TEST OF AN ORBITING HYDROGEN MASER CLOCK SYSTEM USING LASER TIME TRANSFER

Robert F.C. Vessot, Edward M. Mattison, and G.U. Nystrom
Smithsonian Astrophysical Observatory
and

Rudolph Decher

George C. Marshall Space Flight Center
National Aeronautics and Space Administration

Abstract

We describe a joint SAO/NASA program for flight testing an atomic hydrogen maser clock system design for long-term operation in space. The clock system will be carried by a shuttle-launched EURECA spacecraft. Comparisons with earth clocks to measure the clock's long-term frequency stability ($\tau > 10^4$ seconds) will be made using laser time transfer from existing NASA laser tracking stations. We describe the design of the maser clock and its control systems, and the laser timing technique. We discuss the precision of station time synchronization and the limitations in the comparison between the earth snd space time scales owin to gravitational and relativistic effects. We will explore the implications of determining the spacecraft's location by an on-board GPS receiver, and of using microwave techniques for time and frequency transfer. The possibility of a joint SAO/NASA/ESA (European Space Agency) test with a second hydrogen maser and a microwave time and frequency transfer system will be discussed in a separate paper.

INTRODUCTION

A number of future space applications will need high stability oscillators, such as hydrogen masers, having frequency stability better than 10^{-15} for time intervals between 10^3 and 10^5 seconds. Such applications include tests of relativistic gravitation[**1**], operation of Very Long Baseline Interferometers[**2**], high precision space tracking, and time synchronization by orbiting clocks[**3**]. When high-stability microwave signals are transmitted through the earth's atmosphere and compared with a high-stability oscillator, as in earth-based VLBI or microwave Doppler tracking, the measurement accuracy of the system is limited by fluctuations in atmospheric propagation, rather than by the oscillator's frequency stability. Such a system in space, however, would be almost completely free of propagation effects. Under spaceborne operation, measurement precision would depend primarily on the frequency stability of the maser oscillator, and could fully exploit the high frequency stability provided by an H-maser.

A joint NASA/SAO technology experiment to demonstrate the performance of this maser in space is now in progress. The frequency of the space maser will be compared with terrestrial clocks and time scales by means of laser pulse techniques and time measurement. This work, which is supported by the NASA Office of Aeronautics and Exploration Technology (OAET) "In Step" program, is currently in Phase B, during which we are defining the experiment and developing a plan for its implementation.

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Development at SAO of an atomic hydrogen maser for space operation began in 1972 with the design and construction of a maser for the 1976 SAO/NASA Gravitational Redshift (Gravity Probe-A, or GP-A) test of the Einstein Equivalence Principle[4], in which a maser was launched by a Scout rocket to an altitude of 10,000 km in a nearly vertical two-hour flight. The next generation of space masers, designed for four years of continuous operation in space, has been under development at SAO, and a preliminary demonstration model has been built and operated.

Figure 1 shows the expected stability of the spaceborne SAO maser, represented by the Allan deviation $\sigma(\tau)$. As an example of the precision attainable with such an oscillator in space, one can consider Doppler ranging measurements. The limits imposed by this level of oscillator frequency stability on hour-to-hour determination of range-rate is 1.8×10^{-5} cm/sec, while the limit on range distance is 0.065 cm. These values are about two orders of magnitude better than can be achieved with current earth-based systems.

Maser frequency stability over short time intervals - less than roughly 10^4 seconds - is governed by the inherent thermal noise within the maser's oscillation linewidth and by the signal power to the receiver system. These characteristics are determined largely by the design of the maser's hydrogen storage bulb and hydrogen beam optics, all of which are similar in the space maser to the design of SAO's VLG-11 terrestrial H-masers. Systematic frequency variations, occurring for times beyond about 10^4 seconds, result in the up-turn in the $\sigma(\tau)$ curve shown in Fig. 1, and are the focus of interest in our investigation. The slanted lines in Fig. 1 represent the limits on frequency stability determination resulting from uncertainties of 20 picoseconds and 50 picoseconds, respectively, in the laser time transfer technique. With a 50 ps system, for example, we will be sensitive to maser frequency variations on the order of 2×10^{-15} for intervals of greater than roughly half a day.

In the planned SAO/NASA Space Maser experiment, the new space maser will be flown on a European Space Agency (ESA) EURECA spacecraft, and frequency measurements will be made by time transfer using existing laser ranging stations. A possible joint NASA/ESA experiment is also being considered, to test simultaneously a second H-maser on the EURECA spacecraft. This maser will be developed by the Neuchatel Observatory, Switzerland, led by G. Busca. In addition to the laser time transfer system, the joint experiment would use a microwave time transfer system developed by the Deutsche Forschungsanstalt für Luft und Raumfahrt (DLR), Oberpfaffenhofen, Germany, led by by S. Starker. This joint project would greatly broaden the technological goals of the experiment to include international time transfer at the sub-nanosecond level.

THE EXPERIMENT CONCEPT

The concept for making frequency comparisons between a spaceborne clock and an earth station originated in the early 1980s with a NASA-sponsored study of a Satellite Time and Frequency Transfer (STIFT)[5] mission, for which a combination of laser time transfer and microwave time and frequency comparison was proposed. Here the idea was to use highly precise laser timing, which is limited to clear sky conditions, to calibrate a pseudo-random-noise modulated microwave time transfer system, which would be useable under nearly all weather conditions. The study involved SAO, the US Naval Observatory, the National Bureau Of Standards, and the University of Maryland.

The present plan is to operate the maser on the EURECA spacecraft, which will be deployed from the NASA Space Shuttle, and boosted to an altitude of 525 km in a 28.5° inclination orbit. The spacecraft will remain in operation for approximately 6 months, after which it will be returned to a lower orbit and retrieved by the shuttle.

The EURECA spacecraft is shown in Fig. 2 with its solar panels extended. Magnetic torquers and cold nitrogen gas jets maintain its orientation in space with its solar panels facing the sun. Because EURECA's earthward-pointing surface will change as the spacecraft circles the earth, laser reflector/detector arrays will be mounted in three places to allow laser time transfer under all orientations. The procedure for time transfer is straightforward. When the spacecraft comes into view of the laser station, laser pulses are fired at the spacecraft. The time of reception of these pulses is recorded at the spacecraft in terms of the time kept by the space maser clock system. In addition, the pulse transmission times (epochs) and their round-trip propagation intervals are recorded on earth. One-half the propagation interval, with appropriate corrections, is then used to determine the spacecraft pulse reception time in terms of the earth clock, thus giving a comparison of time kept by the earth and space clocks.

The space maser's frequency will be measured over averaging intervals of approximately 94 minutes, EURECA's revolution period about the earth, as well as for intervals of a day and longer. Each day the spacecraft will be visible from the Hawaiian laser ranging site during several consecutive passes, separated by 94 minutes. With a laser timing precision of 20 ps, we expect to be able to make short-term frequency measurements with a precision of $\sigma_y(94) \sim 4 \times 10^{-15}$. For longer intervals, the precision improves with the time interval between measurements, as indicated by the straight lines in Fig. 1. The dominant factors likely to limit the frequency comparison precision are errors in correcting for gravitational and relativistic effects, owing to uncertainties in the spacecraft's position and velocity. The random processes that affect the stability of H-masers for periods less than roughly 10^3 seconds are well understood and not likely to be changed by the space environment. In the planned test, the goal is to measure any systematic effects that affect the operation of the maser; these effects will be observable at averaging intervals beyond one day.

Of particular interest are the effects of magnetic field and temperature variations, including the possible long-term effects of radiation in space. Environmental processes will be correlated with systematic variations of frequency. Continuous monitoring will be done of all relevant temperatures, the maser's internal vacuum, hydrogen source pressure and dissociator efficiency, and the maser's output signal level.

Figure 3 shows a block diagram of the experimental system, including the major EURECA electronic systems and the maser's control electronics, r.f. receiver, and clock and event timer. The receiver's frequency synthesizer operates from a 64 bit number-controlled oscillator; its settings can be adjusted by telecommand with a granularity of 7 parts in 10^{18}. The arrival time of the incoming laser pulse is registered by the event timer with a resolution of about 20 picoseconds and is stored in memory for subsequent telemetry to the EURECA ground control station, along with readings of the monitored system parameters.

During the mission, occasional telecommands from earth will be send to the maser's microprocessor to adjust the maser's operating parameters, such as its source H_2 pressure and internal magnetic fields. The microprocessor performs several functions, including controlling maser parameters; monitoring maser operation; and carrying out programmed sequential operations, such as determining the maser's internal magnetic field by varying the Zeeman oscillator's frequency and measuring the corresponding maser output power.

THE SPACE MASER

The internal structure of the second generation SAO space maser is based on design of the maser used in the GP-A mission, in that the cavity resonator, storage bulb and beam optics are similar. Figure 4 shows a cross section view of the new space maser. In the present maser we have substantially improved the thermal control system by taking advantage of the longer mission duration and the vacuum of space, which permits us to use multilayer insulation (MLI). The new thermal design evolved from the development at SAO of small passive masers, sponsored by the U.S. Naval Research Laboratory[6]. This design permits operation under atmospheric conditions, for testing, as well as in the vacuum of space. The technique employs a segmented cylindrical aluminum isothermal oven. The independence of the oven segments allows the oven to control heat flowing through the multilayer insulation, which dominates under atmospheric conditions, as well as heat flowing through structural members, which is most important when the maser is in vacuum.

The maser's cavity resonator is isolated from structural variations in the vacuum belljar that result from the atmospheric pressure change encountered when going from earth to space. Isolation is achieved by mounting the CER-VIT cavity resonator and storage bulb, as a subassembly, on a circular baseplate that is attached to one of the belljar necks near the center of the belljar endcap. The baseplate is almost completely isolated from the belljar, and is not affected by variations in belljar shape. The effects of axial thermal expansion of the cavity mounting structure are minimized by clamping the cavity onto its baseplate with a zero-rate Belleville spring; radial expansion is reduced by supporting the cavity on the baseplate by a quasi-kinematic roller mount. This mounting structure is identical to that used in the GP-A maser, which coped with 60 g shock and 20 g static accelerations generated by the solid fueled Scout rocket system.

A three-section printed-circuit magnetic field solenoid fits closely within the innermost magnetic shield that surrounds the titanium alloy vacuum belljar. The belljar is equipped with two demountable metallic vacuum seals. The cavity resonator's mechanical tuner is adjusted through a port sealed with a gold "O" ring. The belljar is joined by another gold "O" ring to a manifold, made of thin-walled stainless steel, that contains vacuum pumps and the hydrogen beam forming system. Four hydrogen-sorbing cartridges in a cross-shaped array on the manifold surround the hexapole state-selector magnet. A small ion pump scavenges non-hydrogen gases. Extrapolating from our experience with the GP-A maser, which operated continuously for one year with a single hydrogen sorption cartridge, the four sorption cartridges are expected to permit more than four years of continuous operation.

As in the GP-A maser, hydrogen for the maser is obtained from $LiAlH_4$ contained in a thermally-controlled vessel and maintained at about 40 psig. Hydrogen flow is regulated by servo control of the temperature of a palladium-silver diaphragm to maintain a constant pressure in the hydrogen dissociator. Molecular hydrogen is dissociated into atoms by an external r.f. power supply. Heat generated by the r.f. power dissipated in the vacuum-enclosed glass dissociator is conducted through the dissociator's walls to the bottom manifold flange, from which it is dumped to the EURECA heat sinks.

The maser's size, weight and expected power consumption are summarized in Table 1. Because EURECA's magnetic torquers produce magnetic field variations as high as 0.1 Gauss at the location of the maser, we will add a fifth layer of magnetic shielding, enclosing the entire maser, in order to prevent magnetic field inhomogeneity frequency shifts[7] that can result from these field variations.

A photograph of the engineering demonstration model that was built to test the thermal design is shown in Figure 5. Its measured oscillation parameter[8] is $q = 0.14$, its storage bulb relaxation rate

is $\gamma = 2.0$ sec^{-1}, and its oscillation line Q is $Q_l = \omega/2\gamma = 2.2\times 10^9$. Thermal measurements in room temperature (25°C) air closely follow the design predictions, with 18 watts required for thermal control. In vacuum, we predict a power consumption of 7.5 watts with the maser mounting baseplate held at 20°C and the maser surrounded by MLI. Thermal tests in vacuum will be made on the demonstration model early in 1992 to verify the design.

LASER TIME TRANSFER

The space maser will be compared with ground maser clocks by laser time transfer. Laser transfer is the most accurate method of comparing separated clocks. The principle of laser time transfer is shown in Fig. 3. The laser ground station transmits short laser pulses (~200 ps duration) at a rate of up to 8 Hz that are reflected back to the ground station by corner reflectors mounted on the spacecraft. Timing of the ground station pulses is controlled by a hydrogen maser that is compared with primary time scales by means of GPS time transfer. The emission time t_{e1} and the arrival time t_{e2} of the reflected laser pulse are measured in terms of the time scale t_e of the ground clock. One half the pulse round trip interval $t_{e2} - t_{e1}$ provides the propagation delay to the spacecraft and allows us to predict the time of arrival $(t_{e1} + t_{e2})/2 = (t_{e1} + [t_{e2} - t_{e1}]/2)$ of the laser pulse at the spacecraft as measured in the ground clock's time scale. At the spacecraft, a photodetector located near the corner reflector, senses the arrival of the laser pulse and provides a signal to the event timer controlled by the onboard maser clock. The event timer determines the arrival time $t - s$ of the laser pulse in the time scale of the onboard clock. The difference between the two epochs (onboard and ground pulse times) is the time difference between the ground and space clock. Fig. 6 shows a light-time diagram of the laser time transfer technique. The laser time transfer technique can provide sub-nanosecond accuracy. We expect that a precision of 20 to 50 picoseconds in the comparison of the space and ground clocks should be achievable.

The primary laser ground station is the existing laser ranging station on top of Mt. Haleakala on Maui (Hawaii). Because of Federal Aeronautics Administration regulations, laser ranging is not available below an elevation of 20°. The sun-fixed attitude of the EURECA spacecraft requires three cube-corner reflector arrays on the spacecraft in order to obtain full angular coverage. We expect to perform laser tracking and time transfer during both day and night transits of the spacecraft.

EXPERIMENT OPERATION

The nominal duration of the EURECA mission is 6 months but could last up to 9 months. The EURECA spacecraft will be in a circular orbit of altitude between 525 and 485 km with 28.5° inclination. Onboard experiment data will be transmitted through the EURECA telemetry system to the ESA ground station and relayed to SAO. Several equipment functions will be controlled by command from the ESA ground station, enabling us to perform in-flight diagnostic tests and to adjust parameters for optimal operation of the experiment. Details concerning data collection and data flow from telemetry and laser ground station, distribution of data to the user, and other aspects of the experiment are being defined as part the now ongoing Phase B study.

While the primary ground station for laser time transfer is the existing laser station on Maui, Hawaii, other laser stations, such as at Matera, Italy, and Shanghai, China[9], are able to contact the spacecraft, and may participate in the experiment. These laser stations are presently equipped with hydrogen masers and high resolution event timers. Because of the low inclination of the orbit, only

a small number of existing laser stations are able to see the spacecraft. However, there are mobile laser stations available in the USA and in Europe that can be set up in locations providing optimum visibility of the spacecraft.

For the Maui laser station, up to five consecutive contacts with the spacecraft can be anticipated during a 24 hour time period. The maximum period available for time transfer during a spacecraft transit over the station is approximately seven minutes. A sample ground track calculation of consecutive laser contacts with Maui is shown in Figure 7.

Accurate position and velocity data of the spacecraft are needed to determine relativistic corrections. For precision of relative frequency comparison at a level of 1 part in 10^{16}, we require position tracking accuracy of approximately 1 meter, and velocity accuracy of approximately 1mm/sec. At present, the standard ESA tracking process does not provide the required accuracy. Several options are available to obtain the necessary orbit data accuracy, including use of laser tracking data and operation of an onboard GPS receiver.

This experiment could provide an opportunity to perform global high precision (100 picosecond) clock synchronization experiments.

POSSIBLE JOINT NASA/ESA SPACE H-MASER EXPERIMENT

A joint NASA/ESA H-maser space experiment is being studied by ESA and is the topic of another paper at this meeting[**10**]. This experiment would add to the SAO/NASA experiment equipment, a second space H-maser built by the Observatoire Cantonal de Neuchatel and a microwave time and frequency transfer system, probably a modified PRARE ranging system[**11**], provided by the DLR. The combined experiment would permit direct on-board frequency comparison of the two H-maser clocks, as well as and time and frequency transfer to a number of existing PRARE ground stations. While the microwave frequency comparisons would last for only about 7 minutes, and the frequency stability measurement would be correspondingly limited, the resulting time synchronization, using phase modulation of the one-way and two-way microwave links, is expected to be well into the sub-nanosecond domain[**12**]. The possibility of recovering the phase of the microwave carrier signal from orbit to orbit so as to retain the phase coherence of the frequency comparison has been advanced in an earlier publication[**13**]; however, close attention to the tracking requirements and atmospheric propagation delay measurements will be required to enable this "reconnection" of phase. The microwave time transfer, which is essentially independent of weather conditions, would be calibrated with the more precise laser time transfer method.

ACKNOWLEDGEMENTS

This work is supported by the National Aeronautics and Space administration. We thank G. Busca, S. Starker and S. Feltham for many interesting and informative discussions.

Table 1. Space Maser Characteristics

Dimensions	Weight	Power Requirements	
442 mm (17") diam	67 kg	Physics unit:	17 watts
863 mm (34) long		Receiver/synthesizer:	10 watts
		Total:	27 watts

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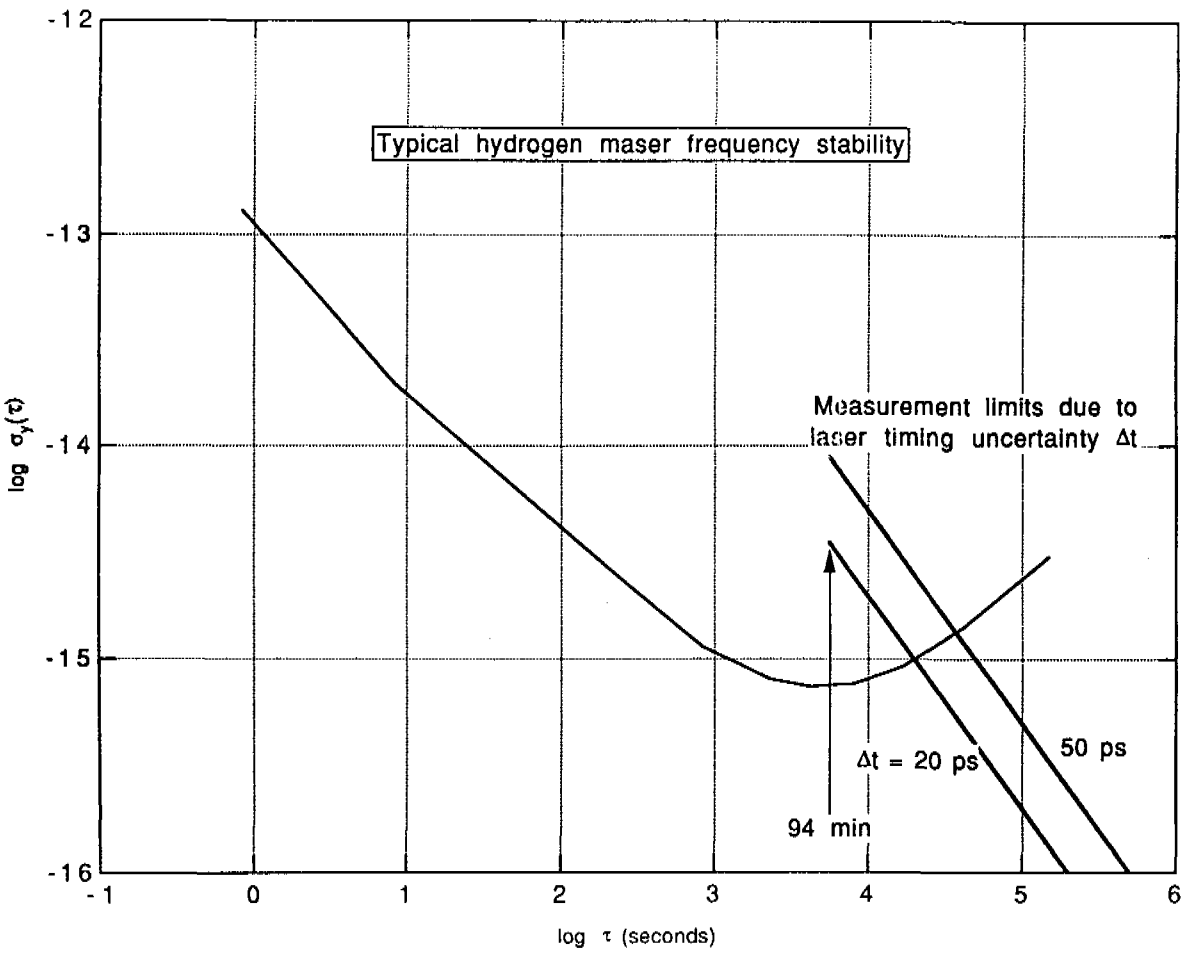


FIGURE 1. TYPICAL H-MASER FREQUENCY STABILITY

The overall EURECA configuration has been primarily determined for a maximum payload volume, while minimizing Shuttle launch costs, both providing an optimum spacecraft length-to-mass ratio and a direct attachment to the Shuttle via a three-point latching system, for a variable positioning of the platform throughout the length of the Shuttle's cargo bay.

The EURECA flight configuration is shown in Figure 2

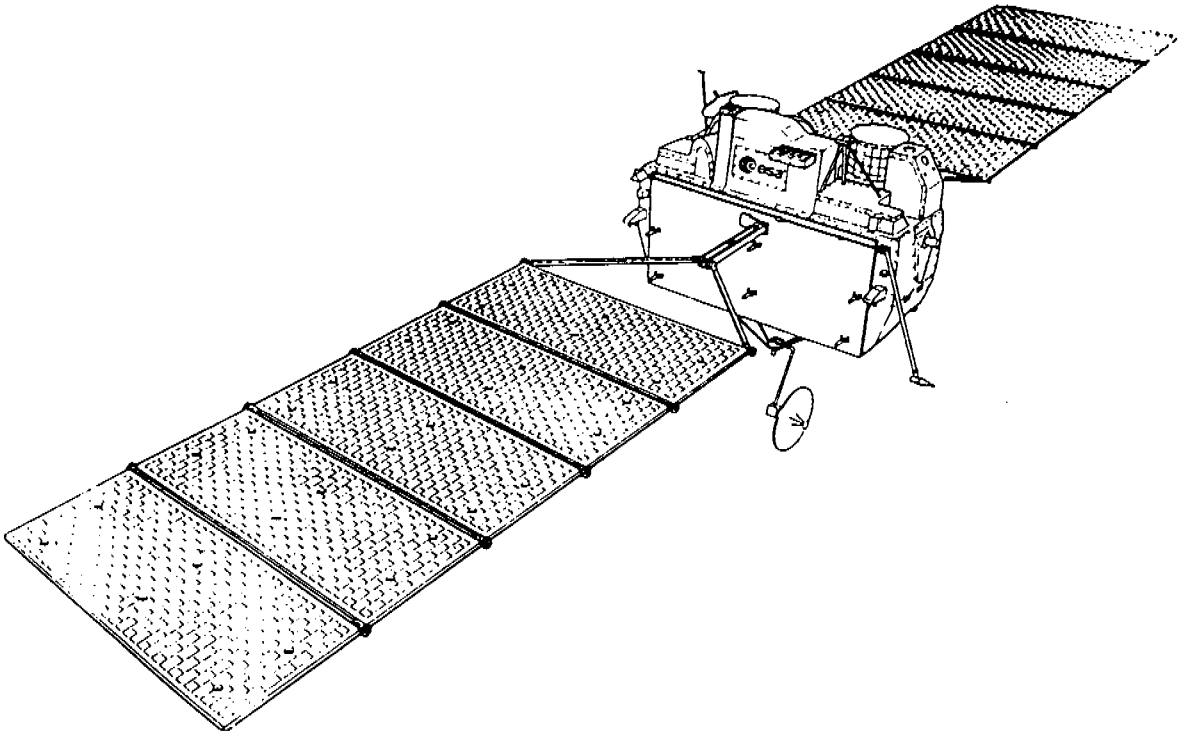


Figure 2 Eureca Flight Configuration

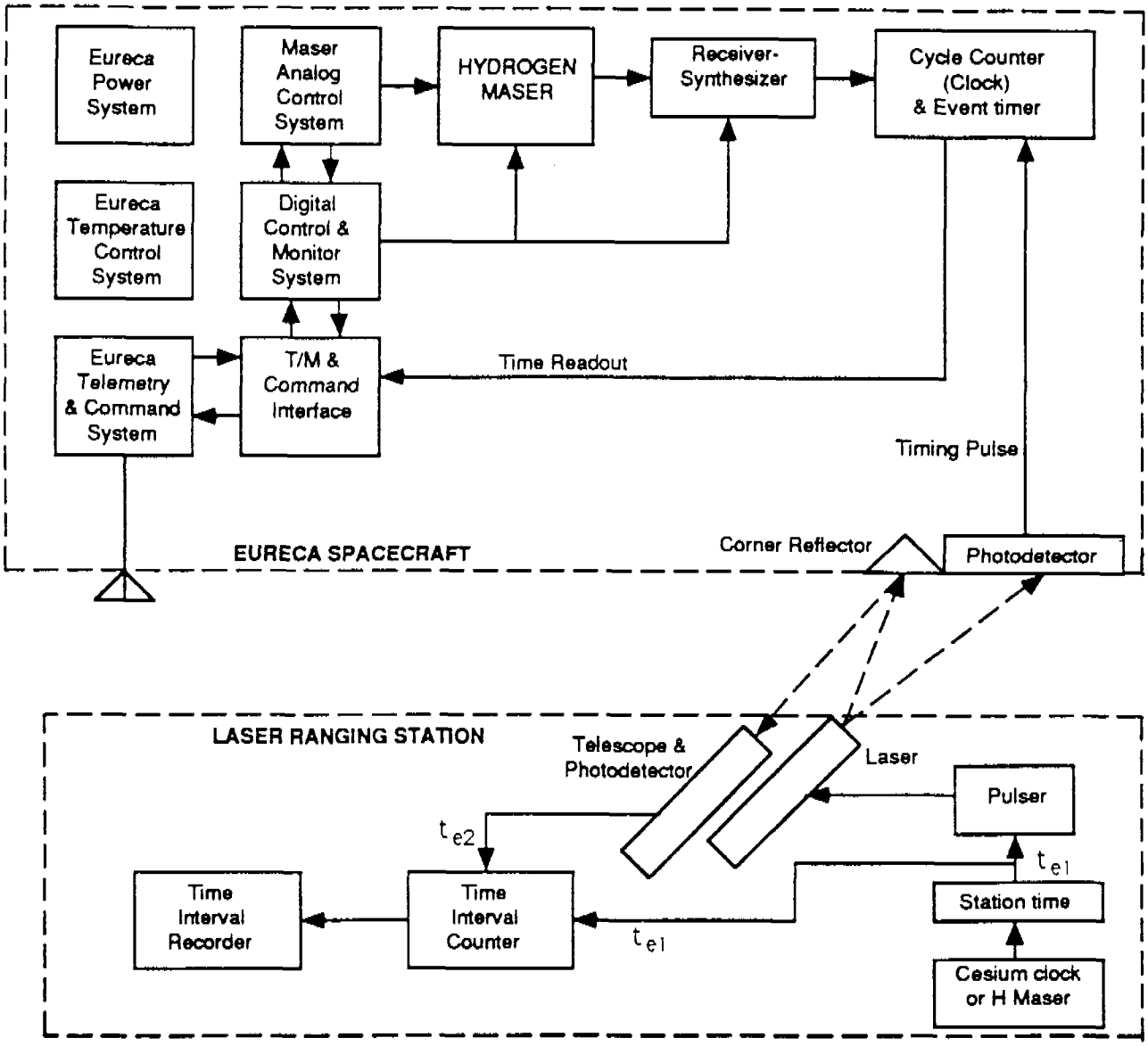
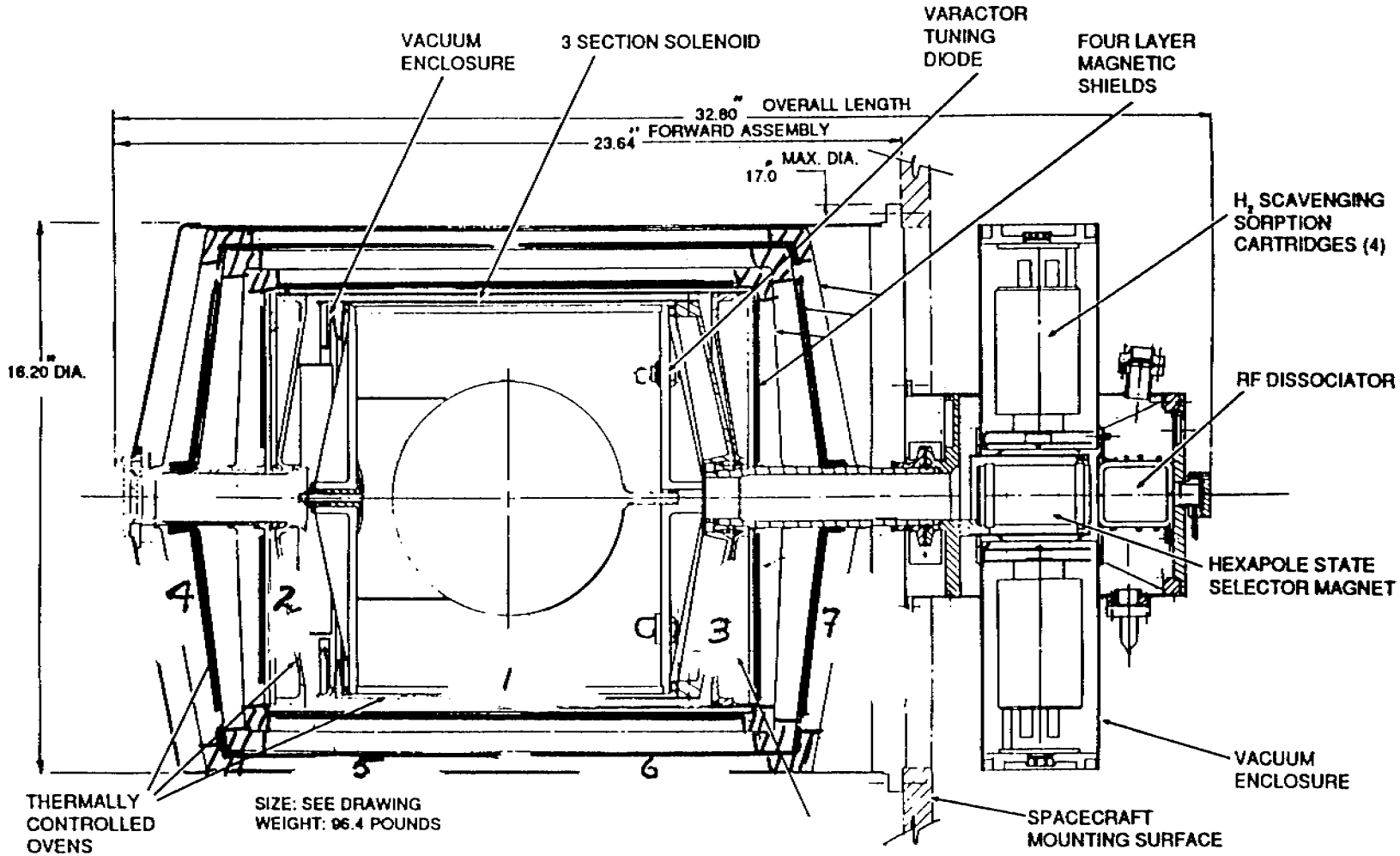


Fig. 3 – Space Maser timing system conceptual block diagram



1,2, and 3 BELL JAR HEATERS

4,5,6, and 7 THERMAL GUARD STATIONS

CROSS SECTION VIEW OF SPACE MASER

FIGURE 4.

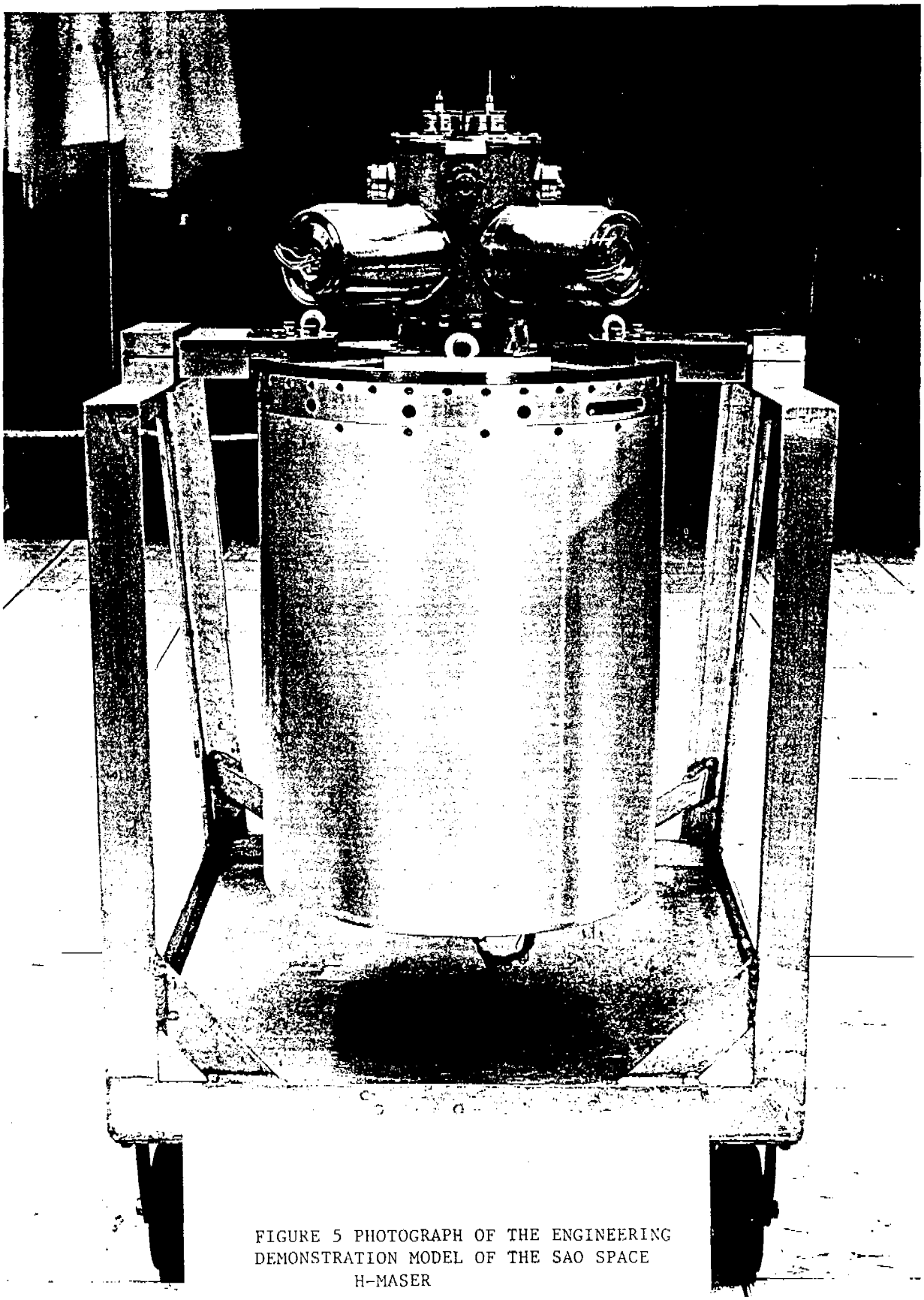
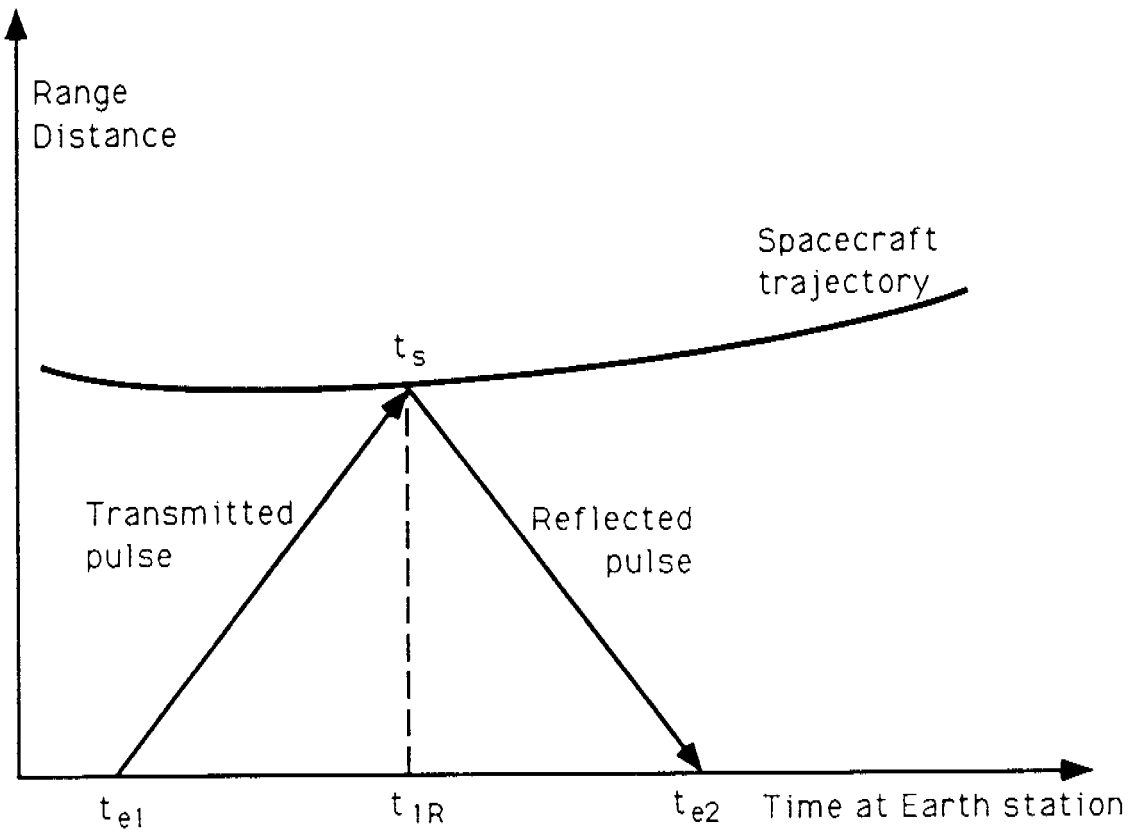


FIGURE 5 PHOTOGRAPH OF THE ENGINEERING DEMONSTRATION MODEL OF THE SAO SPACE H-MASER



t_{e1} = time of laser pulse transmission as measured by earth station clock

t_s = time of detection at spacecraft as measured by spacecraft clock

t_{1R} = time of pulse arrival at spacecraft in terms of earth clock $=(t_{e2}-t_{e1})/2$

$\Delta t_{se}=t_s-t_{1R}$ is the difference between the pulse arrival times measured by the space and earth clocks, corrected for propagation delay:

$$\Delta t_{se}=(t_s-t_{1R})=t_s-\left(\frac{t_{e1}-t_{e2}}{2}\right)-t_{e1}=t_s-\left(\frac{t_{e1}+t_{e2}}{2}\right)$$

FIGURE 6 LIGHT TIME DIAGRAM OF LASER TIME TRANSFER TECHNIQUE

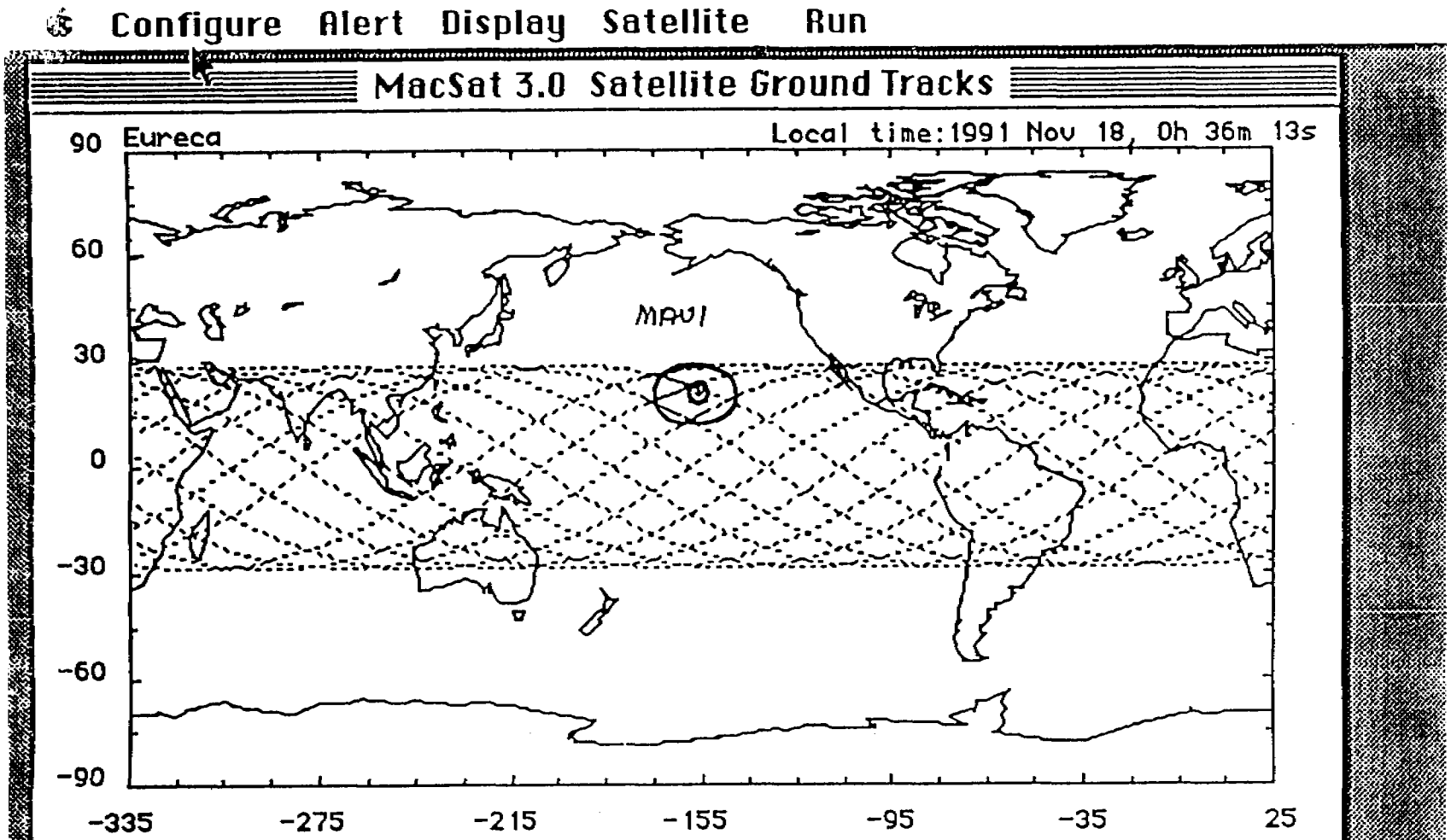


FIGURE 7.GROUND TRACK OF THE 28.5 DEGREE INCLINATION EURECA ORBIT

QUESTIONS AND ANSWERS

Dr. G. John Dick, JPL: First, what do you feel are the most important environmental problems. You have the temperature effects due to coming in and out of sunlight. Secondly, what would you have to say as to the utility of a super time standard in a low orbit like this, as opposed to a geostationary orbit.

Dr. Vessot: The first question is hard to answer, because if we knew what we were looking for, we would test it on the ground. It is usually said that there are combinations of environmental effects that are not possibly realizable in ground testing. I suspect that temperature gradients are likely to be the hardest thing to beat. We will introduce them in testing to determine the response times and the effects. There is also the question of particle radiation. From the discussions with the people who make Teflon, it appears that this type of radiation may even be beneficial. The problem is that a change is not good, so we will watch the wall shift very intently. That is something that we will measure when we recover the vehicle when it comes back to earth. It is likely to be in a powerful radiation belt in the planned orbit. For the second question about applications-there is no real application in this experiment other than to test the clock in this very low orbit. If could have polar orbit at a high altitude, then we could have world-wide coverage, which was the proposal envisioned for STIFT. This should have been able to do sub-nanosecond timing with a microwave system. From what I have seen today, it is not wrong to expect that we could get 100 picoseconds with a laser. The laser would not be an all weather system, but some people would settle for that in order to get 100 picoseconds.

Mr. Busca: I would like to add just one point. For time transfer this will be a really unique situation. We will be able to stay on a cycle of the 10 GHz for a full orbital period. The signal-to-noise and the clocks allow that to be done.

David Allan, NIST: That brings me to my question. I am very happy to hear you say that you can keep track of a cycle, because if you can, going back to the STIFT experiment, we were able to show that, if you can do the relativity well enough, meaning that you have to keep track of the vehicle position to a few meters for the full orbit in order to adjust for all the relativity terms, then you can use the phase, or the zero crossings of the carrier, as a timing edge. That would take you down to the sub-ten picosecond level. You do that from pass to pass and then talk about comparing clocks in parts in the 10^{16}, 10^{17} and 10^{18}. In terms of long term timing we hope that you remember what we tried to wrestle with before. If that could be integrated into this experiment it would be very useful.