldn't it still help if you use ionic excited states in the cavity which really wouldn't make any difference, right?

DR. CUTLER: I didn't understand that remark.

DR. REDER: You can either go from excited to unexcited or from unexcited to excited.

DR. CUTLER: That makes no difference.

DR. REDER: Right. So, Suppose you would have a very good homogeneity, but have eliminated those higher states. Let's say you use f=4 states and you want to use M-0.

DR. CUTLER: That's right.

DR. REDER: If you eliminate M = 1, 2, 3 and 4 states, and f = 4, and you have a good homogeneity, couldn't you stand to reduce the magnetic field, without being bothered by these additional transitions?

DR. CUTLER: Well, you could if you had sufficient homogeneity to guarantee that you could not make a transition to any of the other lower states.

UTC WORLDWIDE ADJUSTMENT

by

Dr. G. M. R. Winkler

Dr. Winkler is Director, Time Service Division, U. S. Naval Observatory, Washington, D. C.

It is the purpose of this paper to provide one more opportunity to remind you of the coming changeovers, to give you some of the reasons and details, to solicit questions, and to find out if you anticipate any problems.

To review the situation, it has become evident during the last couple of years, to those responsible for time-keeping, that one could not continue to allow the possibility of frequency changes every year. The old UTC system approximated UT 2, the astronomical mean solar time, by slight frequency changes in multiples of 50 parts in 10^{10}. If the system were not to be changed this coming January, we would now have to make one step of 100 milliseconds on 1 November, the first of this month. I am positive we would have had to announce a change in the frequency offset from 300 to 400 parts in 10^{10} because we have observed a continual retardation of the earth. I am telling you this in order to make you feel easier about the difficulties of the coming transition. What we are doing is taking this opportunity to make a last change, unless some of our successors again change their minds. I always have to admit this possibility because requirements do change. Still, I think it is going to be a good system. All timing systems will be on standard frequency without offset. This means that we will have to increase our frequency by 300 parts in 10^{10} on 1 January 1972. Approximate synchronization with universal time will be kept by introducing a leap second whenever it is necessary. At the present rate, that will become necessary for the first time at or before the end of next June. When we approach midnight of June 30, we will count 23 hours, 59 minutes, 50 seconds, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60. At the next second (61) it will be midnight and the beginning of the next month. The change will always be introduced as the last thing in the month. It is the intent of the Bureau International de L'Heure (BIH) to announce these steps well in advance. It is absolutely necessary that every nation conform to this, and it is anticipated that each will.

It is the intent to make these steps at the beginning of July and at the end of the year, when necessary. This will happen, on the average, once per year, but it may not be possible at all times to adhere to the dates because there is also an obligation to keep within a maximum tolerance of .7 seconds. This is considered an absolute upper limit and the intent is really to keep as much as possible within one-half second of universal time. Many users require universal time to a greater precision than this tolerance. The correction, the difference between the time signal and universal time, will refer you directly to UT 1 and not to UT 2 any more, because UT 1 is what the observer needs. It will be available by every means of communication; it will certainly be published in advance; it will be listed on our Time Service circulars, Bulletin #7; it will be broadcast by WWV, by WWVH, by every standard frequency station, and by every time signal. It was intended that the form in which this broadcast is made be standardized. Unfortunately, due to largely unforeseen difficulties, there will be at least three different formats in existence. Probably the most widely used will be the standard CCIR format in which the first seconds of every minute are marked by doubling. The number of marked seconds is counted. This gives the correction, in multiples of one-tenth of a second, which is to be applied to the time signal. If it is a minus correction, the marking will start at second 9 and continue through as many of the following seconds as necessary. This format will be applied on most of the standard frequency stations (standard in the sense that they operate on the standard frequencies designated for standard frequency dissemination; that is, 2-1/2, 5, 10, 15, 20 and 25 megahertz). It will also be used on CHU, Canada, on its several frequencies.

The CCIR format will definitely not be used on two time services: The Russian time service and the U.S. Navy time service. We intend to issue an addendum to the Time Service Announcement, Series 1, which gives all the time signals transmitted globally, and the exact format of the codes used[1]. The Russian code will be slightly different than the CCIR code because they intend to provide greater precision than one-tenth of a second. Their intent is to give multiples of 20 milliseconds, because that kind of precision is necessary for modern automatic celestial systems and geodetic operations.

The time service of the United States Navy is in a similar predicament. However, we have preferred, in the face of many boundary conditions and additional points of view, to use the alternative method allowed by the CCIR format which is to transmit the information in Morse.[2] This is possible because up to now there has been a gap between seconds 55 and 60 of every minute. This gap will be filled with an "A" and the Morse digit for "add" and an "S" with the Morse digit to "subtract." This is necessary because we have been notified by several elements of the U.S. Government that they are still thinking about a precision greater than one-tenth of a second. These requirements have to do with celestial navigation and the need to know the rotational position of the earth.

There has been an additional complication in the code which should be mentioned. That is the coming introduction of frequency shift keying (FSK) time signals. The Naval time signals are bound by the fact that on VLF stations it is impossible to provide voice code. One cannot announce the second or the minute or the time of day; one has to provide for a code and since the beginning of the Naval time signals (going back to the station here in Arlington), a so-called American code has been used for this purpose. This code is

1. T.S.A. Ser 2 #14.

2. This is also done by the French time signals.

discussed in Time Service Announcements, Series #2. The American code gives a minute indication, and it consists of straight CW keying; high frequency stations and VLF stations are keyed from the same programming clock.

The advent of frequency shift keying has forced the Naval Research Lab, under Mr. Stone, to develop a FSK time signal format. The difficulty, technically, is due to the fact that a VLF antenna has a very narrow bandwidth. In the interest of efficiency, a VLF antenna has to be tuned to the carrier in the case of CW keying and to the center (between the "Mark" and "Space" frequency) in the case of FSK keying. This tuning is done between the two keying modes but it is very inconvenient for the station to shift the tuning before each time signal. In view of this, NRL put an experimental service on the station at Northwest Cape, Australia in February; FSK time signals are available on this station. I hear from NELC that these time signals can be picked up across the Pacific with a resolution of the order of ten microseconds. CW keying comes on/off with one megawatt of power radiated suddenly. The antenna must start ringing first, and after the signal is removed the antenna continues to ring. Therefore, it is clear that the true beginning of the signal cannot be recognized with great precision, and one millisecond is about what one could get. However, if keying is done by shifting the frequency, it is possible to resolve the transition from one frequency to the other with much greater precision, because the antenna is always under power. This provides the possibility of increasing the resolution to a degree which will allow cycle identification and, therefore, a more precise timing which is the additional benefit to be had from switching to FSK timing.

These changes, however, have put additional constraints on the selection of the time signal format. The NRL and the Naval Communications Command have undertaken a long series of audio tests. They used a number of receivers as phase track receivers and communication receivers and eliminated those formats which would not have been able to convey reliably the time tick information. At any rate, the ΔUT code will be available on most standard frequency transmissions.

At the moment of the changeover we will also make a small time step; we will retard all clocks by 107,600 microseconds. This number, incidentally is slightly different from the one announced by the BIH. The reason is that, at the moment, the Naval Observatory has accumulated a difference of roughly 150 microseconds against UTC as kept by the BIH. Since we incorporate these 150 microseconds, and have selected a round number to make it easy for operators at the stations, and since the time step will be a delay, we will accomplish another thing. We will have an epoch (the fraction of seconds only) in the new improved UTC which will be very close to International Atomic Time as kept by the BIH. The BIH in Paris uses the information from all major timing centers and produces a composite clock time scale known as International Atomic Time (IAT). The stepped form, or the adjusted form of this, is known as Universal Coordinated Time (UTC), and UTC will always differ from IAT in an exact number of seconds. Therefore, there will be two international time scales: one which will not suffer adjustments, the other which will be stepped exactly one second. It is clear that the major time services, and certainly the Naval Observatory, will attempt to anticipate the BIH international time scales (UTC) to as great a precision and uniformity as possible. This anticipation is necessary because IAT is not available in real time; it is available one month after the fact in the form of correction bulletins which are published by the BIH and distributed by the Naval Observatory in this country. However, this cannot be completely implemented in January; we will have to wait another half year or year. In the meantime, it is anticipated that some decisions will be reached jointly between the BIH and the contributing time services as to the necessary very small frequency changes. We intend to coordinate frequencies to within one part in 10^{13} so that we will stay together within very narrow tolerances. We have an excellent example of what can be accomplished in coordination in that which has been going on between the National Bureau of Standards and the Naval Observatory since October 1968. Since that year we have been together with a sigma of 2.5 microseconds. At the moment we are apart two sigmas.

In closing I come back to the possible applications. It is clear that electronic systems which refer to this coordinated time scale will be "on time" automatically. By participating in this time step and the frequency change, they will be reproducing and anticipating very closely the international coordinated time and/or the International Atomic Time. Some of these systems, for example Loran-C, should not be stepped, since there is no need to do so. Next June, when a step in our wall clocks will be made, the step will be done on paper in the Loran system because the new time-of-coincidence tables will go only to June, and in the July table of coincidences they will be shifted one second. Therefore, any operator tracking a Loran-C station will be synchronized and only has to set his wall clock. He does not have to set the receiver because the paper relationship, the time-of-coincidence tables, will reflect that change of the wall clock. It is, in my opinion, the simplest possible procedure, and it will do justice to the requirements of both time-keeping operations, astronomical or navigational and electronic on the other side.

This will also be the procedure to be followed by Omega. It will be a very attractive one because Omega will automatically be on International Atomic Time since the difference will be exactly ten seconds on 1 January; if we make the step adjustment of 107,600 microseconds, we will have the system very closely on International Atomic Time. This is important because the concept of that system is to have it operated as an international system, and it should be on an international time scale as precisely as possible.

Some confusion caused by the changes is inevitable; the greatest confusion and difficulty I see is in those stations which have to tune a crystal oscillator because a change of 300 parts in 10^{10} will be a serious interference with the standard operation of a crystal clock. It will affect the Transit system and Timation. Mr. Easton's satellite clock is not going to like that either, I'm afraid, but let's hope for the best; let's be prepared for it and if you see any difficulty or any other requirement, then please inform the Naval Observatory. We will try our best to assist in the changeover and to accomplish it as smoothly as possible. Many additional clock trips have been scheduled to provide the necessary additional service and confidence in the new system for those users who require high precision time.

PANEL DISCUSSION FOLLOWING THE THIRD DOD PTTI STRATEGIC PLANNING MEETING

PANEL MEMBERS

Dr. A. Berman
J. L. Brennan
J. F. Bryant
A. R. Chi
Dr. L. S. Cutler
R. S. Day
H. C. Folts
Dr. J. C. Hafele
Dr. E. Hafner
LCDR C. E. Potts
Dr. F. H. Reder
Dr. F. W. Rohde
Dr. L. J. Rueger
R. R. Stone
Dr. G. M. R. Winkler

MR. PARSONS:

In the FSK mode of time marking at Northwest Cape as discussed by Dr. Winkler, is it not possible to increase the time resolution by use of a coded sequence, pulse compression?

MR. STONE:

Were you asking whether it were possible to increase the time resolution from Northwest Cape by a coded sequence? There is a problem there in that when we went on to these stations we agreed not to interfere with communications whatsoever. We are just a little bit bound by what they do. It would be possible, yes, if we were allowed to use some segment of time. In fact, the 20-millisecond pulses we have can be used just by the fact that they are repetitive at 20 milliseconds.

UNIDENTIFIED:

I left the Bureau of Standards some years ago and as a user of time announcements on the standard frequency signals, I have found a shortage. I noticed here in the backroom that CHU is being used to get some type of time response. The signals are too weak nationally and we have lost a lot on the East Coast. I'm wondering if the people charged with disseminating time are going to give us back our nationwide NBS-transmitted coverage of time signals on the East Coast? We have the problem of data

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acquisition which must be retrievable by non-trained personnel and I see a loss in the nation's scientific capabilities due to the lack of the time announcements on standard frequencies.

DR. WINKLER:

I would like to answer that and ask that Mr. Gatterer also comment. I think NBS is very much aware of some of these difficulties. The following steps have been taken: one, within the new format of WWV there is an announcement every minute instead of every five minutes. I think the new format is a much better one, much more useful; two, NBS has, of course, made a great effort to accomplish a nationwide television time transfer. Considering the fact that almost everyone has a television set, it will be quite easy to get time--without any sophistication--to at least the precision of WWV, provided that some safeguards are installed to prevent very large propagation changes. But there is no question in my mind that it will be a valuable service. Also Mr. Gatterer has reported on the experimental satellite dissemination of the WWV format, which according to our experience in Perrine, Florida, is a fine system. With a little bit more instrumentation, I think what Mr. Gatterer described would become a useful system. My main concern is that it might provide justification to shut off the remaining high-frequency time signals; I am concerned about that because they are still, I think, the backbone of timing. There are additional things I have been thinking. For instance, you can receive WWV here on the East Coast at practically any time of the day; you just have to remember that the frequencies will be quite different from what we used to receive here in the local area. I think people have not realized that they are still listening at 2-1/2 megacycles instead of at 15 or 20, and at these frequencies the service is very clear and reliable. At the Naval Observatory the times of arrival change at those frequencies only by 100 microseconds from day to day, unless there is severe interference on the air. Also, CHU is a valuable additional service available here on the East Coast. The only reason it is used here is that it comes in more clearly in this noise-infested environment of a major laboratory; CHU is much closer, of course. Also, there is the new, very high-powered station, NSS: Hopefully, when it comes back on with something like a megawatt radiation we will have the time signals on VLF as we used to. The deficit of service you mentioned is of grave concern to us also and we will try to provide some additional services. But I think that in summarizing, some of these systems which are in development and have been mentioned will help to improve the situation. Mr. Gatterer, would you care to comment?

MR. GATTERER:

I think you covered the subject adequately, but I would like to add that after a suitable evaluation, we may be much more optimistic about the accuracy of the television time transfer than you thought possible. With regard to the satellites, I add only that it appears to me a certainty that there will be, from now on, a good, usable satellite service available in the United States; in particular, the experimental ATS satellite service is available so cheaply that anyone who really has any problem receiving WWV has no reason to go without time right now.

DR. WINKLER:

I would like to add one more comment and that is that one should not underestimate some of these difficulties in operating a normal station. If operators have trouble getting WWV to milliseconds--and I know many who have--then the trouble will be compounded with the new systems; they will necessitate more intensive training, there is no question about it. You may underestimate that. The application of much larger corrections will force everyone into that when in fact most people today don't bother about receiver delays, or propagation delays of 8 milliseconds or things like that. I think one should be optimistic but also should be prepared for the additional training that will be required to use some of these more sophisticated methods.

MR. GATTERER:

It has been my experience that WWV is receivable virtually everywhere in the United States. There are some people who have some trouble; for example, down in Florida, in the Miami area, they use a half rhombic antenna to receive it, but they need only one because WWV is distributed by telephone in the Miami region, so all they have to do is get a telephone to hear it without even buying a receiver. The same is true of course in Colorado, in Los Angeles, and here in Washington, D. C. We are becoming increasingly aware that there are very simple things we can do at NBS to make our "nuts-and-bolts" service more readily available to those who need it.

UNIDENTIFIED:

I think there is one point that perhaps I didn't make clear: this is an unmanned, automatic data reception center. No one is there to tune the receiver and the background of time information is necessary on the recorded information; therefore you are limited by the problem of multiple frequency selection on the receivers. The basic fact is that we'd like to see the same kind of service we had before they moved WWV to Colorado.

DR. WINKLER:

In this case, why don't you receive WWVB? WWVB can be received very well as it has a continuing time code and all you have to make sure of is that in your initial installation you install your antenna in a way that will reject or greatly reduce the interfering MSF signal. But WWVB can be received anywhere in the continental United States with plenty of signal strength. I recommend you look into that.

MR. GATTERER:

I'm sorry I can't quite agree, because there are some null spots that give some people a lot of trouble. I can't be quite as optimistic as you've just been, but even in the case of individuals that are unfortunate to be in a null spot, we are broadcasting on the satellite the NASA time code that is broadcast on WWV.

DR. WINKLER:

The satellite service is not available on a 24 hour a day basis, which you seem to require. Am I not correct that these null spots to which you refer are multimode interferences which are not too very far away from Ft. Collins?

MR. GATTERER:

I am thinking of some troubles I've had in receiving it in Washington, D. C. Obviously you are a better authority on that than I am.

DR. WINKLER:

Here in Washington it comes in very well. No problems, if you only want the time code. High precision phase tracking is where the problems are.

DR. RUEGER:

The question was raised as to what the Transit navigation satellite system might do about the time. I want to make it perfectly clear that there will be absolutely no interruption of the accurate service of the system throughout the time changeover. The ground navigation programs use the satellite time as broadcast and the position of the satellite is in terms of the time carried aboard the satellite. On the other hand, this change in frequency did cause us some concern and the solution has been that we will change over to the new UTC time system and we will follow leap seconds. The only real problem arises at the changeover period when we want to predict the orbit in the new time frame. This means we will ride on a longer prediction--for one to three days--and the accuracy of the system could be degraded by thinking in terms of using it fixed-site-for-survey for the three days around the change of the year. On the other hand, the accuracies required for service at sea are easily realized by the prediction of a longer period of time. The change itself has not been issued. It will be published to all users in sufficient time so thay can take account of it. But we expect that all satellites will be on the new time system within three days before or after the time change.

MR. LIEBERMAN:

Since this was billed as a planning conference I wonder if we could discuss the real need for real time, for PTTI. We've skirted it, we've talked about what we've done, but we're just not climbing a mountain because it's there. I wonder if we could address some real need in the immediate future and what we see in accuracy required.

DR. WINKLER:

If I understand, Mr. Lieberman, you want to find out who needs something that he can't get today.

MR. LIEBERMAN:

The question always comes up with communication people and navigation people: Why do we need precise time, to what accuracy? We have put out a questionnaire, but the questions are general and I wonder if we can get into a discussion here of the real need for precise time.

MR. BRENNAN:

Well, I can only repeat what I said this morning: while a basic decision hasn't been made within the FAA on a requirement or national standard collision avoidance system, our prime efforts have been devoted to a synchronized system--time frequency system--and the requirements as evolved in the ATA's technical working group call for a ground synchronizing network in which each ground station is to be within plus or minus a half a microsecond of a master time, which hasn't been decided on yet either. So I can only say that if in the future the decision were made to select the time frequency system as a CAS, then a ground station network would be needed and therefore we would need PTTI. The methods by which the ground station would be synchronized to a master time are still conjectural. We have heard various methods described and we should take a look at them all and try to pick the most efficient, optimum system.

UNIDENTIFIED:

I would like to turn Mr. Lieberman's question around and suggest that generally speaking one develops something new and then finds ways of using it. I recall the days of the Laser, which was often cited as a "solution in search of problem". I think this may be, to a very large extent, true of time standards and particularly this example of a collision avoidance system, which wouldn't have been dreamed of had there not been a prospect of very precise timing and some generally well-accepted experiments perhaps ten years ago.

MR. BRENNAN:

I think that's true.

DR. REUGER:

Navigation happens to be one of the frontiers opened up by precision time and frequency. It wouldn't have been possible many years ago to have a satellite with the quality of oscillator and timing we now have. I forgot to mention that we do have a problem with satellites in orbit in the Transit Program--we can't change their frequency; but fortunately the system was devised to have the time and the frequency as independent variables and we can take care of the time independently. In the future, the quickness with which we can get a position fix has to do with the time synchronization and using technologies other than Doppler, primarily the ranging type systems. You heard that the Loran-C system has hundreds of nanoseconds resolution. If I understand some of the aircraft people's needs and desires, they would like to have a 50-foot resolution on a ranging system. This represents a timing system that has significance, either relative or absolute, to 50 nanoseconds. And these are things I think we can't do today.

DR. ROHDE:

I'd like to mention also that in navigation or in survey and positioning techniques very precise clocks are highly desirable. If we had clocks available with one-or-two orders of magnitude more accuracy, the Long Range Precision Determination System (LRPDS), which I discussed yesterday, would automatically be a one-ranging system and calculation and data reduction and many other things would be much easier. The same would apply to the Defense Navigation System where the Army is the potential user for positioning. So I would say there is a need for more advanced clocks which are field worthy rather than say there are no requirements.

DR. WINKLER:

I would like to go back to some of the basic philosophies in the use of time frequency. I think in each case the primary question of systems concept would be "why do we want to introduce clocks?" For example, we have a television system that is a synchronized system: every user locks onto the synchronization signals on the air on the same carrier from the same transmitter providing the service. In this case, hypothetically, we would say if that is a candidate for a true time-frequency modification, why would we like to have a clock in the receiver? The answers I see in those systems which have turned towards the application of clocks have been these: one, precise one-way ranging measurements, distance measurements, that are one-way because you don't want the user to retransmit; two, the collision avoidance system, where you are forced to communicate on just one frequency but have many, many users who have to operate on a time-sharing basis, the same requirement you have in channel packing; three, you want to use a clock because of its anti-jam capability, because you know what the other side is doing without having to receive it continuously. In my view these are the main applications. When it comes to making such precise measurements as 50 feet (which is 15 meters, I think) it may be useful, in the system's conceptual development stage to ask if it is necessary to have this in the form of a worldwide system. If not--to do it regionally, if a regional system is sufficient--you suddenly have no problems whatsoever and can get the system into operation immediately. I am suggesting these alternatives because I think we ought to keep our minds open and we have here, I'm sure, quite a few people responsible for the development of systems concepts. It is necessary to intercompare other possibilities. Considering the problem of many users operating, necessarily, on the same channel, one can make a virtue out of the problem by correlation. The same thing is being done in communications where you can superimpose several different channels on one channel by using spread spectrum methods, as Mr. Stone has mentioned. In addition, his timing application can also be superimposed on existing communication channels so that they don't interfere crosswise. We have heard another presentation concerning the same principle. It can be extended, given a sufficient signal-to-noise ratio of course, to hundreds or thousands of different channels. So there is a variety of ways out, and I think it may be a mistake to discount all of these without really investigating them on their merits. My greatest concern is that maybe some of these 10-foot or 50-foot precisions may have overlooked the substantial difficulties of propagation time effects, geodesy uncertainties, and things like that. There are really substantial effects which are at least of the same degree of difficulty as the unavailability of clocks which will keep one part in 10^{15} for a year.

DR. REUGER:
There is one I think you may have left out, which has to do with the LORAN-C type of operation on a range-range basis. It is very hard to keep a clock to the correct value over very many days without some kind of reference.

DR. WINKLER:
That is also not 100 percent correct. In the Journal of Navigation, I think of last year, there is a description of an iterative method by which you first get your hyperbolic position and then you get your time and you find better solutions in using the circular geometry. You bootstrap yourself into greater and greater precision and you don't need time from the beginning at all.

DR. REUGER:

That's very fine if you are in a favorable location. If you are in range of only two stations, I do not think that system works.

DR. WINKLER:

Yes, I agree.

DR. CUTLER:

I'd like to just make one comment in regard to worldwide time synchronization. We're rapidly approaching the point in our accuracy (or stability) and measurement capabilities where we are going to run up against a fundamental limitation: the earth is rotating with respect to "fixed" stars and if one looks at the problem of clock synchronization in a rotating coordinate system--that is, rotating with respect to the fixed stars--he finds that it's impossible to synchronize clocks around a closed path, which encloses the origin of this rotating coordinate system. These are small effects, but nevertheless they are starting to become noticeable. In fact that has a lot to do with Professor Hafele's experiment. I just wanted to make that comment, that this is a fundamental limitation.

LCDR POTTS:

I would like to comment on Dr. Hafele's presentation. I think the real significance--the practical significance--is to make clock comparisons with greater precision than we are doing now, 100 nanoseconds, plus or minus. If we are going to compare clocks which are at different gravitational potentials then we are going to have to apply the principles investigated by Dr. Hafele.

DR. HAFELE:

I would like to suggest something that might be amusing. To bring the effect out more clearly you could imagine you have a string of cesium beam clocks on the surface of the earth around the Equator; line them up every mile or ten miles and start synchronizing them by the Einstein Synchronization Convention, by sending a light beam to the next clock in the row, reflecting it back, then assuming the time it takes for the light to go from one clock to another and back is just twice what it takes for light to go from one clock to the other clock. By the time you get the string synchronized all the way around you find that the last clock in the string is not synchronized with the first clock, and the difference is 240 nanoseconds or a quarter of a microsecond, considerably larger than the kind of synchronization we've been talking about here. So in fact this is at the Equator; as you go to higher latitudes the circles get smaller and the effects get smaller, but any closed loop on the surface of the earth in principle cannot be synchronized using that synchronization convention. There will always be a little bit of difference; it takes light a different amount of time to go around the loop one way than it does around the other way, so in principle it is not possible to synchronize the clocks exactly. This is a question I think the world community will have to decide: How shall we synchronize our clocks? If we synchronize them according to Einstein's convention, there will always be these discontinuities in the synchronization. In 10 or 50 or 100 years we may come to the point where we set up a coordinated network of times over the surface of the earth or choose another synchronization method that would eliminate these discontinuities in the synchronization. Of course you can calculate, knowing the rotation of the earth and the location of each clock on the earth, how the synchronization should be adjusted so there would be no discontinuity.

MR. PARSONS:

The use of LORAN-C is not universal. If one has to observe an unpredictable event or even a controlled event over which he has some uncertainty as to its time of occurrence, we will be a long time getting to better than microsecond accuracy I should think, if we are now talking about times and coordination in the realm of 10 microseconds. To me this amounts to a problem of looking at time resolution elements for an unpredictable event involving perhaps, as it stands today, 50 million resolution elements, the synchronization of stations is that poor. Now if it got down to 5,000 or 50,000 resolution elements, I'd still have a problem. We're talking here about uncoordinated time and it's just not being effective. Mr. Folts, in his efforts in the DCA, is trying to get a coordinated viewpoint on what the requirements are. Hopefully, we'll get ten microseconds throughout the world--hopefully we'll get one.

MR. WATSON:

I have an observation relative to timing needs versus the user's operation that ties in somewhat with Dr. Hafele's comments on time gradients and the concern over time shear. Basically the user of long-haul communication links or long-time transfer travelling clock type applications may have to be content with a time resolution, a communication event recognition, that is defined by the anomalies or the variation or the noise in his communication media. That, basically, will set his timing requirements. In the case of collision avoidance we can take a time gradient over the United States that is time shear in a local area, that we could administer without two ground stations in an immediate area and exhibit a time shear to airplanes coming into that area. We could think of time for the CAS system or time for any of these other systems having controlled gradients staying away from time shear. Say that we have a hard and fast master, a master for reference to the CAS system; then within the United States, I think, time can undulate or be a potential level as long as the gradients within an immediate area do not present shear to the user.

I don't want people to be overwhelmed with this number of plus or minus a half a microsecond. I think that within the immediate area of two ground stations having access to a single airplane, we're thinking in terms of the plus or minus one half a microsecond. But I think that the West Coast and the East Coast can be as potential levels operating as a membrane of time.

DR. REDER:

I have a question for Professor Hafele. Will you run into the same problem you have when you line up the string of clocks around the Equator if you line up the string of clocks along a meridian?

DR. HAFELE:

First, I'm thinking of the ideal case where the surface of the earth is equivalent to the average sea level so that we don't have altitude problems changing the rate of the clock; and I am assuming we have the ideal standard clock, something like an ideal cesium clock, which has an intrinsic frequency that can only be varied by the two relativistic effects. If you have a string of clocks in a great circle going around the poles, you can use Einstein's Synchronization Convention along the latitude. The speed of light in a rotating system is different with the rotation and against the rotation and that's what causes the discontinuity in the synchronization. But crosswise to the rotation it doesn't matter which way you go, so if you synchronize the clocks around the poles the last clock will indeed be synchronized with the first.

DR. REDER:

How would it be if we plaster the whole earth with cesium standards both along the meridian and along the Equator and take parallels and then synchronize all the clocks along the meridian to the ones on the poles?

DR. HAFELE:

If you set a clock at the pole and let that be the master and synchronize along the meridian you will find that along the latitude lines where you go, say, from Washington to Los Angeles, those clocks will not be synchronized, they will not be in perfect synchronization. You defined your synchronization procedure -- there's ambiguity in the synchronization, there probably are some more facts. Fortunately the earth doesn't turn all that fast, so we're only talking about, at most, a quarter of a microsecond. But you're right, that would be a different synchronization procedure and if you started at the pole and synchronized down then as you went from one meridian to the next, they would not be synchronized.

DR. CUTLER:

Just another couple of comments along this same line. No matter what synchronization technique you assume to use you will find it is inconsistent in a rotating frame of reference. For example, if you tried to synchronize by carrying a clock, and tried to synchronize each clock as you went by, you'd find the same sorts of results as you would with the Einstein convention. Also, if you carried a clock along a meridian so that it crossed the poles, you would find that as you closed the loop there the results would be consistent. Everything hangs together and you get into trouble whenever you enclose some component of the rotational axis.

LCDR POTTS:

It seems this discussion has circled around a problem which is going to crop up in the future; the problem which was tackled last year at the meeting of the Consultative Committee for the Definition of the Second. That was the specification of an origin for an international atomic time scale, something which is extremely difficult. First of all you'd like the location to be accessible, so the center of the earth is obviously not convenient; it's convenient mathematically but not practically. Then, from the point of view of space travel, the center of the earth is not as convenient as the center of the sun, which is even more difficult to get to. This is an important consideration and will have to be tackled in the future.

DR. WINKLER:

I don't think it is. You can always place a reference point on the pole, and on the pole you wouldn't have any difficulty except with the temperature. But I don't think there is a problem because you just have to specify one location to which you refer all operations.

DR. HAFELE:
I think there is a solution to the problem: not using Einstein's Synchronization Convention. We simply choose a synchronization convention which gives all clocks being synchronized no discontinuities. There's nothing wrong with Einstein's convention, it just causes discontinuities in the synchronization. If you choose a convention that's compatible with the particular angular rotational speed of the earth, then they'll all be synchronized.

DR. HAFNER:
This is a very interesting subject; however, for practical applications, I don't feel it is going to be very important in the future. For the practical application of timing we are concerned about two different things, one being the synchronization of a rather large communications system; here the nanoseconds are not terribly important. For navigation and position-finding, the position determination systems--the really high requirement appears to be 10 nanoseconds or less; however, here we are not talking about very long distances either, and there will be no conflict between systems which are worldwide synchronized to, let's say, half a microsecond and having local synchronization to a much higher degree. The emphasis here is that even in the future we are not going to be very much troubled. However, as far as the requirements of stability are concerned, if we are thinking of one-way ranging and the applications existing in the Army, the size of the equipment that is going to be used in the LRPDS and the size of frequency standards that have the stability better than a part in 10^{11}, are in no measure comparable to what is in existence now. At the present time you can't put the cesium standards on a man's back and this is what the Army is going to need, frequency standards that can be put on a man's back if the one-way ranging systems come to fruition.

MR. WILCOX:

In geodesy we worry a great deal about polar motion, nutation, precession, and I'm wondering, since we are talking about time and mean solar time, how will all this be when we develop that observatory on the pole. I'm sure that sounds like a very nice solution to a light problem, but it's a very serious problem to a geodesist.

DR. WINKLER:

I'm not sure that I understand the full context of the question. You are concerned with improving XY coordinates of the pole.

MR. WILCOX:

My main problem is that in our computations in geodetic astronomy we have to worry about the nutation of the poles and I'm wondering if, first finding the North Pole would be a problem and second, once we found it, would our International Latitude Service tell us we had a wobble since we have a cyclical process of nutation and every 26,000 years we precess? I'm wondering if this will be a problem in terms of this half a microsecond.

DR. WINKLER:

No, we are talking about clock time on one hand and astronomical time or UT-1 on the other. There is no link between these two except the coming 1-second step and the corrections bringing you from the time signal to the clock time you need. But to understand your worry in a larger context, the Naval Observatory is well aware of the need to improve the polar coordinates and the evolution of the UT-1 determination. To place an observatory on the pole is something we have quite actively investigated, and we may yet do it, but there are horrendous difficulties. If you put it on a piece of ice it will drift across the North Pole and you really don't have the stability to measure .01 second of arc. If you go to the South Pole there are other difficulties, among them that the ice is still moving at a speed of 19 meters per year and we are here trying to measure decimeters expressed in angular resolution. So the problem you are touching on is really an astronomical, geodetic, geophysical problem and is not directly connected to the questions with which we are concerned in this conference. But I think it will be of interest to a smaller group and would like to have more private discussions with you on that point.

MR. CHI:

I would like to concur with the statement made by Mr. Lieberman. I think this is probably a good opportunity for us to find more applications in light of the fact that the present funding is low and many people who are working in the field, particularly in frequency and time, will need justification. If we could classify those who might need from 1 microsecond on down and maybe 1 to 10 and 10 to 100 -- if we could only find out where you need it and what you need it for--it probably would help us in long-range planning.

LCDR POTTS:

It seems to me one of the most important things is to conserve our government's dollars. One of the ways we can do this is to coordinate the requirements of the users for time. We've heard of a lot of systems described both this year and last year and many of these systems could exist in their own timeframe without any reference to someone else. There is no reason why the CAS system, for instance, has to be referred back to some master clock somewhere; it could have its own master clock. In fact the Bell System is now planning a scheme for its digital communication facilities by which each facility would have its own master. Some people are attempting to persuade the Bell people to change their mind. The consequence of course would be a proliferation of cesium standards. We would have all these little independent masters--master of this, master of that, master of everything, and it would become difficult for users of one service who want to shift to another service, in another part of the world or local community, to coordinate. There are benefits to be derived from using a common time reference or common frequency reference and to this end I would like to see some efforts devoted in this meeting.

MR. LIEBERMAN:

I think most of our discussion here has been devoted to time rather than time interval and frequency. I wonder if we could discuss that in the next two minutes.

DR. WINKLER:

I think what surfaced in the last ten minutes is something like an identity crisis within the PTTI community. Why is the subject worthy of the simplest consideration as an entity and why is it useful for time-ordered systems to be coordinated so they can interface easily with each other? That we discussed last year. I think it is of continuing concern in respect to an element in which our subject area appears--it's clear the simplest one to satisfy is synchronous frequency. You can accomplish what you need by putting standards with great absolute accuracy into each location where you need it. Reference is the cesium atom--wherever you have it. You get it by buying a cesium standard. Depending on your requirements, you may be satisfied to buy a secondary standard which you send to a calibration center regularly. In designing a system of operations one has to weigh costs doing it one way versus the other one. On the other hand you want to standardize, you want to have a few different types in service, you don't want to get examples of all the possible frequency standards. These are the general considerations. The next level would be synchronization. You don't worry about what you synchronize as long as within your communication or within your measurement area you operate synchronized. That is a timing concept. And finally, the third level is to know epoch or date. Some people prefer the term "real time", but the best in my view is simply "date", the time of the day. This is the most difficult to satisfy because it requires absolute accuracy in timing and the adoption of a reliable reference.

MR. FOLTS:

I just want to comment on the project "Music Man". The things we were talking about this morning seemed to get right back to what we are trying to do in our approach to the worldwide distribution and application of precise time and time interval. In communications we have a definite need for not really so much for epoch time or precise time, as much as the time interval, frequency. Another point is that means of getting the time around the world-- it's just another piece of information--can be passed electrically by various means, and obviously a communications system is a means. This can be done with various levels of precision, accuracy and so on. So really we've found that the DCS has two roles in this area. We need to establish something to satisfy our own requirements and this subsystem can also be available to many other users, perhaps saving a redundancy on individual systems that could be tied in together because it doesn't seem to be any more difficult to put them all onto one than it does having each person run by themselves and of course they don't have anything to fall back on either. Mr. Watson of McDonald-Douglas, commented earlier on this grid system, that we must develop a basic system hierarchy which really falls into that concept. Major prime nodal points can be distributed throughout the world and tied-in quite easily on down the hierarchy at varying degrees of accuracy and precision. This is by the means of getting further on down the different media to the requirements of the user you are trying to reach. So this is where it all falls into a hierarchy type of system. In the initial stages of Music Man, we're really just getting rolling into this. We have two committees working right now; the Requirements Committee is really trying to find throughout DOD all your requirements for time and frequency that you are aware of, both immediate requirements and future requirements; we're trying to basically catalog these, yet have it flexible enough where they can keep being thrown in as they come along. The other committee, the Concepts Committee, is really in two parts; in the first part, while requirements are being brought together, we're trying to look through the complete state-of-the-art, all the technology methods, possibilities, and their potentials to bring them into a central plane. Also there is one very important point here - people think they know where they need time and frequency, but I would venture to say that there are an awful lot of applications for a subsystem or use of time and frequency that people aren't aware of where great potential benefit can be gained. Any type of system or equipment that is time or frequency dependent can benefit. You say we only need a part in 10^3 or part in 10^{11} for this particular equipment, perhaps that piece of equipment was developed back when that was all that was economically available. Today, if we can get up into parts in 10^9 parts in 10^{12}, how would the design concept of that equipment be changed, simplified, made more efficient, so on. When we get all this together, then we will try to define a system hierarchy that can solve these immediate requirements and be dynamic and evolve with everything in the future.

MR. GATTERER:

I assume that most people here are aware of the coming special spring issue of the Proceedings of IEEE on the subject of time and frequency dissemination, generation and applications. For those of you who are not, I'll tell you it will be a tutorial issue that will attempt to provide an accurate appraisal of the state-of-the-art and of the state-of-the-practice of time and frequency matters. It is hoped that a particularly valuable section of this issue will be the Letters to the Editor which will give people an opportunity to update information and report on recent research results. For example, Mr. Brennan could make a valuable contribution by submitting a letter on what is new in CAS. Since we'll want the most recent results, the deadline on the letter will be flexible. If you are willing and feel compelled to contribute your observations from recent results, please don't fail to contact Jim Jespersen, guest editor of this special issue.

DR. WINKLER:

I would like to ask each one of the authors, whose contributions we very deeply appreciate, to please add any reference, any additional source of information to any comments made in the written material, at the time it comes around to you for editing. Also, any second thoughts or any additional graphs or anything that will make the book more valuable.

Appendix A

THIRD DOD PRECISE TIME AND TIME INTERVAL STRATEGIC PLANNING CONFERENCE

AGENDA*

Tuesday, 16 November 1971

MORNING:

OPENING ADDRESS
Dr. A. Berman
Director of Research
Naval Research Laboratory

ADMINISTRATIVE NOTES
LCDR B. M. Atwood, USN
Technical Officer
U. S. Naval Observatory

INTRODUCTION
CAPT J. R. Hankey, USN
Superintendent
U. S. Naval Observatory

TIME AND FREQUENCY STANDARDIZATION
RADM R. J. Schneider, USN
Vice Commander
Naval Electronic Systems Command

THE SPACE SHIFT INCREMENTAL OSCILLATOR AND PRN TIME TRANSFER
Dr. R. B. Kershner
Head, Space Development Department
Applied Physics Laboratory

TIMING RECEIVER FOR TIMATION
Mr. R. L. Easton
Head, Space Metrology Branch
Naval Research Laboratory

TIME AND FREQUENCY ADJUSTMENT ON THE LORAN-C SYSTEM
LCDR J. F. Roeber, USCG
Systems Development Branch, Electronics Engineering Division
U. S. Coast Guard Headquarters

* The agenda was modified during the conference and the actual order of speakers is reflected in the Table of Contents.

LUNCH AND DISPLAYS

AFTERNOON:

OMEGA TIME TRANSMISSIONS AND RECEIVING REQUIREMENTS
Mr. A. R. Chi/L. Fletcher/C. Casselman
Network Engineering Division
National Aeronautics and Space Administration

MINI MODEM FOR PTTI DISSEMINATION
Mr. J. A. Murray
Time and Frequency Systems Unit
Naval Research Laboratory

VLF PHASE TRACKING FOR PTTI APPLICATION
Dr. F. H. Reder
Chief, Antennas and Geophysical Effects
Research Technical Area
Electronics Technology and Devices Laboratory
U. S. Army Electronics Command

PTTI RELATING TO THE VERDIN COMMUNICATION SYSTEM {SECRET}
Mr. L. S. Woznak
Head, Information Processing Branch, TACAMO
Division, Special Communications Project Office
Naval Electronic Systems Command

DISCUSSION PERIOD

Wednesday, 17 November 1971

MORNING:

DSCS PTTI TRANSFER {SECRET}
CAPT R. E. Enright, USN
DCS Program Project Manager
Defense Communications Agency

PRECISE TIME/FREQUENCY FOR THE DEFENSE COMMUNICATIONS SYSTEM
Mr. H. C. Folts
Electronics Engineer
Defense Communications Engineering Office

ABSOLUTE PATH DELAY EFFECTS IN TDM LONG HAUL DATA TRANSMISSION {SECRET}
Mr. R. A. Day
Chief, Engineering Staff, Office of Telecommunications
National Security Agency

DISCLIPINED TIME AND FREQUENCY OSCILLATOR
Mr. R. R. Stone
Head, Time and Frequency Section
Naval Research Laboratory

ATOMIC STANDARDS TEST AND EVALUATION
Dr. E. Hafner
Leader, Frequency Control Devices Team
Electronics Technology and Devices Laboratory
U. S. Army Electronics Command

LUNCH

AFTERNOON:

STABILITY CHARACTERISTICS AND APPLICATION TECHNIQUES FOR PRECISION FREQUENCY SOURCES
Dr. L. S. Cutler
Director, Physical Research Laboratory
Hewlett-Packard Company

PERFORMANCE AND RESULTS OF PORTABLE CLOCKS IN AIRCRAFT
Dr. J. C. Hafele
Assistant Professor
Washington University

A NBS EXPERIMENTAL SATELLITE TIME DISSEMINATION SERVICE
Mr. J. L. Jespersen
Chief, Frequency and Time Dissemination Research
National Bureau of Standards, Boulder

LONG RANGE PRECISION DETERMINATION SYSTEM {CONFIDENTIAL}
Dr. F. W. Rohde
Engineering Topographic Laboratory
U. S. Army Topographic Command

DISCUSSION PERIOD

Thursday, 18 November 1971

MORNING:

FREQUENCY SELECTION AND TRACKING REQUIREMENTS FOR UNDERWATER RANGES {SECRET}
Mr. C. S. Soliozy
Weapons Department, Systems Division
Naval Underwater Systems Center

TIME AND FREQUENCY RELATING TO COLLISION AVOIDANCE SYSTEM
Mr. J. L. Brennan
Sub-program Manager, Collision Avoidance Systems
Federal Aviation Administration

UTC ADJUSTMENT OF THE OMEGA SYSTEM
Omega Project Office
Naval Electronic Systems Command

SYNCHRONIZATION BY COMMERCIAL TV LINE 10 IN THE WASHINGTON, D.C. AREA
Mr. J. D. Lavanceau
Section Chief, Control of Time and Time Interval, Time Service Division
U. S. Naval Observatory

UTC WORLDWIDE ADJUSTMENT
Dr. G. M. R. Winkler
Director, Time Service Division
U. S. Naval Observatory

PANEL DISCUSSION

LUNCH

AFTERNOON:

PANEL DISCUSSION

Appendix B

DOD PRECISE TIME AND TIME INTERVAL (PTTI)
STRATEGIC PLANNING CONFERENCE
16-18 November 1971

LIST OF ATTENDEES

Name	Activity	Code	Address	Tel. No.
Abresch, P.E.	NAVOCEANO	3120	Washington, D.C. 20390	201/763-1534,1408
Acrivos, H.N.	NAVOBSY	62L	Washington, D.C. 20390	202/254-4587
Acton, B.A.	State Dept.	OC/E-S	Washington, D.C. 20520	202/632-1165
Akers, O.M.	NAVOCEANO	3110	Washington, D.C. 20390	202/763-1270/1
Aldrich, J.H., CAPT	CNO(RM4D486)	OP-352	Washington, D.C. 20350	202/OX7-9376
Alley, C.O., Dr.	University of Maryland	Phy.& Ast.	College Park, Md. 20742	301/454-3405
Ambler, E., Dr.	NBS	Div 200.00	Gaithersburg, Md. 20234	301/921-3301
Anderle, R.J.	NWL	DA	Dahlgren, Va. 22448	703/663-8259
Anderson, J.C.	Wheeler Industries, Inc.	------	Washington, D.C. 20036	202/223-1938x214
Ashinsky, M.	Sperry Rand Corp.	Sys. Mgt. Div.	Syosset, N.Y. 11791	516/938-9300x349
*Atwood, B.M., LCDR	NAVOBSY	6D	Washington, D.C. 20390	202/254-4597
Au, B.D.	NRL	5365	Washington, D.C. 20390	202/767-3140
Bailey, S.O.	NRL	5424A	Washington, D.C. 20390	202/767-3449
Baker, C.H.	APL	S2C	Silver Spring, Md. 20910	301/953-7100x2623
Baker, W.W.	LTV Electrosys.	8-53400	Greenville, Tx. 75401	214/455-3450x326
Baltzer, J.C.	Austron, Inc.	-------	Austin, Tx. 78753	512/836-3523
Barnaba, J.F.	AGMC	MLPE	Newark AFS, Oh. 43055	614/522-2171x344
Barnes, D.S., LTCOL	AFS	CF/DVH	Los Angeles, Ca. 90045	213/643-0050
Barnes, J.P., CDR	DCA	473	Washington, D.C. 20305	202/692-2621
Bartko, A.C.	NAVAIRSYSCOM	53343E	Washington, D.C. 20360	202/692-7825
Beck, H.	NRL	5418	Washington, D.C. 20390	202/767-2285
Berg, W.B.	NRL	5424C	Washington, D.C. 20390	202/767-3654
Berman, A., Dr.	NRL	4000	Washington, D.C. 20390	202/767-3301
Bigelow, H.L.	OASD	Telecom	Washington, D.C. 20301	202/697-6820
Bitter, R.H., Dr.	DCA-SEF	T212	Reston, Va. 22070	703/437-2273
Blakeley, K.A.	NAVELECSYSCOM	LANTDIV	Portsmouth, Va. 23709	703/393-7510
Bodily, L.N.	Hewlett-Packard	------	Santa Clara, Ca. 95050	408/246-4300
Bowman, J.A.	NRL	5424C	Washington, D.C. 20390	202/767-2061,2661
Breetz, L.D.	NRL	7967	Washington, D.C. 20390	202/767-2595
Bright, D.C.	NAVOCEANO	7120	Washington, D.C. 20390	202/767-2875
Brown, J.D.	NRL	7701	Washington, D.C. 20390	202/767-2997
Bryant, J.F.	NELC	2500	San Diego, Ca. 92152	714/225-6421
Caldwell, C.L.	NAVSEC	6178B02	Hyattsville, Md. 20782	301/436-1571
Carden, O.R., LCDR	NAVELECSYSCOM	0111	Washington, D.C. 20390	202/282-0621
*Carroll, D.L.	NAVOBSY	63E2C	Washington, D.C. 20390	202/254-4548
Cavanagh, E.J.	NAVELECSYSCOM	01113	Washington, D.C. 20390	202/282/0510
Chapman, W.H.	Geological Survey	-----	McLean, Va. 22101	703/343-5543
Chi, A.R.	NASA - GSFC	810	Greenbelt, Md. 20771	301/982-2502
Chrisman, C.H.	NRL	7930	Washington, D.C. 20390	202/767-2891
Clements, D.E.	USCG RADSTA	-----	Alexandria, Va. 22310	703/971-1600x46,11
Cochran, D.	Wheeler Industries, Inc.	------	Washington, D.C. 20036	202/223-1938x218
Collings, P.J., LTJG	COMNAVSECGRUHQ	G53	Washington, D.C. 20390	202/282-0751
Copenhaver, H.W., Jr., MAJ	DCA	482	Washington, D.C. 20305	202/692-2773/5
Crippa, E.R.	NELC	2460	San Diego, Ca. 92152	714/225-7072
Cutler, L.S., Dr.	Hewlett-Packard	------	Palo Alto, Ca. 94304	415/493-1501x3337
Daniels, L.H.	USAMCC	AMSMI-MSE	Redstone Arsenal, Al. 35809	205/876-1132
Davis, G.W.	21st Comp. Wg.	LGMP	Elmendorf AFB, Ak. 99506	907/753-3219
Davis, W.E.	NELC	1300	San Diego, Ca. 92152	714/225-7351
Day, R.A., Jr.	NSA	T103	Ft. Meade, Md. 20755	301/688-7500
deSocio, G.	NAVELECSYSCOM	00T211	Washington, D.C. 20360	202/692-8961
Dever, D.A.	NAVELECSYSCOM	0463	Washington, D.C. 20360	202/692-3976
Dickson, A.M., CAPT	AFTAC	TD-3A	Alexandria, Va. 22313	703/325-7138

* Detached 19 Nov 71.

Name	Activity	Code	Address	Tel. No.
Doherty, J.J.	COMNAVCOMM	N4213A	Washington, D.C. 20390	202/282-0533
Duckworth, D.T.	NWL	TI	Dahlgren, Va. 22448	703/663-8471
Dunnell, C.A.	APL	------	Silver Spring, Md. 20910	301/953-7100x2619
Duys, D., COL	DCA	470	Washington, D.C. 20305	202/692-2624
Easton, R.L.	NRL	7960	Washington, D.C. 20390	202/767-2595
Ebken, A.F.	NAVELECSYSCOM	05621	Washington, D.C. 20360	202/282-0394
Engel, B.J.	NAVPRO - MEC	MTWB	Pomona, Ca. 91766	714/629-5111x4551
Enright, R.E., CAPT	DCA	480	Washington, D.C. 20305	202/692-6067
Epstein, B.	NSSNF	-----	Brooklyn, N.Y. 11251	212/625-4500
Fields, V.C., CAPT	AFTAC	TD-3A	Alexandria, Va. 22313	703/325-7138
Finnegan, E.W.	NAVOCEANO	8430	Washington, D.C. 20390	202/763-1249
Fisher, L.C., Mrs.	NAVOBSY	62F	Washington, D.C. 20390	202/254-4555
Fiske, P.E.	NELC	230	San Diego, Ca. 92152	714/225-7472
Fleishman, L.E.	Westinghouse	370	Baltimore, Md. 21203	301/765-2043
Folts, H.C.	DCEO	H710	Reston, Va. 22070	703/437-2266
Fosque, H.S.	NASA HQ	OTDA - TA	Washington, D.C. 20546	202/755-2434
Foster, J.W., Jr.	SSPO	24232	Washington, D.C. 20390	202/697-1225/6
Freeman, J.J., Dr.	NRL	5767E	Washington, D.C. 20390	202/767-2654
Friedl, R.S., CAPT	DCEO	H830	Reston, Va. 22070	703/437-2450
Garlets, D. K.	USASTRATCOM	SCC-FD-MLR	Ft. Huachuca, Ar. 85613	602/538-6061
Gatterer, L.E.	NBS	273.01	Boulder, Co. 80302	303/449-1000x3995
Gaydos, D.J.	AFTAC	TD-3A	Alexandria, Va. 22313	703/325-7138
Gilchrist, C.F.	DIA	DIAMC-3A	Washington, D.C. 20301	202/697-3020
Goff, N.R.	1st GSS	DOHZ	F.E. Warren AFB, Wy.82001	307/775-2780
Greenhouse, S.C.	Mitre Corp.	W375	McLean, Va. 22101	703/893-3500x2468
Guay, A.R.	NAVELECSYSCOM	00M	Washington, D.C. 20360	202/692-8969
Gunar, M.	AFETR	ENID	Patrick AFB, Fl. 32925	305/494-5107
Hafele, J.C., Prof.	Washington Univ.	-----	St. Louis, Mo. 63130	314/863-0100x4687
Hafner, E., Dr.	USAETDL-ECOM	AMSEL-TL-SF	Ft. Monmouth, N.J.07703	201/535-1878
Hakkarinen, W.	NWESA-MID WNY Bldg 200	131E	Washington, D.C. 20390	202/693-2618
Hall, R.G., Dr.	NAVOBSY	62B	Washington, D.C. 20390	202/254-4547
Hallowell, R.E., MAJ	DCEO	H920	Reston, Va. 22070	703/437-2247
Hankey, J.R., CAPT	NAVOBSY	6	Washington, D.C. 20390	202/254-4564
Haupt, R.F.	NAVOBSY	61B	Washington, D.C. 20390	202/254-4598
Herring, J.C., MAJ	AFCRL	LWG	Bedford, Ma. 01730	617/861-4139
Hickey, C.B.	USCG RADSTA	-----	Alexandria, Va. 22310	703/971-1600x4[illegible]
Hockenmaier, H.	NSSNF	SPY 95	Brooklyn, N.Y. 11251	212/625-4500x702
Holleman, H.Y.	NOAA-NESS	-----	Hillcrest Hgts, Md. 20031	301/440-7546
Holman, W.	NELC	4500	San Diego, Ca. 92152	714/225-7064
Horowitz, M.W.	DCEO	H720	Reston, Va. 22070	703/437-2316
Hoskins, G.W.	SSPO	SP2431	Washington, D.C. 20390	202/697-4365
Howell, W.R.	Army (OACSCE)	DACE-EDC-L	Washington, D.C. 20314	202/693-6954/5/6
*Johnson, F.R., Jr., LCDR	NAVOBSY	6D	Washington, D.C. 20390	202/254-4597
Jones, H.H.	DCEO	H720	Reston, Va. 22070	703/437-2316
Kaufmann, D.C.	NASA-GSFC	814.2	Greenbelt, Md. 20771	301/982-[illegible]239
Kay, J.	NSP	PM-16	Washington, D.C. 20390	202/692-3797
Kellogg, R.L., ENS	COMNAVSECGRU	G54	Washington, D.C. 20390	202/282-0409
Kershner, R., Dr.	APL	-----	Silver Spring, Md. 20910	301/953-7100x2801
Kleczek, C.J.	NAVAIRSYSCOM	370H1	Washington, D.C. 20360	202/692-2120,[illegible]
Klepczynski, W.J., Dr.	NAVOBSY	62K	Washington, D.C. 20390	202/254-4555
Krutz, R.A.	DCEO	H610	Reston, Va. 22070	703/437-2261
Kudell, P.D.	NAVMAT (NVSATPROJOFF)	PM16-221	Washington, D.C. 20360	202/692-3796
Lamb, S.L., SSG	USASTRATCOM SATCOMSTA	-----	Lakehurst, N.J. 08733	201/657-8441
Lavanceau, J.D.	NAVOBSY	62E	Washington, D.C. 20390	202/254-4548
Lawson, R.B., LT	NOAA-NOS	C13	Washington, D.C.	301/496-8307
Leavell, C.N., SSCT	21st Comp. Wg.	-----	Elmendorf AFB, Ak. 99506	907/753-3219
Leeuwenburg, B.	DCEO	H710	Reston, Va. 22070	703/437-22[illegible]
Lerner, L.	NAVELECSYSCOM	034B	Washington, D.C. 20360	202/692-6412[illegible]

* Relieved LCDR Atwood.

Name	Activity	Code	Address	Tel. No.
Lesnick, D. R.	NAVSEC	6178E	Hyattsville, Md. 20782	202/436-1715/1717
Lieberman, T.	NAVELECSYSCOM	051832	Washington, D.C. 20360	202/692-7368
Lipp, R.E.	DCEO	H520	Reston, Va. 22070	703/437-2361
Lockamy, C. R.	USASTRATCOM SATCOMSTA	------	Lakehurst, N.J. 08733	609/562-6179
Lowell, P. M.	NAVSEC	6178B.02	Hyattsville, Md. 20782	301/436-1571
Mancini, A., Dr.	USATOPOCOM - ETL	TPCTL-TD-EA	Ft. Belvoir, Va. 22060	703/664-6728
Martin, A. J.	NRL	7937	Washington, D. C. 20390	202/767-2891
Martin, M. D.	NAVMAT	034T	Washington, D. C. 20360	202/692-0432
McConnell, V. I.	NSA	W65	Ft. Meade, Md. 20755	301/688-6551
McCrumb, J.B., LCDR	NAVMAT	03423	Washington, D. C. 20360	202/692-0433/2
McDermott, J. H.	NAVOBSY	62E1M	Washington, D. C. 20390	202/254-4437
McIntire, O. E.	FAA	RD241	Washington, D. C. 20591	202/426-8576
Moore, R. B.	NRL	7962	Washington, D. C. 20390	202/767-2595
Murray, J. A., Jr.	NRL	5424D	Washington, D. C. 20390	202/767-3309
Newhard, A.S., LT	DCA	473	Washington, D. C. 20305	202/692-2491
Nuber, G. E., Jr.	Wheeler Industries, Inc.	------	Washington, D. C. 20036	202/223-1938x221
Oakley, P.M., SSG	USASTRATCOM SATCOMSTA	------	Lakehurst, N.J. 08733	201/657-8441
Orr, C. B., Jr.	DCEO	H710	Reston, Va. 22070	703/437-2266
Osborne, E.F.	APL	------	Silver Spring, Md. 20910	301/953-7100x2628
Parker, C. V.	NRL	5760	Washington, D. C. 20390	202/767-3396
Parsons, P.H.	NSA	R33	Ft. Meade, Md. 20755	301/688-6506
Percival, D. B.	NAVOBSY	62F4	Washington, D. C. 20390	202/254-4555
Perfetto, H.	Wheeler Industries, Inc.	------	Washington, D. C. 20036	202/223-1938
Periquet, F. M.	USASTRATCOM SATCOMSTA	------	Lakehurst, N.J. 08733	609/562-6041
Peterkin, E. W.	NRL	7004	Washington, D. C. 20390	202/767-3086
Peters, H. E.	NASA - GSFC	524	Greenbelt, Md. 20771	301/982-4682
Peterson, H. L.	NRL	8103B	Washington, D. C. 20390	202/767-3623
Petrey, H. E.	USATOPOCOM	14351	Washington, D. C. 20315	202/756-5165
Phillips, D. H.	NRL	5424C	Washington, D. C. 20390	202/767-2061
Phillips, R. E.	NRL	5424C	Washington, D. C. 20390	202/767-2061
Pillsbury, J. S., CAPT	AGMC	ML	Newark AFS, Oh. 43055	614/522-3750
Pitsenberger, J.W.	SSPO	SP2701	Washington, D. C. 20390	202/695-0775
Plebanek, A., Jr., MSCT	SAMTEC	LGM	Vandenberg AFB, Ca. 93437	AV 276-5117
Poling, A.A., Jr.	NOAA - NOS	C-124	Rockville, Md. 20852	301/496-8620
Potts, C.E., LCDR	USCG HQ	EEE/63	Washington, D. C. 20590	202/426-1193
Pritt, D. W.	NRL	5424D	Washington, D. C. 20390	202/767-3309
Putkovich, D.	NAVOBSY	62E1	Washington, D. C. 20390	202/254-4437
Raizer, H. L.	NAVELECSYSCOMLANTDIV	-----	Portsmouth, Va. 23709	703/393-3223
Ramsey, J. L.	Mitre Corp.	B-172	Bedford, Ma. 01730	617/271-2095
Reder, F. H., Dr.	USAECOM-ETDL	AMSEL-TL-A	Ft. Monmouth, N.J. 07703	201/535-1624
Riegger, W. J.	NAVELECSYSCOM	0518	Washington, D. C. 20360	202/692-7565
Rivamonte, J.M.	USAMCC	AMSMI-MME	Redstone Arsenal, Al. 35809	205/876-4969
Robatino, V. G.	USASATCOMA	AMCPM-SC-5	Ft. Monmouth, N.J. 07703	201/532-2832
Robinson, T. A.	USATOPOCOM	TPCTP(14220)	Washington, D. C. 20315	202/227-2158
Roeber, J. F., Jr.	USCG HQ	EEE-4	Washington, D. C. 20950	202/426-1193
Rohde, F. W., Dr.	USATOPOCOM - ETL	TPCTL-TD-EA	Ft. Belvoir, Va. 22060	703/664-6728
Rueger, L. J.	APL	-------	Silver Spring, Md. 20910	301/953-7100x378
Savarese, R. T.	NAVELECSYSCOM	0561521	Washington, D. C. 20360	202/692-8363
Schlehr, P. R., CW02	COMNAVCOMM	N4213B	Washington, D. C. 20390	202/282-0561
Schmid, J. G.	SAMTEC	ENDS	Vandenberg AFB, Ca. 93437	AV 276-4871
Schneider, R. J., RADM	NAVELECSYSCOM	09	Washington, D. C. 20360	202/692-3008
Scull, D. C.	NAVOCEANO	3120	Washington, D. C. 20390	202/763-1534
Seeley, H.G., LCDR	CNO	OP-352E2	Washington, D.C. 20350	202/697-9376
Severo, F. E.	USAF HQ	TSG	Washington, D. C. 20332	202/692-2266

Name	Activity	Code	Address	Tel. No.
Short, J. R.	NUSC	WA-2	Newport, R. I. 02840	401/841-3415
Shostack, B.	NSSNF	SPY-95	Brooklyn, N. Y. 11251	212/625-4500x277
Shostak, A. A.	ONR	427	Arlington, Va. 22217	202/692-4216
Smith, C. N.	NASA	752	Greenbelt, Md. 20771	301/982-5774
Smith, D.W., Jr., CDR	CNO	OP-986F	Washington, D. C. 20350	202/697-7594
Stearns, F. P.	AFCS	EICCS	Richards-Gebaur AFB, Mo. 64030	816/331-4400 x 3813
Stone, R. R.	NRL	5424	Washington, D. C. 20390	202/767-3454
Strand, K. A., Dr.	NAVOBSY	6C	Washington, D. C. 20390	202/254-4539
Takaki, S., CW3	USAES	D/TOPO	Ft. Belvoir, Va. 22060	703/664-2347
Talbott, J. W.	USAF HQ	TSG	Washington, D. C. 20332	202/692-2266
Taylor, A. W.	ACIC-DET 1	DOB	Arlington, Va. 22202	202/697-3915
Tendick, C. B.	NAVSEC	6856	Port Hueneme, Ca. 93041	805/982-4818,4711
Toms, J. L.	Austron Inc.	-----	Rockville, Md. 20850	301/762-2885
Tsiang, R. C.	SAO	-----	Cambridge, Ma. 02138	617/864-7910x492
Tucker, A.	NSSNF	-----	Brooklyn, N. Y. 11251	212/625-4500x207
Uliana, E. A.	NRL	7134U	Washington, D. C. 20390	202/767-3185
Vessot, R. F. C.	SAO	-----	Cambridge, Ma. 02138	617/864-7910x276
Vickers, D.B., LTCOL	AFTAC	TD-3A	Alexandria, Va. 22313	703/325-7138
Walcek, A. J.	Hewlett-Packard	-----	Rockville, Md. 20850	301/948-6370x316
Walker, W. C.	Pan American	ASD	Patrick AFB, Fla. 32925	305/494-5391
Walsh, T. M.	NAVELECSYSCOM	WESTDIV	Vallejo, Ca. 94592	707/646-3494
Watford, S.E.	USACEEIA	SCCC-CED-SYT	Ft. Huachuca, Ar. 85613	602/538-6750
Watson, F.	McDonald-Douglass Corp.	------	St. Louis, Mo. 63166	314/232-0232
Wenglin, S.	Mitre Corp	------	Bedford, Ma. 01730	617/271-2477
White, J. H.	NAVELECSYSCOM LANTDIV	------	Portsmouth, Va. 23709	703/393-7544
Wiesman, F. R.	DCEO	H710	Reston, Va. 22070	703/437-2266
Wilcox, D. J.	USAES	ATSEN-TO-GE	Ft. Belvoir, Va. 22060	703/664-2347
Wilcox, D.L.	WILTRONIX, Inc.	------	Rockville, Md. 20853	301/460-1454
Wills, A., Jr.	Sperry Rand Corp.	Sys.Mgt. Div.	Syosset, N.Y. 11791	516/938-9300
Winkler, G.M.R.,Dr.	NAVOBSY	62	Washington, D.C. 20390	202/254-4546
Wojanis, W. S.	COMNAVCOMM	N6	Washington, D. C. 20390	202/282-0888
Wolter, H. A.	NSA	T-103	Ft. Meade, Md. 20755	301/688-6603
Wood, D. C.	NSA	R333	Ft. Meade, Md. 20755	301/688-6506
Woznak, L.S.	NAVELECSYSCOM	PME11722	Washington, D. C. 20360	301/692-8861
Wyatt, J. A.	NAVELECSYSCOM	05183	Washington, D. C. 20360	202/692-7368
Yeager, J. A.,CDR	NOAA-NOS	C13	Rockville, Md. 20852	202/496-8307
Zborofsky, R. A.	NRL	5424	Washington, D. C. 20390	202/767-2347

Appendix C

EQUIPMENT EXHIBITS

1. Anadex Instrument Inc., 7833 Haskell Ave., VanNuys, Ca. 91406

   a. Digtal Printer DP-650

2. Austron Inc, 10214 No. Interregional Highway, Austin Texas 78753

   a. Disciplined Frequency Standard Model 2010B/1680
   b. Frequency Multiplier CV-2929/GSQ-174
   c Navigator System 5000 Loran - C
   d. Phase microstepper Model 2055
   e. Printer Interface Model 6015
   f. Receiver Automatic Timing Model 2055A Loran - C
   g. Receiver Loran R-1776/GSQ-174
   h. Standby Power Supply Model 1290

3. Datapulse Div., Systron-Donner Corp. 10150 W. Jefferson Blvd., Culver City, Ca. 90230

   a. Pulse Generator 101

4. Digtal Equipment Corp., Maynard, Mass. 01754

   a. Digtal unit pdp 8/E

5. Frequency Electronics Inc., New Hyde Park, N.Y. 11040

   a. Disciplined Time/Frequency Standard Module FE-150A
   b. Power Supply FE-350A

6. General Dynamics, P.O. Box 1128, San Diego, Ca. 92112

   a. Receiver Radio R-1051 B/URR HF 2.0-30 M+12

7. General Radio, 300 Baker Ave., Concord, Mass. 01724

   a. Digital Synchrometer 1123A

8. Honeywell, Inc., 1100 Virginia Ave., Ft. Washington, Pa. 19034

   a. Recorder class 16, 6 channel model 16303846

9. Hewlett Packard, 1501 Page Mill Road, Palo Alto, Ca. 94304

   a. Clock cesium Beam Frequency Standard 5061-03
   b. Clock Cesium Beam Frequency Standard (Flying Clock)

c. Computer Counter 5360A
d. Digital Recorder paper feed output 5050B
e. Dual channel Vertical Amplifier 1801A
f. Electronic Counter 5248L
g. Input Module 5365A
h. Keyboard 5375A
i. Oscilloscope 180A
j. Rubidium Vapor Frequency Standard 5065A
k. Time Base 1820A
l. Time Interval Unit 5267A
m. Time Interval Unit 5379

9. McBee Laboratories, Washington, D.C. 20016

a. Receiver Television Line 10 Device Model E71-1

10. McDonnell-Douglas Corp. St. Louis, Mo. 63166

a. EROS Collison Avoidance
(1) Micro CAS
(2) Indicator
(3) CAS Unit

11. Timing Systems, Marblehead, Mass. 01945

a. NANOCLOCK Model 915

12. Tektronix, P. O. Box 500, Beaverton, Oregon 97005

a. Oscilloscope protable type 422 AC/DC power supply (Commercial Standard)

13. Tracor, 6500 Tracor Lane, Austin Texas

a. Linear Phase/Time Comparator Model 895A