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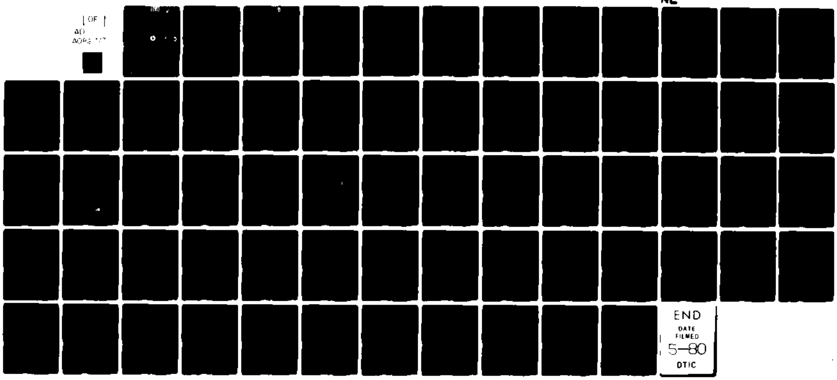

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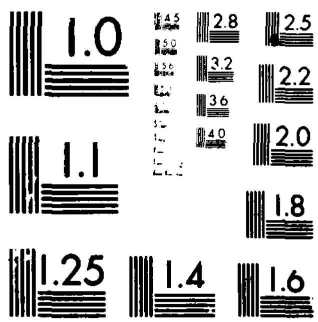

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USCG/MARAD STATIC TESTS OF THE GPS NAVIGATION SET-Z (LOW COST)

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MARCH 1980

FINAL REPORT
Phase I

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16. Abstract
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When signal conditions are optimum, they reveal a four-satellite fix accuracy and variability which was considerably better than the set's readout precision of 1.0 arc-second. Underlying effective ranging errors were estimated to fall in the 5-10 meter, rms, range. Fix errors increased by a factor of five when 24-hour old orbit and clock parameters were used, and they increased the same amount when only three satellites were available with poor GDOP. The set exhibited no failures during the tests, and satisfactory operator I/O. Fixes obtained in a vehicle agreed with topographic map location at 14 of 15 sites around Los Angeles, with the one fix failure ascribed to building shadow.

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Navigation Set-Z (Low Cost)

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ABSTRACT

One of six Type Z Navigation sets, which use the C/A code signal that will be available to civil users, was provided the U.S. Coast Guard and Maritime Administration for a joint test and evaluation program. The goal of these tests is to determine the suitability of this form of GPS for civil marine use. The first static tests were conducted in May-September 1979 in Long Beach, California. Following a tutorial summary of the Z-set operating principles, results from these tests are presented.

When signal conditions are optimum, they reveal a four-satellite fix accuracy and variability which was considerably better than the set's readout precision of 1.0 arc-second. Underlying effective ranging errors were estimated to fall in the 5-10 meter, rms, range. Fix errors increased by a factor of five when 24-hour old orbit and clock parameters were used, and they increased the same amount when only three satellites were available with poor GDOP. The set exhibited no failures during the tests, and satisfactory operator I/O. Fixes obtained in a vehicle agreed with topographic map location at 14 of 15 sites around Los Angeles, with the one fix failure ascribed to building shadow.

Acknowledgement

The execution of this Phase I CG/MARAD test program on very short notice was achieved through the cooperation and assistance of many people. Heading the list is CAPT James Culbertson of the Eleventh Coast Guard District, who attended to every detail there, with SAMSO, Transportation Systems Center and Magnavox Research Laboratories (MRL). At SAMSO Colonel Donald Henderson and his staff provided every resource that was needed, and all of MRL, engineers and marketeers, assisted us. Mr. Robert Skeans of MRL loaned an MX-1502 Transit Surveyer and helped process the site survey data to confirm that the Z-set did provide a high quality fix.

1.0 Background

1.1 Historical

The satellite navigation system NAVSTAR GPS began more than ten years ago with experiments in the technology of space-qualified atomic frequency standards. Such standards are the heart of a satellite based navigation system with continuous world-wide coverage because a user may infer distance from time-of-arrival measurements of radio signals synchronized to these standards. With the inauguration of the NAVSTAR program in 1974, the U.S. Maritime Administration (MARAD) of the Department of Commerce supported certain studies and receiver design tasks looking towards the civil maritime use of GPS. This use was based upon the trans-oceanic navigation potential of the C/A GPS signal to an accuracy far surpassing anything available today from either Omega or Transit. At that time the Department of Defense had intended to use the C/A coded GPS signal on board certain transport aircraft whose lower dynamics and usual mission could be supported by this signal at a desirable reduction in user equipment cost. MARAD in effect was planning to test the application of a receiver designed for this type of aircraft in the trans-ocean civil environment.

In 1978 the DOT began to investigate the potential use of GPS navigation in all civil transportation modes. While the U.S. Coast Guard was monitoring GPS developments throughout this period with its own mission applications in mind (e.g. Arctic and Antarctic icebreaking), it began at this time to investigate GPS for all civil marine navigation applications in U.S. coastal waters (referred to as the Coastal Confluence Zone-CCZ, and Harbor & Harbor Entrance Environment (HHE). Shortly after this the DOD changed program plans and abandoned the use of C/A signal on board any of their vehicles. This terminated production plans for their C/A-only receiver, the Z-Set. This also left MARAD without any immediate source of production equipment but with an interest in further testing of GPS, while the Coast Guard likewise needed to test and evaluate civil use of GPS. They joined forces in a joint CG/MARAD GPS Field Test Program in 1979, with the first phase being a static test of the shipboard packaged Z-Set. This test was conducted at the Coast Guard District Eleven offices in the Union Bank Building at Long Beach, CA, 8 May 1979 to 9 Sept 1979, by Verdes Engineering consultants and was assisted by the Transportation Systems Center of DOT.

1.2 MARAD Interests

There is an obvious economic potential for a continuous world-wide navigation system in oceanic commercial shipping. A system that could provide harbor-to-harbor real-time navigation meets a need conventionally filled by celestial navigation and shorter range shore-based systems. In addition, it offers attractive future possibilities when combined with auto-pilots and satellite communication systems for more energy efficient passage, and more economic control by the vessel's owners. A navigation system that provides 1/4 n.m. accuracy meets many trans-oceanic and off shore coastal shipping needs, and GPS has been expected to provide this level of accuracy via the C/A code. Thus MARAD interests were to test and demonstrate this potential (as opposed to measuring how much better it might well be) and explore operator interface and application questions in the commercial marine environment.

1.3 Coast Guard Interests

The U.S. Coast Guard, exclusive of its own mission interests, faces a complex set of questions in the civil application of GPS. These involve ultimate accuracy potential of the C/A signal for use not only in coastal activities but also in the HHE environment. At the same time, the civil maritime community in the CCZ/HHE involves not only large commercial shipping, but also much smaller commercial operators such as fishers and recreational users. Most of these categories have needs that can be met with existing shore-based systems such as Loran-C, and hence GPS performance and economic factors are crucially important. For these general reasons the CG program in GPS is oriented towards measuring the ultimate accuracy potential of C/A-only GPS, as well as studying the competing factors of receiver performance and cost. The CG/MARAD field test program is a first step in both of these categories; measuring GPS C/A-only accuracy, studying the receiver technology and complexity that produced it, and simply comparing performance with other radio navigation aids in the seaborne environment. Two other activities will support these goals over the next several years, while this first phase of CG/MARAD programs addresses these questions of ultimate accuracy and receiver technology. Phase II of this program will take place aboard the Texas A&M research vessel r/v Gyre and will tackle the practical at-sea comparisons.

2.0 Executive Summary

2.1 Z-Set Receiver

The Z-set is a single channel user equipment which utilizes signals from four GPS satellites to compute user position. This position fix is displayed in Latitude and Longitude coordinates, and other navigation functions such as course and distance to a waypoint are provided based upon this fix. The set was designed for airborne application in both the form and function of these various outputs, and we ignored the impact of these factors in our tests to the maximum extent possible. The single channel design of the set is the logical outgrowth of minimizing cost through minimizing set hardware, a tradeoff acceptable for a slowly moving user who can sequentially track four GPS satellites to obtain the necessary fix information--four independent measurements. This low velocity is exactly the marine situation and the Z-set represents one of the prime candidate architectures for civil marine GPS receivers.

The marine user is also concerned with maximum accuracy obtainable from GPS and while the airborne application calls for less accuracy, the Z-set has internal accuracy capabilities that surpass the basic airborne need. This arose due to sharing of technology in the Z-set with other higher performance equipments; and it is a fortuitous outcome for our interests. On balance then the Z-set is a user equipment that is very representative of potential civil marine designs in most important aspects, and its performance is such that the underlying GPS C/A-only navigation accuracy potential will be revealed in field tests.

2.2 Test Results

The tests reported here were based upon an installation and operation of the Z-set at the Eleventh Coast Guard District Offices in Long Beach, CA, through the 1979 summer. Beyond basic familiarization with the set and system, we recorded the fix readout at periodic intervals during the two hour period that fixes from GPS could be obtained in California. Our interests were to establish the Z-set's fix stability and average accuracy. The readout is quantized to one arc second, or about 100 feet, and this was the limit of our observation precision. Due to electrical problems on board the satellites, normal four-satellite navigation could only be performed about 30% of the entire test period. Within this 30%, the performance of C/A only navigation was distinctly better than the readout precision; the readout rarely changed from the correct value.

This statement of performance is subject to two important caveats: nearly all observations were made during local darkness when the error contribution of the propagation path between satellite and receiver was minimum, and the observations of performance were made after the satellites had been "uploaded" by the Vandenburg AFB control station with the most recent data message. These data tell the user exactly where the satellite is; necessary information for the user to ultimately fix his position. When we observed four-satellite navigation before this upload occurred, meaning the set was using a 24-hour old message from the satellites containing errors, distinct fix errors on the order of several hundred feet appeared.

The Z-set was 100% reliable throughout the test, and while we had various quibbles with its airborne-optimized outputs and behavior, it was overall a most impressive and to all intents operations-ready instrument. Both the Z-set and the characteristics of the GPS system we could observe using it were impressive, and validated the advertised performance of the Concept Validation Phase system. This level of performance encouraged and justified the follow-on testing that the joint Coast Guard/MARAD program plans to do with the Z-set during the next several years.

3.0 <u>The GPS Receiver</u>

3.1 The GPS System

The GPS navigation system will eventually consist of 24 satellites orbiting in three planes of eight each. The reader is referred to the summer 1978 Journal of the Institute of Navigation for descriptions of the GPS system, its various elements, and the signals and general receiver technology. The program has just completed the Concept Validation Phase in which four pre-operational satellites provided two-plus hours per day of actual coverage for tests of the user equipments. These are termed Phase I equipments, and consisted of X,Y,Z and manpack sets. They were all tested in various DOD user vehicles, mainly at the Yuma proving ground in Arizona, with some tests aboard naval vessels at the FORACS range off San Clemente Island. Most tests utilized the P-code signal, and they eminently validated all of the major space vehicle and user equipment concepts. As a result the DOD has approved full scale equipment development or Phase II of GPS. This will lead to an Interim Operational Test and Evaluation Phase by the mid-eighties, with full operation at 24 satellites planned for 1987. The many Phase I user equipments that have completed their major role in concept validation are now being made available to secondary GPS users for evaluation, and the CG/MARAD Z-set falls in this category.

3.2 Overview of the Z-set

3.2.1

The Z-set was developed for the Joint Program Office of USAF Space and Missle Systems Organization (SAMSO) by Magnavox Research Laboratories (MRL) in Torrance CA. It was intended to be a production prototype (as compared to the X, Y sets which were for test and development only) for use in military transport aircraft and also available in a shipboard physical package with identical navigation performance. The receiver's technology is largely common to that of the Manpack and forms the basis of Phase II Manpack development by MRL for SAMSO. The Z-set was designed-to-cost as this first MILSPEC production attempt, and it did meet a 1974$ goal of $25K, although this is not verified by actual production. As previously noted, these plans were terminated by changing DOD requirements and today the six Z-sets actually delivered stand as the only C/A-only examples in the GPS inventory. They are representative of overall receiver technology for low-dynamic users, they represent a significant portion of the low performance Phase II production concepts, and they are capable of an instrumental accuracy that does not degrade the C/A signal potential. While these six examples are an evolutionary "dead-end," they are representative of the genre and provide useful insight into the ultimate performance of the C/A-only signal. Because the Z-set was designed for operational deployment, it also provides considerable information about complexity and resulting performance from the operator's point of view. This includes not only simple operator I/O, but also the more diffuse issues of the receiver being able to deal with transient or abnormal situations and maintain automatic operation or inform the operator of its problems. These boundary conditions are often the Achilles' heel of radio navigation systems in practical applications. The Z-set, then, fully meets the field test interests of MARAD and USCG in 1979; not as a unit being tested for individual acceptance but as a tool to learn about and infer potential performance of the GPS system, as well as practical marine operations.

3.2.2

The major performance specifications of the Z-set as a black box navigation instrument are given in Table 3-1. As all GPS satellites transmit orthogonal PN Gold-code signals simultaneously, the receiver can track many at one time, or sequence amongst some number of satellites. The sequencing receiver has a considerable savings in hardware, needing only one-of-everything, with some additional overhead in extra computer processing to schedule or control the sequential functioning. The penalty of a sequential set is of course dynamic performance; as the user platform is capable of greater accelerations, several signals must be tracked simultaneously to maintain an accurate real-time fix. When we consider the C/A code with a chip length of some 300 meters we need only ask if our proposed vehicle can manuever in a way to "outrun" such a chip length of signal within a sequence period, and hence have to search for the signal on the next cycle (recall that the code has essentially zero correlation beyond one chip). We see that for the Z-set specifications such a manuever is not possible and hence our transport aircraft is compatible with this sequential receiver, and our ultimate ship-of-interest is similarly suited.

Table 3-1 reveals a fix accuracy specification of 150 m for all worst case combinations of error sources. For HHE navigation this accuracy is insufficient, but we must keep in mind the violent aircraft manuevers with satellite shadowing by the aircraft that this includes. An important and revealing specification is that on individual ranging error (recall that static fix accuracy = GDOP x range sigma, or 30-45 meters) which is quite good. This value is likewise a worst case and includes the signal jamming condition and weakest signal level of -163dBw. Ranging performance is, for nominally benign civil applications with signal levels at the -157-dBw presently realized, distinctly better. Thus the receiver does provide the desired insight into accurate civil application of the GPS C/A signal. The 3/4 ATR case is a fairly small enclosure although the shipboard version inserts this case into a far larger USN-style enclosure which includes 400Hz power converters. The sophistication and performance of the Z-set packaged in this small ATR unit is most impressive, particularly considering that the technology is largely CMOS/LSI/Linear and IC/discrete RF/IF.

3.3 The Z-set "Receiver"

The Z-set consists basically of a hardware "receiver," and a computer program portion termed the ZUSCP. The latter is the complex heart of the Z-set, while the "receiver" is the bulk of the set's electronic hardware, shown functionally in Figure 3-1. This receiver sub-system is helpless by itself, requiring control instructions and mode setting from the computer to perform the required signal measurements. Those measurements are C/A code time-of-arrival, carrier phase tracking, and data demodulation. Following the down-conversion which is controlled by the reference oscillator, all of these measurements are performed by hardware circuits/loops in the baseband and C/A coder modules. The technology is largely single/quad operational amplifiers & discrete passive components. All of the loops except the COSTAS have two bandwidth settings controlled by the computer. Other functions such as automatic search patterns (e.g. slewing the C/A coder and freq/code presetting) are realized in hardware, but activated by software with parametric control.

The C/A coder module is basically a controllable clock which generates the C/A code along with all lower frequency clock timing associated with the GPS signal format. This clock is time-aligned with the received signal. The time alignment is affected by tracking loops (code, freq, phase) driven by error signals from code and I/Q (In-phase/Quad-phase) correlators. The C/A clock, differenced against the local reference clock--the user time module--provides the basic psuedo-range measurement for GPS navigation. The two fundamental timing signals in the set are generated by these clocks; the 0.02s CT (channel time) interrupt and the 0.1s UT (user time) interrupt. These serve to schedule all ZUSCP tasks, and in particular insure real-time synchronization with the GPS waveforms. (Recognize that the 0.02CT interrupt is the bit period of the GPS data message, itself divided off the carrier-to-code timing chain.) Cross-connection between UT and CT is under software control, and provides epoch synchronization (data/bit/word/frame boundaries) to the UT, and VCXO calibration to the CT.

Table 3-1

GPS Z-SET MAJOR SPECIFICATIONS

4 Satellite sequential tracking at 1.2 sec/sat GPS Navigation Set

Fully USAF-Standard cockpit compatible

Signal Level -163 to -150 dBw at L_1 frequency 1575.42 MHz

Time to First Fix: 15 min osc warmup/init + approx. 5 min to a fix with 500 m accuracy, and 3 m/s and 175 km velocity/position uncertainty

Ranging Error: Set measures individual satellite ranges 15 m 1-sigma and velocity 0.02 m/s 1-sigma

Jamming: Set operates with 25 dB broadband jam-to-signal ratio.

Navigation: Navigation fix accuracy for all space/line/set errors 150m.

Vehicle Dynamics: Velocity 0-400 m/s (700 knots)
Acel 0-5 m/s^2 (10 knots/sec)

15kg, 120-watts in 3/4 ATR chassis with doghouse
Design-to-cost Target 25K 1974$ exceeded by 10%

Z-Set Receiver System (Hardware)

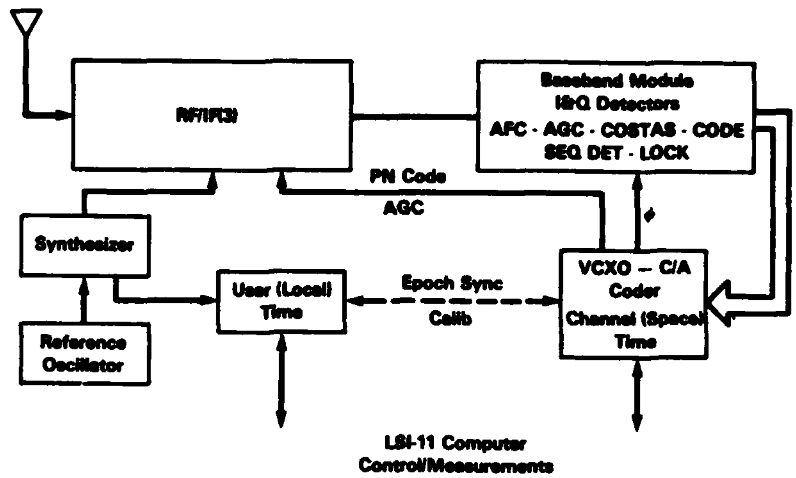


FIGURE 3-1

Z Set Major Software Functional Modules

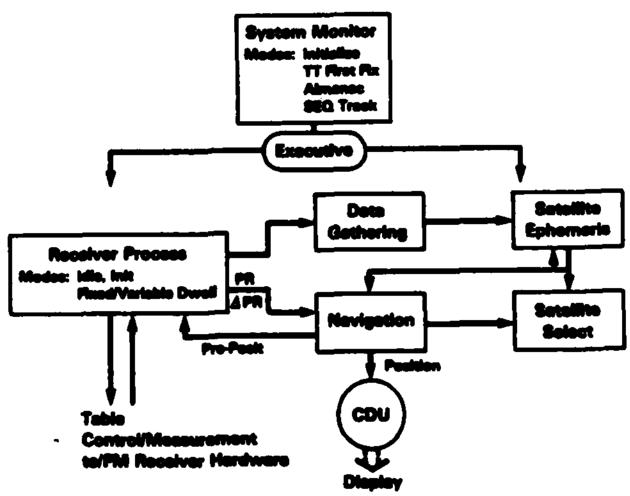


FIGURE 3-2

In Tables 3-2 and 3-3 we have listed some of the major performance specifications of the receiver subsystem, and the generic types of computer control commands and measurement transfers. The oscillator stability is extremely good, probably better than necessary, but was chosen to use the previously designed X-set's oscillator. The COSTAS phase tracking loop is a Type II and, since the set must operate with no lag error in an aircraft, this loop is closed to the VCXO of the C/A coder module, which directly aids the code loop (Type I). This structure is analogous to a Loran-C receiver in which the PLL controls fine-timing functions via the VCO, and coarse timing is set by a Type I envelope or cycle-index loop. In fact not only can we draw a functional parallel between the two, but the tau-dither code tracking loop of this GPS receiver is mathematically identical, excepting a 3dB signal loss, to the delay-and-add envelope loop used in most Loran-C receivers. The code loop has a precision of 1/64 chip and a tested tracking bias less than 0.01 chip. This level of performance insures that the set meets the Table 3-1 specification of 15 m rms ranging error, and provides us potentially better performance with presently transmitted signal strengths and marine vessel dynamics.

Table 3-3 delineates the loops/functions controlled by the software. They are largely binary controls (start/stop, wide/narrow) and when taken together they allow a powerful repertory of signal search/pull-in/ tracking strategies. These are controlled in the ZUSCP as outlined below and provide the Z-set with its wide adaptability to manuever/signal conditions. Feedback from the receiver hardware is almost exclusively measurement results: timing and binary indicators such as sequential detector dismiss events, COSTAS lock and of course the timing interrupts themselves.

The hardware provides the raw measurement capabilities, but to understand the Z-set operation we must build upon these hardware capabilities with the integration/control/computation of the software, the ZUSCP.

3.4 The Z-set Computer Program

3.4.1 Functions

There are eleven major software functions defined in CP-US-305, the "B5" specification for the ZUSCP. The eight which are central to set performance are shown in Figure 3-2. The system monitor provides the overall set intelligence. It commands the other modules, sets their individual modes and execution times, and controls the basic mode of the set. These modes are shown on the figure, and are basically transient conditions driving towards the desired or normal mode, sequential tracking of four satellites. The executive is the actual task scheduler and bookkeeper in its usual programming context. The other five modules are interactive in exchanging data and supporting each other under system monitor control. The CDU module outputs the display information as shown, and of course accepts operator data/commands. The navigation program operates in ECEF (Earth Centered Earth Fixed) coordinates, and

TABLE 3-2

Z-Set Receiver Hardware: Major Performance Measures

Antenna 10-90° Pattern Conical Spiral

Noise Figure (4MHz BW)... 5dB BW_3..25MHz BW_{70}..200MHz

IF Freq 184,33,7MHz AGC Rug 40dB

Synthesizer Freqs..6 w/Phase Noise 2 deg rms

Oscillator Stability.. 3×10^{-11}/100 secs, 3×10^{-7}/yr

COSTAS BW.20Hz(SS) Type II Loop ± 2kHz Acquisition

AFC Loop..2 or 5 Hz Type I ACG..Ø.16Hz Type I

Seq Detector D/Accept..10/100, 20/200, 40/400 ms

Code Loop Precision..0.02 CHIPS, BW..0.4Hz, RMS ERROR..0.05 CHIPS

TABLE 3-3

Z-SET Receiver System/Computer Communication

Control	Measurement
C/A Coder-step size, loop BW, Loop Start Time & phase adjust, satellite address, coder search	0.15 User Time, 0.025 channel time interrupt Data Samples
VCO - Calibrate, preposition, AFC BW	CT & UT Word, coarse/fine range
Seq Detector - D/Accept rate, start	Search counter overflow
Data - Sample rate, phase adjust	

the primary output function of the CDU module is conversion to the operator's grid and incorporation of the necessary waypoint guidance information. The physical CDU is microprocessor based and will not be discussed here, nor will other software modules such as the instrumentation output driver, altimeter input module, and AFI (Automatic Fault Indicator).

3.4.2 System Monitor

The set's operating modes normally proceed from initialization, in which the operator is required to input data (estimated position and time), through Time-To-First-Fix (satellite signal search, acquisition, and position refinement), to the desired steady-state operation of sequential track with accurate continous navigation fixes available. These first two conditions correspond roughly to the CDU "STANDBY" light being ON, and the final state to this light being OFF and the "NAV" light being ON. There is an overlap in these two CDU displayed conditions which occurs when all satellites are acquired and valid ephemeris messages collected, but the fix error (uncertainity) has not yet been reduced to the 0.25 nautical mile that defines accurate airborne navigation. The monitor can also decide to collect an almanac in the unlikely event that non-volatile memory has been lost, or the existing almanac is more than two weeks old. This is a lengthy process that is usually avoided through the use of non-volatile RAM memory. It can be commanded to this collection task by the operator. This latter step proved useful as a means to restart a portion of the TTFF process during the tests, the goal being to force the set to collect a new ephemeris (data blocks I and II) after these were uploaded to the satellites by the control station at Vandenburg AFB.

The system monitor is the overall software decision maker and sub-policy specifier. The INIT-TTFF process is an example of this overall strategic decision making, while more specific direction to the other software functions (e.g. specifying receiver search stategy or dwell-time on a given satellite to the receiver process module) illustrate tactical decision making by the monitor. The monitor is event driven, it controls Z-set mode and issues its commands based upon the declaration of events by the other modules (e.g. power up, data block collect failure, TTFF success/failure, etc). The monitor is the only software function that can be directly commanded by the operator.

3.4.3 Receiver Processing

The function of this module can be inferred from the discussion of section 3.3. Basically it must set each specific bit of the hardware control lines to accomplish the strategies assigned by the system monitor (e.g. there are twelve tabulated search stategies, twelve pull-in strategies and sixteen classes of receiver dwells), provide real-time execution of these assigned modes (e.g. deciding that the proper CT interrupt has occurred to disable the code tracking loop and enable code-lock verify), and extract and preformat the measurement data for use by the other software functions. In accomplishing these it executes various conversion calculations, such as user/satellite position to C/A coder slew increment.

In Figure 3-3 we see the time-sequence of these receiver control functions in the normal sequential track mode (3 of 16 dwell classes). This is termed a fixed-time dwell and is characterized by an assumption that the user position is known to an accuracy such that the C/A code time-of-arrival is known within one chip and the net doppler is within the AFC bandwidth. It does not therefore include any search stategy, but rather prepositions code and frequency, assumes lock-on, and then simultaneously takes a pseudorange measurement and commands verification that lock was achieved. Variable-time dwells are used during acquisition and special functions which are more complex than Figure 3-3 and invoke the hardware-operated search routines.

After pre-positioning both the C/A coder in time and VCXO in frequency (satellite plus user doppler), all three hardware loops are enabled at the same time. After locking out the code loop, the sequential detector is enabled to verify code lock. A dismiss at this point is a transient condition, passed to the system monitor, causing HOBYT mode to begin.

The presumption here is that an especially violent manuever has begun, and a limited re-search ensues in both code and frequency, with similarly coarser navigation processing to follow. During the last 0.4 sec of dwell only phase tracking is accomplished with data demodulation of the bit stream possible when a longer fixed dwell has been scheduled after 0.9 sec. Note that as the CT clock is divided off the C/A VCXO, the change in clock timing during this 0.4 secs is a doppler count when PR^2 is differenced with PR^1. The first PR is thus a position measurement and the difference is a ΔPR or velocity measurement.

The receiver processing module also provides the bit and frame synchronization necessary to remove all "lane" ambiguities. They would be present in GPS navigation if the user could only synchronize to the C/A code epoch with its 300 m period, or "lane" in marine navigation jargon. Synchronization is accomplished during monitor commanded variable-time dwells and involves probablistic decision making in the case of bit-sync, and use of the HOW word for frame sync (bit sync is the process of finding which one of twenty consecutive C/A code epochs occuring every millisecond defines the data's 50 BPS bit boundary). Binary data decisions at the output of a hardware/matched filter are passed to the processing module to accomplish these operations. Data is transferred from receiver processing in 32-bit words.

3.4.4 *Navigation*

The navigation function converts PR and ΔPR data to user position, and sometimes incorporates external altitude measurements in this process.

The basic element of this function is an 8-state Kalman filter shown in Figure 3-4. The filter states are

$$S = [\delta x \;\; \delta y \;\; \delta z \;\; \delta t \;\; \delta \dot{x} \;\; \delta \dot{y} \;\; \delta \dot{z} \;\; \delta \dot{t}]^T$$

thus modeling user position and velocity, and reference oscillator phase

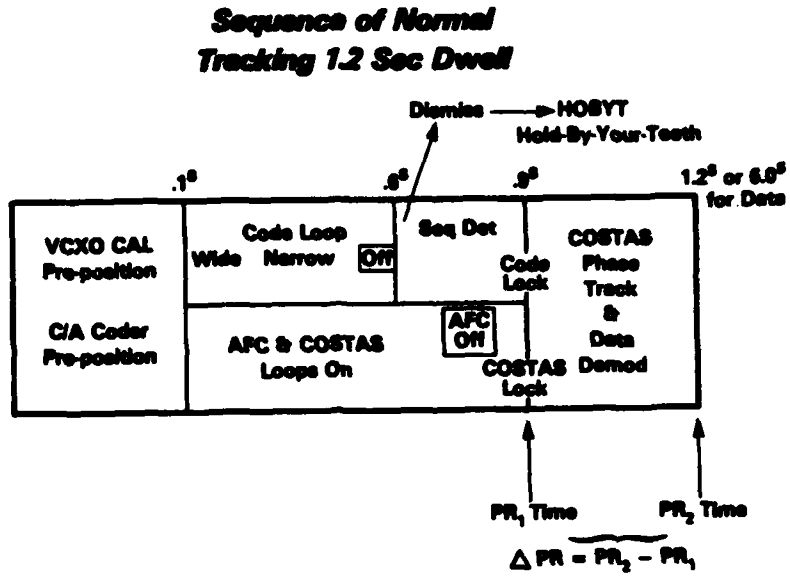


FIGURE 3-3

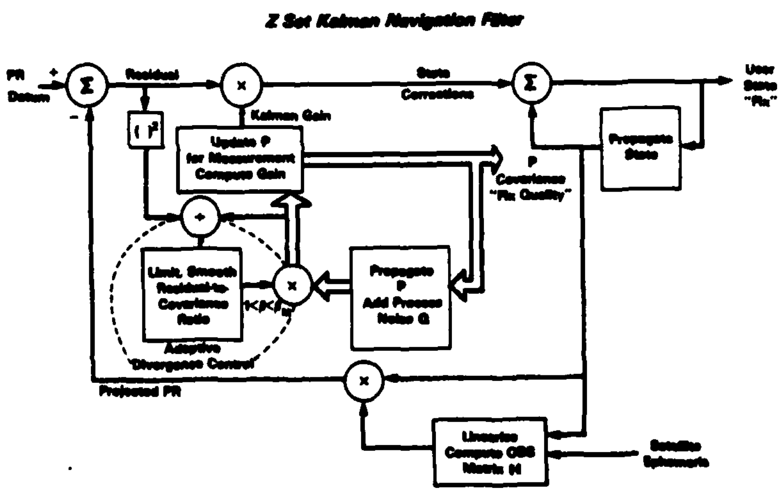


FIGURE 3-4

and frequency offset from GPS system time. The filter is linearized each iteration about estimated user position, and incorporates an adaptive feature for control of divergence that often accompanies such linearized filters. This divergence control is implemented with a gain term which is applied to all filter covariance estimates. The gain term is driven by a ratio of actual squared residuals to expected, the latter based upon the previous estimate of covariance projected into the measurement dimension. When expected (δPR) differs from that measured, this gain increases the modeled state errors. The subsequent Kalman gain computation responds to this by increasing Kalman gain, using more new information to correct the state (i.e. filter bandwidth increases). This form of adaptation/divergence control is claimed to offer superior response, as compared to the more usual method of modifying the process noise or "Q" matrix. In fact, the process noise data base is never modified, although differing initial covariances are used in TTFF and reacquisition modes. The updated state covariance is used to compute the Estimated Position Error (EPE), which is displayed to the operator and is used to control some portions of the system mode.

The measurement noise associated with each datum is altered in real-time according to the source of satellite emphemeris (data block I/II or almanac) and the quality of PR measurement reported by the receiver processing module. This in turn is based upon the various lock indications provided by the hardware. Thus we see that the linearized Kalman filter uses both measurement quality adaptivity and an ad-hoc adaptability that amplifies state covariance directly based upon measurement residuals.

In Figure 3-5 we see the major program steps in iterating this filter. With four satellites in normal tracking, the filter runs twice per dwell. In this sequence, any altitude data supplied by the external unit is NOT processed into the filter. Rather, user state is used to estimate errors in the external input (i.e. GPS is presumed more accurate than the altimeter, a not unreasonable assumption). An operator injected value of altitude will be processed into the filter once, and then ignored (a perhaps more debatable assumption is that the operator cannot possibly know more about his altitude than the GPS estimated user state).

When only three satellites are available (four user states cannot be accurately solved-for with only three measurements), the external or CDU altitude data is used as a measurement. Since the filter is ECEF based, the altitude datum is incorporated by computing an H (observation) matrix and then processing in effect as if the altitude were a PR measurement to a satellite located at earth center. Finally, the measurement variance for this altitude datum grows with time, reflecting the airborne applications where altitude uncertainty often increases with time. All altitudes within the Z-set and in the output are referred to the WGS-72 ellipsoid and hence do not contain geoidal height.

The Kalman filter as used here is an excellent structure for a maneuvering/adaptive situation. It is also ideally suited to the non-stationary condition of this sequential receiver in that it continously alters its gains to serially incorporate measurements, automatically weighted by their quality, and automatically compensated for

Z Set Navigation Function

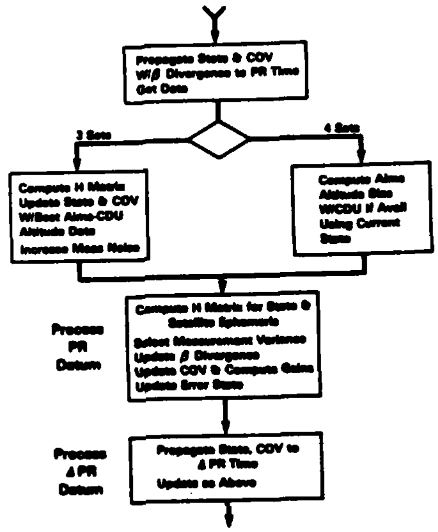


FIGURE 3-5

receiver dwells longer than 1.2 sec. The H matrix distributes each observation's information (the residual) to the appropriate state via the "Kalman gain." This mechanism would, for example, use a satellite bearing 000 to correct only North position and velocity. A totally missed measurement will be reflected in the next filter execution by larger state covariances and higher gains, while all sorts of partial measurement situations can be easily incorporated. Examples include valid code lock for PR_1, no COSTAS and no PR_2, or shadowing of a satellite in a turn and use of a corrected altitude measurement to effectively "fill" in its place. The Kalman filter also makes a smooth transition to degraded operation in the three satellite mode and will provide extended operation into the two satellite region with a simultaneous measure of growing position uncertainty due to growing reference oscillator error.

A "CAL" mode also exists in the receiver that should be used in the start-up process. This sets all process noise variances to zero except those associated with the reference oscillator, and zeroes velocity coupling to position in the transition matrix. This tells the filter that the set is not moving and all information from the measurements is then diverted into reducing initial position uncertainty and estimating the two oscillator states. Computationally the Kalman gain matrix terms that couple residuals to the position and velocity states tend towards zero in CAL, and the set becomes insensitive to movement. Proper care in CAL use must be observed in experimental procedures. It is a useful mode for this type calibration, and for the stationary user perhaps checking set accuracy at a known point.

3.4.5 Satellite Selection

This function is not of any current interest since only four satellites are available at present for field tests. It does represent a small overhead burden to the software. The act of satellite replacement will degrade navigation accuracy somewhat during the transition period. In the Z-set, satellite constellation selection/review is undertaken periodically by the system monitor. The selection module runs as a background task and evaluates the position error improvement that could be obtained by replacing any one satellite with another in-view (this one-for-one "slow replacement" mode is primary). All possible replacements are evaluated. This calculation is a GDOP calculation (see 4.4) and differs only in that a diagonal weighting matrix is incorporated along with the user geometric considerations. This weighting is a sum of numerical factors that reflects:

i) Low elevation angles have increased PR error due to the ionospheric obliquity factor.

ii) How much longer the satellite will be in-view.

iii) Quality factor for past experience with reception of this satellite's code and data. These data are contributed from system monitor and navigation functions.

iv) Health class of the satellite, taken from the almanac.

Hysteresis is built into the decision based upon this weighted trial of all possible satellite replacements so that a replacement will only be effected when the advantages are significant. A rapid selection procedure to first discriminate and rank order satellites by geometric considerations only ("geometric fill"), followed by a first level of bulk refinement, is also provided and commanded by the monitor. This would be used in TTFF situations and other transient conditions.

3.4.6 Satellite Data Gathering

Gathering data from GPS satellites is a most significant housekeeping function, one that alternate signal-structure designs have approached as a means to reduce receiver cost/complexity. In the sequential receiver it is even more difficult than in a parallel receiver since satellite dwell time while navigating will always be less than the time necessary to simultaneously receive an entire data message frame. This may force intricate interleaving of data demodulation in small non-contiguous "chunks," or degraded navigation for periods of intense data collection.

The Z-set represents a considered tradeoff in these problems. The data gathering module itself is basically a handler for the data words (32 bits) passed from the receiver processing module. It checks parity, and assembles these words into complete subframes, and these into complete data block I/II or almanac groupings. It further tests these for time coherency, and tests ephemeris calcualted from I/II against that from the alamnac as a final ad hoc test. They must agree to better than 15 kilometers if the I/II ephemeris data is to be declared valid. The gatherer is of course driven by and replies to the system monitor. In the following description, the indivudual roles of the monitor, receiver and gatherer are not differentiated.

3.4.6.1 Almanac

An almanac collection mode is a separate distinct set mode. It is entered by the monitor if it determines that no valid almanac exists in protected memory, or if commanded by the operator. The former is termed "search the sky" mode and requires a search over code, frequency and satellite addresses to find any one signal to obtain the almanac data. Once this lock is achieved, an extended 12.5 min dwell on that satellite is operated to take a complete almanac. A commanded almanac avoids the "search the sky" routine, utilizing a satellite in code-lock to obtain the almanac over the 12.5 minute period. The monitor then returns to the normal sequence of operations that lead through INIT and TTFF, to sequential tracking operation. An almanac is not collected as a background task to normal sequential tracking, as it would most likely never be completed before satellite transitions occurred.

3.4.6.2 Data Block I & II

Data blocks I & II, the precise ephemeris data, are collected from each satellite as part of the normal TTFF state transition, and periodically as the data ages. In the TTFF mode a 24 second dwell on each satellite in succession collects the data I/II in the shortest possible time. As the data message is 30 seconds long, the balance of each message cycle is used for reacquisition of the other satellites and PR measurement. This procedure maintains fix convergence and is an example of the ability of the Kalman filter to accept such asynchronous measurements.

Once the set enters normal sequential track mode, data is not demodulated. No attempt is made to interleave demodulation and assemble complete subframes. The operator of course has the option to command an almanac, otherwise no data is taken until the system monitor determines that current CT on any satellite exceeds the TOE time by a data base constant, currently 60 minutes. TOE time is a message parameter which specifies the GPS time of applicability of that satellite's ephemeris data. This value is set by the GPS system controller and can vary with all sorts of conditions such as orbit predictability, control segment performance, etc. When TOE is exceeded by the requisite amount, block I/II collection is scheduled for that satellite. This is accomplished with extended fixed-time dwells that demodulate an entire subframe (6 sec) worth of data. After any one such dwell, another is prohibited within that data frame (30 sec), and various other tests are also effected to minimize disruption. This type of I/II collection proceeds on only one satellite at a time and typically requires about 4 minutes to collect and validate a new ephemeris. A similar procedure is used when a satellite is replaced in the constellation. The net effect is a slight degradation in navigation accuracy, but well spread over the time period from a marine user's point of view. Various test are also made so that a satellite with poor telemetry conditions that cannot supply a validated data block is eventually dropped after six subframe attempts. Again we see the power of the Kalman filter to adapt to such asynchronous operations (and hence acceptably deal with the GPS data message problem).

3.4.7 Satellite Ephemeris

The formulas and definitions required for this calculation are documented in CP-US-305. They are composed of an initial calculation for certain orbit parameters which is updated once per hour, and less complex calculations to return position and velocity as required by the other software functions during Z-set navigation.

3.4.8 Ionospheric Delay Models

Many GPS references refer to the intent or even the availability of parameters within the data message to model ionospheric errors. While room is reserved in the present message for such parameters, none are in fact transmitted today and the Z-set does not have any routines for making these calculations and incorporating them as pseudorange corrections. The test period reported here encompassed largely the minimum diurnal ionospheric delay period, and the set itself made no attempt to further minimize such delay errors. The contributions of ionospheric delay errors to DOD use of the C/A signal are insignificant. Therefore, we do not expect to see any attempt at the transmission of model parameters in the near future.

3.4.9 ZUSCP Processor

The processor itself is an LSI-11 with KEV-11 hardware floating point processor. ROM memory occupies some 32K words with RAM another 6K. Approximately 20% of the code is devoted to the receiver processing function, a similar amount to the total navigation package, and 10% to the system monitor. The Kalman filter requires about 40% of sequential run time with no other dominant functions. A 15% headroom remains in this sequential mode of operation. Thus the Z-set software, which performs a multi-task complex function, largely utilizes the full resources of the LSI-11.

4.0 USCG/MARAD Z-set Phase I Test Results

4.1 Test Location

The GPS Phase I user equipment set-Z, manufactured by Magnavox Research Laboratories (MRL), was installed at the Coast Guard District Eleven headquarters in the Union Bank Building, 400 Ocean Gate, Long Beach, CA. The test period spanned 8 May 1979 to 9 September 1979 and was almost totally a fixed site, manual data collection program. Its goals were general education in the subject of GPS user equipment and a systematic observation of C/A-only signal accuracy. The latter is a performance measure not widely available because of the fact that the GPS developer, the DOD, is not very interested in C/A accuracy limits. The long range goals of MARAD and the Coast Guard were discussed in section 1, this test phase was a first step in meeting those.

The test was largely conducted by the Verdes Engineering consultants, with occassional assistance from the TSC representative and Coast Guard personnel. At the conclusion of the program a brief sequence of tests in an automobile in the greater Los Angeles area were also conducted and are reported herein.

4.2 Installation

The Z-set was installed in the CG Operations Center on the eighth floor of the Union Bank Building. The building has 14 floors, so there was about 100 ft vertical separation between the antenna and receiver. The antenna was mounted near the northeast corner of the roof. This was done for clearance from the small penthouse in the center of the roof, on top of which are a number of whip transmitting antennas.

The antenna is a CHU Associates model CA-3224--a conical spiral specified for the Z-set--mounted on a bent aluminum plate forming a small ground plane. The preamplifier is mounted directly beneath it, connected by one foot of RG-58/U cable. The cable from the preamplifier to the receiver, RG-213/U, is about 280 ft long, and should have about 30dB attenuation at 1500 MHz.

Despite the relatively long cable, there was no apparent evidence of any deleterious effect on receiver performance due to the 30dB loss. Nevertheless, the receiver was moved temporarily to a location where the cable loss was less than 10dB to determine if any performance changes could be observed. None were noted. MRL checked this installation and agreed that the cable loss, while well outside of specification, would not affect performance as the NF was only degraded 1 dB, and the satellites are presently transmitting some 3-4 dB above specification and 6-7 dB above worst case. The loss would affect overall gain and might perhaps produce problems with low elevation satellites, but there appeared to be none. Apparently the overall design was overly conservative.

4.3 Site Calibration

In order to verify the accuracy of the GPS Z-set, it was necessary to determine the position of the antenna by independent means. Use of a demonstration model of a Magnavox model MX-1502 Satellite Surveyor was obtained on 14-16 May 1979. It was set up with its antenna within 2 meters of the GPS Z-set antenna on the roof of the Union Bank Building.

During the period of operation, seven 3D fixes were obtained, with the following results, in satellite datum:

	Mean	Std. Dev.
Lat	33° 46' 1.716" N	6.1m
Long	118° 12' 5.867" W	11.8m
Ht	33.416m	6.7m

Converting to WGS-72 datum and correcting for geoidal height gives the following Z-set antenna position:

Lat 33° 46' 01.72" N
Lon 118° 12' 05.60" W
Ht 66.9m

4.4 GPS Coverage in Long Beach CA

In order to mechanically collect the Z-set operating data, and to interpret it, we must know something about the coverage from the satellites. In Figure 4-1 we see the satellite "look angles" in a polar elevation/bearing angle plot. This was run by TSC from an algorithm supplied by SAMSO. This coverage pattern moves with satellite precession approximately 4 minutes per day. Full four-satellite coverage began at 2345 hours local in May, and this beginning advanced to 1545 hours local by 9 September. This pattern resulted in most of the experiment being conducted during local darkness, which is the period of minimum

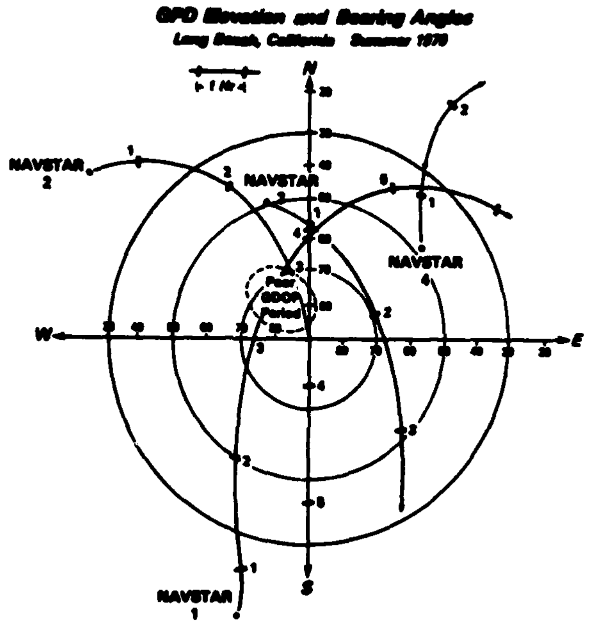


FIGURE 4-1

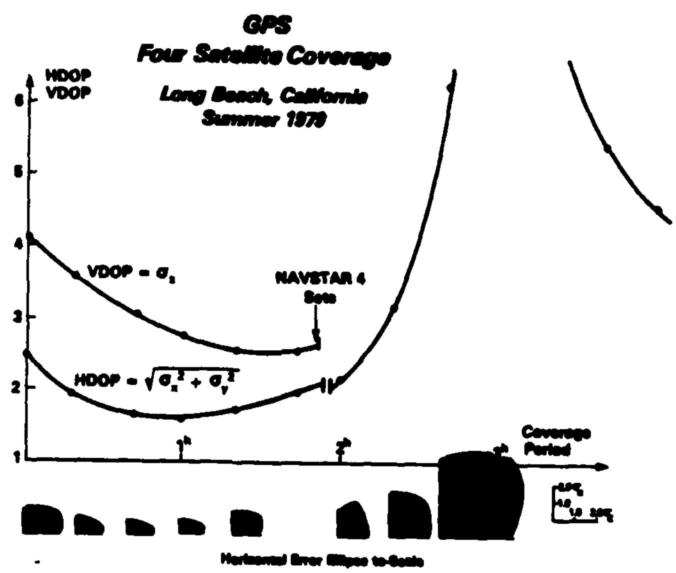


FIGURE 4-2

icnosperic delay error. While the impact of ionosperic delay is crucial to the Coast Guard interest in GPS, it was probably fortuitious to have eliminated this as a "noise" source in this first test phase, allowing us to concentrate on other facets and self-education.

The GDOP calulation, which is the scale factor for converting ranging error into position error, is:

$$GDOP = (G^T G)^{-1} = P$$

$$g_i = (\cos E_i \sin B_i \quad \cos E_i \cos B_i \quad \sin E_i \quad 1) \quad i=2 \text{ to } 4$$

The horizontal position error is in general described by an ellipse which can be computed from the σ_E, σ_N) and σ_{EN} terms as follows:

$$\theta = \tfrac{1}{2} \operatorname{atn}(2\sigma_{EN} / (\sigma_E^2 - \sigma_N^2))$$

$$\begin{bmatrix} \sigma^2_{major} \\ \sigma^2_{minor} \end{bmatrix} = \begin{bmatrix} \cos^2\theta & \sin^2\theta \\ \sin^2\theta & \cos^2\theta \end{bmatrix}^{-1} \begin{bmatrix} \sigma_E^2 \\ \sigma_N^2 \end{bmatrix}$$

Performing these two calculations on the "look angle" data yields the coverage plot for Long Beach in Figure 4-2, with the accompanying East/North error ellipse sketch. We see from this figure that only the first four-satellite coverage period is of real interest, the following 3-satellite period has large and variable GDOP, with a "GDOP hole" where it grows beyond 100. It will be difficult to infer any real performance information from data in this 3-satellite period. The operating experience with three satellites did, however, turn out to be useful.

4.5 Data Collection

Set operation procedures were adapted from the published operator's manual, and slightly revised based upon experience. The procedure is given in Table 4-1, while the data collection procedure follows in Table 4-2. The procedure was entirely manual, with the fix being limited in its precision by the readout quantization of one arc second. This has unfortunately reduced the total amount of information available from this Z-set test phase, but not fatally so. The internal navigation fix precision is much greater than the CDU readout recorded here, but these data were inaccessible during this test phase. The next test sequence in the CG/MARAD program aboard the r/v Gyre will solve this problem by accessing this precise information in its ECEF coordinate form directly from computer memory.

In Appendix A the summarized valid data base collected by Verdes Engineering is given along with an example of the raw data. A commentary on each day's operation is also included where appropriate.

1 Turn BRT control CCW to click off. Switch POWER ON, turn BRT control CW. -If set doesn't come ON, open front and flip up 400 cycle switch.

2. Observe: Yellow INIT Light ON, F in Waypoint.

3. Switch SELECTOR to 6 o'clock position - should read 040000, indicating oscillator error.

4. Press CAL, observe yellow light ON.

5. Set selector to LAT, press FRZ-ENT.

6. Observe 33 46 xxN (xx anything). Correct with keyboard if necessary. Press STR.

7. Set selector to LON, press FRZ-ENT.

8. Observe 118 12 xxW. Correct if necessary. Press STR.

9. Set selector to ALT, press FRZ-ENT.

10. Observe 240. If necessary, clear using CLR Key, correct, press STR.

11. Set selector to GS. See reading is ZERO. Press FRZ-ENT, STR.

12. Set selector to TRU-GTK. See reading is ZERO. Press FRZ-ENT, STR.

13. Set selector to DAY/TIME. Press FRZ-ENT. ENTER GMT DAY, TIME, press STR. (First number is day of week. GMT is 7 hours later than PDT. Sunday - 1. Example: 3 2200 PDT = 4 0500 GMT).

14. INIT LIGHT GOES OUT. STBY ON.

15. Record TIME - Initilization complete.

16. After oscillator is warmed up (F has changed to 0) switch to EPE, press 5/A to collect almanac. Observe A at left of display disappear within 10 minutes (must be in STBY).

17. Set selector to 6 o'clock position. Numbers on right should go to 44 if four satellites are tracked. If 33, reset altitude.

18. When STBY light goes OFF, turn CAL OFF.

19. Follow procedure for data recording.

20. To collect new ephemeris:

NOTE: ON POWER OFF - TURN BRT OFF FIRST

TABLE 4-1 - INITIALIZATION PROCEDURE

1. Switch SELECTOR to DAY/TIME.

2. Press FRZ-ENT one second before selected time.

3. Record time.

4. Switch SELECTOR to EPE - Record.

5. Switch SELECTOR to LAT - Record.

6. Switch SELECTOR to ALT - Record.

7. Switch SELECTOR to ALT - Record.

8. Switch SELECTOR to 6 o'clock position - record last two numbers in S/S column.

9. Press FRZ-ENT - LIGHT OFF.

TIME - Satellite time, accuracy 1 sec (nominally GMT)

EPE - Estimated Position Error, accuracy .01 nm, derived by the set from the variance of the filtered Navigation Solution.

LAT - Latitude, WGS-72 coordinates, accuracy 1 arc second.

LON - Longitude, WGS-72 coordinates, accuracy 1 arc second.

ALT - Altitude above WGS-72 geoid, feet.

S/S - Satellite Status - two numbers; first the number of satellites providing acceptable navigation data; second the number of satellites from which ephemeris (data block I/II) data have been collected.

TABLE 4-2
DATA COLLECTION PROCEDURE

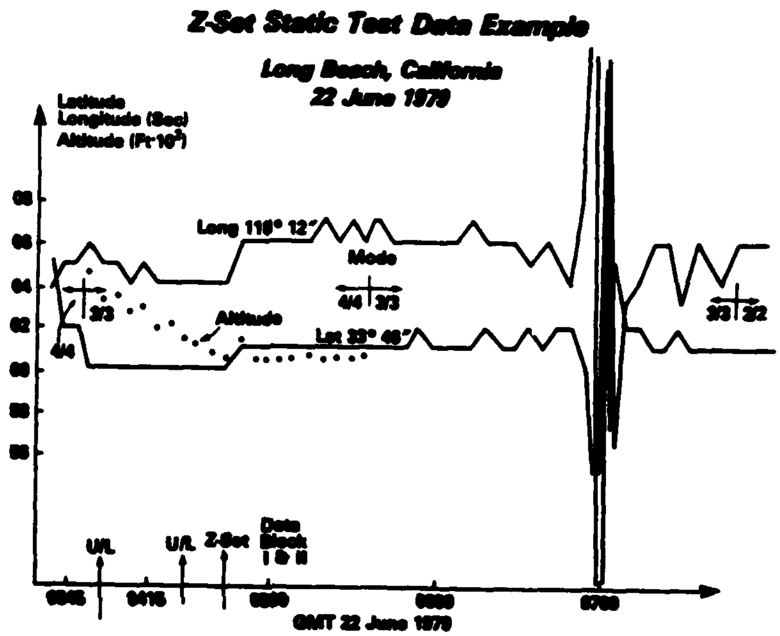

Z-Set Static Test Data Example
Long Beach, California
Latitude
Longitude (Sec)
Long
Mode
4/4
3/3
Altitude
Lat
3/2
U/L
Z-Set
Data
Block
GMT

FIGURE 4-3

In Figure 4-3 we show an example from this data. We see here the method of vertical scaling for a common axis display of approximately equal precision, and the three major events of a coverage pass at the test site. The first mark after the data record begins (which commences after the "NAV" light is lighted, meaning EPE is below 0.25 n m) marks upload time. This was determined post-mission from the primary control station at Vandenburg, and marks the time at which the new data block I/II parameters were successfully injected into the satellite. These update both the satellite ephemeris model and the clock model, and are based upon control data from all three monitors. This update represents data corrections after twenty-four hours worth of clock and orbit variability. The next mark is when the Z-set collected new ephemeris data and hence "read" these new messages and began to navigate with current vice 24-hour-old data. About halfway through the test, we learned what this entire process involved, and in the Appendix data you will see that most later figures do not show this "reset" action. The test start was delayed until VAFB had uploaded (determined by telephone 805-866-5948/FTS 981-5448) or a new ephemeris was called by the operator. This was done by calling and then canceling an almanac, which had the effect of starting TTFF over, which leads to data block I/II collection along the way.

4.6 Test Results

4.6.1 Z-set Reliability

The Z-set was essentially one-hundred percent reliable throughout this Phase I test. About five false failure indicators did occur (the Automatic Fault Indicators were not described in Section 3, but copiously exist). They were all computer self-diagnostic false alarms and were recognized as such, cleared, and normal operations resumed without incident.

4.6.2 GPS Navigation Availability

Navigation with the Z-set was attempted on 76 days during this period, and 25 such attempts resulted in "good" data. These were defined as no external manifestations of set malfunction, no reported problems from the Vandenburg control segment, and satellite fix data which appeared reasonable. On 7 of the other 51 days problems were experienced with the data message; the Z-set indicated via the S/S readout that code lock was achieved, but the ephemeris data could not be demodulated and validated. The balance of experiment-days, some 44, produced other than four-satellite "good" data due to clock problems on board either NAVSTAR One or Two.

4.6.3 Four Satellite Navigation Performance

In Figures 4-4 and 4-5 histograms of position fixes using four satellites before and after data block I/II upload is shown. A tablulation of the 25 days of four-satellite fixes after upload is given in Table 4-3.

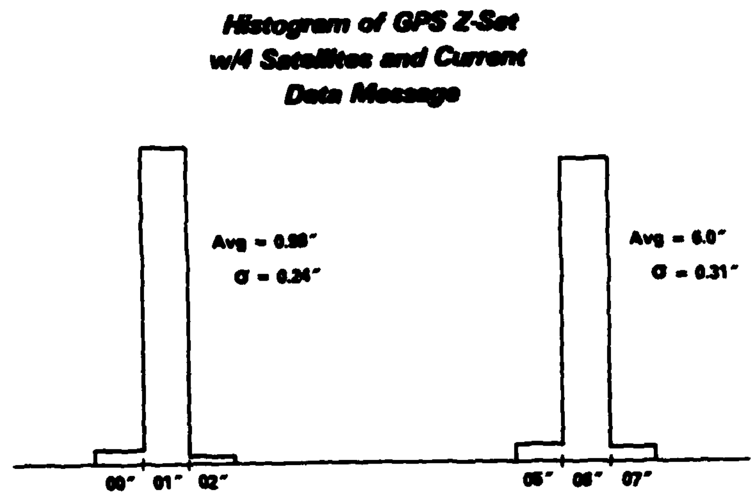


FIGURE 4-4

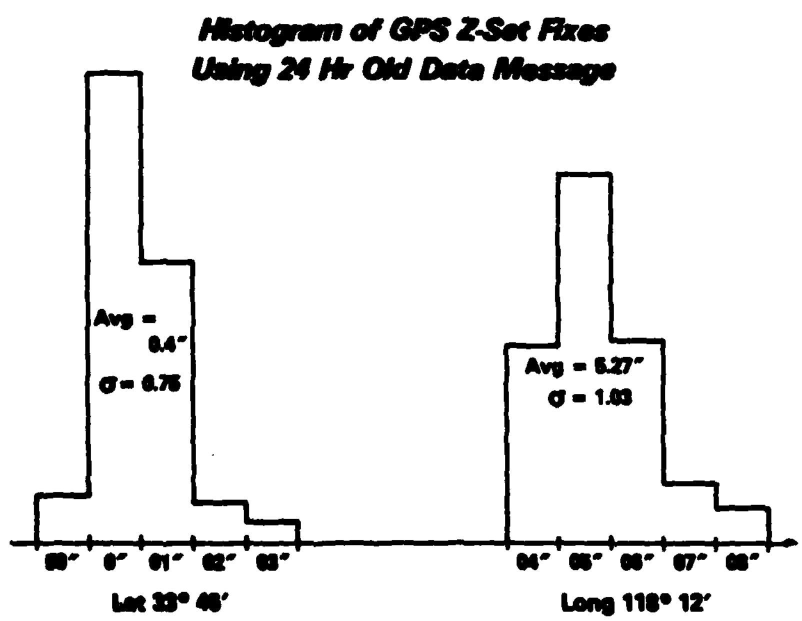


FIGURE 4-5

If we compare the long term GPS position with the Transit surveyed position, we find differences on the order of 10 meters. These divergences are within two-sigma (sigma estimated from the Transit data) of the Transit position, and we cannot state that the two disagree at a 90% confidence level. The altitude estimates differ by several meters when the GPS estimate is corrected for geoidal height.

The difference in satellite data messages as reflected in Z-set position error is shown in Figure 4-6 as drms circles of the respective fix ensembles, plus the bias offset. Finally, if we look again at Table 4-3 we see a few samples taken near the end of the program when the coverage period had advanced into the afternoon--a time of greater ionospheric delay. There is a distinct change in longitude fix variability as well as change in average value. This sample is too small for any strong conclusion, but we can at least say that the change to a smaller value of longitude is in the correct direction for the physical situation. Referring to the "look angle" diagram (Figure 4-1), NAVSTAR 2 at the start of coverage has a sub-ionospheric point considerably to the west towards the point of maximum solar-induced ionospheric delay. NAVSTAR 4 on the other hand is located to the east near the terminator. These two satellites are the primary determinants of longitudinal position, and the relative imbalance of ionospheric delay due to the time of day should produce the easterly longitude errors observed.

4.6.4 Three Satellite Performance

Figure 4-7 is the histogram of fixes taken from the Z-set after NAVSTAR 4 set and we reverted to three satellite navigation, with operator entered altitude at the CDU. The generally poor GDOP during this period and its rapid change, coupled with the Z-set propensity to seemingly not always use CDU supplied altitude values to the best extent, weaken conclusions from this data. Data when EPE 1.0 nm was not used in this plot. Much of the data was taken from the period after the "GDOP hole" and, though it is not shown on Figure 4-2, the horizontal error ellipse becomes very elongated in an E-W direction with ratios of 3-4:1. This can be seen qualitatively from the "look angles" since, when 1 and 2 are nearly overhead and 3 bears SSE, there is little E-W information available. This ellipse behavior explains the increased longitude histogram scatter, but not the "outliers" which all occured on one evening with no obvious Z-set or control-segment explanation.

While the three satellite fix error increased by a factor of 4-5 over four satellites, this is the expected range of HDOP change. The average value changed by only 1 m in lat and 16 m in long. The latter is caused largely by the outlying points from the one day, and is thus suspect.

4.6.5 Estimated Ranging Error Sigma

In keeping with our overall goals, we would like to determine something about the underlying effective ranging error for the Z-set, under the operating conditions in the Long Beach tests. Due to the generally

Comparison of Z Set drms Fix Error for Current & 24 Hr Old GPS Data Message

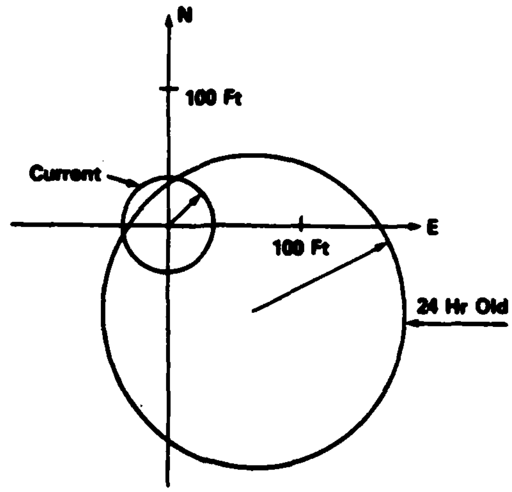


FIGURE 4-6

Histogram of GPS Z-Set Fixes With 3 Satellites

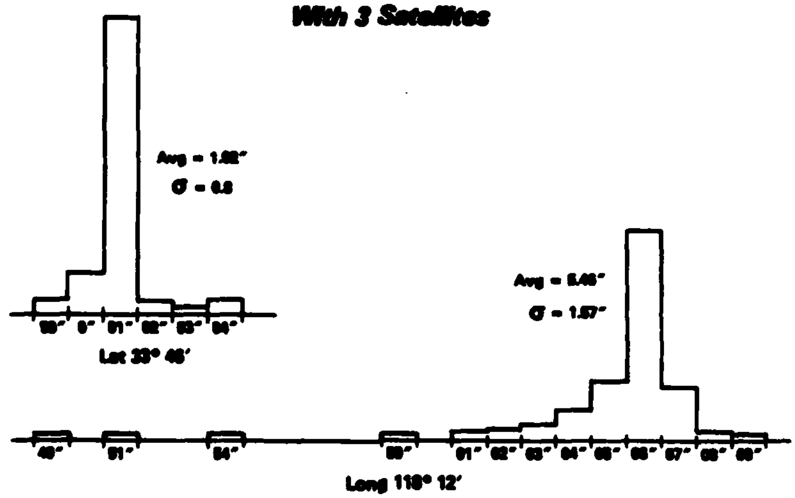


FIGURE 4-7

very good performance and quantization of the fix to one arc-second, this cannot be done very accurately; the readout rarely changed during uploaded/four-satellite-navigation conditions. We can make some coarse estimates, using the Figure 4-2 values of normalized position standard deviations caused by geometery, as follows:

Table 4 -3

4 Satellites		C/A Estimated DOP	Pseudorange Sigma
Altitude Sigma	11 m	2.8	4 m
Long Sigma	10 m	1.2	8 m
Lat Sigma	8 m	0.9	8 m
3 Satellites			
Long Sigma	45 m	5	9m
Lat Sigma	21 m	1.5	14m

These estimates are an effective sigma-PR(C/A), after smoothing by the navigation filter whose bandwidth is unknown. They also include some daily variations such as marginal clock performance. They are not the sigma associated with a single PR measurement from one dwell.

We consider the four satellite altitude data to be the best overall indicator of underlying ranging error since it was not quantizied as severly as Lat/Long in readout, and was taken from the period of full normal operation. The three satellite data is most tenuous involving poor GDOP and potential internal degradation of the fix due to the navigation filter's method of processing and degrading the CDU input-altitude with time.

4.6.6 Update Rate

Update rate is an ill-defined parameter often associated with navigation systems. Externally the Z-set appears to have an update rate of one second, for the CDU display is updated by the CDU software function at this rate. For update rate to be meaningful, however, it must say something about the time-spacing of new information from the navigation system, or alternately about the time-correlation of random variability of the output. This is a difficult definition to implement in the case of the Z-set with its time-varying Kalman filter structure. For a desirable constellation with direction cosines spread around the horizon and an accurate measure of the reference oscillator in memory, the Z-set can potentially produce new fix information every two satellites, or 2.4 seconds. This would however depend upon the navigation filter's gains, i.e. how much new information was added to the old state estimate, and this as we have seen is variable. It can be measured in steady state (constant velocity) conditions, but only with direct access to the internal ECEF user state, followed by correlation analysis. We could not do this in these Phase I CG/MARAD tests, but in preparation for Phase II tests, actual ECEF data was recorded at Texas A&M University (College Station, TX) in November 1979.

In Figure 4-8 we see the autocorrelation of 100 samples of ECEF position taken from the Z-set during a four satellite period. The raw standard deviations agree fairly well with the altitude estimate--adjudged most accurate--from Table 4-3. More important is the correlation time of the fix data, about 7 seconds. This is roughly equivalent to a first-order filter operating on white noise with a 14 second time constant. In steady state (any constant velocity including zero), we can say that the Z-set has an information update rate of 14 seconds. This is indicative of parameter choices in the Kalman filter, not indicative of GPS system limitations. It does allow us to scale estimates of sigma-PR to other filter time constants (square root of time-constant change) so that we can compare GPS navigation to other forms of radio navigation.

4.6.7 Time to First Fix

At the start of each day's navigation exercise of the Z-set, this time was measured and recorded if a valid fix was in fact obtained. The average of the TTFF, after oscillator warmup (about 5 minutes at room temperature) and almanac verification, was 3 minutes and 20 sec, almost exactly on specification.

4.6.8 New Ephemeris (Data Block I/II) Gathering

As seen in the Appendix data and commented on before, the Z-set if started before satellite upload, would often take considerable time to initiate a routine gathering of a new ephemeris. The time required, for those days where appropriate, averaged 34 minutes with a sigma of 12 minutes.

4.6.9 Miscellaneous Performance Observations

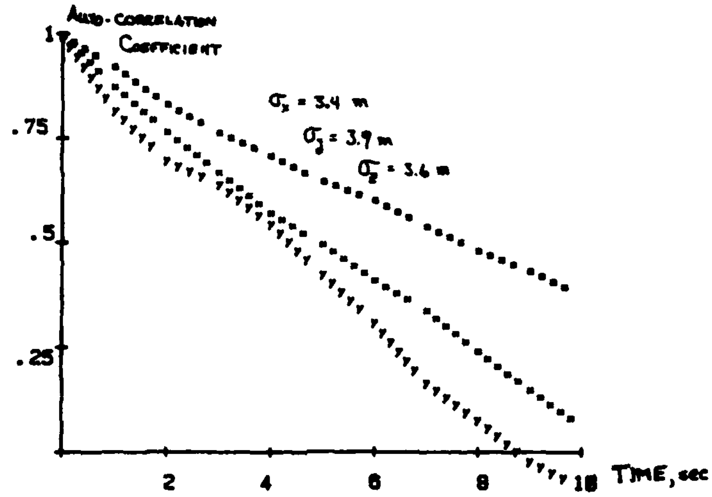
4.6.9.1 CAL Mode

The CAL mode, as previously described, converts the navigation filter to modeling zero motion, and as a result the filter becomes totally insensitive. In Figure 5 of the Appendix we see the result of an operator error in leaving CAL on. The set continued to navigate perfectly through the "GDOP hole" when it should have blown up as most other data show.

4.6.9.2 Estimated Position Error (EPE) Readout

The EPE is the root-sum-square of the three diagonal covariance terms associated with the position states:

$$EPE = \left(\sigma_E^2 + \sigma_N^2 + \sigma_{alt}^2\right)^{1/2}$$



AUTO-CORRELATION COEFFICIENT
1
.75
.5
.25
σ_x = 3.4 m
σ_y = 3.9 m
σ_z = 3.6 m
2
4
6
8
10
TIME, sec

FIGURE 4-8

This proved to be a usefull readout at most times, during initial lock-on and fix stabilization, and during the transient periods from 4 to 3 satellites and the 3-satellite GDOP hole. On a number of other occasions it was quite misleading, as a measure such as this from a linearized filter must, at times, be. In Appendix Figure 40 we see a day when NAVSTAR 2 was operating on only its crystal oscillator and the navigation solution just walked off due to this drift problem. It was a perfect fix all the way, however, with an EPE always below 0.02 n m. This occasion was pathological, but on many others in which the altitude diverged during the 4-3 satellite transition the EPE similarly indicated good fix quality.

4.6.9.3 Velocity

The velocity states of the navigation filter are not of a great deal of interest to marine applications. This is because they are driven largely from the delta PR measurements, and these may be quite noisy at sea due to antenna motion on the end of the ship's mast lever arm. While these errors may be prefiltered, or suppressed by using a large Kalman measurement noise, the correlation time of these errors fall within the range of maneuvering frequencies. The entire issue of fix smoothing, or trackers, with this type of Kalman filter is difficult in the marine environment because it also involves the vessel pilot's cognitive processes and the vessel dynamics; even channel characteristics. We endeavor to keep this subject separate from radionavigation system tests to the maximum extent possible since all systems must ultimately use a similar type of tracker prior to information usage by the pilot. The Z-set velocity output was not subjected to serious scrutiny, although random sampling in this fixed-site test revealed an average value of about 1 knot at a random course angle, with peak values never exceeding 2 knots.

4.6.9.4 Altitude

We have tabulated altitude performance under the four-satellite "good" data category. When the set was in any condition other than this normal four-satellite mode, the altitude was invariably the first output to indicate a problem, the most difficult to control, and when controlled, the solution to many problems. The test operator adopted a rule-of-thumb: "always set the altitude via the CDU, and continue to do so, whenever a transient condition or problem develops." Susceptibility to this sort of difficulty, which is itself difficult to articulate from these tests, obviously should not occur in a marine algorithm. Even in the airborne application we had the distinct feeling that things were not quite proper. While the horizontal solution would diverge slowly, the altitude could change very rapidly to extreme numbers, 99999 feet, positive or negative, and of course the filter could just not recover from this problem without help. Considering the relative dimensions of earth radius, orbit position and the user, we intuitively suspect there is both a transient problem involving altitude and a poor algorithmic use of available/operator information when satellites or constellations degrade.

4.6.9.5 Operator I/O

We had originally intended the Coast Guard petty officer on watch at the Operations Center to take a few samples of Z-set fixes on nights when the Verdes Engineering operator could not. While the latter had no problem in operating the Z-set, the watch personnel never really obtained any useful data. While this experience would not consistute an objective test of the I/O, and certainly not in an aircraft cockpit situation, it is a useful benchmark in many marine situations. A simple way to deal with it would be the recognition that most navigation begins where the last use ended. If coarse real-time were maintained in non-volatile memory, then an automatic start-up procedure could be provided, as this seemed to be when the CG operators consistently failed to enter all the required data correctly.

4.6.10 Vehicle Tests

At the completion of the static tests, the Z-set was placed in a ground vehicle for a brief test of its performance in that environment. The antenna and preamp were mounted on the roof of the vehicle, a station wagon, with the Z-set inside with a small gasoline powered motorgenerator providing 115V 60Hz power. The objective of the test was to evaluate the performance and accuracy of the Z-set in typical rural and urban environments.

Readings were taken in a total of 15 locations. In only one of them did the Z-set fail to perform. In the TORMED Medical Center complex in Torrance, approximately 50 ft from an 8 story building, it lost two satellites, and the position was off by several miles. After moving away from the buildings, the altitude was reset and the signals re-acquired. In front of the Union Bank building it lost one satellite, but gave a good fix. Several locations were under high votage power lines, which caused no problem. Several others were among and under trees, which also presented no problems, although it should be noted that Southern California trees in September are notoriously dry.

The 14 points at which good fixes were obtained were located on topographic maps, scale 1:24,000 (1 inch= 2000 ft), estimated to be accurate to within 100 feet plus map error. The readings on the Z-set were converted to North American Datum by subtracting 4 minutes from the longitude readings. Table 4-4 shows the results. The difference between GPS Z set position and map position was a mean of 80 ft north, 25 ft east; a radial bias error of 84 ft, and an rms error of 219 ft.

5.0 Conclusions and Recommendations

5.1 Conclusions

Based upon our four months of static tests of the GPS Z-set at Long Beach, California, we conclude the following:

5.1.1 The Z-set is very reliable with no actual failures experienced.

5.1.2 The R&D coverage provided by the present NAVSTAR satellites had a system availability of about 30 percent.

5.1.3 The average three-dimensional position error, provided by the C/A-only signal Z-set using 4 satellites, could not be proven to differ from the position provided by a Transit Survey receiver. This was for nighttime minimum ionospheric error conditions, and after satellite upload when minimum space segment error existed.

5.1.4 When Z-set navigation was performed using satellite data messages that were 24 hours old, fix accuracy degraded about 4-5:1.

5.1.5 Three-satellite fixes provided by the Z-set degraded in variability by about the amount predicted by HDOP for the test site coverage.

5.1.6 The effective ranging error, inferred from the GDOP ratio, lay between 5-10 m rms for the C/A signal during the minimum ionospheric conditions.

5.1.7 Because the accuracy of the Z-set was significantly greater than the precision of its readout (one arc-sec), no measure of effective fix update rate (navigation bandwidth) could be made in this test.

5.1.8 The EPE readout was a useful aid for most "regular" degraded fix conditions, but failed to warn the operator during certain "non-standard" conditions.

5.1.9 Random sampling of velocity errors in this static test showed an average less than one knot, with peak value of two knots.

5.1.10 The altitude readout changed rapidly during transient coverage conditions; more than seemed reasonable. The resulting large altitude errors were always indicative of navigation filter divergence.

5.1.11 The entry of altitude from the CDU was sometimes difficult to make effective, or maintain its effect, in filter processing.

5.1.12 Tests of the Z-set in a vehicle showed excellent fix performance (to within map, plus reading, error) at 14 of 15 sites around Los Angeles. Some loss of signal track occured when the satellite(s) were shadowed by large buildings.

5.2 Recommendations

Based upon our four months of tests and "living" with the Z-set, we make the following recommendations:

5.2.1 The readout precision could usefully be increased. A simple means would be to display range and bearing to a waypoint with greater precision, since blanked digits currently exist in this display mode.

5.2.2 Fixed-altitude navigation should be selectable as an operating mode in which the Z-set does not try to degrade or second-guess the altitude "measurement."

5.2.3 The transition to three-satellite navigation should be studied to insure that it is smooth, in either the present set configuration or after being configured for fixed altitude.

5.2.4 In a marine application, fixed altitude navigation should be referenced to sea level, whence some geoidal height data base should be stored.

5.2.5 The operator should be able to assign satellite health status in order to override constellation selection, if necessary.

5.2.6 The EPE measure should include some other factors that would help its realism in certain conditions. The most obvious suggestion is incorporation of boundary condition altitude values as "tripping" a contribution to EPE.

5.2.7 An auto-start feature should be provided, based upon maintenance of coarse real-time in non-volatile memory.

Comments on the dynamic performance of the Z-set in the marine environment must wait the next phase of these tests.

APPENDIX A - FIELD TEST DATA

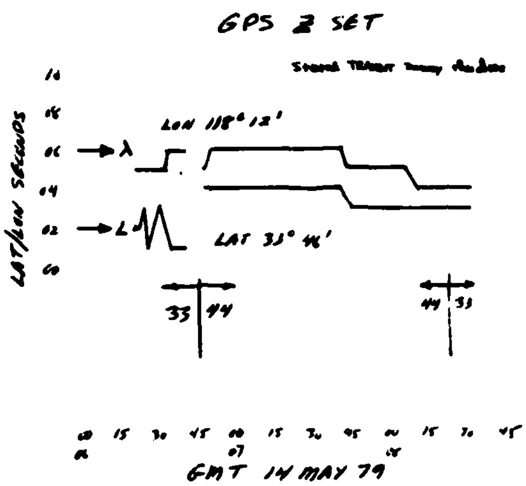


FIGURE 0

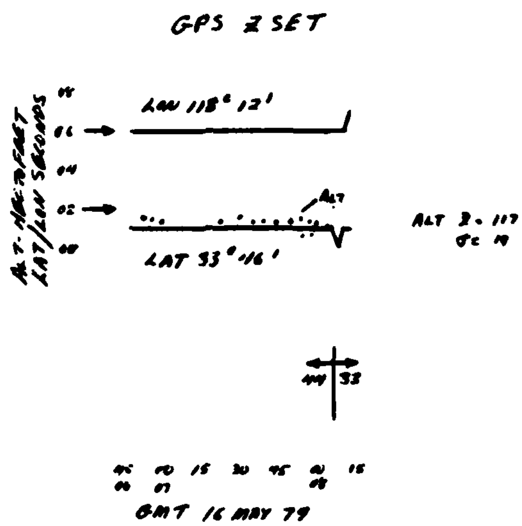


FIGURE 1

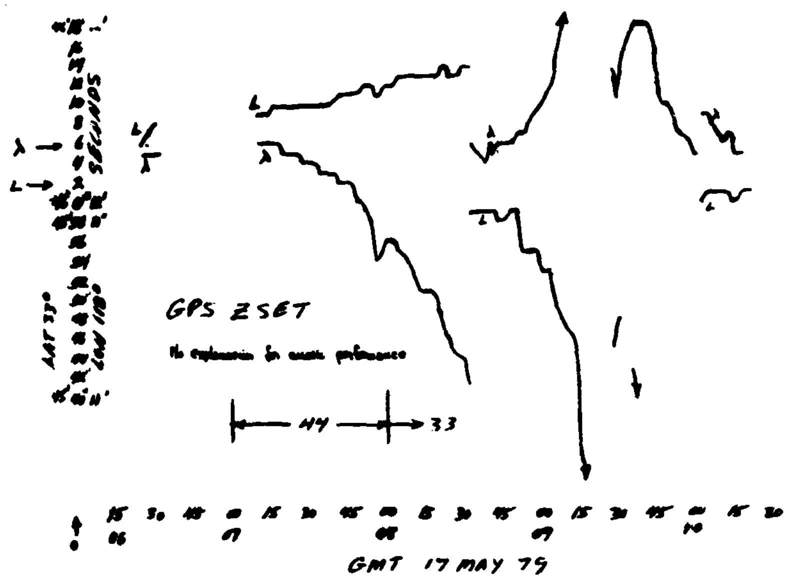
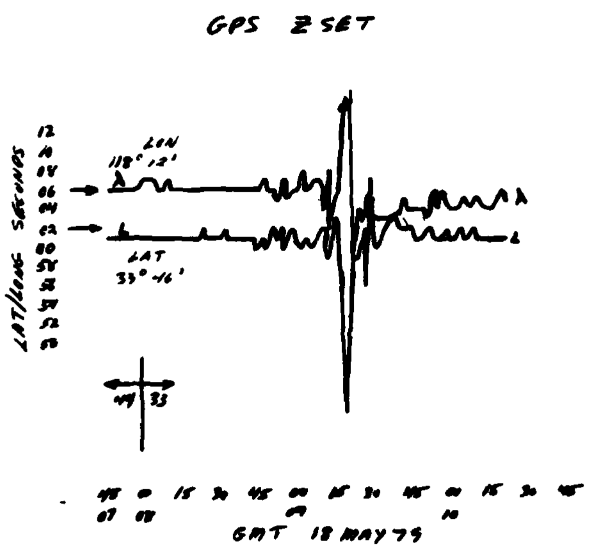


FIGURE 2



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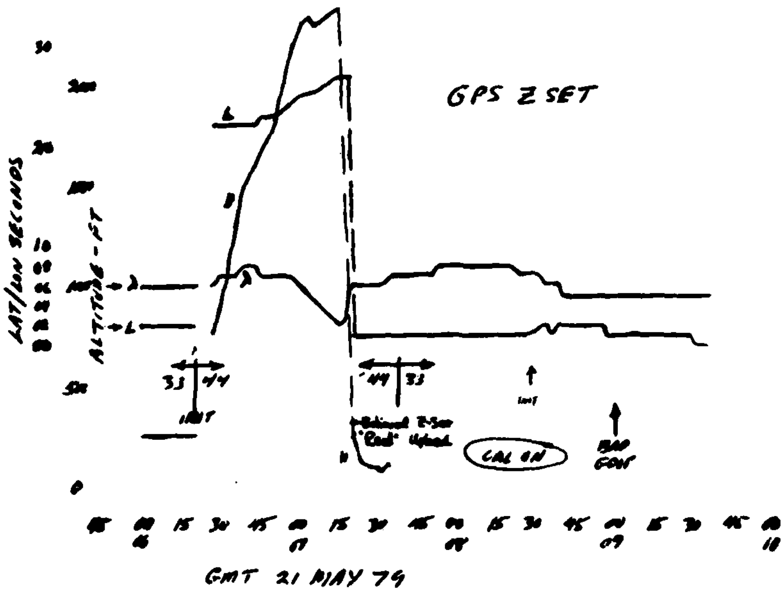


FIGURE 4

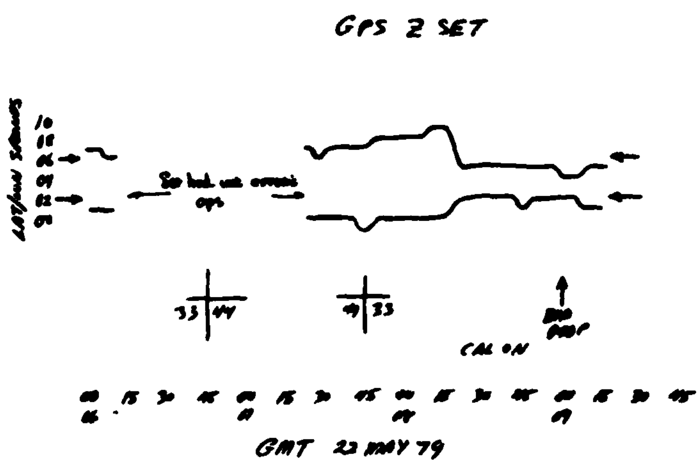
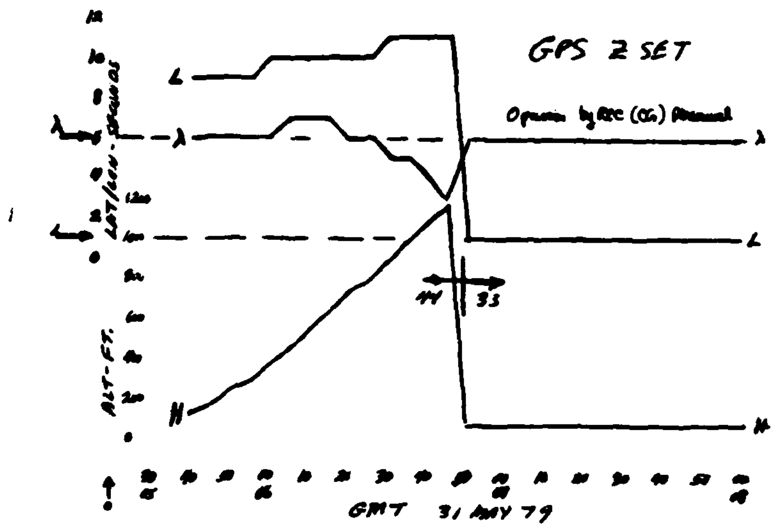


FIGURE 5



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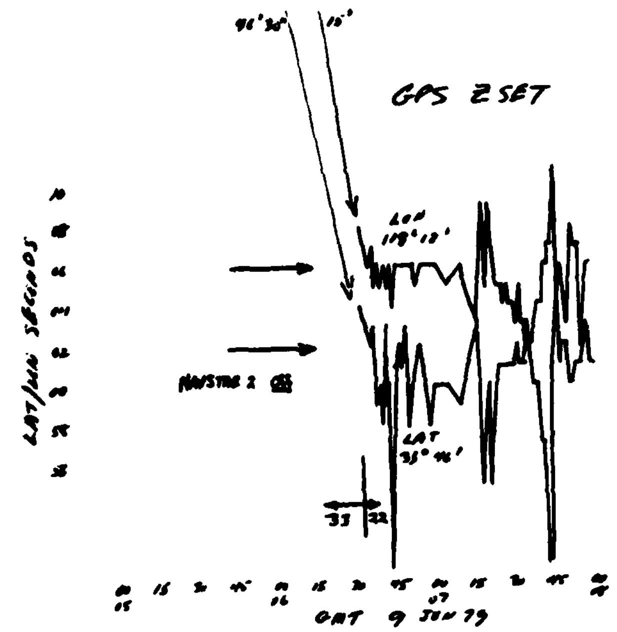

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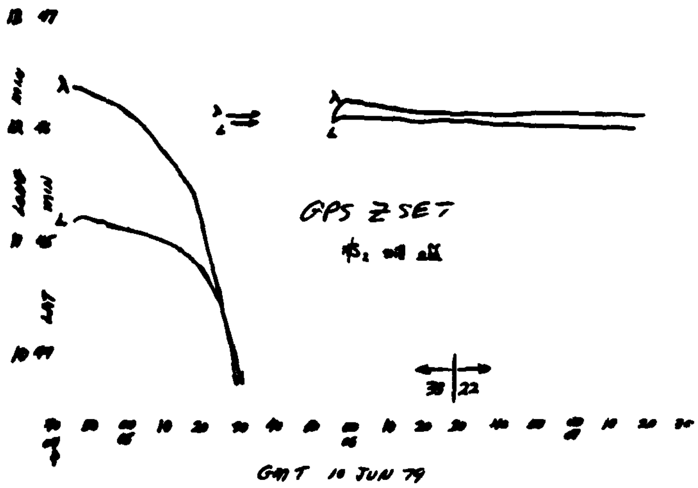

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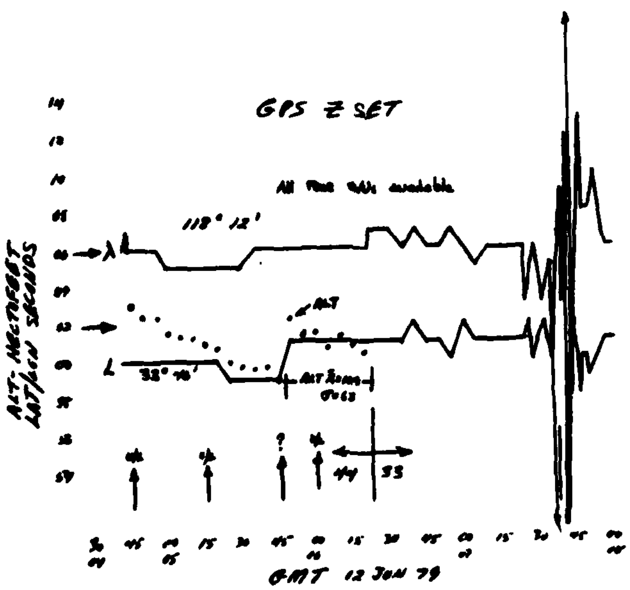

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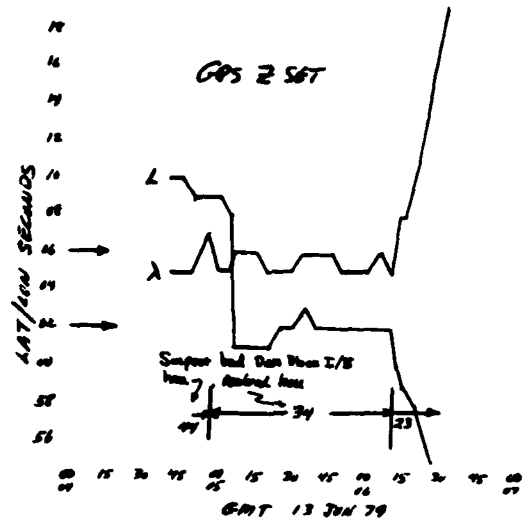

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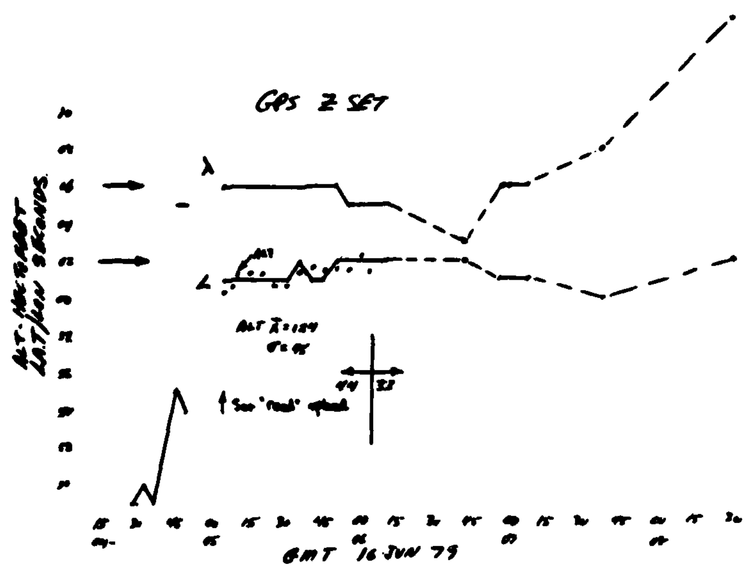

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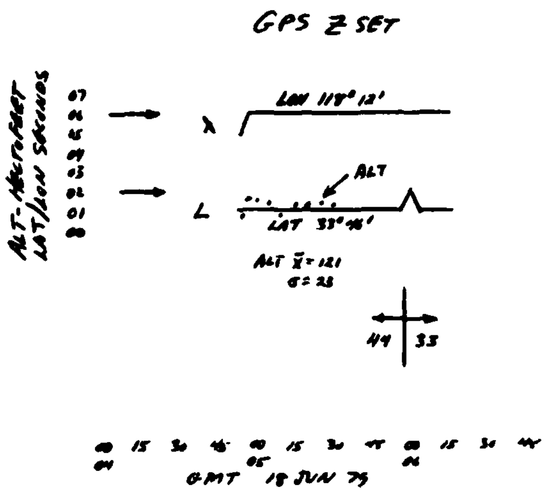

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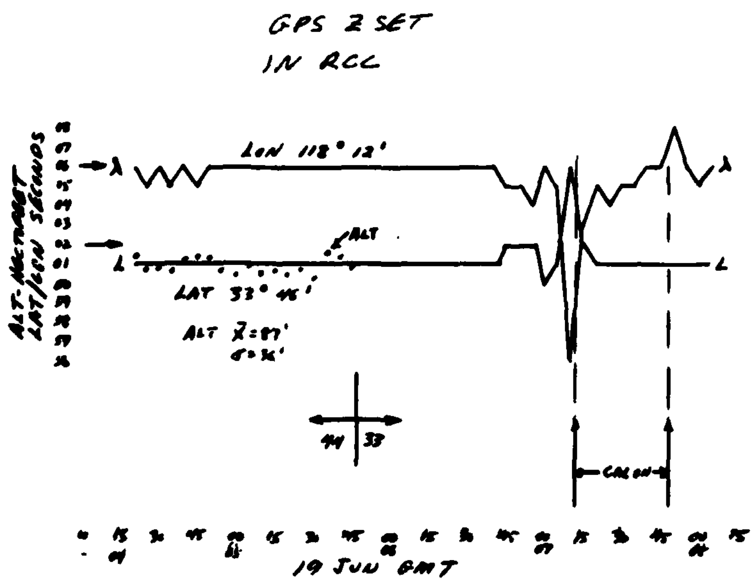

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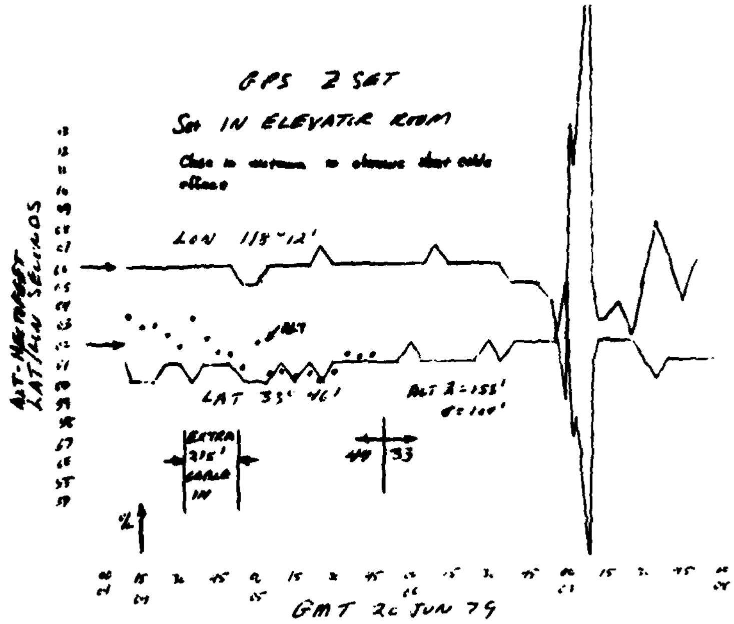

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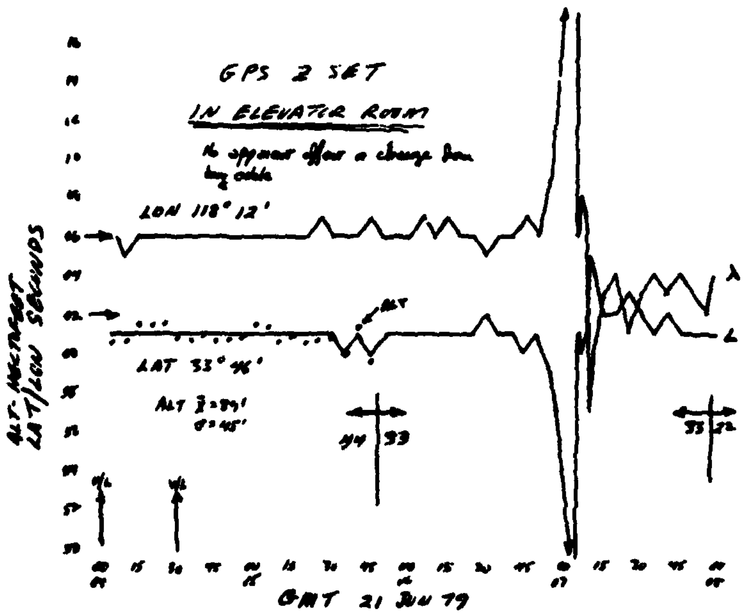

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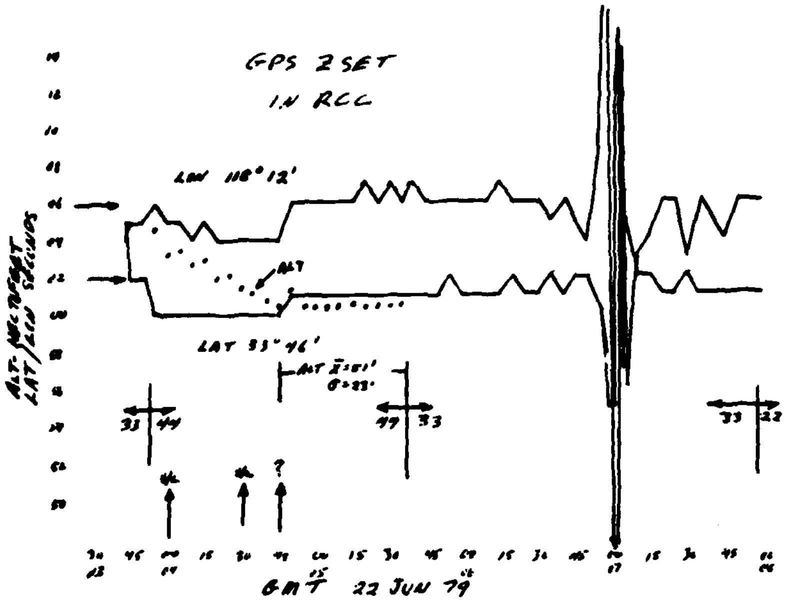

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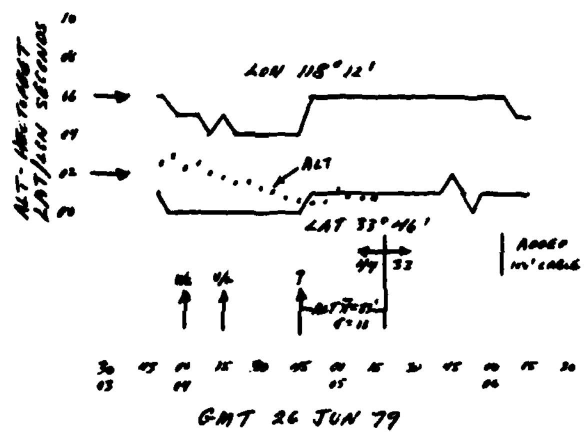

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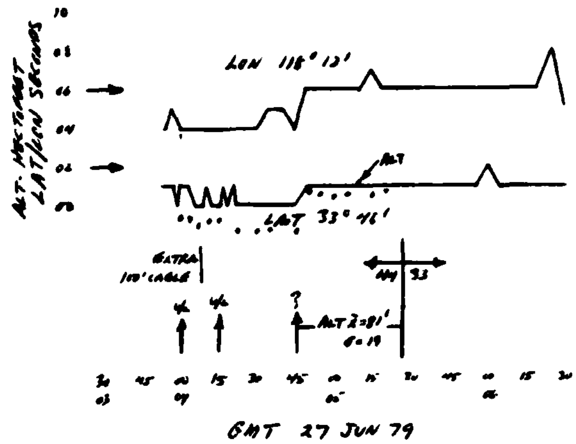
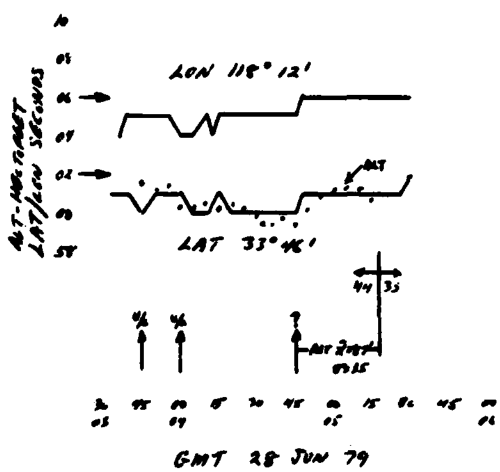


FIGURE 18



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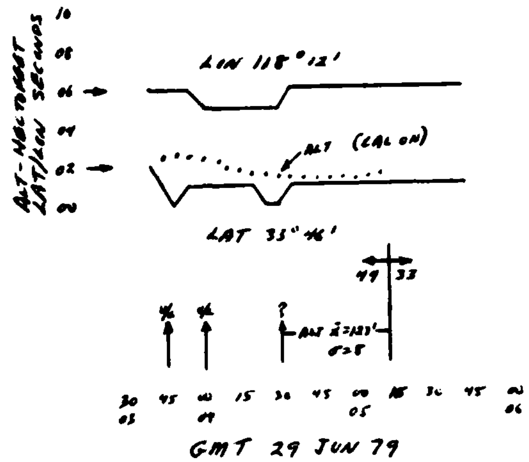
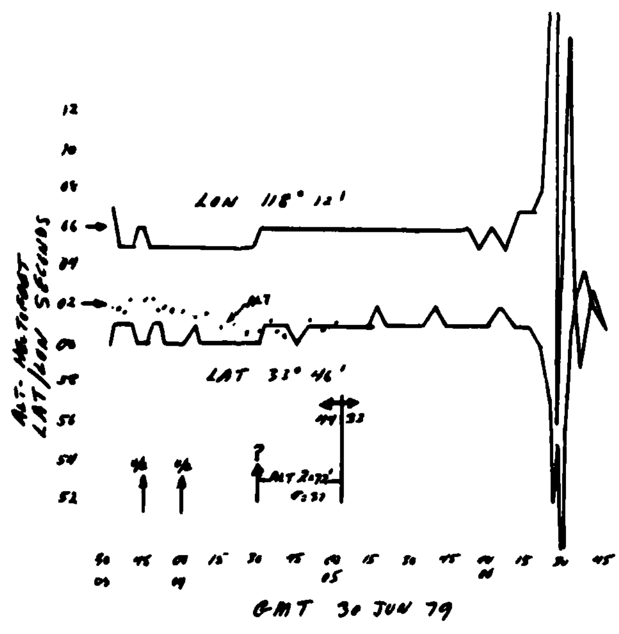


FIGURE 20



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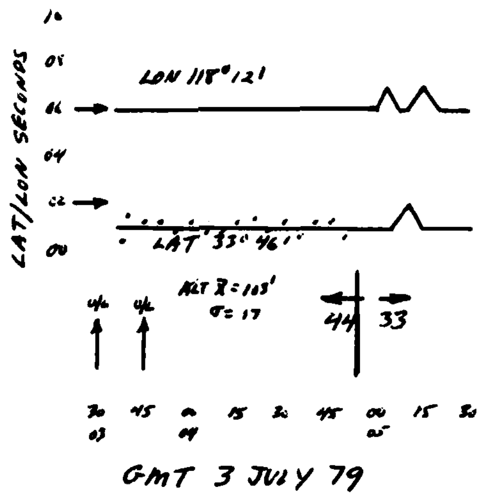

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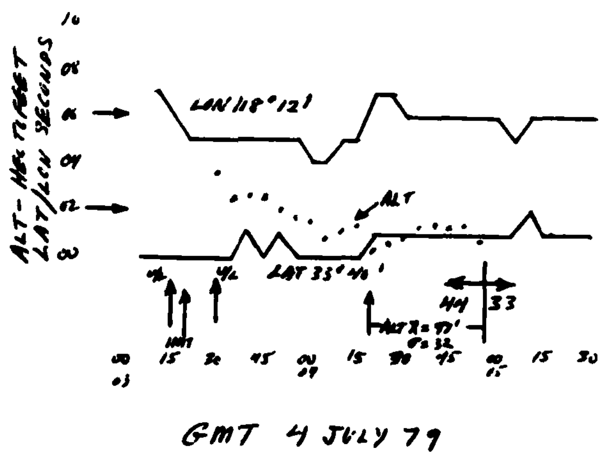

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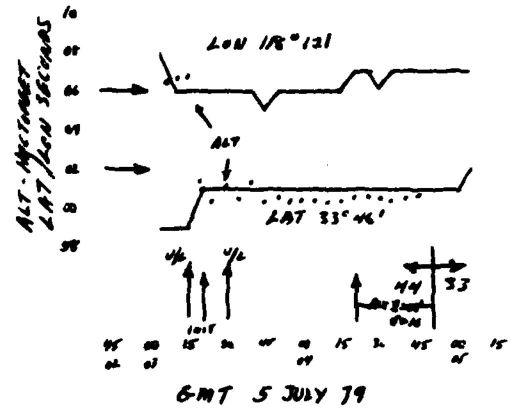

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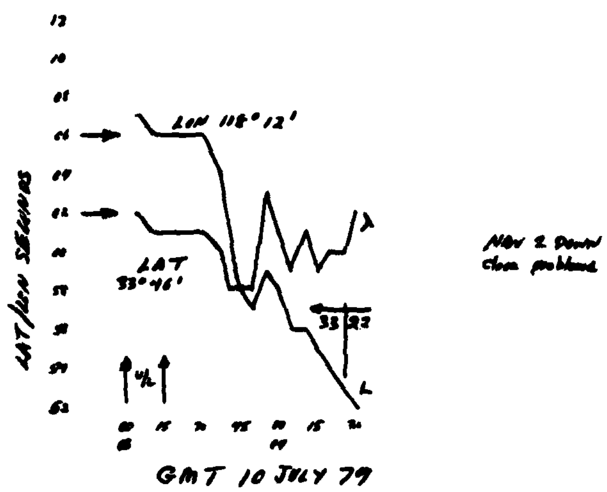

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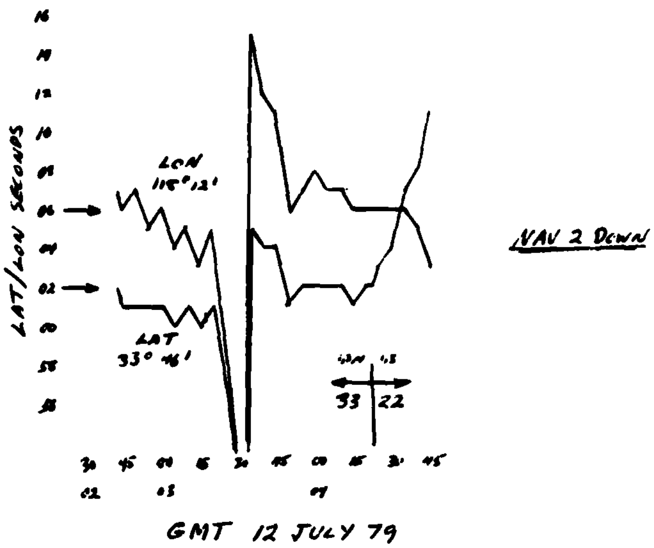

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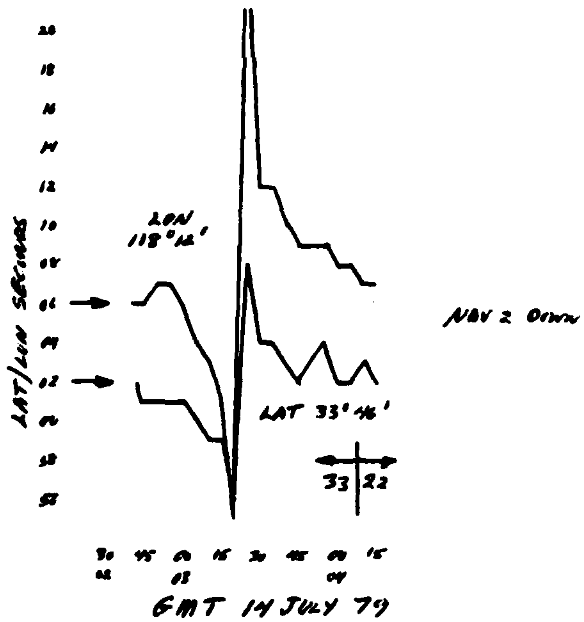

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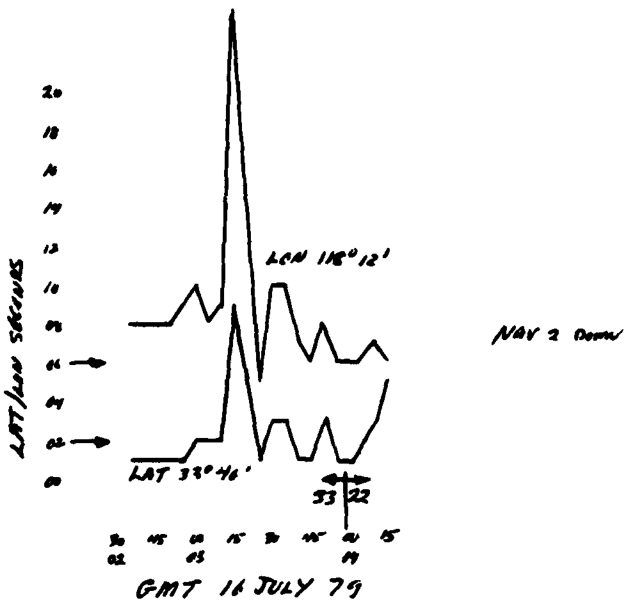

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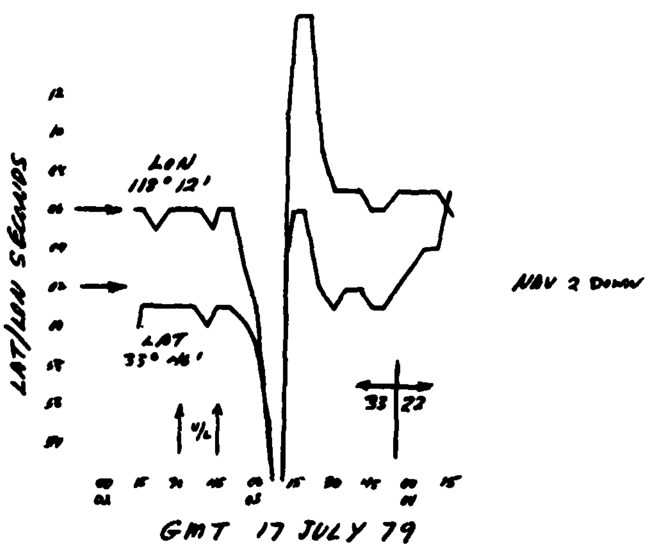


FIGURE 29

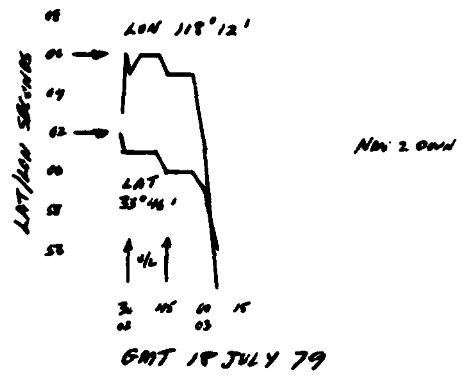


FIGURE 30

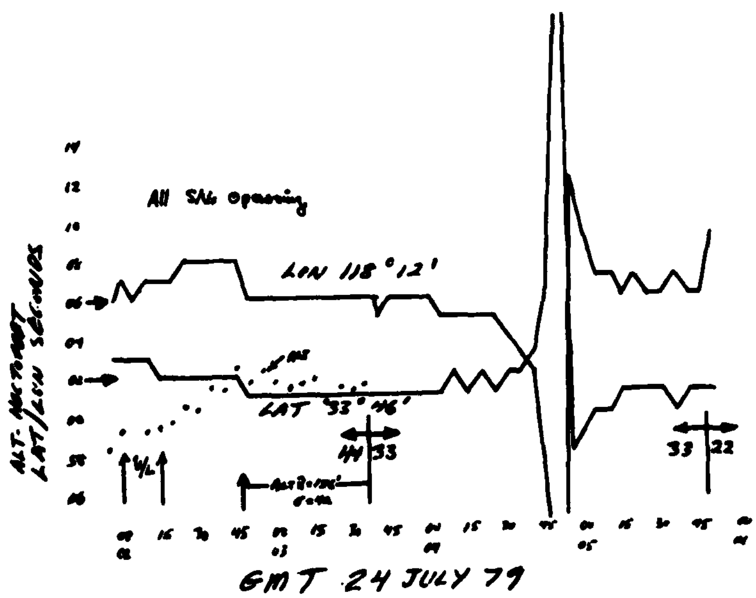


FIGURE 34

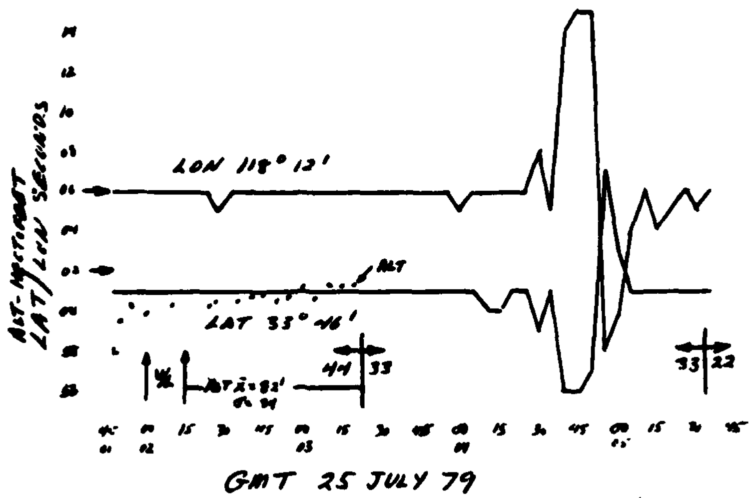
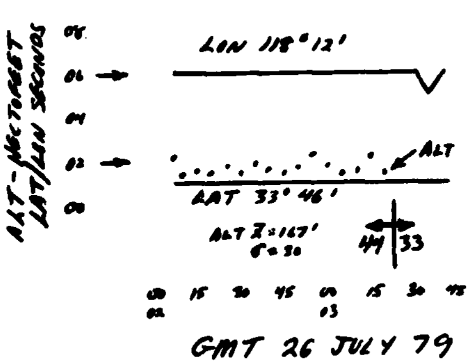


FIGURE 35



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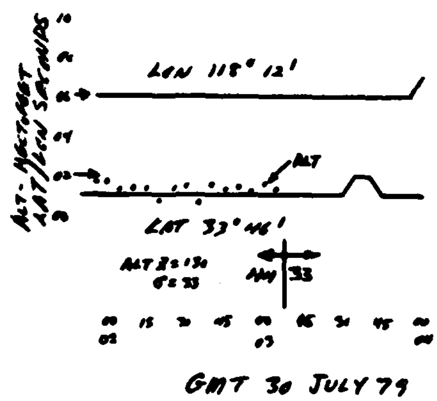

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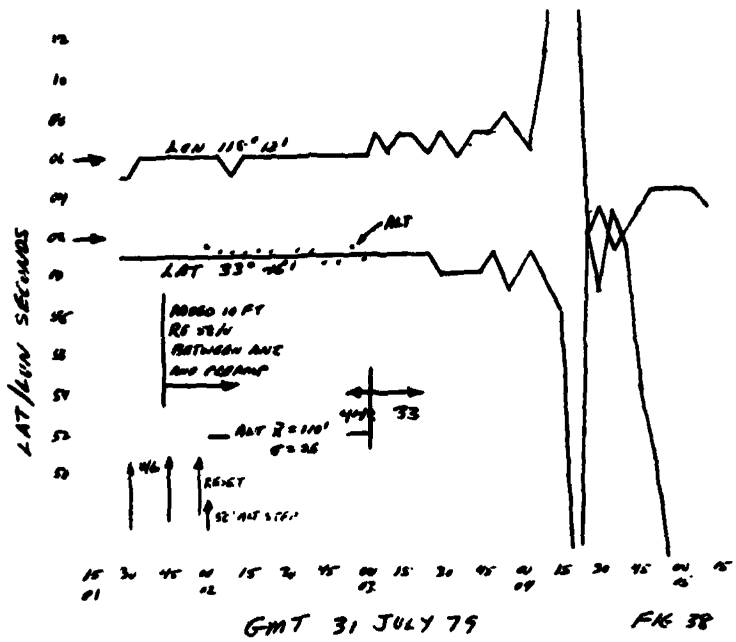

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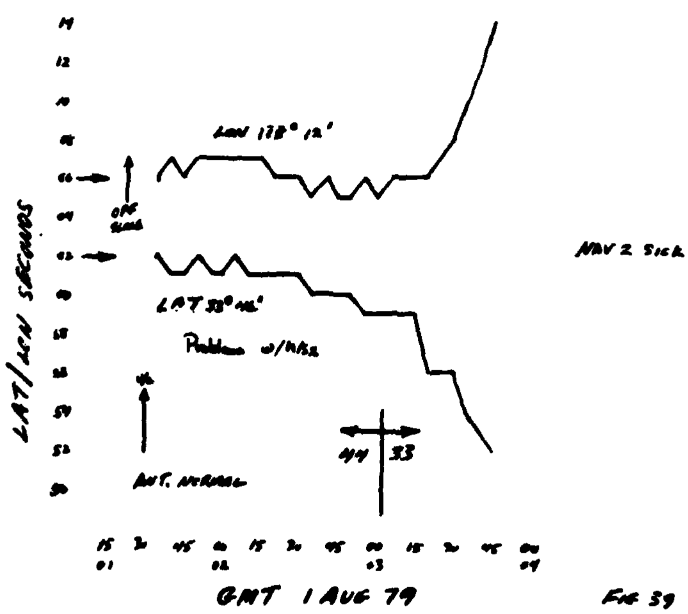

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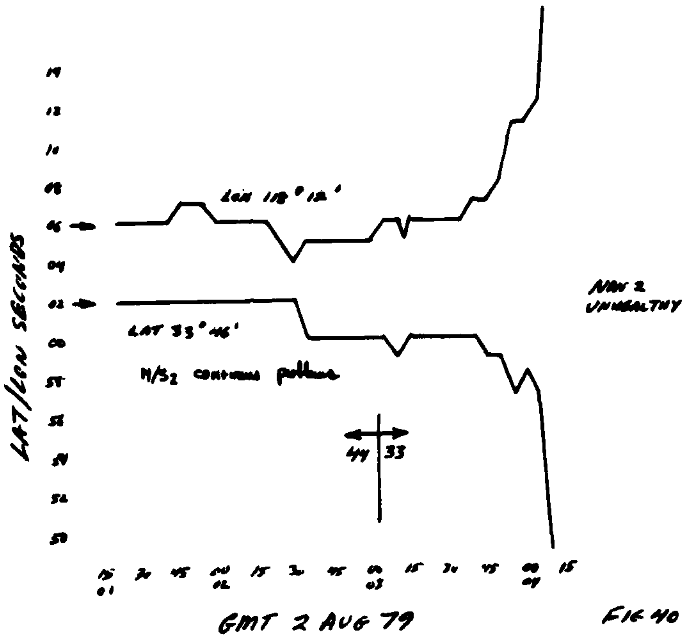

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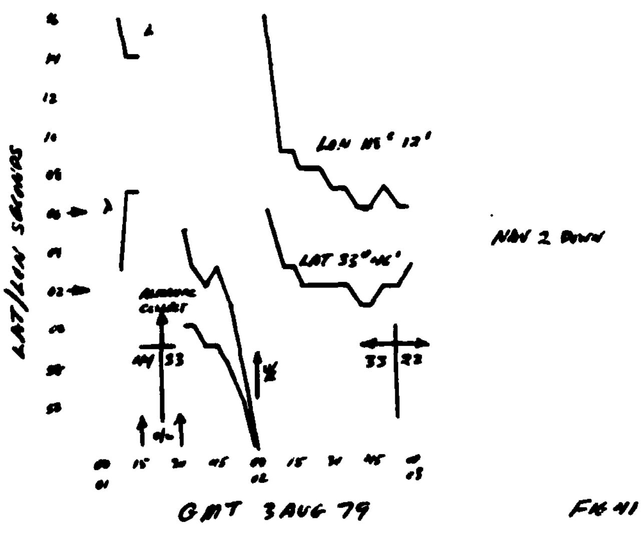

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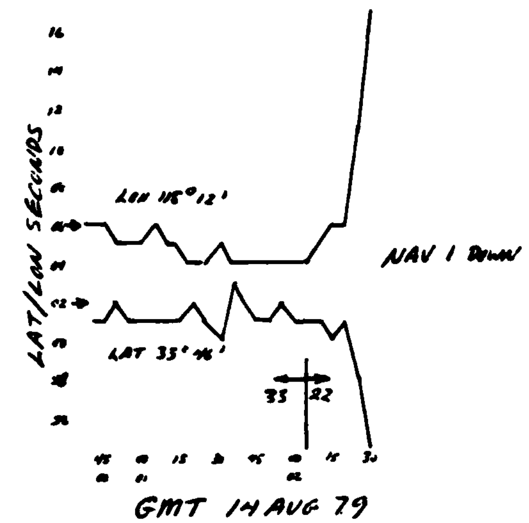
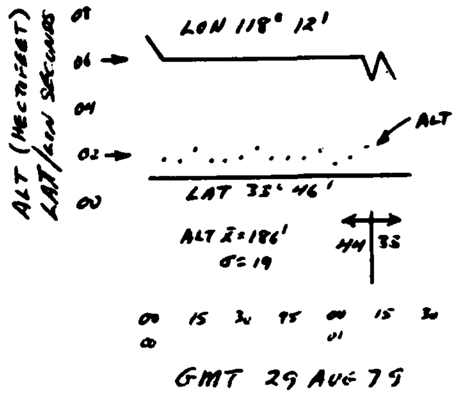


FIGURE 42



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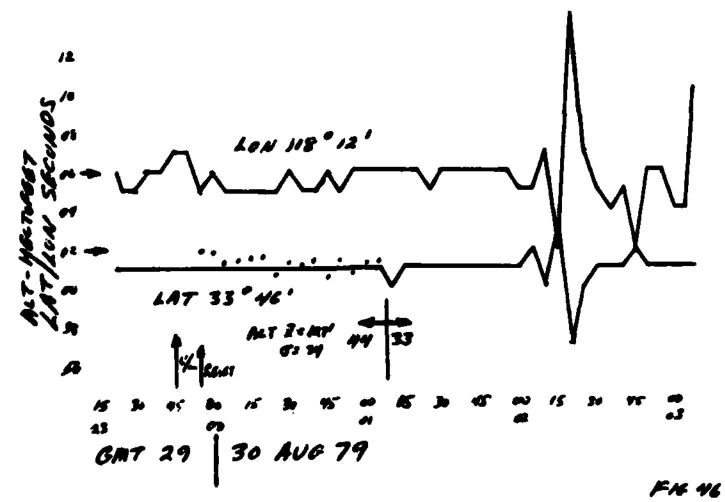

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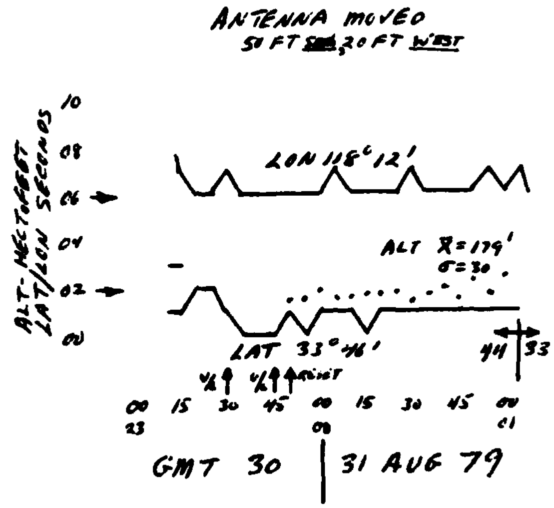
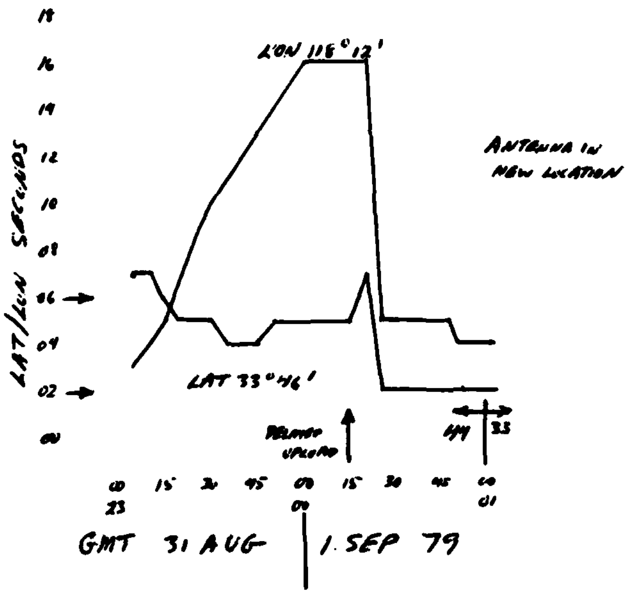


FIGURE 47



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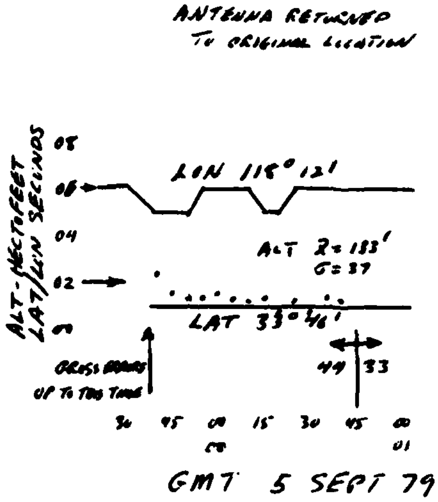

FIGURE 49

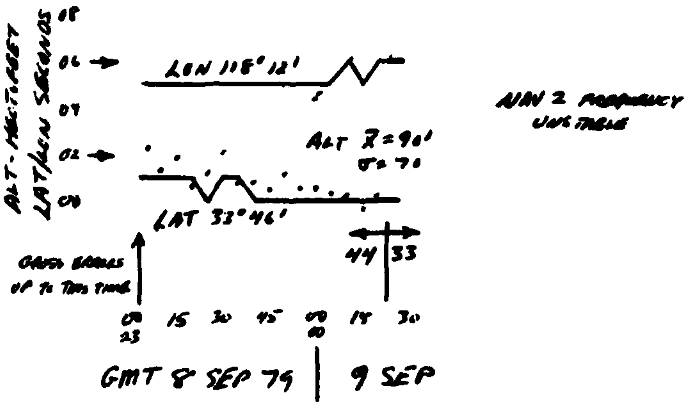

FIGURE 50