NASA PTTI PROGRAMS: PRESENT AND FUTURE

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INTRODUCTION

With reference to Figure 1, this paper discusses the current and future PTTI programs at the Goddard Space Flight Center (GSFC) and the evolution of frequency and time requirements over past years within the various NASA satellite tracking networks. A brief history of the network development is also given.

History of the NASA Tracking Network

Today's network, called the Spaceflight Tracking and Data Network (STDN), is a global complex of tracking stations used to communicate with both the manned and scientific spacecraft. STDN is a combination of networks that have evolved (Figure 2) over the years as requirements have changed.

The first network was called Minitrack, a radio interferometry system which became operational in 1957 (Figure 3). Minitrack originally consisted of eleven stations forming a radio fence in the north-south direction. Stations in the network were added and deleted as the space program fluctuated. Some sites are part of the present network. The first internationally agreed to satellite transmitting frequency was 108 MHz which was changed to 136 MHz in 1960. This new frequency was assigned by the International Telecommunications Union for the purpose of space research, a recognition of the rapid growth of the aerospace technology. The basic function to be performed by the Minitrack system was to collect tracking data for satellite orbit determination. A second function and one which grew more important with time was to receive and record the spacecraft telemetry data, which was then sent back to the Vanguard Data Reduction Center in Washington, D.C.

Sputnik I was launched on October 4, 1957 transmitting on a "surprise" frequency of 40 MHz. Quick modifications were made to Minitrack and, in less than 24 hours, tracking data from Sputnik I were being sent to Washington, D.C. for analysis.

During the 1958-1962 period several Minitrack sites were closed and several others were established. The Minitrack Network grew in capacity and complexity and in 1967, Minitrack evolved into the Station Tracking and Data Acquisition Network (STADAN)(Figure 4). Stations in Alaska, Newfoundland and England were added to improve geographical coverage and to add a new support capability for tracking satellites in polar orbit.

Early in 1959, the major ground-rules for the man in space Mercury Project were established. An orbital inclination of 32.5 degrees became firm. The Atlantic Missile Range would be utilized for launch and recovery. The tracking network would be worldwide (Figure 5) and operate in as near real-time as communications technology would permit.

The building of the Mercury Network was an enormous task requiring government, military and industry working together. The Network became operational on June 1, 1961, ready for the first man in space launch which occurred on February 20, 1962.

There was little change in the Mercury Network for the Gemini Network (Figure 6) which became operational in 1964.

The Apollo Network or Manned Spaceflight Network (MSFN) became operational in 1967 and was developed separately from the Mercury-Gemini Network (Figure 7). The early Mercury-Gemini sites used separate systems for tracking, command, and communications. The Apollo Network combined these three functions by using the Unified S-Band (USB) system which employed 26-meter and 9-meter antenna systems. The more significant parts of the USB system were the range and range rate equipment supplied by the Jet Propulsion Laboratory and the antenna systems which were nearly identical to those used in the STADAN. Like STADAN, the MSFN tended toward site consolidation with fewer, better instrumented, primary sites handling the complete mission support. Analog techniques gave way to digital techniques, and mission control was centralized with the field stations acting as data collection and relay points.

Finally, today's Network (Figure 8), the Spaceflight Tracking and Data Network (STDN) is a combined Network made up of the former Manned Space Flight Network (MSFN) and the former Station Tracking and Data Acquisition Network (STADAN). Administratively, this coming together was done in 1971; operationally, the merging took place over a period of several years.

During the 1970's, most of the STDN tracking facilities were fixed land sites. However, tracking ships have been used to give special support such as oribt-insertion and re-entry for the manned missions. Apollo Range Instrumentation Aircraft (ARIA), operated for NASA by the Air Force, were part of the Apollo support and later a part of the STDN supporting SKYLAB, Apollo-Soyuz, and a variety of scientific missions.

In staying abreast of the tracking technology, STDN uses a standardized data handling system to aid the NASA Communications System (NASCOM) function of efficiently transferring data from the tracking sites to Goddard Space Flight Center. Increased command and telemetry functions have necessitated the use of small on-site computer systems. Also, the STDN has had to move to higher frequencies to accommodate the greater volume of data produced by today's sophisticated spacecraft.

The Network of the 1980's will be the Tracking Data Relay Satellite System (TDRSS), the result of a conceptual study which started in 1966. In support of TDRSS a contract has been awarded to provide 50 MBS data service from the TDRSS White Sands, New Mexico ground terminal to GSFC and to Johnson Space Center, Houston, Texas. The service will use a domestic satellite system and existing earth stations to provide either 50 MBS, 4.2 MHz analog data, or television services on a switchable basis.

Chronology of Time and Frequency Requirements

Throughout all the Network growth, changes, and mergers precise time requirements have increased from tens of milliseconds to sub-microseconds. Frequency stabilities have improved from parts in ten to the eighth (1 x 10^{-8}) to parts in ten to fifteen (1 x 10^{-15}).

Figure 9 shows a chronology of precision frequency and time requirements from the late 1950's to the present and on into the year 2000, and the techniques used to achieve the needs, and some of the projects that were and will be supported over this time span.

During the Vanguard and early Mercury flights NASA relied on HF time transmissions from WWV and WWVH for millisecond timing. Figure 10 shows the first timing system that was installed in the Minitrack Network, Ventage 1958. This system was built at the Naval Research Laboratory and used a quartz crystal oscillator to develop various pulse rates and sine waves. HF receivers were used for time synchronization to within several milliseconds.

During the early to mid 1960's NASA depended on VLF phase tracking techniques to monitor the performance of station crystal clocks. This, along with HF time transmissions improved time keeping capability by about an order of magnitude to within 500 microseconds; with frequency stabilities of one part in ten to the ninth (1 x 10^{-9}).

Figure 11 is a picture of the second generation timing system that was installed in the Network in 1961. The systems used basically the same instrumentation as the first system. Note the Hermes Model 101 quartz crystal oscillator.

From 1966 through 1968 NASA conducted world wide time synchronization experiments using the Loran-C Navigation System and Loran-C timing receivers developed for NASA. A Loran-C capability was implemented in the Network during 1968 and 1969.

Between 1965 and 1967 the two rack timing systems in both Networks (STADAN and MSFN) were replaced with sophisticated "fail safe," redundant timing systems which used the latest state-of-the-art electronics in the frequency and time generation and distribution systems. These same systems are still in use today with the STDN. In the mid to late 1960's the crystal clocks were replaced with rubidium gas cell frequency standards, improving frequency stabilities to parts in ten to the tenth (1×10^{-10}).

Present Network Timing Systems

As a consequence of the two Network merger, the MSFN and the STADAN in 1971, the present Network (STDN) has several different timing systems and sub-systems. The two prime systems are the Collins TE-411 timing systems which are at the former MSFN sites and the Astrodata 6600 timing systems which are in the former STADAN sites. Both of these systems have been modified and updated numerous times over the past ten years to keep pace with frequency and time requirements.

The TE-411 system shown in Figure 12 provides a wide spectrum of sine waves, pulse rates and NASA/IRIG serial and parallel time codes. The frequency signals for the time systems are provided by the Precision Frequency Source (PFS) rack shown on the left in Figure 12 and utilizes three frequency standards with a high performance cesium as the on-line standard and rubidium and crystal standards as secondary. Some systems have two cesium standards with a crystal backup. Automatic switchover to a backup standard is accomplished if loss of amplitude or out-of-lock failure occurs in the primary standard. In addition, the frequency and phase of the backup standards are controlled by the master standard.

A dual 5 MHz output from the frequency combiner drives the PFS distribution amplifiers which provide outputs to the timing system at 5 MHz, 1 MHz and 100 KH_3. All outputs are metered and monitored and are individually amplitude adjusted. The PFS unit has a minimum of 10 hours of battery backup in the event of a power failure. A recent addition to the timing system provides triple redundancy and majority logic to the clock generation unit.

Time synchronization is accomplished via HF, Loran-C, and portable clocks. The STDN worldwide Network is presently maintained to within 25 microseconds of the Naval Observatory Master Clock. However, stations are typically within 5 microseconds and selected sites are within 1 microsecond.

The former STADAN sites have triple redundant Astrodata 6600 timing system shown in Figure 13. The systems presently use one cesium beam frequency standard with either an additional cesium or crystal as secondary. The 1 MHz from each standard is monitored for both amplitude failure and phase difference. If the master standard fails the backup is automatically switched on-line. The master oscillator drives each of three timing units A, B, and C, the outputs of which are intercompared in majority logic, error detection circuits. Error lights indicate which standard has failed and which of the three clocks (A, B, and C) are in error and where. The systems use WWV, Loran-C and portable clocks to maintain microsecond time. Television is also used for time sync where available such as at GSFC, Hawaii and Guam.

During 1965-1967 NASA began to use crystal rubidium portable clocks to periodically calibrate the remote station clocks to within several hundred microseconds. Figure 14 shows an early Sulzer, Portable Crystal Clock. In 1968 the crystal and rubidium portable clocks were replaced with Hewlett Packard (HP) cesium beam portable clocks shown in Figure 15, thus permitting remote clock calibration to within microseconds depending on the duration of the clock trip. NASA now uses lightweight portable clocks one of which is shown in Figure 16.

Future Considerations

Future requirements for frequency and phase stability, pulse jitter and site-to-site time synchronization cannot be met with the present STDN timing systems. Recognizing this, design concepts were finalized in 1978 for a fourth generation timing system to be installed in the Network during the early 1980's in support of the GSFC Tracking and Data Relay Satellite System (TDRSS) and the NASA/JPL Consolidated Network.

Shown in Figure 17 is the new TRAK Model 8407 timing system which was designed and built to NASA specifications. This system is installed and operating at the TDRSS NASA ground terminal located at White Sands, New Mexico. The system is designed to be driven from a frequency combiner/selector with controlled 5 MHz outputs.

The purpose of the Frequency Combiner/Selector (FCS) is to provide the White Sands NASA Ground Terminal timing system with a reliable and precise source of 5 MHz. The FCS achieves reliability by using more than one precision frequency source of 5 MHz. It uses 5 MHz from two cesium standards and one from a remote source. In the normal mode, one cesium standard is selected to drive all the FCS outputs. If the FCS detects a failure in that cesium, the FCS switches all its outputs to a back up input. If the FCS detects failures in both cesium standards, the FCS will switch all its outputs to the remote 5 MHz input (input 3). The main characteristics of the White Sands timing system are as follows:

1. Fully redundant
2. Highly reliable
3. NASA-quality construction
4. Sub-microsecond precision
5. Built-in fault isolation
6. Minimum down-time
7. Multiple code and rate outputs

The basic timing system (Figure 18) contains three separate and identical time code generators which produce parallel and serial time codes with resolution and coherences of 50 to 200 nanoseconds. The outputs from the three generators are combined in majority voters, assuring that system outputs are maintained if one or two generators fail. A distribution system provides multiple buffered outputs of the generated time codes and pulse rates. A failure sensing subsystem isolates failures to the card level. Individual power supplies are provided for each time code generator and the power supply outputs are ORed for majority voting and fault sensing circuit power.

The three time code generators accumulate time via the external 5 MHz input and distribute serial and parallel time codes and rates to the majority voters and fault sensing logic. The voted outputs from the majority voters are buffered in three types of signal distribution assemblies.

The fault sense logic isolates failures to the card level. Failure indicators are located on a control status panel. This panel also contains switches for selecting generator A, B, C or voted outputs for distribution and for output monitoring on the panel.

Millisecond time is maintained via HF receivers and sub-microsecond time is maintined via Loran-C receivers and the Tracking Data Relay Satellite (TDRSS) Time Transfer Unit (TTU). Portable clocks are also used for periodic calibration to sub-microseconds. The Global Positioning System (GPS) will also be used when it becomes operational.

Figure 19 is a block diagram of the system that will be installed in the NASA/JPL Consolidated Network sites at Madrid, Goldstone, and Canberra in the early to mid 1980's. The basic timing system on the right will be supplied by Goddard and the frequency generation source will be supplied by JPL.

Satellite Time Transfer Techniques

In the late 1960's and early 1970's NASA personnel experimented with the use of satellites for time transfer. This included the use of GEOS and ATS spacecraft. During 1973-1975 NASA conducted two-way time transfer experiments using the synchronous ATS-1 satellite. This technique proved accurate to better than a microsecond between widely separated clocks. In 1974 NASA in cooperation with the Naval Research Laboratory developed timing receivers for use with the Navigation Technology Satellites (NTS). Experiements achieved less than 500 nanoseconds worldwide. In 1976 GSFC initiated studies to look at the use of the Global Positioning System (GPS) and the Tracking Data Relay Satellite System (TDRSS) for sub-microsecond timing. As a consequence of these two studies GSFC is looking to the use of both TDRSS and GPS for timing (Figure 20).

Time Synchronization Via TDRSS

Data communication via the Tracking and Data Relay Satellites is to become available to users in the 1980's. The ranging and data services provided by the Tracking and Data Relay Satellite System are to be an integral part of NASA's post-1980 Spaceflight Tracking and Data Network.

The TDRSS system will consist of two geostationary relay satellites 130 degrees apart in longitude (Figure 21) and a ground terminal at White Sands, New Mexico. The system will also include two spare satellites, one in orbit and one ready to be launched. A real-time bent-pipe concept is used in the operation of TDRSS.

Time transfer communication between the TDRSS ground station at White Sands and GSFC will be in a Multiple Access service standard mode of operation. This mode uses a combination of pseudorandom (PRN) codes and data modulation for ranging and telemetry. The capability of simultaneous ranging and data communication is directly applicable to time transfer. Ranging is accomplished by synchronized forward and return link PRN codes in a "round trip" or "two way" ranging mode (TDRSS mode 1). Forward and return telemetry data are modulated onto the respective codes allowing simultaneous two-way data transfer. The PRN code "epoch" signals or all ones "state indicators" serve as event markers for time transfer. Signal margins are such that these markers will be quite stable and code acquisition time relatively short.

To transfer time via TDRSS, the time interval between a specific event marker and the master station clock's 1 pps is measured. A similar time interval is measured by the user as his transponder receives the PRN code and, hence, event markers. The time interval measurements and other information (time of day in hours, minutes and seconds) are exchanged between master and user by forward and return telemetry. The master site makes a second time interval measurement on the return telemetry to allow estimation of the forward path delay time. A number of relatively simple calculations, using the time interval measurement data, are required for each clock error estimate. A clock error estimate would be obtained once per second. The data processing or "smoothing" would be based on a linear model of the movement of TDRSS and utilize a data span of several minutes. Microprocessor hardware/software is well suited to the synchronization and computational requirements. An important and desirable feature about TDRSS is that for time transfer, the master and user designations are interchangeable. The error in the clock difference measurement is expected to be less than 40 nanoseconds and to be available once each second. The total elapsed time required to complete a time transfer should be less than 5 minutes.

Also shown in Figure 21 is the NASA/JPL Consolidated Network of the mid 1980's and will consist of sites at Madrid, Goldstone and Canberra. All other Network sites within the present STDN are expected to be phased out over a period of years.

Time Transfer via GPS

In order to make use of the highly accurate laser ranging data, it is necessary to time tag the data from the laser stations very accurately. In applications where the data from two or more stations will be merged to determine baselines for geodetic work, polar motion determinations, etc., it is necessary that the clocks at the several stations be synchronized to within ±1 microsecond with respect to a master clock such as that of the Naval Observatory (USNO).

GPS time transfer receivers are being developed jointly by GSFC and NRL. GSFC will use the GPS timing receivers in the Laser Ranging Network which consists of eight mobile vans and permanent installation at GSFC. The Laser Network is separate from the STDN although there may be colocations.

A typical mobile laser van installation is shown in Figure 22. Figure 23 shows an installation at Kwajalein along with the range safety radar system, and Figure 24 shows a laser system at American Samoa. Over the next several years the laser timing systems will be updated and GPS receivers installed.

Use of Shuttle for Timing

There are plans in the formative stage for a Shuttle-based laser ranging system which would transmit pulses to several hundred passive ground based targets located at points of interest. The Shuttle laser system would receive the returned reflected pulses from the various ground targets and use this information to define the Shuttle orbit in real-time, and by using trilateration, to measure the relative position of selected ground targets (Figure 25).

This technique is ideal for transferring time. A ground timing terminal may look like what is shown in Figure 26 and consists of a retroreflector, a constant fraction discriminator, an event clock and a microprocessor data recorder and analyzer.

SIRIO/LASSO Time Transfer Experiment

Other future activities include joint participation by GSFC with the USNO and NRL in the ESA SIRIO/LASSO time transfer experiment during 1981 and 1982. With reference to Figure 27, the missions of SIRIO-2 are twofold; meteorological data dissemination and synchronization of intercontinental atomic clocks.

The aim of the LASSO experiment is to provide a repeatable, near-real-time method for long-distance (intercontinental) clock synchronization with nanosecond accuracy at a reasonable cost. The pioneering aspects of this first experiment will provide the opportunity to compare the international network of atomic clocks with the internationally adopted atomic time scale (TAI) and with each other. It will also have an impact on such practical applications as the tracking of deep space missions, the calibration of other time transfer techniques such as Very Long Baseline Interferometry (VLBI), Tracking Data Relay Satellite System (TDRSS), and the Global Positioning System (GPS), and future generations of space navigation and telecommunication systems.

SIRIO-2 will be launched during October of 1981 from Koarou, French Guiana in South America into synchronous orbit at 25 degrees west longitude which is just off the West Coast of Central Africa near Liberia. The satellite, which has a 2-year lifetime design, will remain in this position for about 9 months to permit time measurements between the United States (Goddard Space Flight Center referenced to the Naval Observatory) and major observatories and time keeping facilities in Europe--principally with the Bureau International de l'Heure (BIH) in Paris, France. SIRIO-2 will then be moved over Central Africa at 20 degrees east longitude and will remain there for meteorological data dissemination until the completion of its 2-year mission. See Figure 28.

S/C Characteristics

The LASSO experiment is based on the use of laser ground stations firing monochromatic light pulses at predicted times directed toward the geosynchronous SIRIO spacecraft.

SIRIO-2 is a Spin-stabilized geostationary satellite spun around an axis vertical to its orbital plane. The spacecraft consists of a drum-shaped central body covered with solar cells. On top is mounted a mechanically despun S-Band (1689.6 MHz) antenna for support of the meteorological and timing missions and housekeeping data. Omnidirectional antennas (VHF 136.14 MHz) serve for command, ranging and backup telemetry (Figure 29).

The LASSO payload is composed of retroreflectors, photodetectors for sensing ruby and neodyme laser pulses and a stable clock for time tagging arrival times of laser pulses.

LASSO Experiment Goals

The goals of the LASSO experiment are as follows:

1. To verify that lasers can be used to perform a two-way time transfer from a geostationary satellite to within nanoseconds or sub-nanoseconds.

2. To determine the limitations and problems of such a laser time transfer technique.

3. To verify the accuracy of other techniques such as the Global Positioning System (GPS) time transfer technique using receivers being developed for use in the Mobile Laser Network.

Description of the GSFC Laser Ranging Systems for LASSO

The GSFC laser satellite ranging system to be used for the LASSO time transfer experiment is an adaption of the laser ranging system presently used for tests and evaluation of advanced laser ranging technologies and components. There are three major systems incorporated in the system (Figure 30): the general purpose tracking telescope, the laser transmitter, and the range timing and data recording system.

The tracking telescope is a 1.2 meter aperature, F/30 Azimuth-Elevation Coudé system, controlled by a general purpose computer system. The system has a servo pointing accuracy better than 0.4 arcseconds and an open loop pointing accuracy relative to the input prediction data of better than 1.5 arcseconds. The Coudé input/outputs of the telescope is directed via a turning mirror and negative matching lens to the laser ranging system located in a clean room 15 meters from the base of the telescope.

The laser transmitter is a cw mode-locked Nd:YAG system incorporating a regenerative amplifier and three single pass amplifiers. The transmitter operates at up to 5 pulses per second with a pulse energy of 0.25 joules in less than 200 picoseconds at a wavelength of 0.53 microns. The output beam divergence is less than two times the diffraction limit. The output of the laser is coupled to the telescope through a transmit/receive switch and expanding optics. The incoming signal from the telescope is directed to the detector with a solenoid activated flip mirror and passes through conditioning optics and a narrow bandpass prediction filter. A constant fraction discriminator with a threshold of one photoelectron converts the photomultiplier detector signal to the appropriate timing signal for measurement.

The range timing system consists of a computer, multi-event range timing unit, real-time clock, and an epic timing unit. The computer controls in real-time (via inputs from the real-time clock) the operation of the laser, range gate generator, epic timer, multi-event range times, visual display unit, and data recording from each element of the ranging system.

History of Hydrogen Maser Program

Since 1961 GSFC has had a program to develop and test field operable hydrogen maser frequency and time standards. After the successful results with an experimental maser (NX-1) in 1967, the NASA Prototype or NP series of masers were developed between 1969 and 1971 providing frequency stabilities of parts in (1×10^{-14})(Figure 31).

The four NP hydrogen masers continue to be the backbone of our frequency standard support. These masers have compiled impressive records in the field. They have accumulated a total of over 35 years of field operation and have traveled nearly 200,000 miles to 40 separate installations in support of various VLBI programs in the geodetic and astronomical work, star mapping, relativity experiments, and time transfer experiments with various worldwide observatories and laboratories.

Presently the program is directed toward the development of a new series of field operable hydrogen masers, the NASA Research, or NR series, in conjunction with the Applied Physics Laboratory. These masers, based on two new experimental masers developed at GSFC, will provide parts in ten to the fifteenth (1×10^{-15}) frequency stability for future NASA requirements.

Over the next 4 years GSFC expects to construct 3 to 4 NR masers per year for a total of about 14.

By 1985, GSFC expects to have a total of 19 to 20 masers for support of NASA programs such as the Crustal Dynamics Program.

The program is also developing primary frequency standards with parts in ten to the fourteenth (1×10^{-14}) accuracy to calibrate and improve the field operable masers. Two novel masers, the Concertina Maser and the External Bulb Zero Wall Shift Maser are being developed.

Based on discoveries made with the Concertina Maser and those at Williams College under a NASA grant, a new experimental field operable hydrogen maser with a line Q approaching ten to the tenth (1×10^{10}) is being developed. This is a factor of 3 greater than the line Q of the NR and NX masers. These masers promise to achieve parts in ten to the sixteenth (1×10^{-16}) frequency stability.

To compliment the work on improved frequency standards, an improved frequency distribution and measurement system has been developed. A modular approach was used based on the CAMAC interface standard. This allows one to combine the various modules being developed into systems tailored for various uses. This modular system is used for the frequency distribution system (frequency combiner/selector) in the next generation of Network Timing Systems and for the measurement and distribution system for the new Frequency Standards and Test Facility.

In the near future, this Frequency Standards and Test Facility will provide the frequency standards program with a controlled undisturbed environment. This will enable long term measurements to be made on the NX and NR hydrogen masers which were previously impossible. Measurements will also be made on the temperature, pressure, and magnetic field sensitivities of the NX and NR masers as well as the frequency stabilities of these masers under various conditions.

The Concertina Maser, and eventually the External Bulb Maser will be used to study the effects of the wall shift on field operable maser stability. After the two new experimental masers are constructed and operating, these tests will be repeated on them to determine their performance and to document their hoped for parts in ten to the sixteenth (1×10^{-16}) frequency stability.

Summary

In summary, Figure 32 shows the timing techniques that have been used over the years and will be used to meet NASA Project needs. Under satellite techniques, GSFC will use TDRSS and GPS for sub-microsecond timing. GSFC will continue to use Loran-C and television for localized timing and will transport portable clocks for several years to come.

GSFC PTTI PROGRAMS
CURRENT AND FUTURE

- **TIMING PROGRAM**
  - HISTORICAL BACKGROUND
  - PRESENT TIMING SYSTEMS
  - NETWORK CONSOLIDATION
  - FUTURE CONSIDERATIONS
- **HYDROGEN MASER PROGRAM**
  - RESEARCH & TECHNOLOGY
  - PROJECT SUPPORT ACTIVITIES

Figure 1. GSFC PTTI Porgrams Current and Future

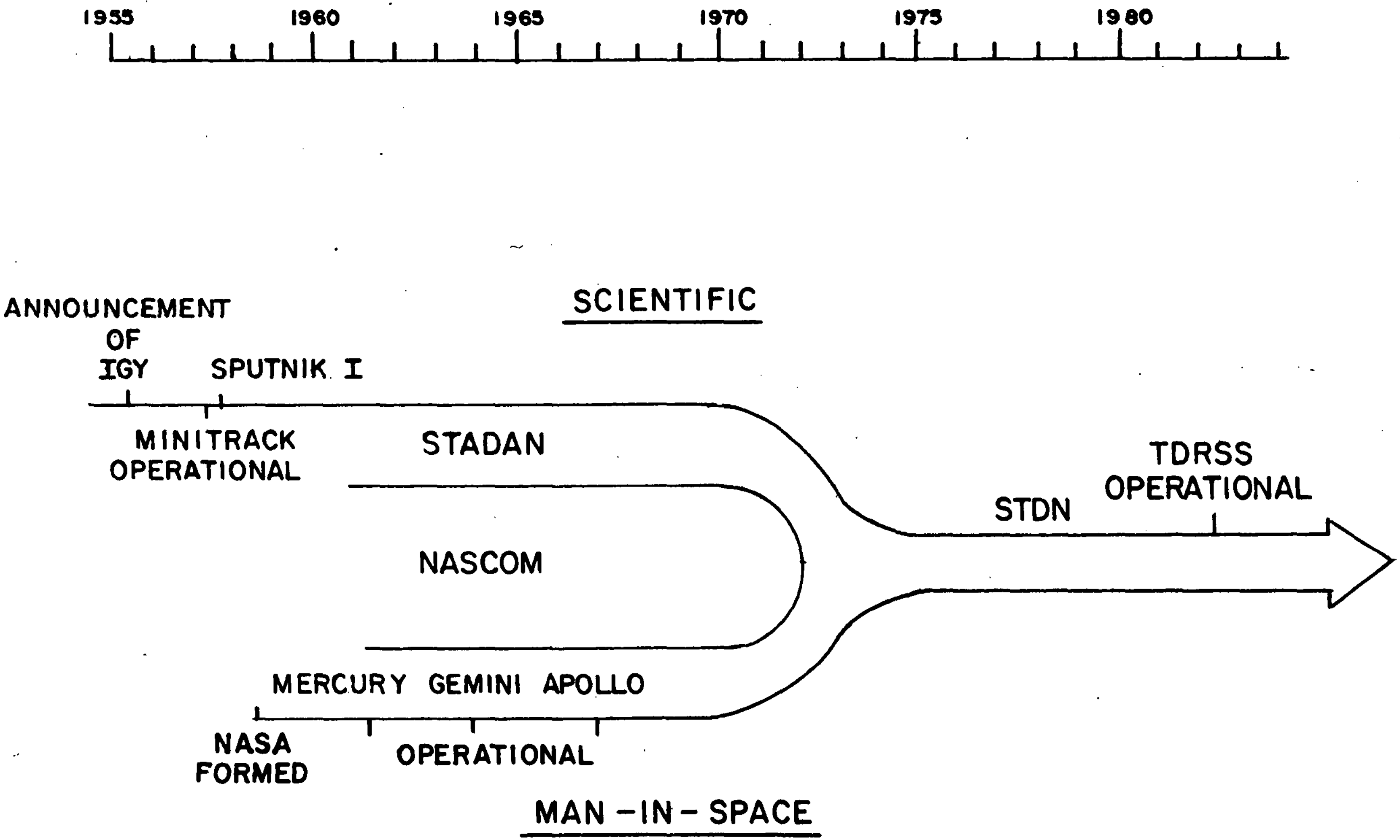


Figure 2. Evolution of the STDN Tracking and Data Acquisition Network

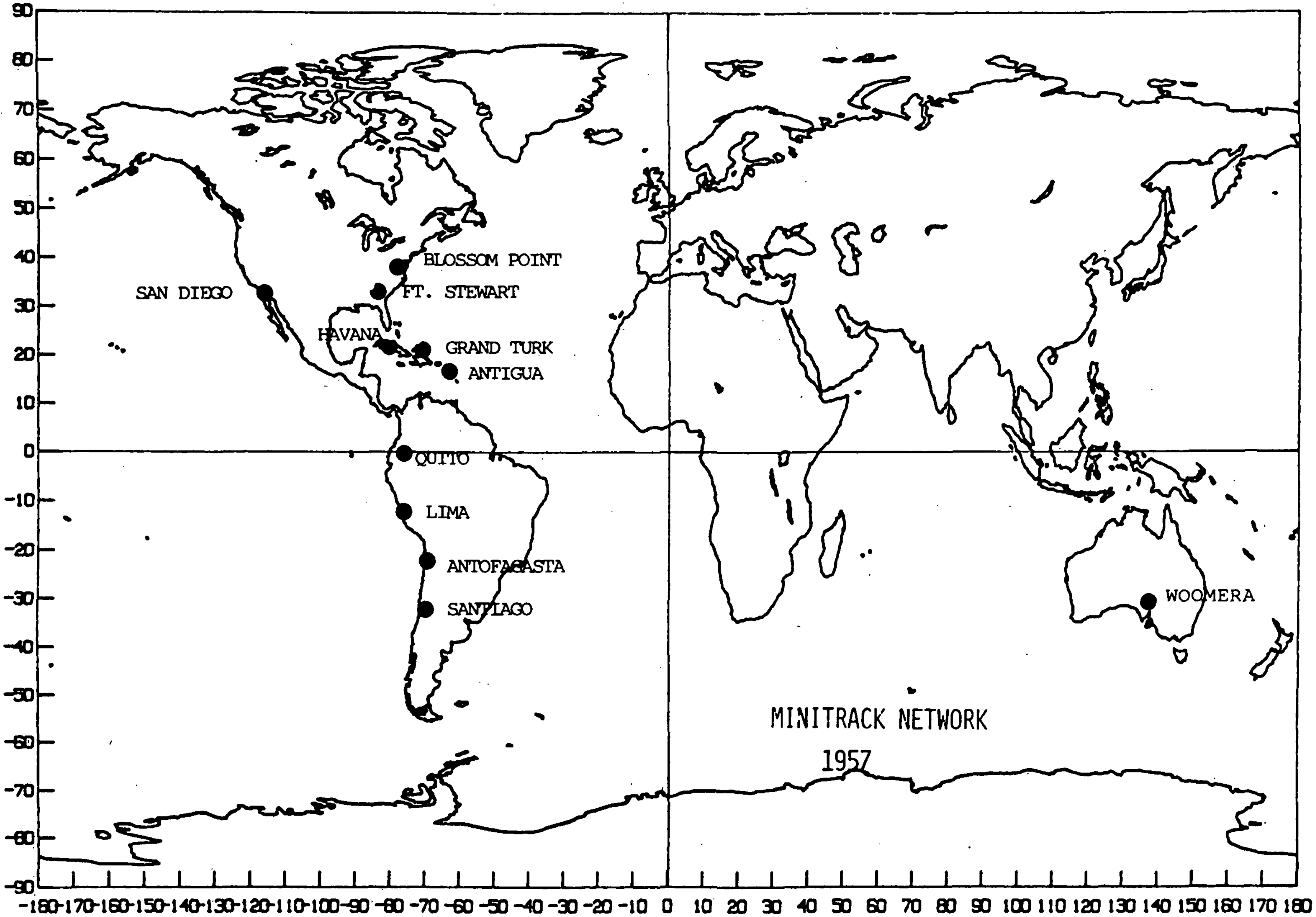


Figure 3. Minitrack Network 1957

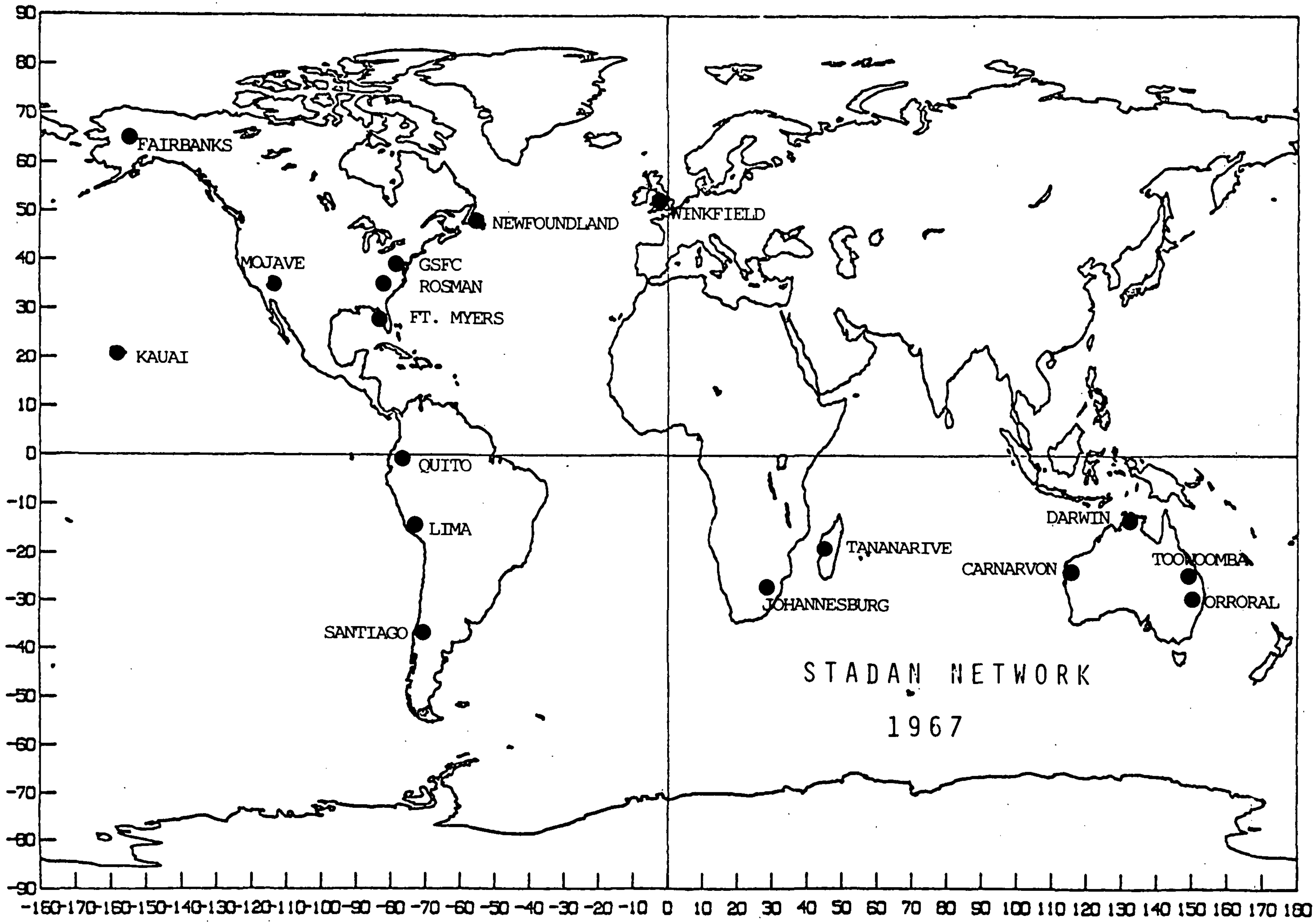


Figure 4. STADAN Network 1967

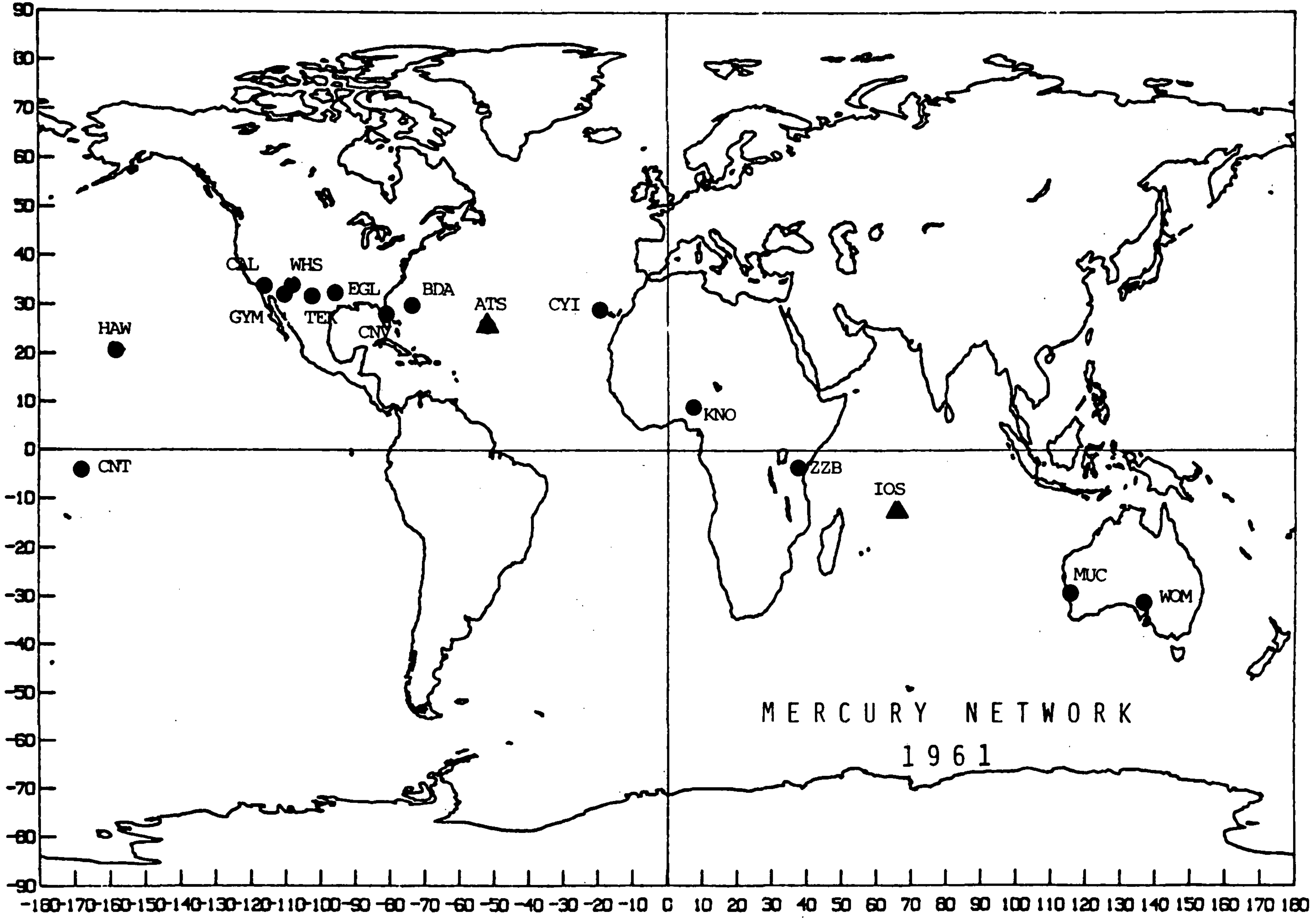


Figure 5. Mercury Network 1961

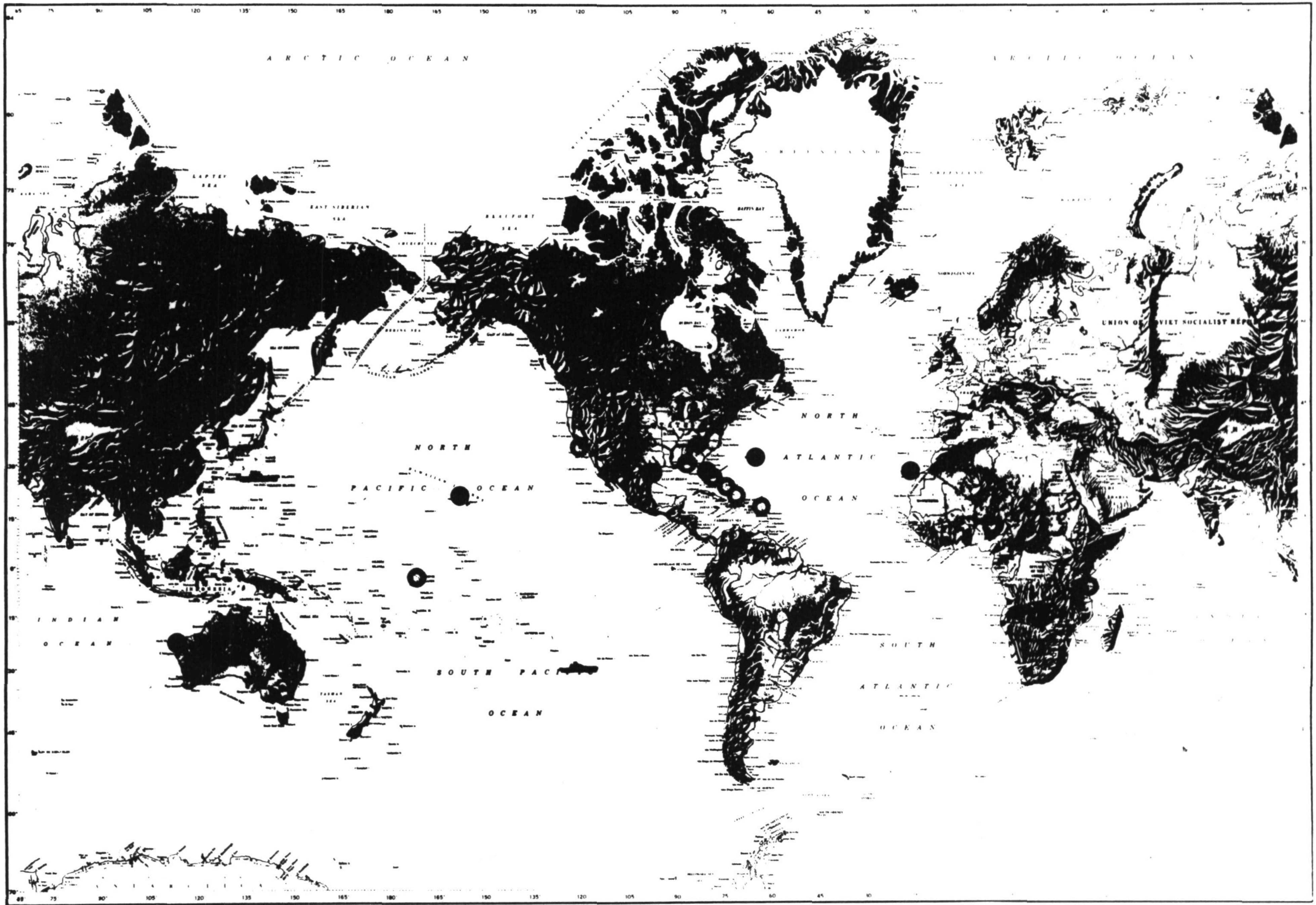


Figure 6. Gemini Network 1964

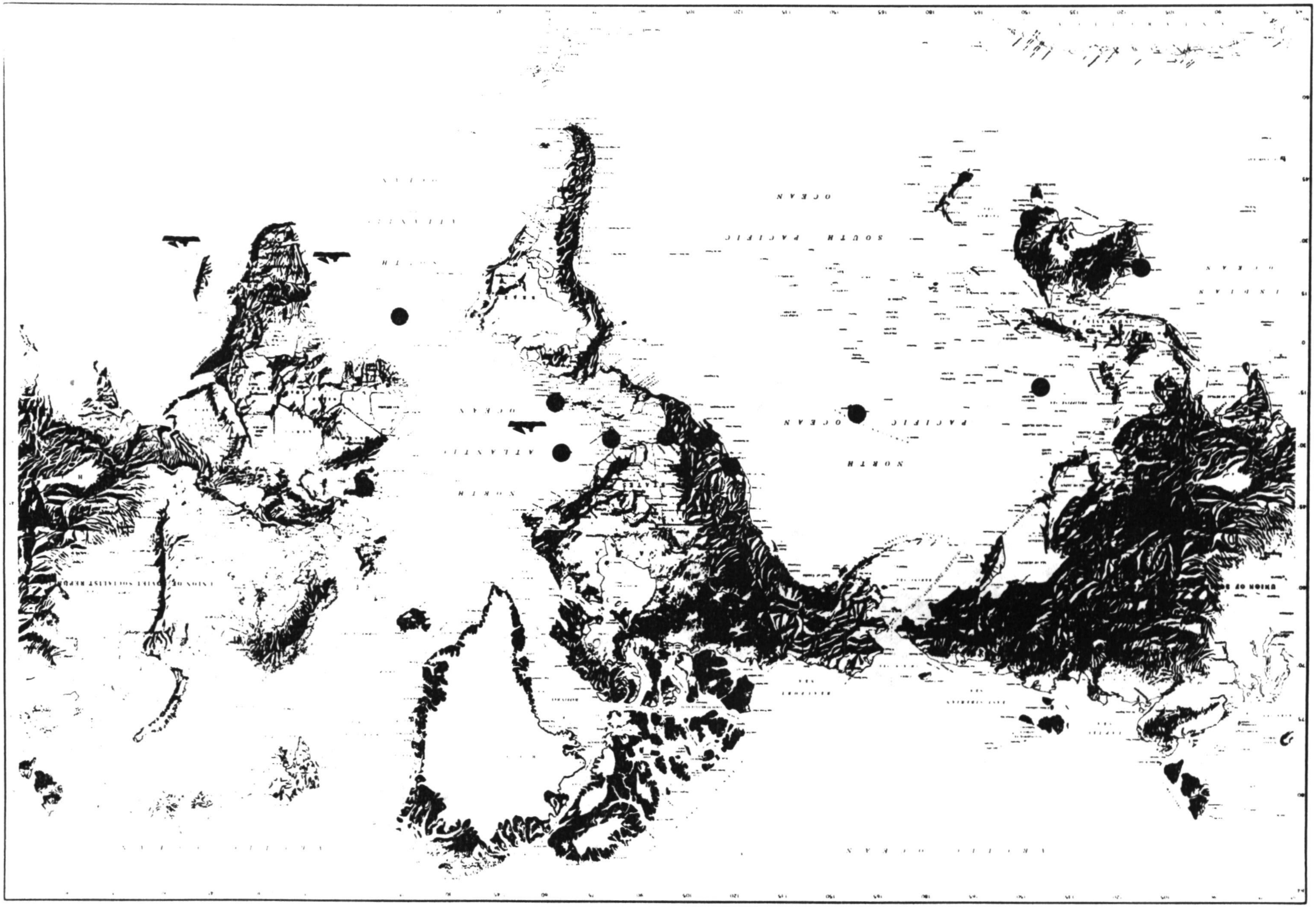


Figure 7. Apollo Network (MSFN) 1967

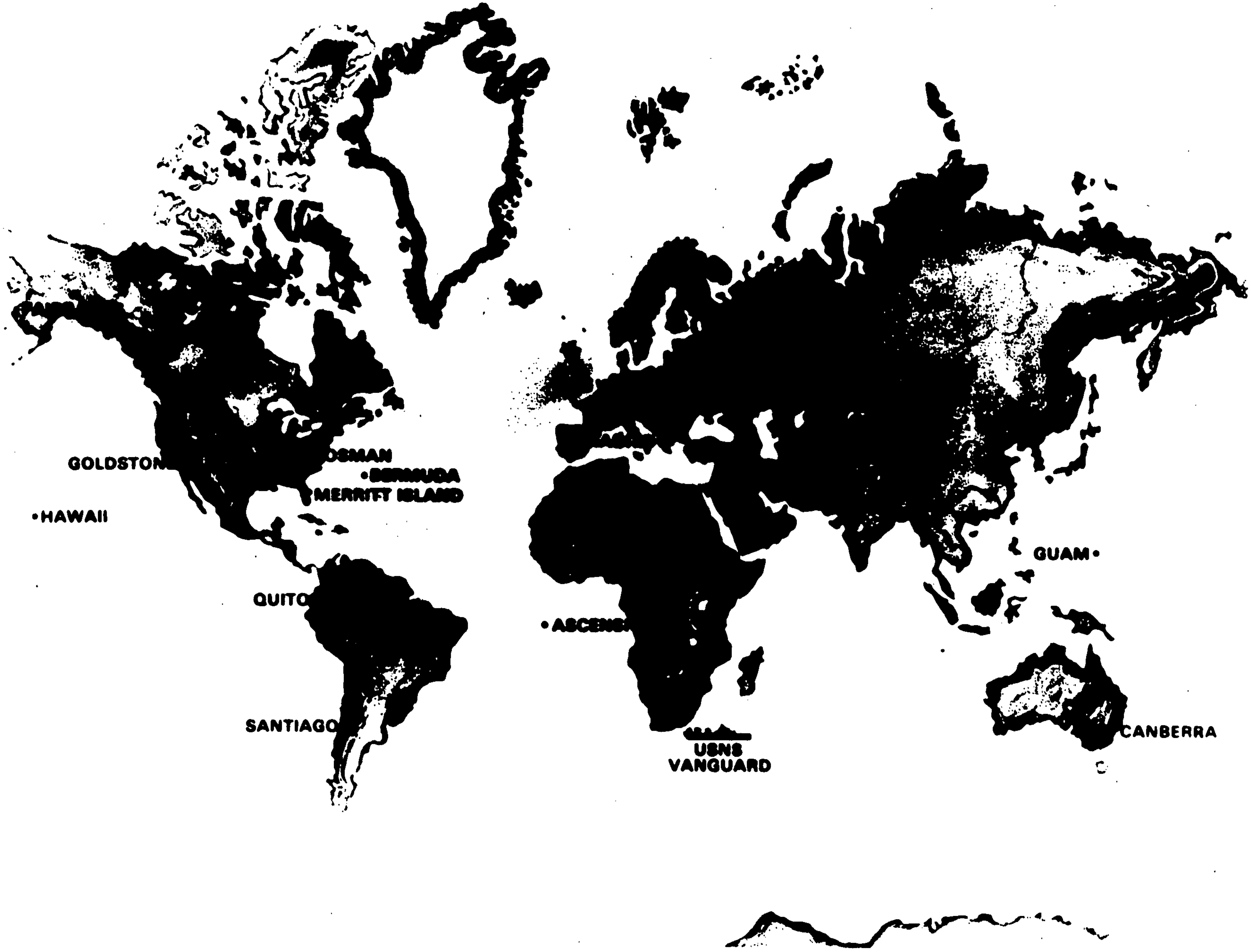


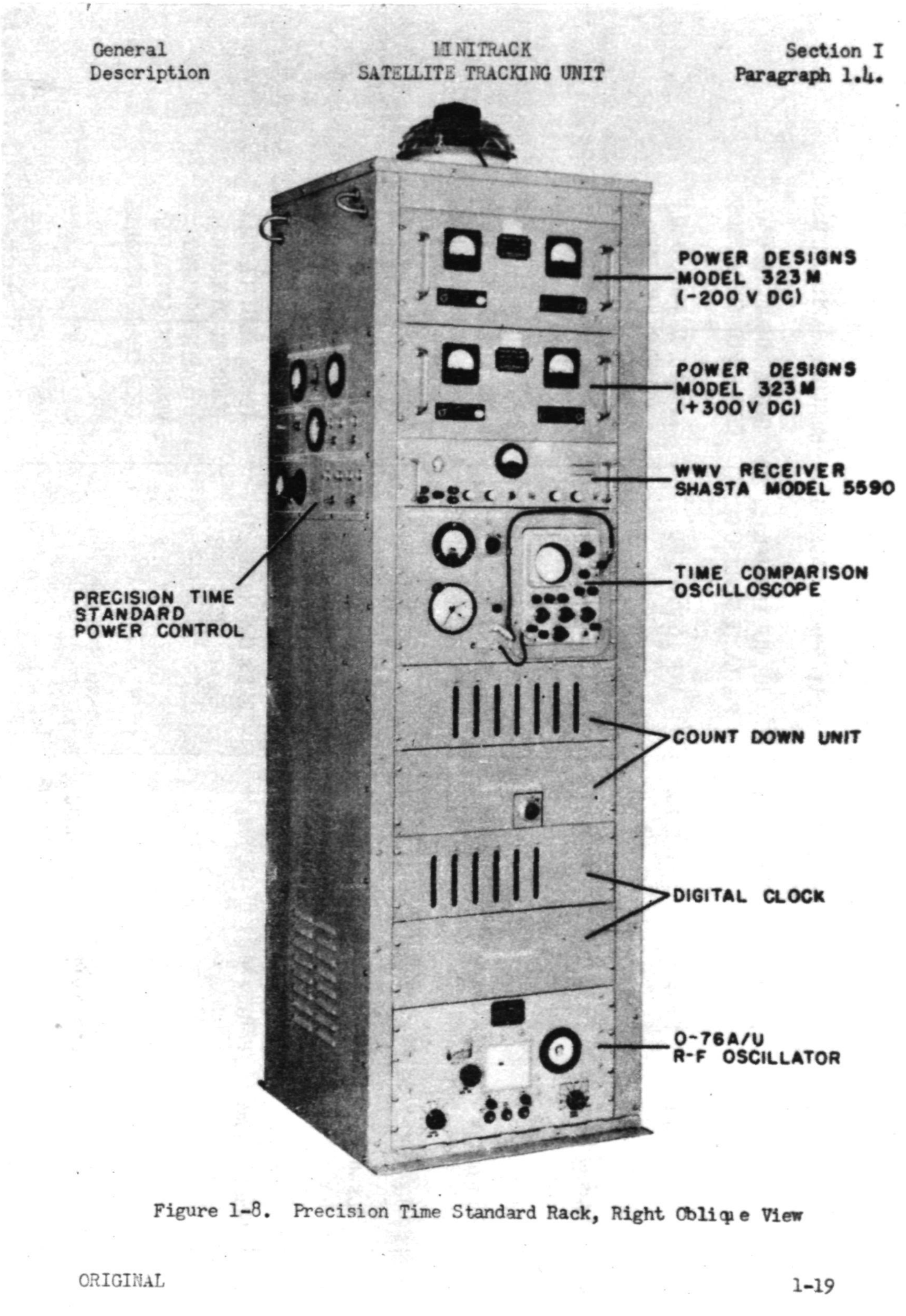
Figure 8. STDN Network 1978

DATE	REQUIREMENTS			TECHNIQUES	PROJECTS
	TIME SYNC	FREQUENCY STABILITY	FREQUENCY STANDARD*		
1958/61	10ms to 1ms	1×10^{-8}	XTAL	NBS, HF TIME TRANSMISSIONS (WWV & WWVH)	VANGUARD AND MERCURY
1961/63	1ms to 500μs	1×10^{-9}	XTAL	HF, VLF PHASE TRACKING	MERCURY, EXPLORER, OSO
1963/66	500μs to 100μs	1×10^{-10}	XTAL, Rb	HF, VLF, LORAN-C PORTABLE CLOCK (PC)	GEMINI, OGO, ATS, OAO OSO, EXPLORER, NIMBUS
1966/72	100μs to 50μs	1×10^{-11}	XTAL, Rb, Cs	VLF, LORAN-C, PC PC	APOLLO, NIMBUS, OAO, PIONEER, ATS, OSO
1972/74	50μs to 25μs	1×10^{-12}	Rb & Cs	VLF, LORAN-C, PC TELEVISION (TV) SATELLITE (ATS)	OAO, IMP, SKYLAB, RAE-B, ATS-F, SMS
1974/77	25μs to 1μs	PARTS $\times 10^{-13}$	Rb & Cs	LORAN-C, PC, TV, SATELLITE (NTS)	GEOS, ATS, ERTS, OSO, LAGEOS, SEASAT, VLBI, LASER RANGING
1977/80	1μs to 50ns	PART $\times 10^{-14}$	Cs & HM	LORAN-C, PC, TV, NTS	GEOS, HEAO, SEASAT, SMM, SHUTTLE, LAGEOS, VLBI, LASERS
1980/85	50ns to $<$ 10ns	PARTS $\times 10^{-15}$	Cs, HM, Hg	TDRSS, GPS, LASER, TV, PC	TDRSS, SHUTTLE, VLBI, CRUSTAL DYNAMICS, LASER RANGING, SCIENTIFIC SATELLITES, DEEP SPACE MISSIONS
1985/2000	1 ps	PARTS $\times 10^{-16}$	ATOMIC STANDARDS		

***NOTATION**

CRYSTAL = XTAL
RUBIDIUM = Rb
CESIUM = Cs
HYDROGEN MASER = HM
MERCURY = Hg

Figure 9. Precision Frequency and Time Requirements 1958-2000



General Description

MINITRACK SATELLITE TRACKING UNIT

Section I Paragraph 1.4.

Figure 1-8. Precision Time Standard Rack, Right Oblique View

ORIGINAL 1-19

Figure 10. Minitrack Satellite Tracking Unit

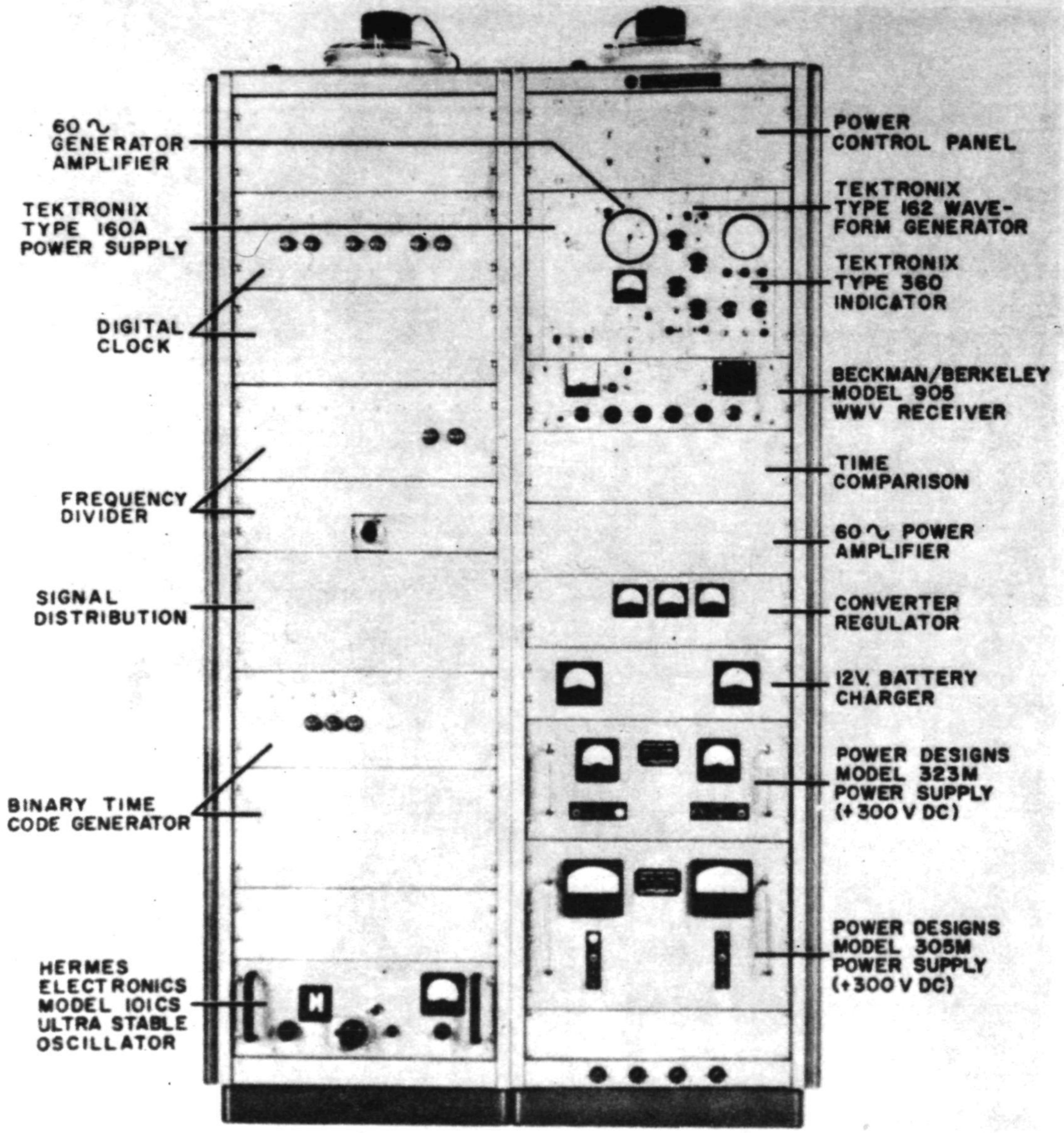


Figure 1-6. Time Standard Rack

Figure 11. Second Generation Minitrack Interferometer Timing System

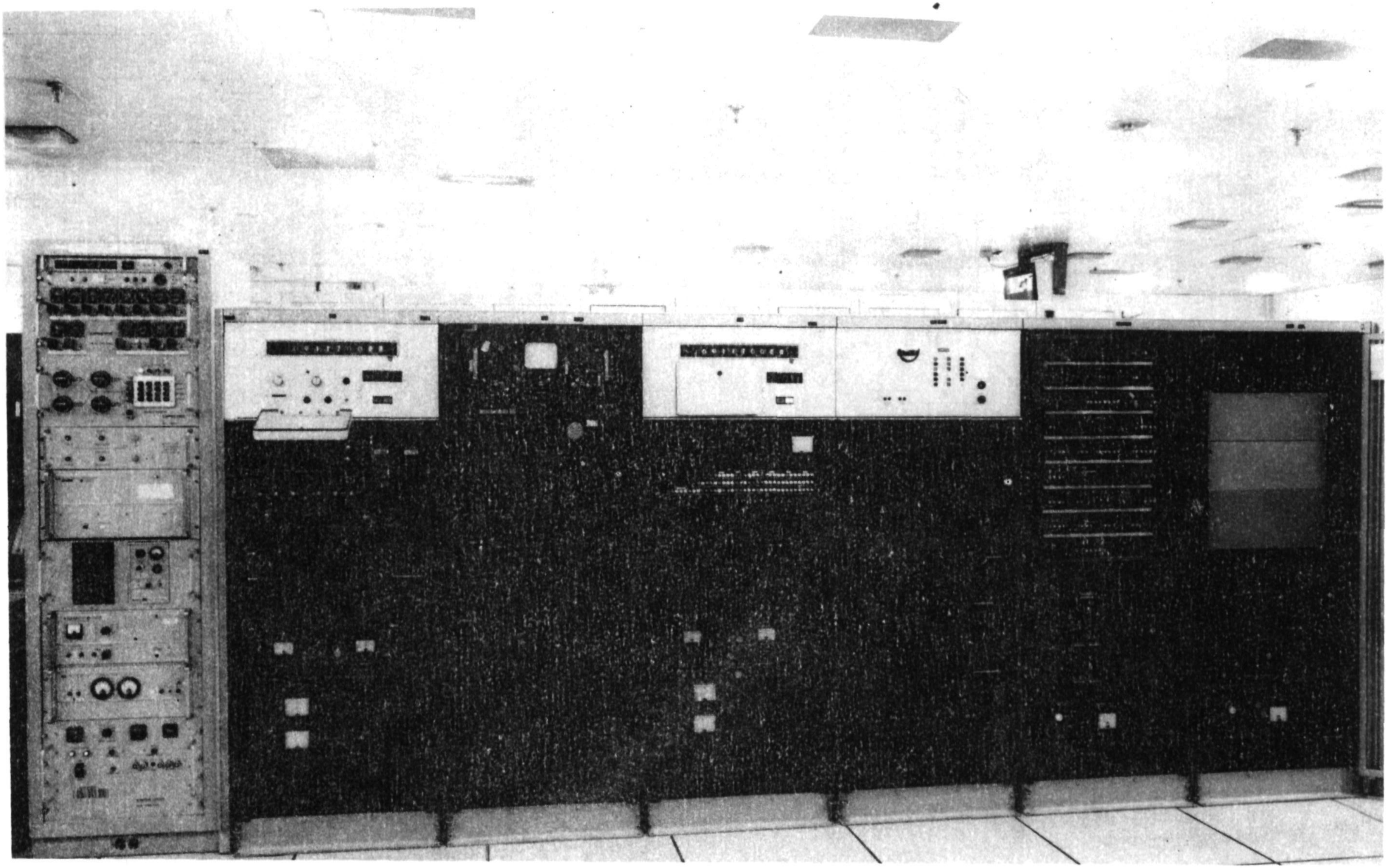


Figure 12. TE-411 System

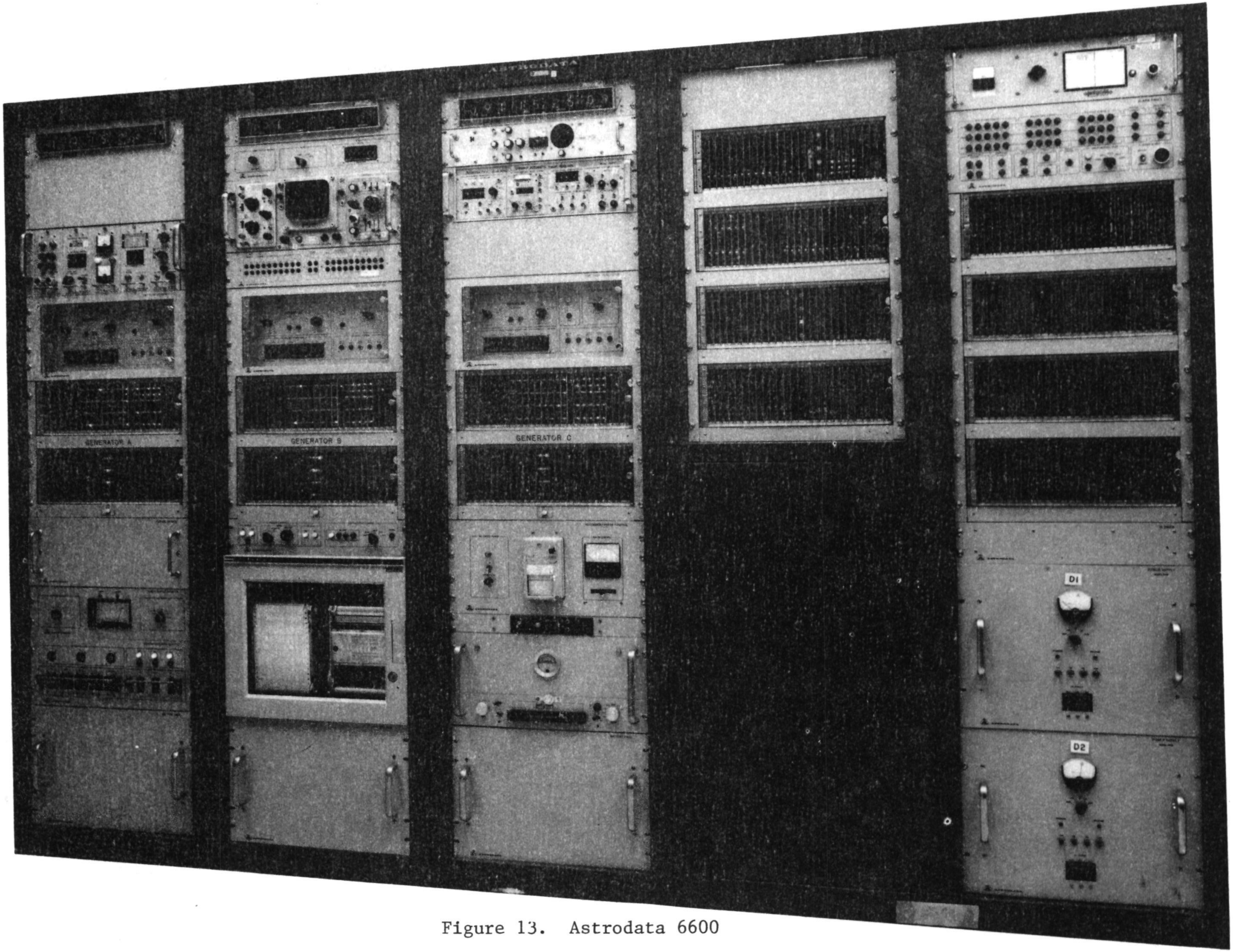


Figure 13. Astrodata 6600

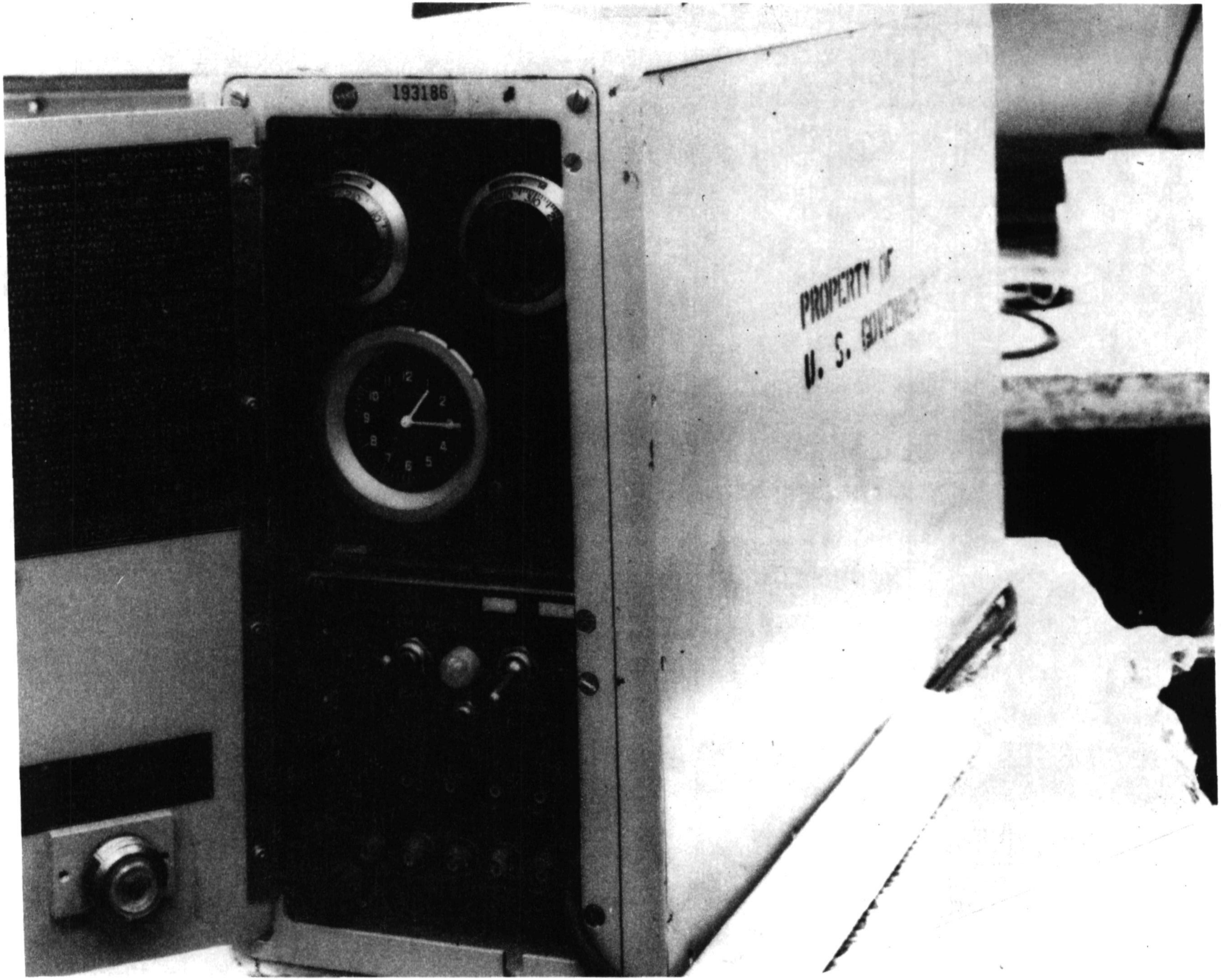


Figure 14. Sulzer Portable Crystal Clock

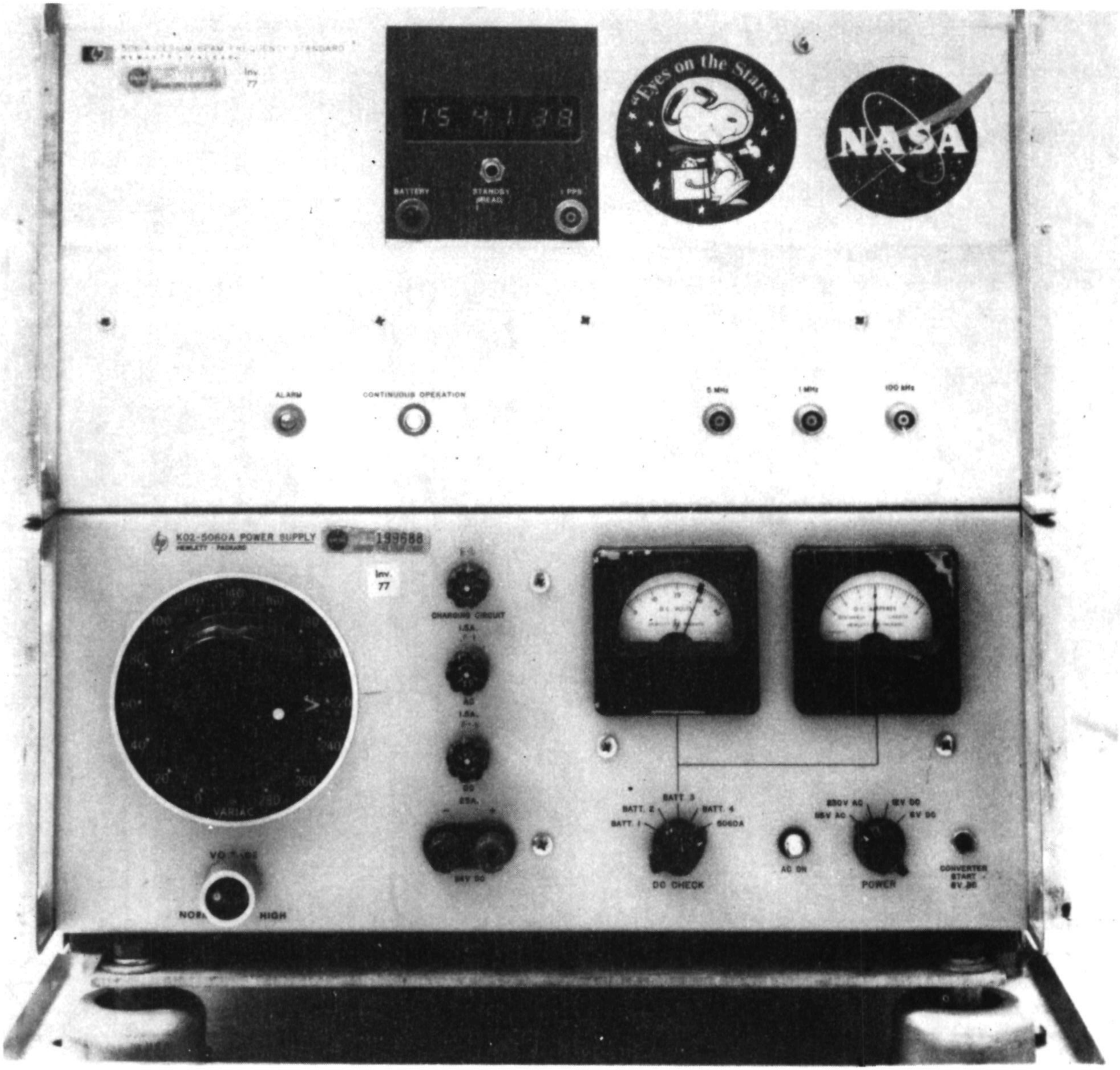


Figure 15. Hewlett Packard Cesium Beam Portable Clock

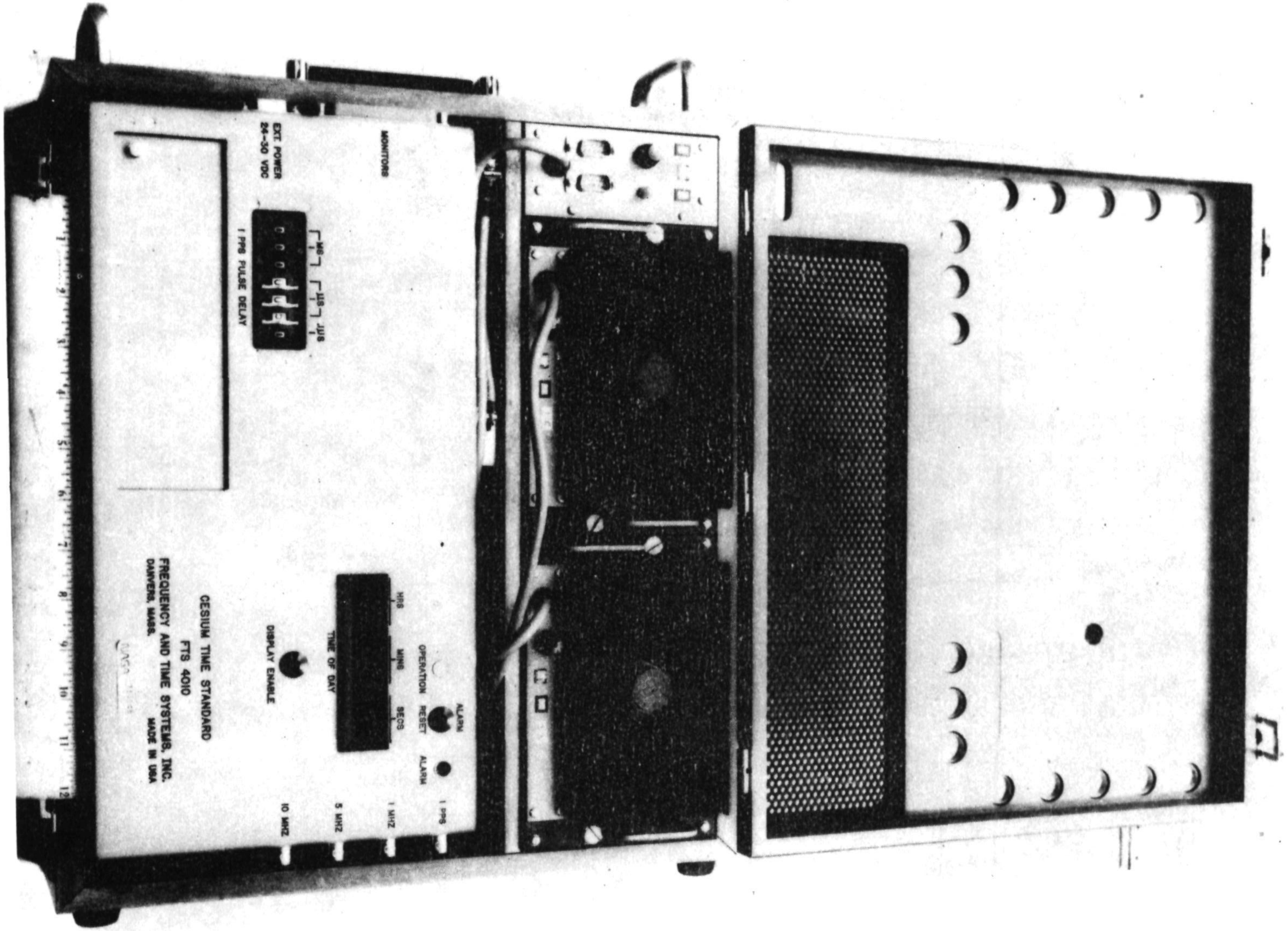


Figure 16. Currently Used Lightweight Portable Clock

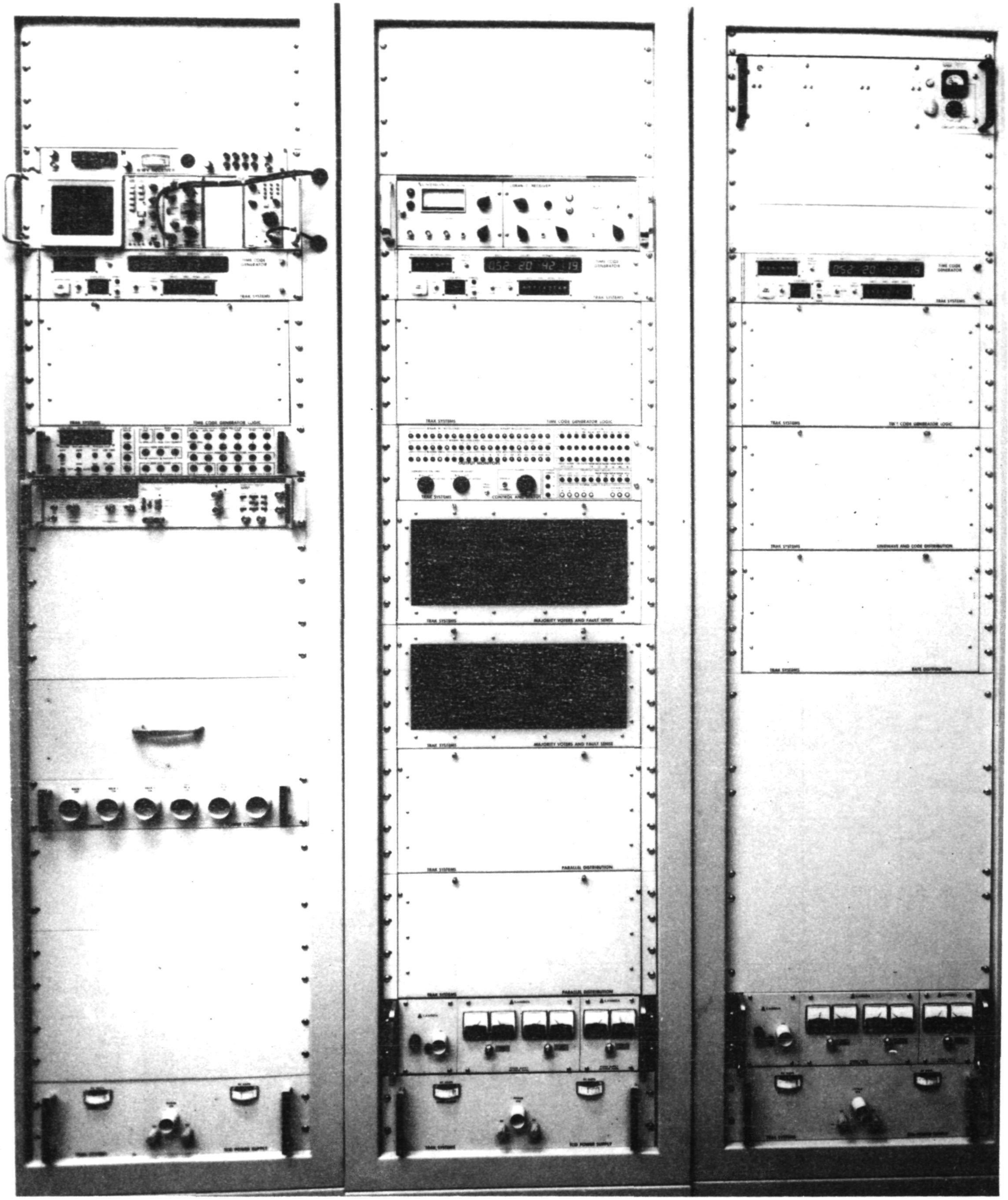


Figure 17. TRAK Model 8407

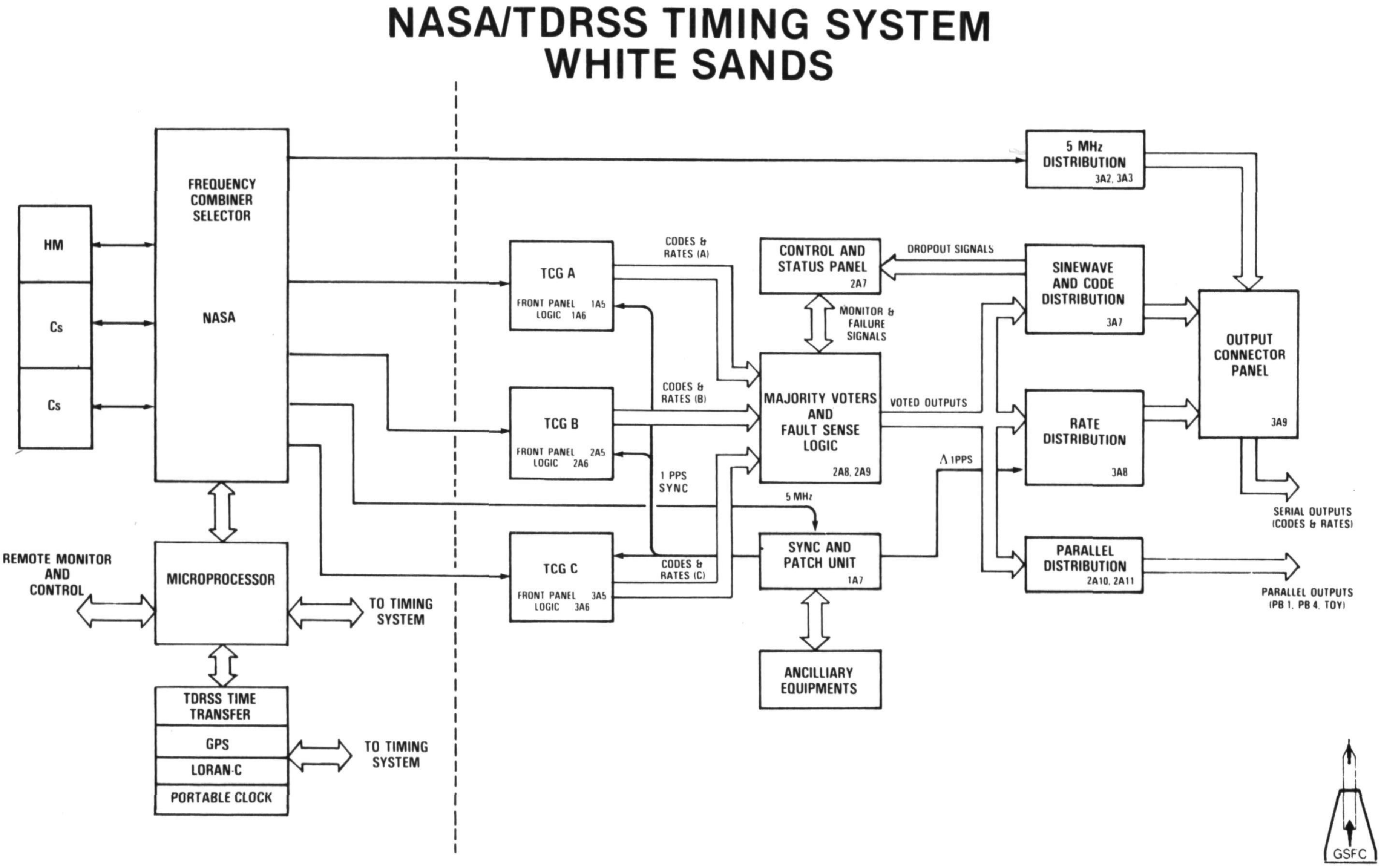


Figure 18. NASA/TDRSS Timing System White Sands

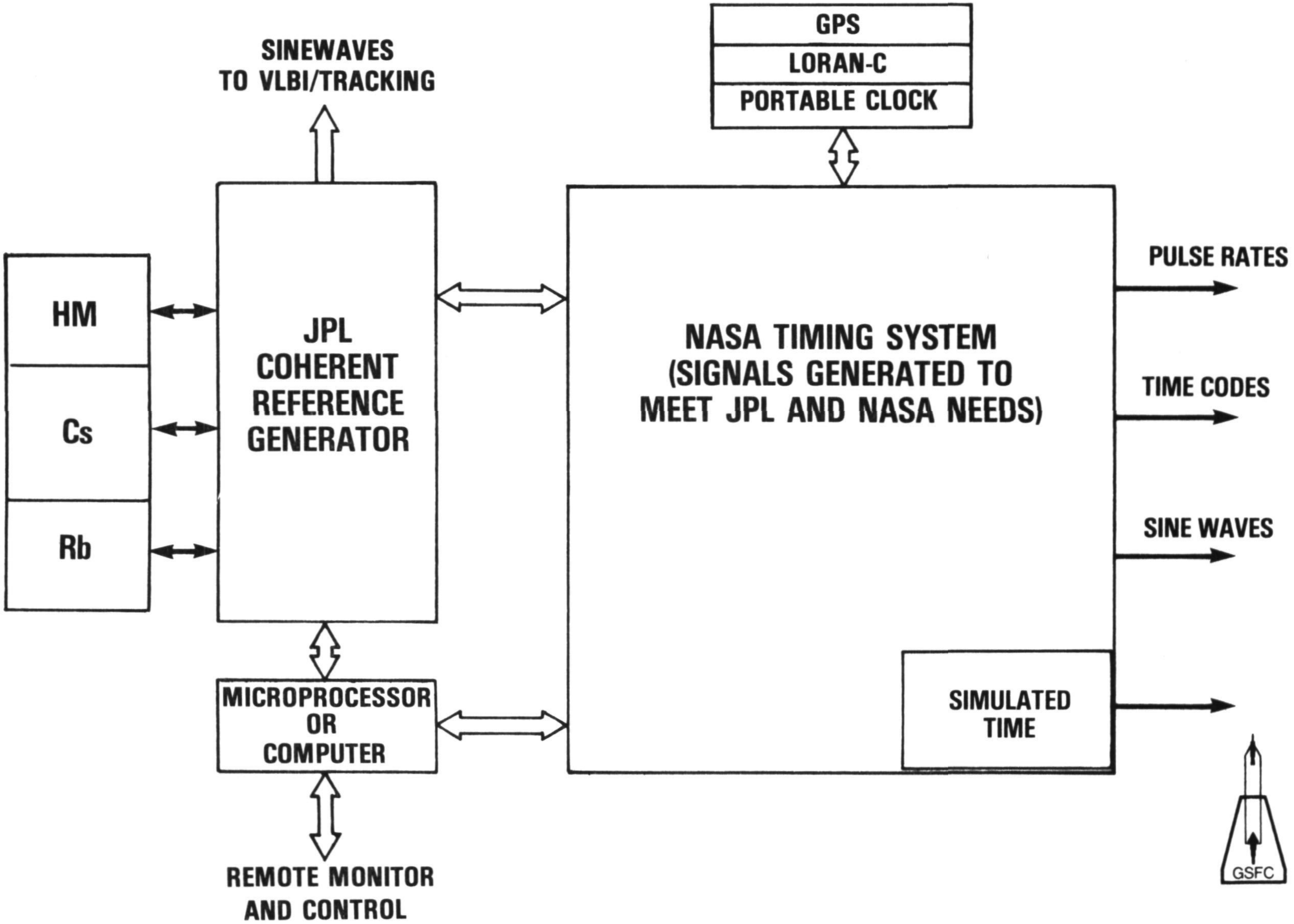


Figure 19. Consolidated Frequency/Timing System for Madrid, Goldstone, and Orroral

LESS THAN 50 NANOSECOND TIME TRANSFER

TDRSS

TRACKING DATA RELAY
SATELLITE SYSTEM

PASSIVE TECHNIQUE

GPS

GLOBAL POSITIONING SYSTEM

ACTIVE TECHNIQUE

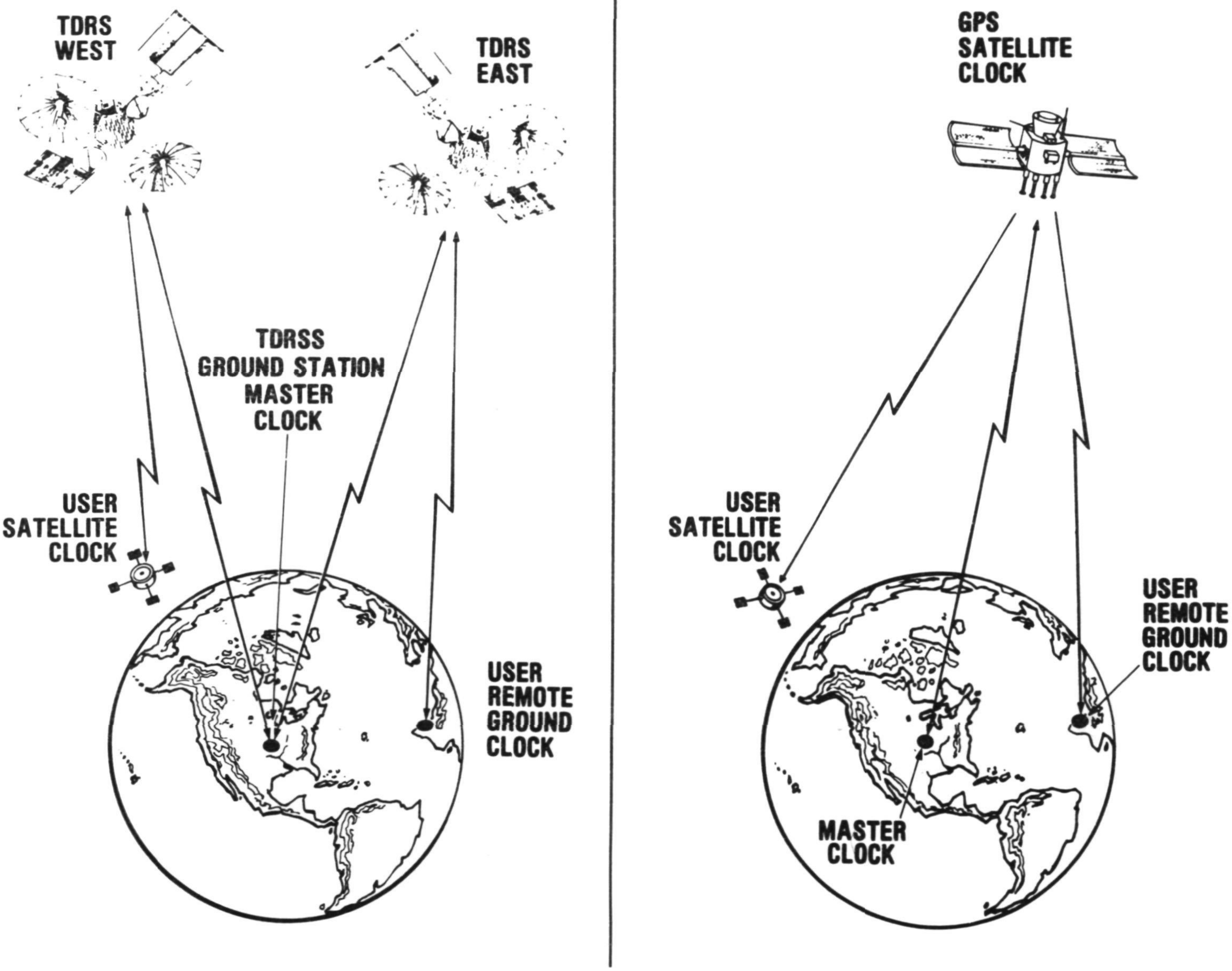


Figure 20. Future Considerations

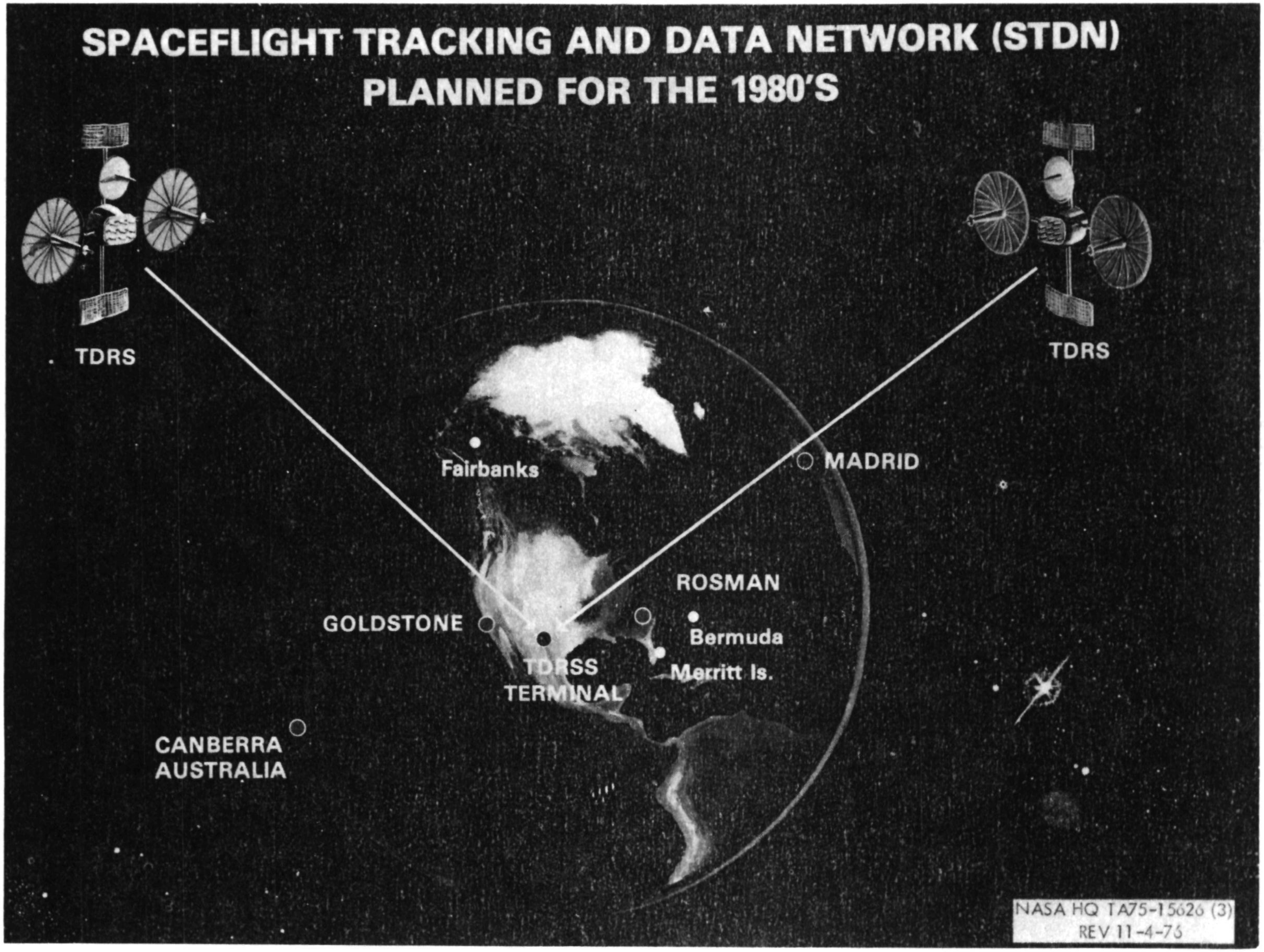


Figure 21. Spaceflight Tracking and Data Network (STDN) Planned for the 1980's

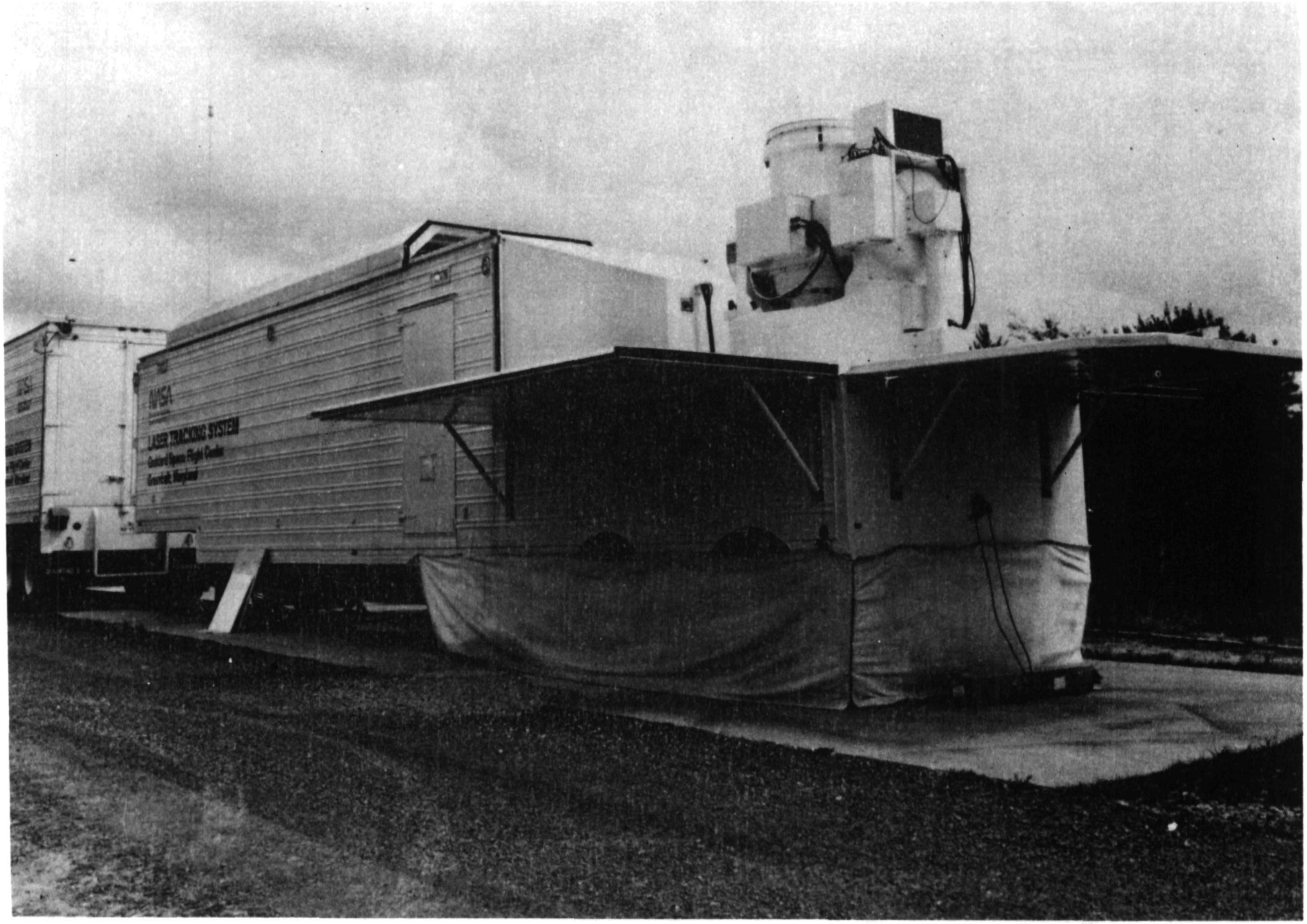


Figure 22. Mobile Laser Van

Figure 23. Kwajalein

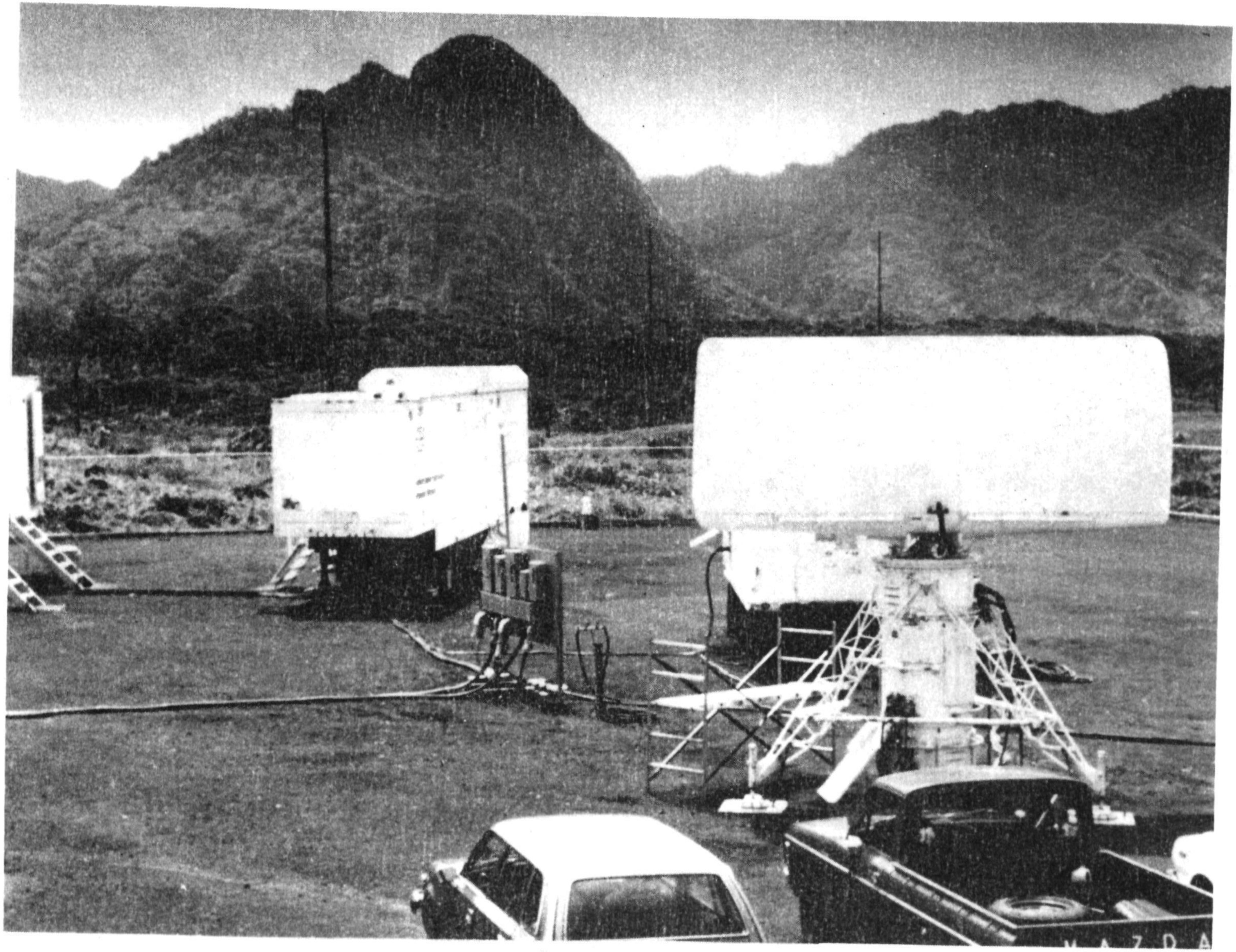


Figure 24. American Samoa

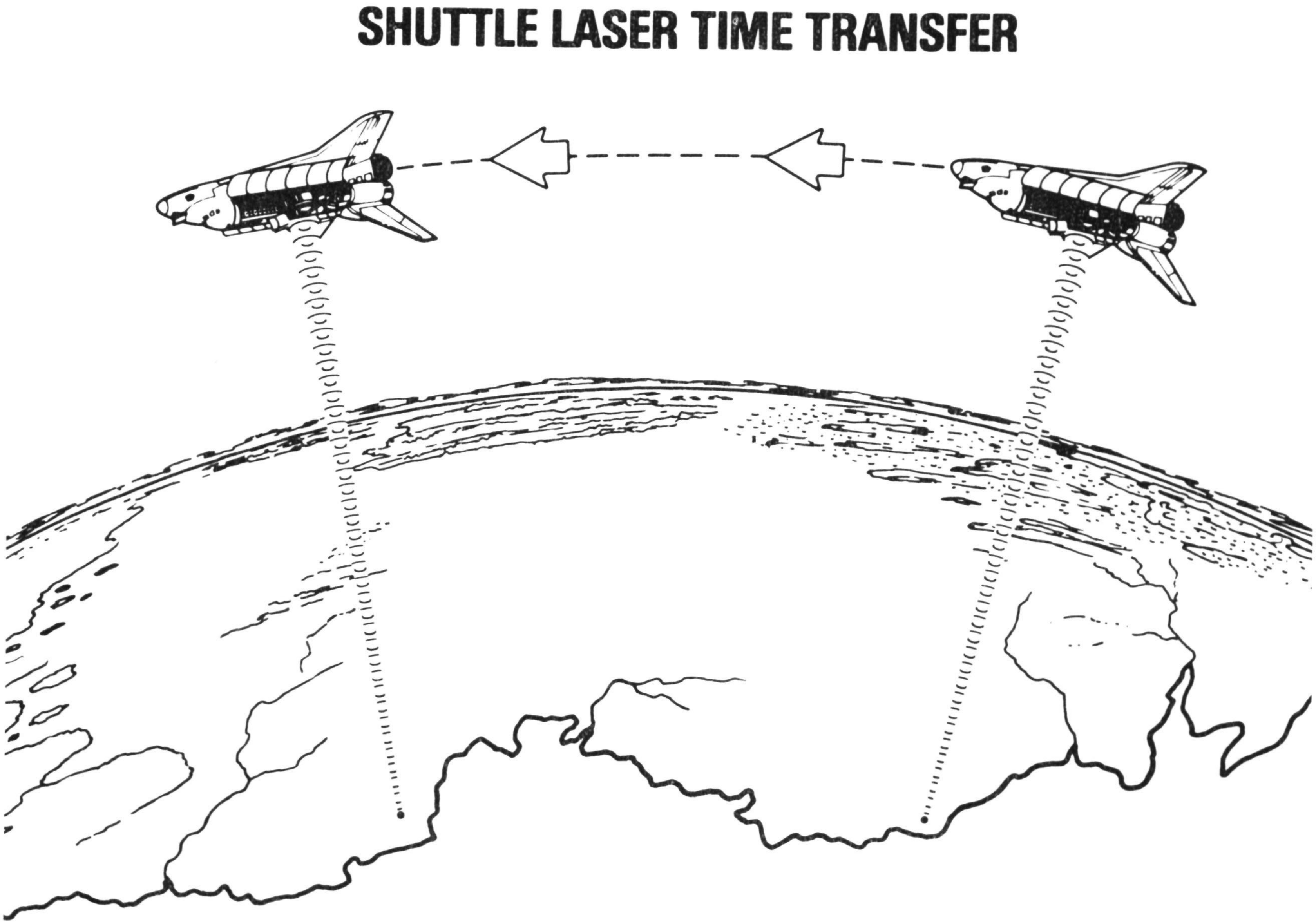


Figure 25. Shuttle Laser Time Transfer

Figure 26. Laser Time Transfer Ground System

U.S./NASA PARTICIPATION IN THE SIRIO-2/LASSO EXPERIMENT FOR COMPARISON OF INTERCONTINENTAL/ INTERNATIONAL ATOMIC CLOCKS AT THE NANOSECOND LEVEL VIA LASER TECHNIQUES.

SIRIO	SATELLILE ITALIANO PER LA RICERCA ORIENTATO (ITALIAN SATELLITE ORIENTED RESEARCH)
LASSO	LASER SYNCHRONIZATION FROM STATIONARY ORBIT

Figure 27. Missions of SIRIO-2

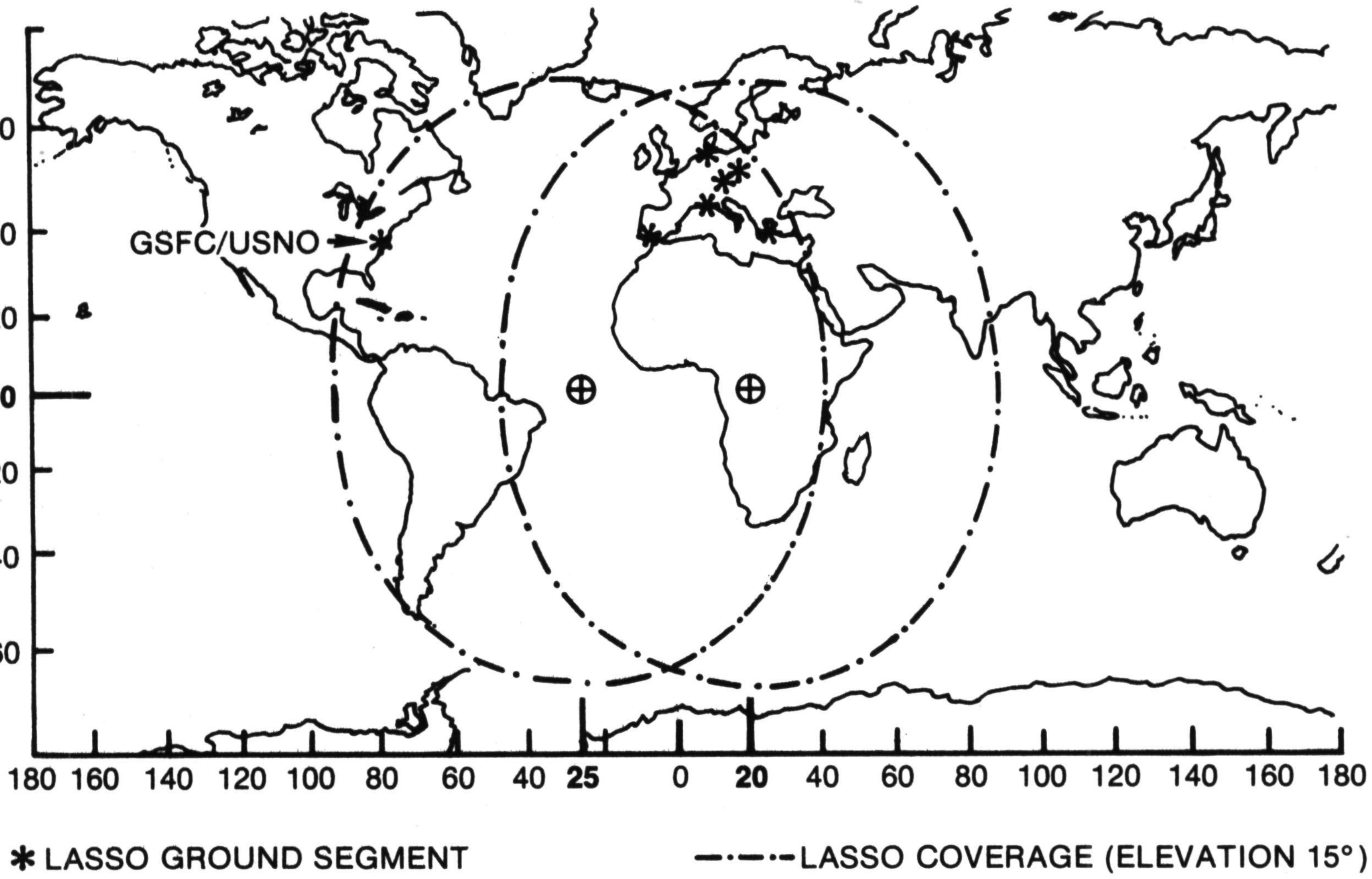


Figure 28. Provisional LASSO Coverage Zones

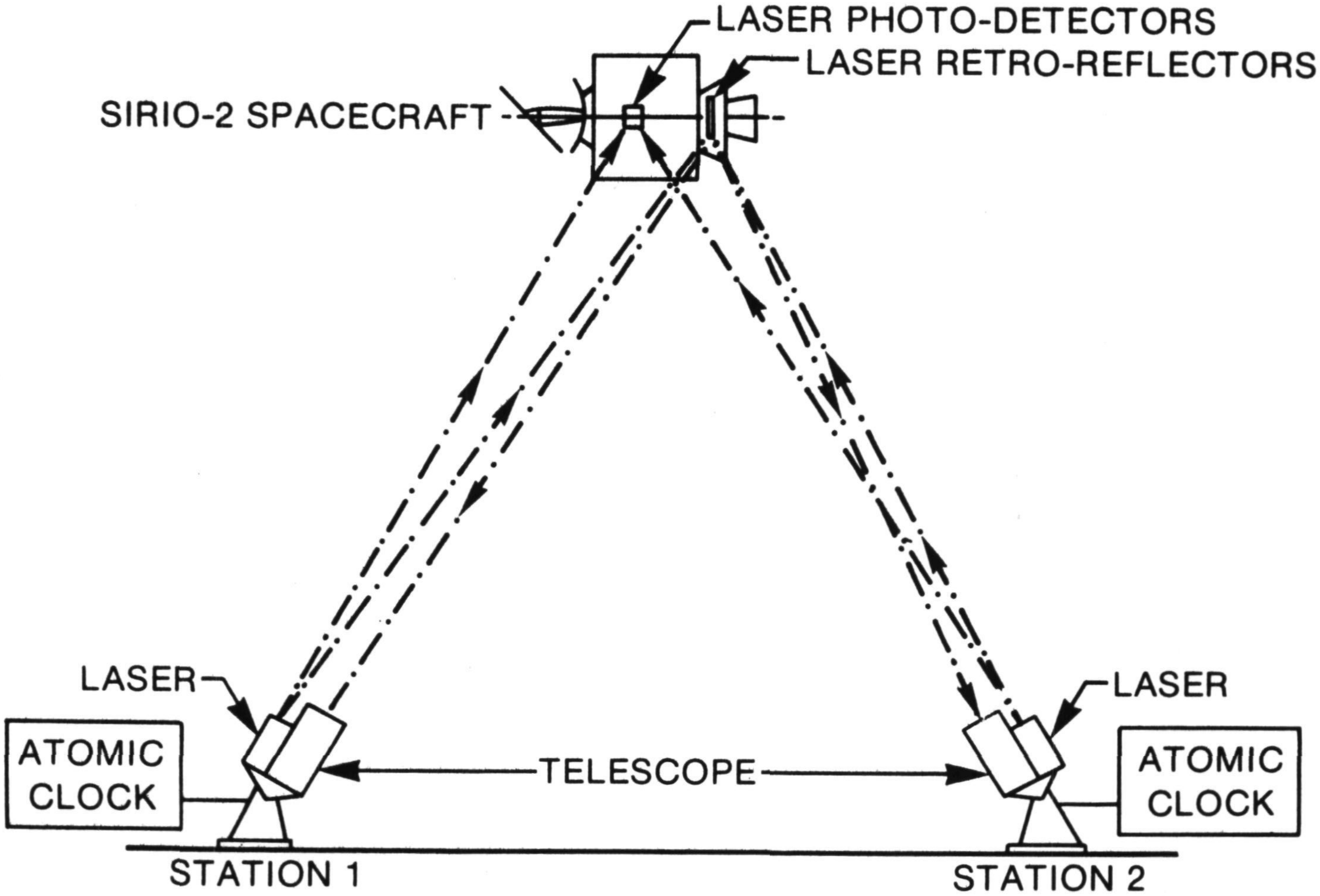


Figure 29. Schematic Diagram of LASSO Experiment

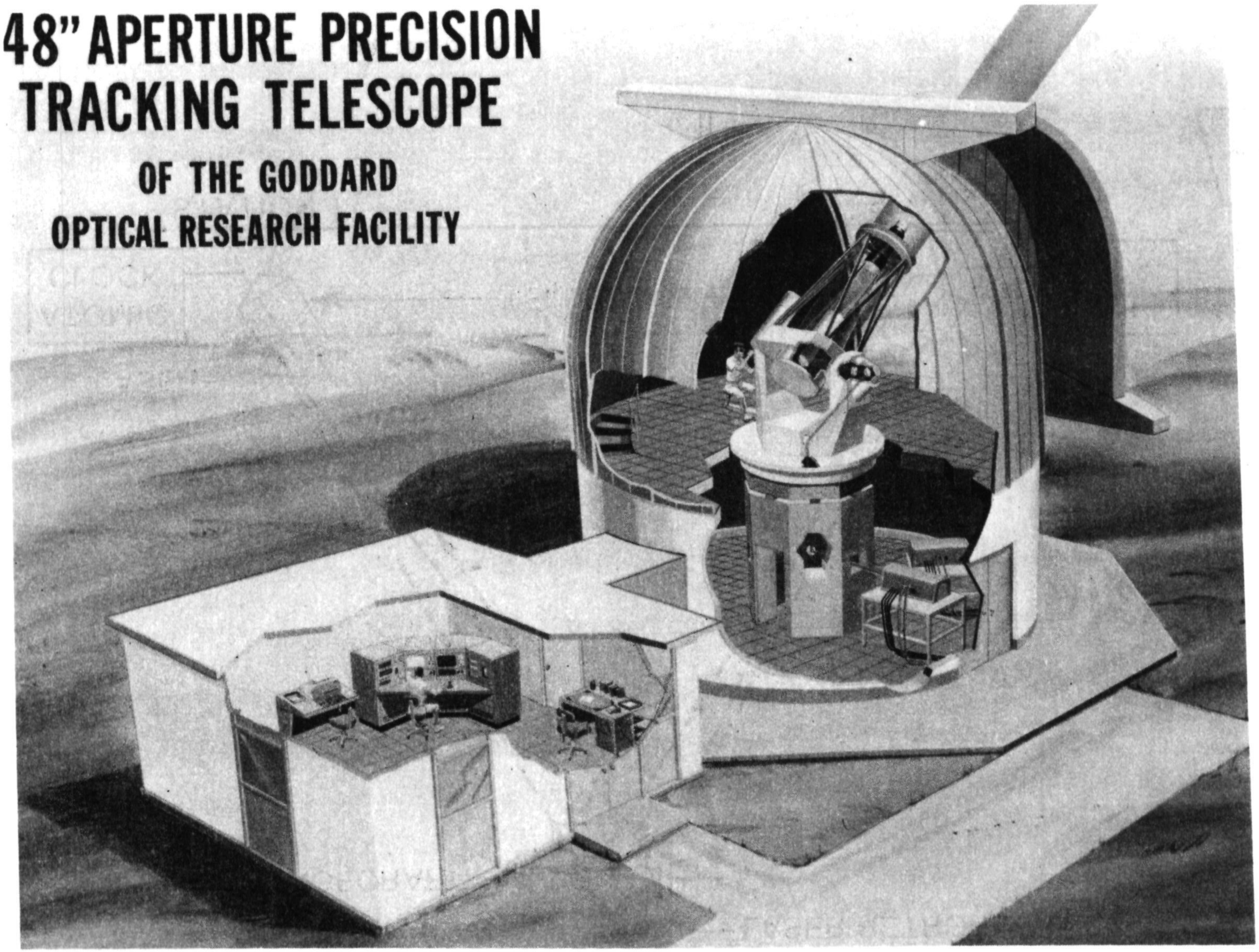


Figure 30. Artist Concept of Laser System at GSFC

HISTORY OF GSFC HYDROGEN MASERS

1967: NX-1, 1ST EXPERIMENTAL
1969: NP, FIELD OPERABLE, BASED ON NX-1
1973: NX-2 & NX-3, EXPERIMENTAL
1981: NR, FIELD OPERABLE, BASED ON NX-2 & NX-3

FUTURE PLANS

1983: IMPROVED NR, FIELD OPERABLE
1984: LOW COST MASER, FIELD OPERABLE
1990: SUPERCONDUCTING CAVITY LOCAL OSCILLATOR

VR028

Figure 31. History and Future Plans of GSFC Hydrogen Masers

SATELLITE TECHNIQUES

DATE	NAME	ACCURACY
1965	*GEOS	40 μs
1970	*ATS	100 ns
1977	NTS	500 ns
1981	*LASSO	1–5 ns
1980's	TDRSS	10–20 ns
1980's	GPS	10–20 ns
1980's	SHUTTLE	10–20 ns
1990's	LASERS	ps

CONVECTIONAL TECHNIQUES

DATE	METHOD	ACCURACY
1950	HF	10 ms
1960's	VLF	100 μs
1965	*DUAL VLF	10 μs
1966	*OMEGA	5 μs
1968	LORAN-C	1 μs–25 μs
1970's	TELEVISION	10 ns
1965	PORTABLE CLOCKS	Sub μs

*EXPERIMENTAL – OTHER TECHNIQUES BECAME OPERATIONAL

Figure 32. Time Transfer Techniques