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Initial Results of the NAVSTAR GPS NTS-2 Satellite

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Navigation Technology Satellite 2 (NTS-2) was successfully launched on June 23, 1977, into a near-12-hour circular orbit. Precise frequency and timing signals are derived from the two cesium frequency standards. This report discusses the launch and preliminary results, which include verification of the relativistic clock effect. An international time-transfer experiment is planned, and a worldwide synchronization accuracy of less than 100 nanoseconds is anticipated, based on preliminary time-transfer results between Cape Kennedy and the U.S. Naval Observatory. A proposed NASA laser-tracking network will be used to verify the accuracy of the Global Positioning System (GPS) orbits.

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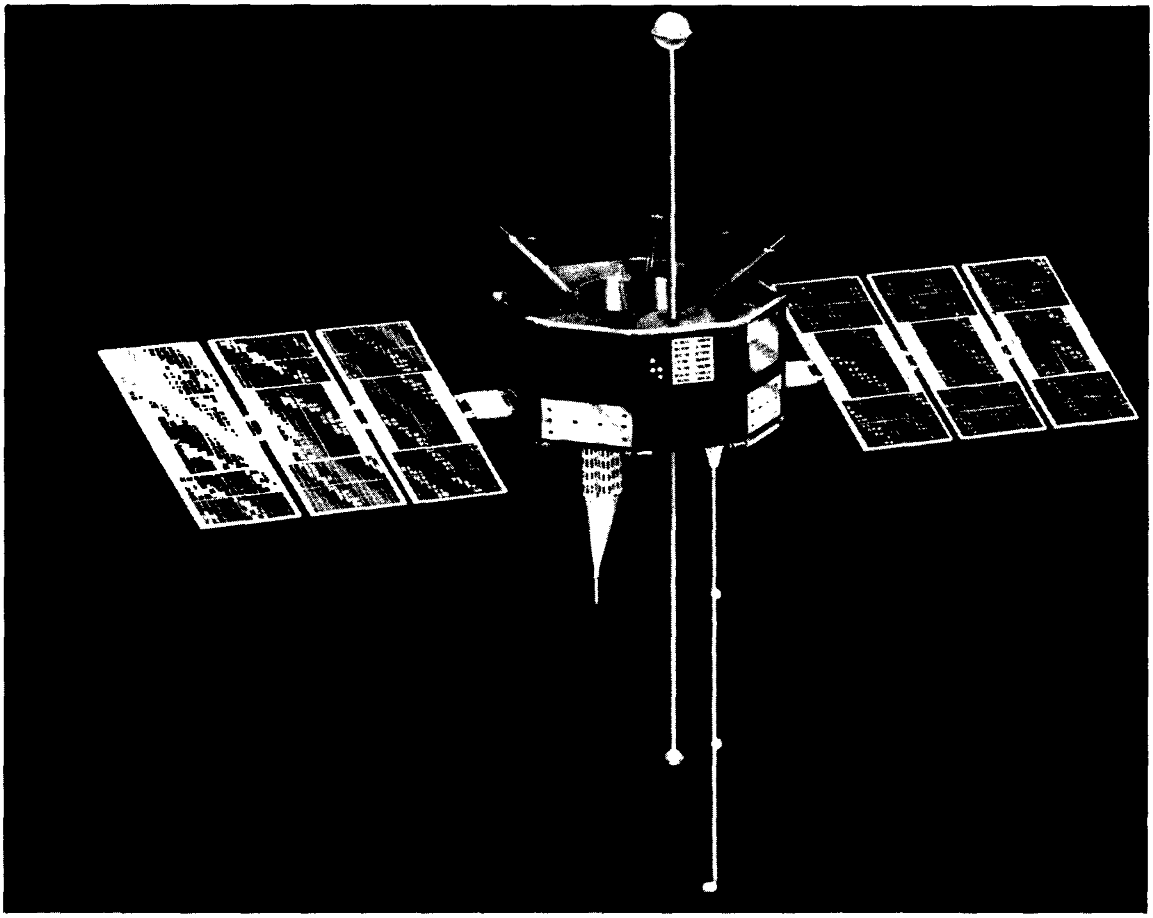

Fig. 1 — NTS-2

INITIAL RESULTS OF THE NAVSTAR GPS NTS-2 SATELLITE

INTRODUCTION

The successful launch of Navigation Technology Satellite 2 (NTS-2) marks the beginning of a new era in navigation and timekeeping history. NTS-2 (Fig. 1) is the first NAVSTAR GPS [1] Phase I satellite, which will provide near-instantaneous navigation and time-synchronization service on a worldwide, continuous basis to the DOD community and a wide variety of commercial users. NTS-2 technological features encompass the world's first orbiting cesium frequency standards, built by Frequency and Time Systems (FTS); a nickel-hydrogen battery, developed by Comsat; three-axis gravity-gradient stabilization with momentum-wheel unloading; control of the spacecraft orbit; and a worldwide network (GE International Time Sharing) for data acquisition. The satellite capabilities include verification of Einstein's relativistic clock shift and a time-interval measurement precision of 3 nanoseconds.

NTS-2 is also the fourth in a series of NRL technology satellites (Table 1) which have carried quartz [2], rubidium [3], and cesium [4] oscillators into orbit. The NTS-3 spacecraft, now under development at NRL, is scheduled to carry the first orbiting hydrogen-maser [5] frequency standard(s). The primary data type for all of the technology satellites has been precise time-difference measurements, which have been used for time transfer [6], navigation [7,8], and orbit determination.

GPS LAUNCH PROCEDURE

The GPS launch procedure (Fig. 2) requires that the spacecraft be inserted into a pre-assigned position in the GPS constellation, by first launching it into a high-eccentricity transfer orbit (Fig. 3) and then kicking it into a low-eccentricity drift orbit (Fig. 4) and waiting until it drifts into position for final constellation placement. A set of orbital values and tolerances was specified; the most critical tolerance was for the orbital period, which was required to be within an accuracy of 1 second of the specified value of 717.973 minutes (nearly 12 sidereal hours).

The NRL-built spacecraft was launched into the transfer orbit from Vandenburg Air Force Base on June 23, 1977, at 0817UTC. First acquisition of signal was made by the NTS tracking station in Panama. NTS-2 was then acquired and tracked from Blossom Point, Md. Calculations of measurement residuals indicated a nominal transfer orbit. The scheduled apogee-kick-motor (AKM) burn at the first apogee was deferred in order to allow processing of measurements from the launch tracking network (Table 2), consisting of two of the NTS tracking stations (Panama and Chesapeake Bay, Md.) complemented by Blossom Point, Md., Millstone, Mass., Sugar Grove, W.Va., and the Range Measurements Laboratory, Patrick AFB, Fla. The tracking network is coordinated by the NRL control center (NRLCC), which

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Table 1 — NRL Technology Satellites

Satellite	Launch Date	Altitude (n.mi.)	Inclination (deg)	Eccentricity	Weight (kg)	Weight (lb)	Power (W)	Frequency	Oscillator	$\Delta f/f$ per day (pp 10^{13})	Range Error (m/day)
T-I	5-31-67	500	70	0.0008	40	85	6	UHF	Qtz	300	750
T-II	8-30-69	500	70	0.002	55	125	18	VHF/UHF	Qtz	100	75
T-III or NTS-1	7-14-74	7,400	125	0.007	295	650	100	UHF/L band	Qtz/Rb	5-10	12-24
NTS-2	6-23-77	10,900	63	0.0004	430	950	445*	UHF/L, L_1, L_2	Qtz/Cs	2	5
NTS-3	1981	10,900	63	0.001	490	1080	475*	UHF/L, L_1, L_2	Qtz/H_2	0.1	0.25

*Beginning of life.

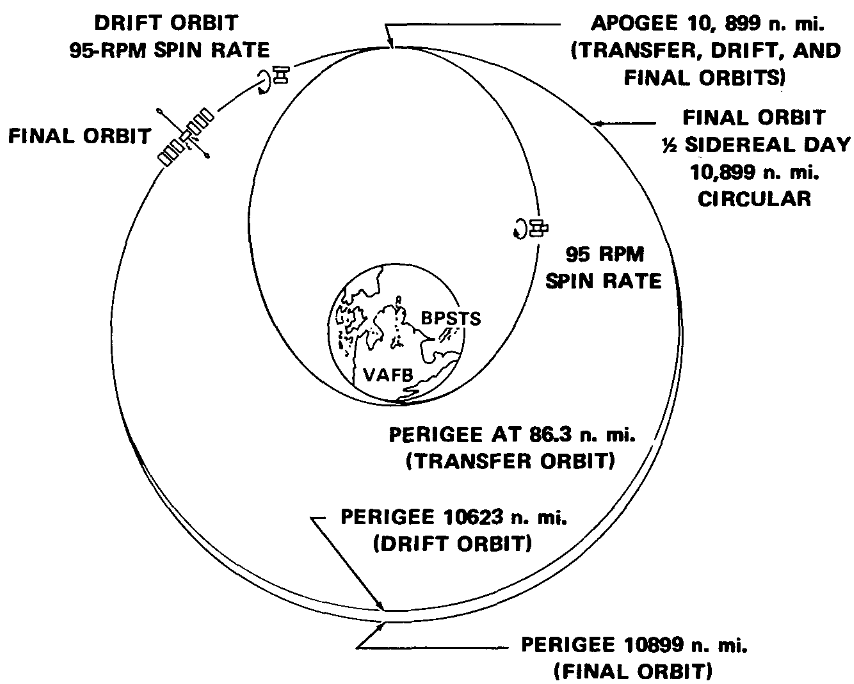

Fig. 2 — Launch sequence of the NTS-2

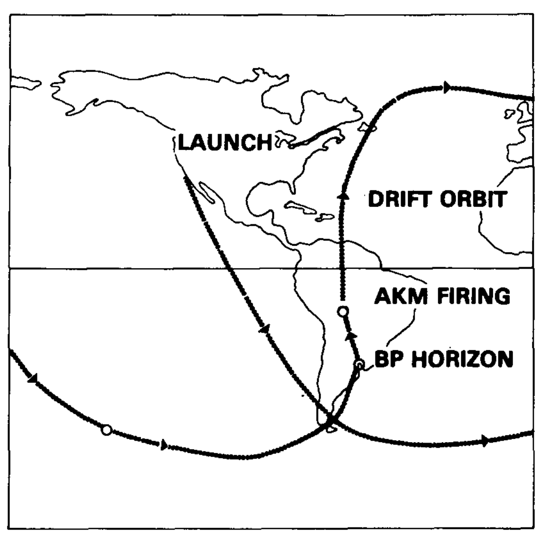

Fig. 3 — Scheduled apogee-kick-motor firing at the first apogee of the transfer orbit to insert the NTS-2 into the drift orbit. The AKM was actually fired at the sixth apogee.

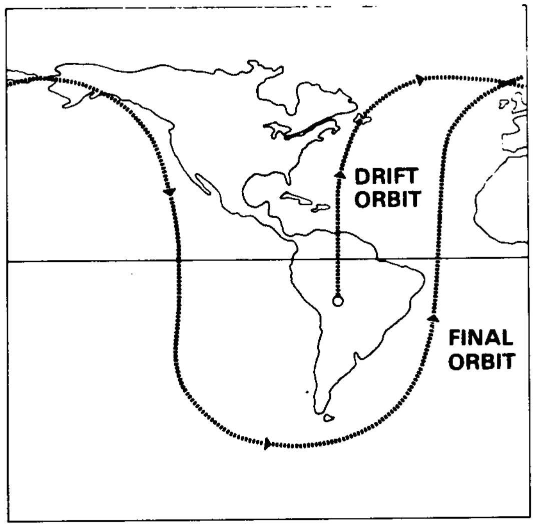

Fig. 4 — Scheduled NTS-2 drift orbit and, after drift and adjustments, final orbit

Table 2 — Network for Tracking the NTS-2 Launch to Achieve a Period Accurate Within 1 Second

Data Type	Station	Location	Antenna Aperture (m)
Azimuth and elevation	Blossom Point	Md.	6
	Sugar Grove	W. Va.	45
	Range Measurements Lab.	Fla.	15 (optically)
Range and doppler	Blossom Point	Md.	6
	Sugar Grove	W. Va.	45
	Chesapeake Bay Div. (NRL)	Md.	1.2
	Panama	C. Z.	1.2
Radar range	Millstone	Mass.	26

has links (Fig. 5) to the GPS master control station. Transfer-orbit solutions using measurements from the launch tracking network were independently made by Bendix personnel at Blossom Point, Md., personnel at the Range Measurements Laboratory at Patrick AFB, and Millstone Radar personnel. A merged orbit solution [9] was performed by the Naval Surface Weapons Center (NSWC), which was compared with the independent solutions using various data subsets. The AKM burn was performed at the sixth apogee, which resulted in a near-circular drift orbit.

The prelaunch drift-orbit profile (Fig. 6) was chosen to allow the ascending node of NTS-2 to drift eastward at a nominal value of 5 deg/day. The actual drift orbit (Fig. 7) had a larger drift rate than expected, resulting in NTS-2 reaching its preassigned position in the constellation of 28 ± 2 degrees west longitude in 5 days. Three velocity increments (Fig. 7)

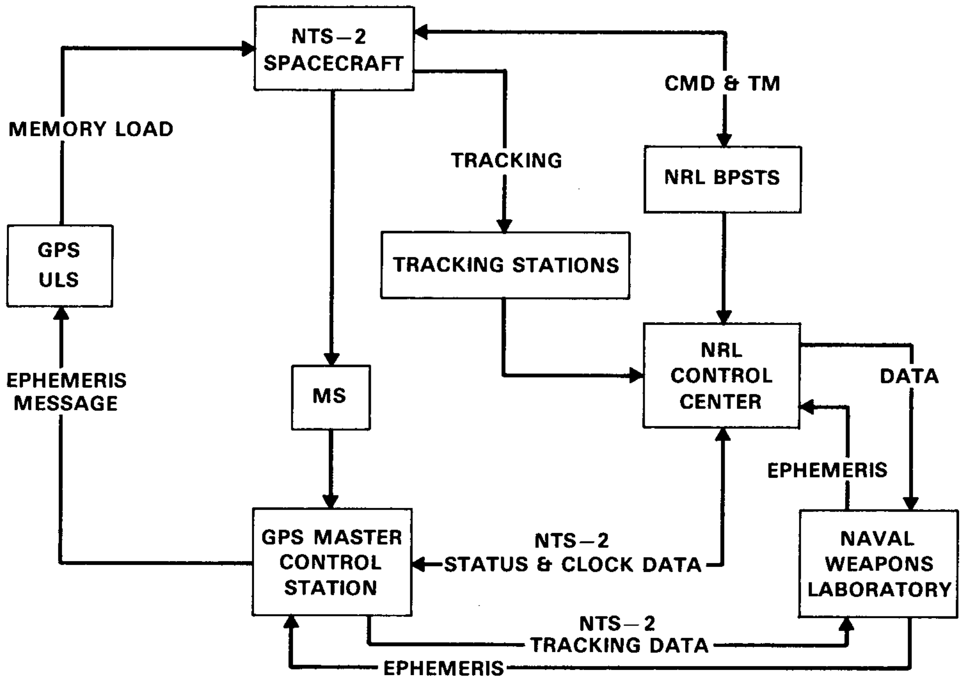

Fig. 5 — NTS-2 command and telemetry links

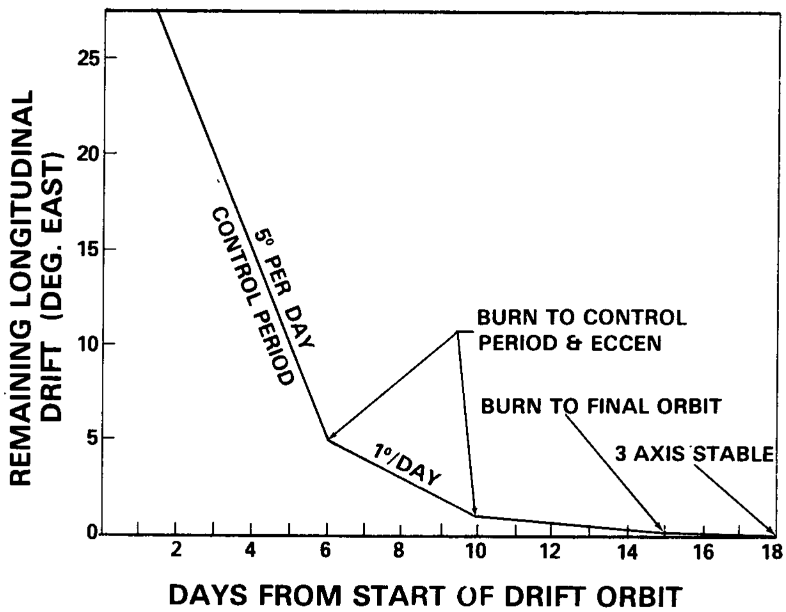

Fig. 6 — Prelaunch NTS-2 drift-orbit profile

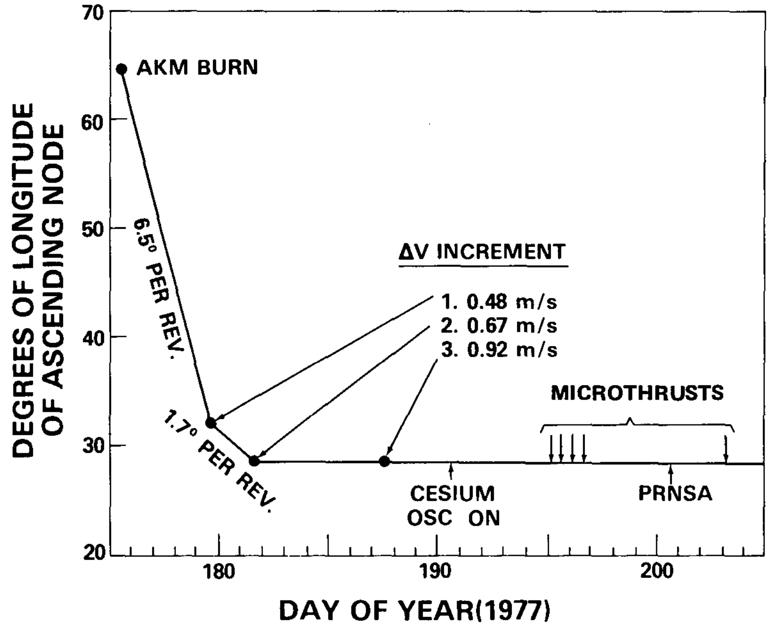

Fig. 7 — Actual NTS-2 drift-orbit adjustments

ranging from about 0.5 to 1 meter per second were used to increase the spacecraft period. The final orbit, excepting small microthrusts, was achieved 15 days after launch. Three-axis gravity-gradient stabilization and solar-panel deployment was achieved within 18 days after launch.

The final drift orbit of NTS-2 in the GPS Phase I constellation is given by Fig. 8. The locations shown for the five Navigation Demonstration System satellites are possible positions; the final satellite positions will be determined later.

NTS-2 follows a constant-ground-track orbit with an inclination of 63 degrees. Occasional orbital maneuvers of the spacecraft are performed, as necessary, to maintain the ascending node within the GPS specifications. Table 3 presents a summary of four of the NTS-2 orbital parameters as a function of time, following adjustments, and the associated GPS specifications.

NTS-2 TRACKING NETWORK

The NTS-2 tracking network (Table 4) consists of U.S. stations in Chesapeake Beach, Md. (CBD), and in the Panama Canal Zone (PMA) and of overseas stations at the Royal Greenwich Observatory in England (RGO) and at the Lunar Laser site in Australia (AUS). United States stations are operated by Bendix Field Engineering; the overseas sites are operated by personnel from England and Australia, all under the direction of NRLCC. The NTS-2 measurements are used by these cooperating countries for time comparison with the U.S. Naval Observatory (USNO), for independent orbit determination, and for polar motion studies. The network provides almost complete tracking coverage of NTS-2; Figs. 9 through 12 depict the portions of the NTS-2 orbit when the spacecraft is above the horizon from PMA, RGO, AUS, and CBD respectively. Figure 13 shows that only a small segment of the

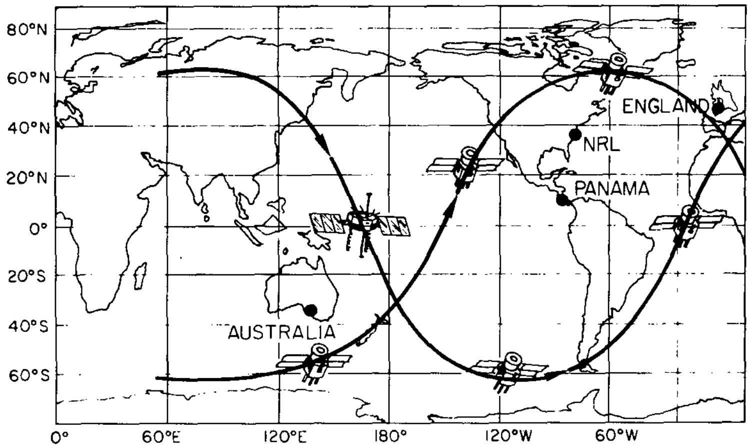

Fig. 8 — NAVSTAR GPS Phase I orbit traces. The Phase I constellation consists of the NTS-2 and five Navigation Demonstration Satellites.

Table 3 — NTS-2 Orbital Parameters

Day (1977)	Period (min)	Eccentricity	Inclination (deg)	Longitude of Ascending Node (deg W)
177*	704.9	0.012	63.4	—
180*	714.5	0.002	63.4	—
184*	717.94	0.0003	63.3	28.48
192*	718.04	0.0004	63.3	—
202*	717.984	0.0004	63.3	28.80
230**	717.967	0.0002	63.4	—
273**	717.956	0.00032	63.43	28.35
295	717.946	0.00034	63.44	28.10
GPS Specifications				
—	717.973	⩽0.003	63 ± 0.67	28 ± 2

*Orbit adjusted.
**Orbit adjusted by microthrust.

Table 4 — NTS-2 Tracking Network

Station Location	Operator	Station Abbreviation
CBD, Md.	Bendix	CBD
Panama, C. Z.	Bendix	PMA
Lunar Laser site*, Australia	Australian personnel	AUS
Royal Greenwich Obs., England	British personnel	RGO

*A site of the Division of National Mapping.

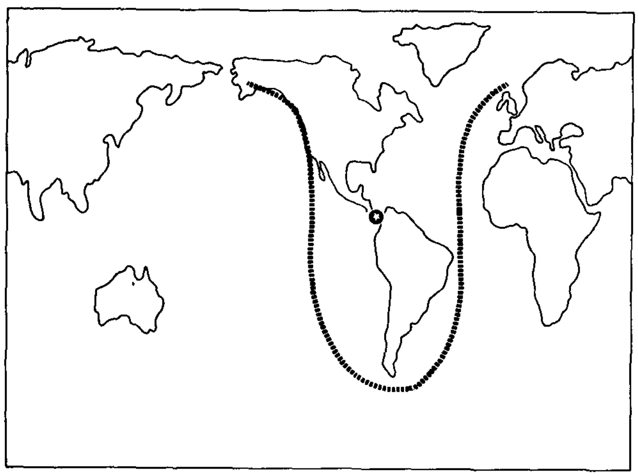

Fig. 9 — Panama NTS-2 coverage

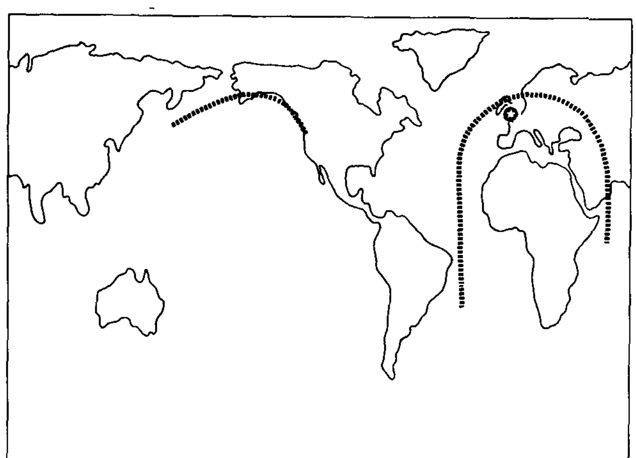

Fig. 10 — Royal Greenwich Observatory NTS-2 coverage

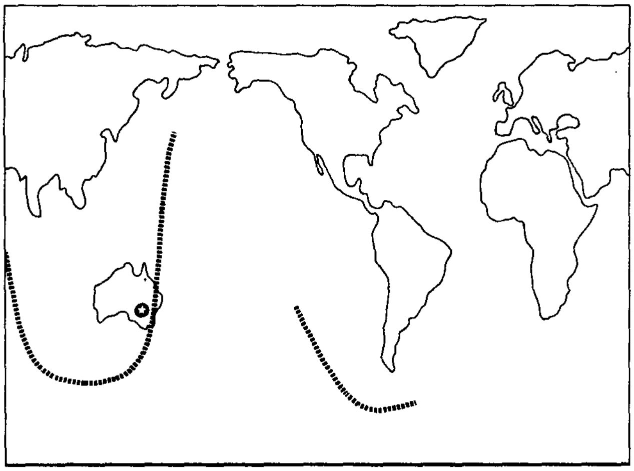

Fig. 11 — Australia NTS-2 coverage

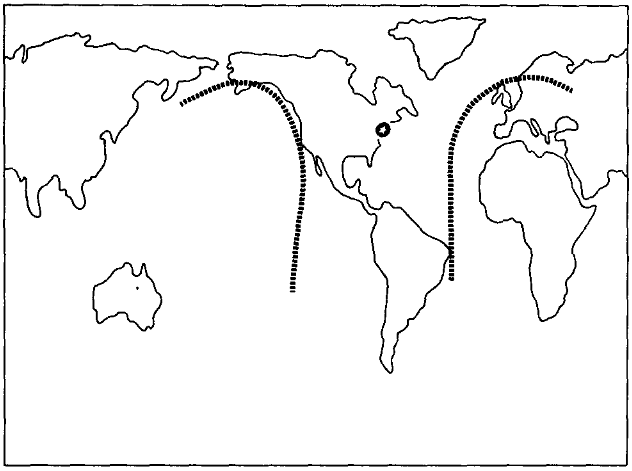

Fig. 12 — Chesapeake Bay Division NTS-2 coverage

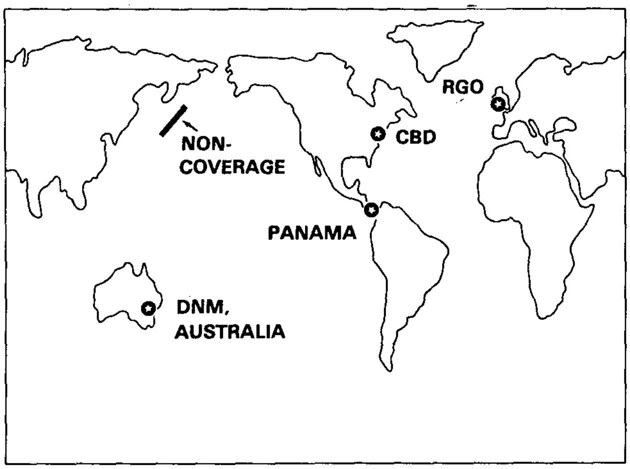

Fig. 13 — Noncoverage of the NTS-2 orbit

NTS-2 orbit is not observable by the NTS network. Noteworthy is the coverage obtained from Panama (Fig. 9); NTS-2 is tracked for one complete revolution every day, thus allowing for immediate analysis of any cesium frequency adjustment performed by NRLCC. Each of these stations has at least three cesium standards whose offsets (independent of NTS-2) are related to USNO master clock 1 by timing links as follows:

- CBD:
  —Three cesium standards,
  —TV (daily),
  —Portable clock trip to USNO (once per week);

- Panama:
  —Three cesium standards,
  —Portable clock (once per year);

- Australia:
  —Five cesium standards,
  —Portable clock (twice per year);

- England:
  —Three cesium standards,
  —Loran C,
  —Portable clock (twice per year).

PRECISE TIME AND FREQUENCY TRANSMISSIONS

Precise frequency signals for NTS-2 transmissions are obtained from one of the two spacecraft-qualified [4] cesium frequency standards built by FTS. Each cesium standard may also be operated in a quartz oscillator mode, which requires less power. The reduced-power, quartz-only mode was used for the first 15 days after NTS-2 launch, while the nickel-hydrogen battery was the sole power source. The cesium standard was locked following solar-panel deployment, which allowed full power operation.

NTS-2 timing information is continuously transmitted in two modes: a side-tone ranging system, called the Orbit Determination and Tracking System (ODATS), and a Psuedo Random Noise Subsystem Assembly (PRNSA). The PRNSA was activated on day 200 (Fig. 7). Time-difference measurements between the spacecraft clock and ground-station clocks are made through special receivers [10,11] which measure time difference by comparing a waveform similar to that transmitted by the spacecraft. These measurements are then used to determine the spacecraft orbit, clock difference [12], frequency difference, and other parameters associated with GPS operation.

FREQUENCY DETERMINATION

GPS requirements for the NTS-2 mission called for cesium-controlled frequency operation after full power was available, following solar-panel deployment. The first FTS cesium standard to be used, designated as PRO-5, was locked up (Fig. 14) on the first attempt on day 190, 1977, at 1418 UTC following a VCXO frequency tune to bring the PRO-5 quartz

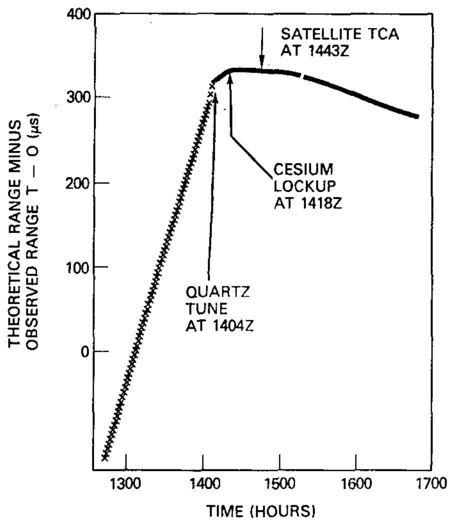

Fig. 14 — Lockup of the cesium frequency standard on day 190, 1977. The (T - O) values measure the offset of the spacecraft clock with respect to the clock at the Panama station.

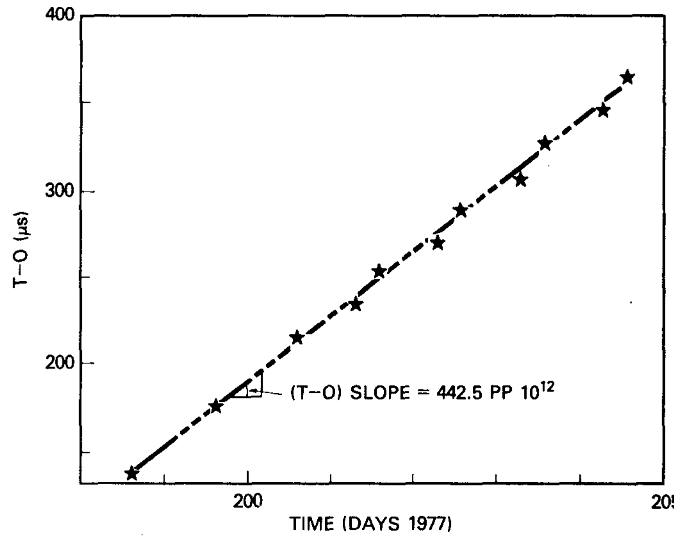

Fig. 15 — Shift in the cesium frequency offset, which is close in value to Einstein's theoretical relativistic frequency shift of 445.0 pp 10^{12}

oscillator frequency close to the cesium resonance frequency. Figure 14 presents the values of the theoretical range minus the observed range (T - O) [13], which are calculated from measurements collected at a 1-minute interval from the Panama site. These (T - O) values yield a measure of the spacecraft clock offset with respect to the Panama clock. Knowledge of the station clock offset with respect to the USNO master clock (MC) permits the spacecraft to be referenced to USNO. Figure 15 presents a plot of (T - O) values [13] from Panama over a 6-day span. The (T - O) slope gives the frequency offset of +442.5 pp 10^{12} with respect to the Panama clock. Inclusion of the Panama frequency offset of +0.6 pp 10^{12} produces an NTS measured value of +443.1 pp 10^{12}. Comparison of this value to the predicted value of the relativistic offset of +445.0 pp 10^{12} gives a difference of -1.9 pp 10^{12}. On day 215, 1977, the NTS-2 PRO-5 output signal was offset (Fig. 16) through the use of a frequency synthesizer [4]. Closer frequency synchronization to the UTC rate is obtainable by use of cesium C-field tuning, which provides a resolution of 1.3 pp 10^{13}. Before the C-field tune was applied, the NTS-2 frequency offset was redetermined using the NRL Chesapeake Bay Division (CBD) station. Figure 17 presents a plot of UTC(USNO MC No. 1) minus UTC(CBD), where CBD denotes the clock used for the CBD receiver. The slope of this line yields a frequency offset of 18.0 pp 10^{13}. Figure 18 represents a plot of NTS - CBD; a frequency offset of 10.1 pp 10^{13} was measured. Combining these results (Table 5) produced a frequency offset of +7.9 pp 10^{13}. On day 287, 1977 (14 Oct.), a C-field tune of six bits was applied. Figure 19 is a plot of the (T - O) values after the C-field tune; a resultant frequency of -6.6 pp 10^{13} was measured. The net measured change was (-10.1 - (-24.6)) pp 10^{13}, or 14.5 pp 10^{13}, which exceeded the expected value of 7.8 pp 10^{13} by 6.7 pp 10^{13}. Table 6 presents the preliminary results of the C-field tune, the cause of the small differences are being investigated. A frequency history of NTS-2 since launch is presented by Fig. 20; a split logarithmic scale is used so that positive and negative values of frequency offset with respect to UTC(USNO) may be included over a large range.

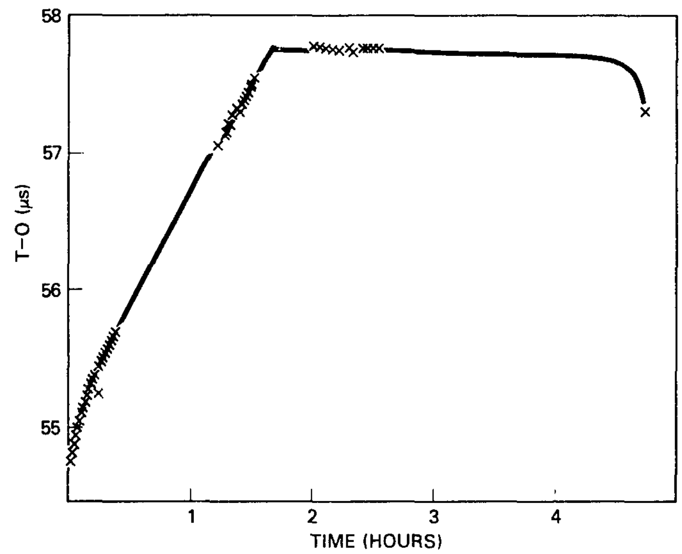

Fig. 16 — Effect of relativity correction, on day 215, 1977, as measured with respect to the Chesapeake Bay Division (CBD) clock

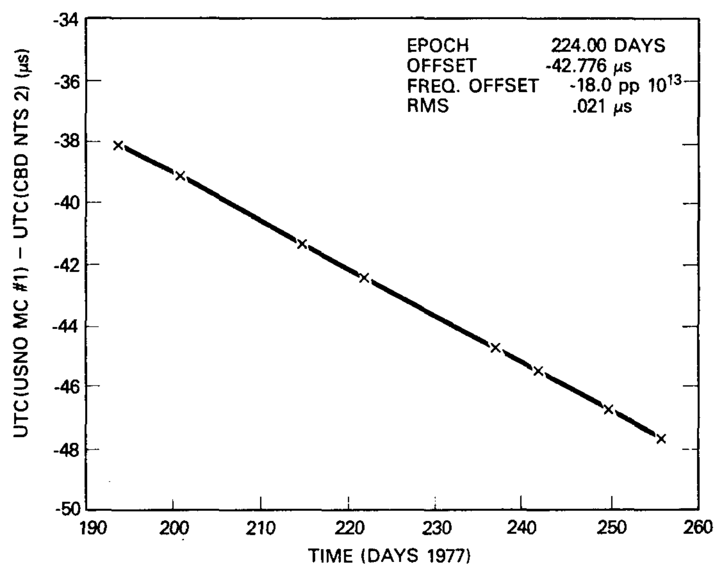

Fig. 17 — Frequency offset determined by the clock rate between the CBD clock and the USNO clock: USNO - CBD

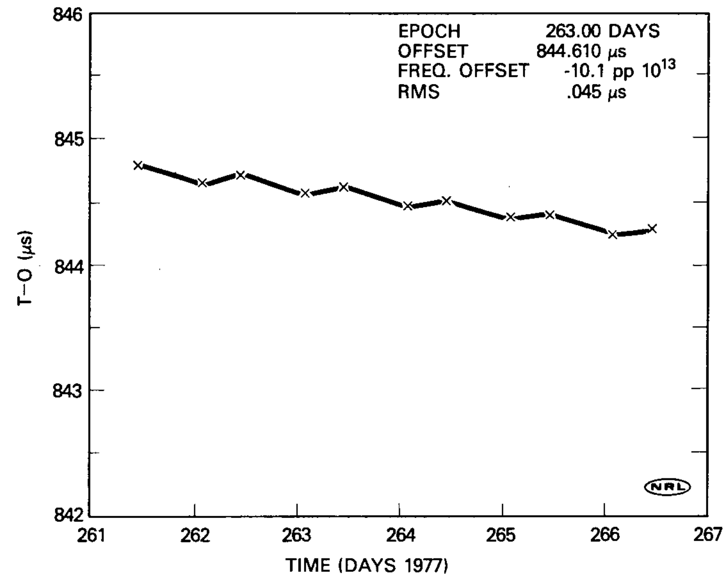

Fig. 18 — Frequency offset determined by the clock rate between the NTS-2 clock and the CBD clock: NTS - CBD

Table 5 — NTS-2 Cesium-Oscillator C-field Adjustment

CBD — USNO(MC 1) via portable clock trips = 18.0 pp 10^{13} (Fig. 12).
CBD — NTS-2 via satellite range observations = 10.1 pp 10^{13} (Fig. 13).
Difference of the two determinations above is NTS-2 — USNO(MC 1) = 7.9 pp 10^{13}.
Six-bit adjustment of the C field, applied on day 287 (Oct. 14, 1977) was 7.8 pp 10^{13}.

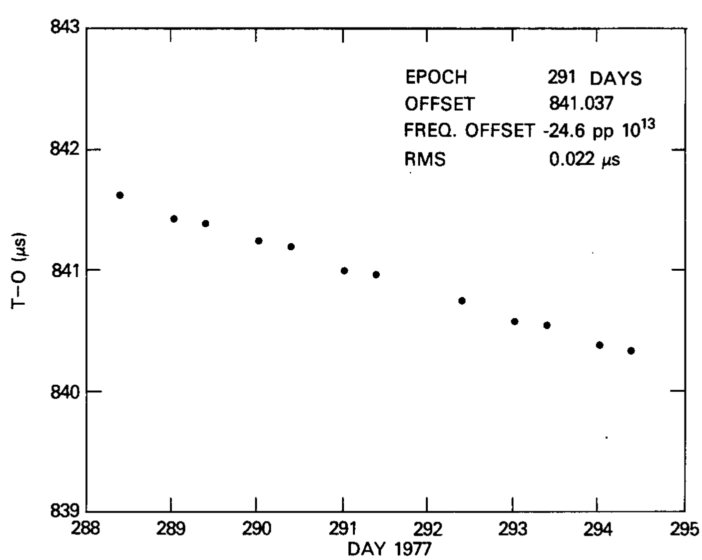

Fig. 19 — Frequency offset determined by the clock rate between the NTS-2 clock and the CBD clock (NTS - CBD)

Table 6 — Preliminary Results (Nov. 10, 1977) of the NTS-2 C-field Adjustment

Preliminary measurement: NTS-2 — USNO(MC 1) = -6.6 pp 10^{13}.	
Being investigated:	value of bit change, telemetry bit insertion, frequency determination, and USNO(MC 1) uncertainty.

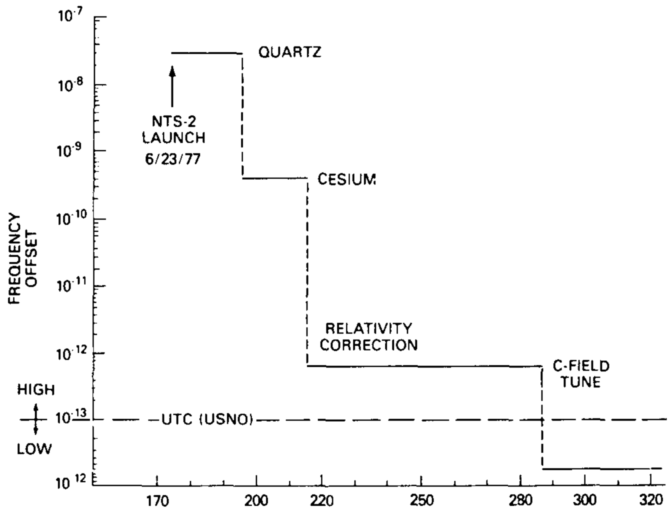

Fig. 20 — History of the NTS-2 frequency offset

TIME TRANSFER

Preliminary time-transfer results have also been obtained. Figure 21 depicts the technique and the links which are used to relate a time difference, measured with respect to the satellite clock back to UTC(USNO). The time-transfer results are of interest to the precise time and time interval (PTTI) community but also are significant for the GPS community, because four simultaneous time transfers measured between a user and four GPS satellites form the basis of a GPS navigation and time synchronization.

Figure 22 presents NTS-1 time-transfer results between the NASA station at Cape Kennedy and USNO via the CBD-ground-station link to USNO. The results in Fig. 23 present time-transfer results using identical ground-station equipment but with measurement obtained from the NTS-2 spacecraft; these results are obtained with a single-channel 335-MHz receiver [14] and are not corrected for ionospheric delay.

A NASA laser orbit-verification network will use receivers such as used at the Cape Kennedy station and will consist of (STALAS) Goddard, (RAMLAS) Patrick AFB, and (MOBALAS) Haystack, Owens Valley, Goldstone, and five additional sites.

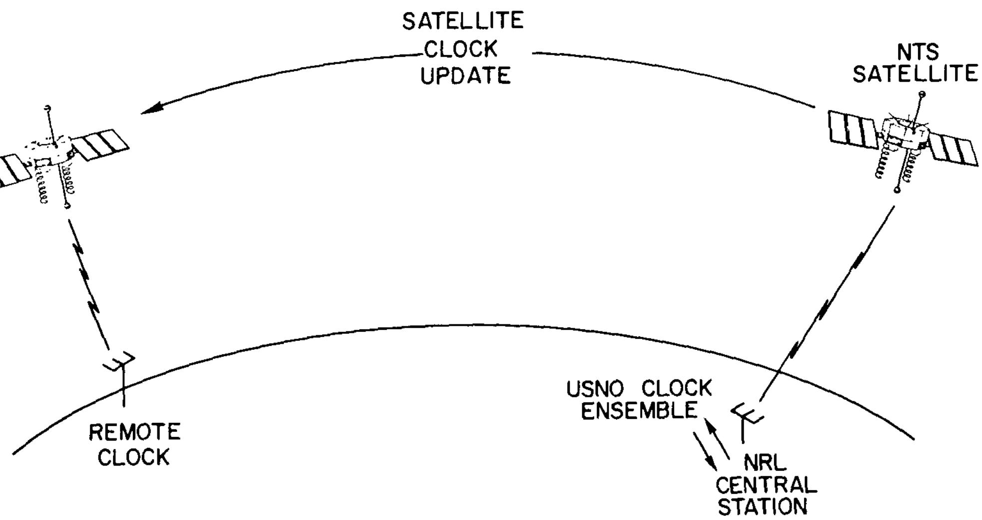

Fig. 21 — Technique of time transfer by the navigation-technology segment of the NAVSTAR GPS

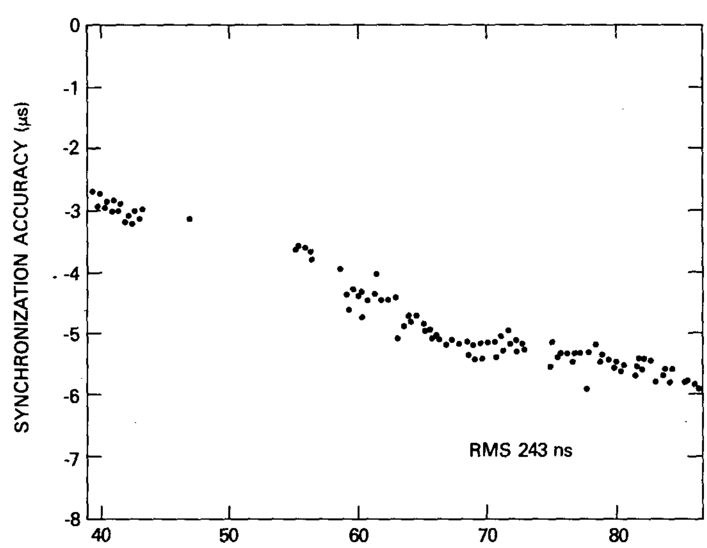

Fig. 22 — NTS-1 time transfer between the NASA Cape Kennedy station and USNO

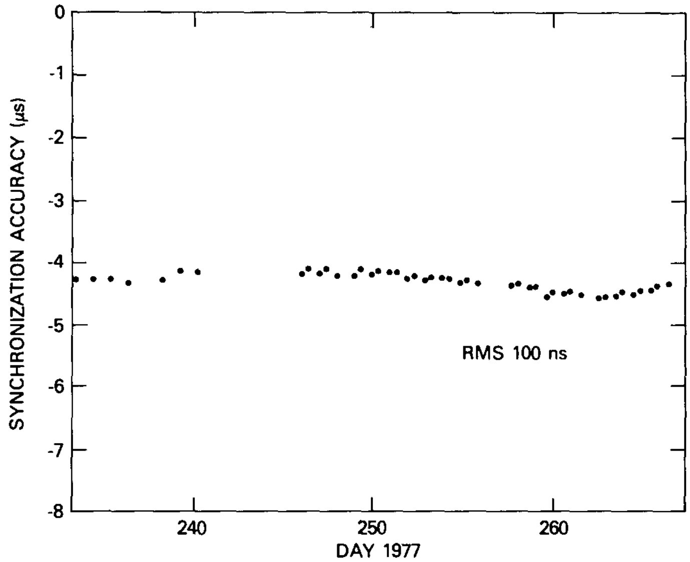

Fig. 23 — NTS-2 time transfer between the NASA Cape Kennedy station and USNO

INTERNATIONAL TIME-TRANSFER EXPERIMENT

As a result of the encouraging time-transfer results, an international time-transfer experiment has been planned in 1978. Table 7 lists the different participants from seven countries. Extensive use will be made of the single-channel 335-MHz receiver; ionospheric delay will be minimized by using measurements at the time of closest approach of NTS-2. It is anticipated that a worldwide time synchronization accuracy of 100 ns or less will be achieved by this effort.

LASER ORBIT-VERIFICATION PROGRAM

A laser program to verify the GPS orbit accuracy has been started. Initially, laser returns will be used to verify one component of the orbit at the time of the observation; later as more laser stations track NTS-2; an independent orbit will be calculated. An important part of the laser program is to obtain near-simulaneous laser and time-difference observations at colocated sites which will be used for precise clock analysis in addition to orbit determination. These and other objectives are summarized as follows:

- Resolve the scale bias problem,
- Determine the long-range station position stability,
- Make laser-network observations,
- Refine the coefficients of geopotential,
- Determine precise GPS orbits, and
- Evaluate the hydrogen maser.

NTS-2 is equipped with a laser retroreflector similar to that which the NTS-1 had. One element of the retroreflector is designed for light emitted in the ultraviolet region. Figures 24 and 25 show the retroreflector elements for NTS-1 and NTS-2. In addition to the NASA

Table 7 — Participants in the Planned International Time-transfer Experiment

Organization	Country
NASA Goddard Space Flight Center	U.S.
U.S. Naval Observatory	U.S.
Naval Research Laboratory	U.S.
National Bureau of Standards	U.S.
The Bureau Internationale de l'Heure (BIH)	France
The Royal Greenwich Observatory (RGO)	England
The Division of National Mapping (DNM)	Australia
The National Research Council (NRC)	Canada
The Radio Research Laboratories (RRL)	Japan
The National Research Laboratory of Metrology (NRLM)	Japan
The Institut für Angewandte Geodasie	Germany

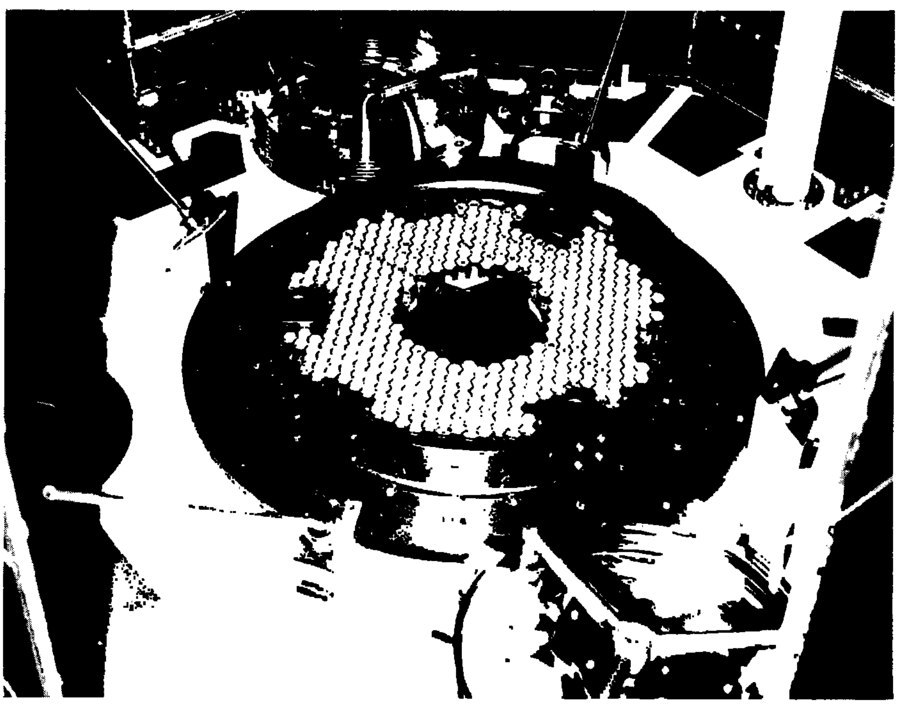

Fig. 24 — NTS-1 laser retroreflector

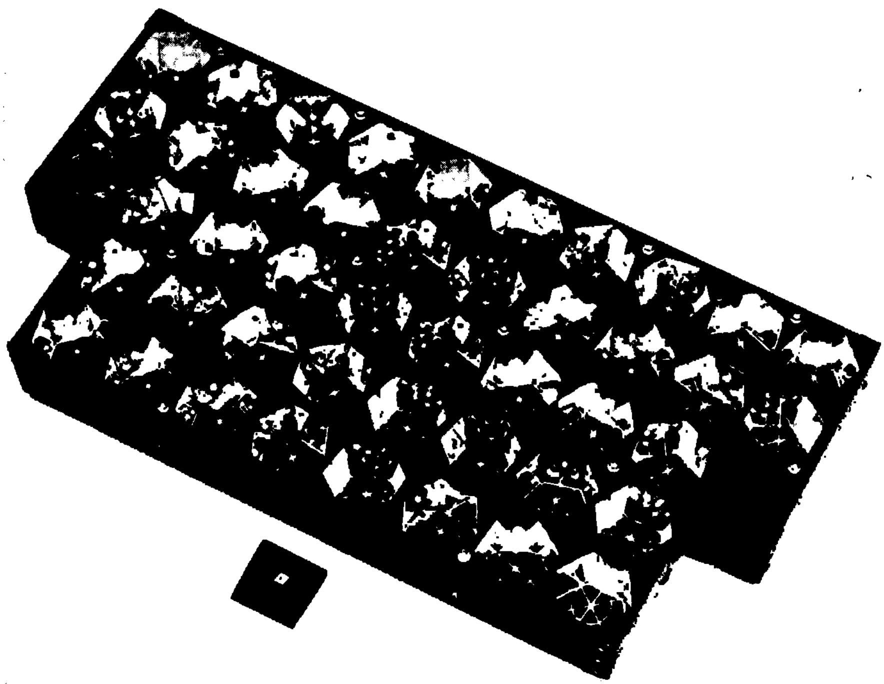

Fig. 25 — NTS-2 laser retroreflector. (The square object is a matchbook to show the size.)

Table 8 — Typical Resolution of Orbit Measurements

Data Type	Stations	Measurement Resolution
Time difference	NTS tracking network	48 cm
Laser	NASA, SAO, Germany, and Australia	15 cm
Optical	Patrick AFB	1 to 2 arc seconds

network, four of the six stations in the Smithsonian Astrophysical Observatory (SAO) network are capable of making laser observations on NTS-2; these four stations are Arequipa (Peru), Natal (Brazil), Orroral Valley (Australia), and Mt. Hopkins (Arizona). Additional laser observations may be obtained from stations at Grasse (France), Wetzell (Germany), Delf (Holland), and Tokyo. Table 8 presents measurement resolutions from some of those stations with NTS tracking capability. Laser returns have already been obtained from SAO Mt. Hopkins, Arizona, site. Figures 26 and 27 present the residuals referenced to the NTS-2 orbit. The measured biases of 56 and 17 ns provide preliminary verification of the NTS orbit. The noise levels of 6 and 5 ns are typical of the expected laser-measurement noise level for this laser configuration; implementation of a more accurate laser pulse should improve these results.

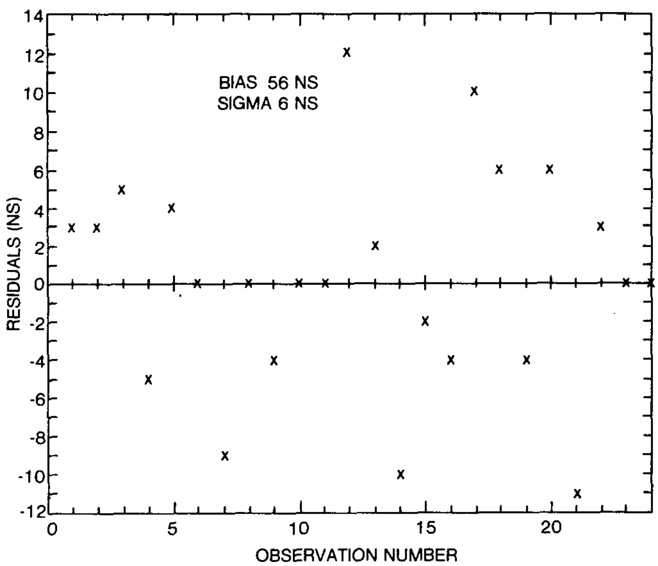

Fig. 26 — Laser-return residuals from the SAO Mt. Hopkins, Arizona, site for day 238, 1977, 0333 to 0403 hours

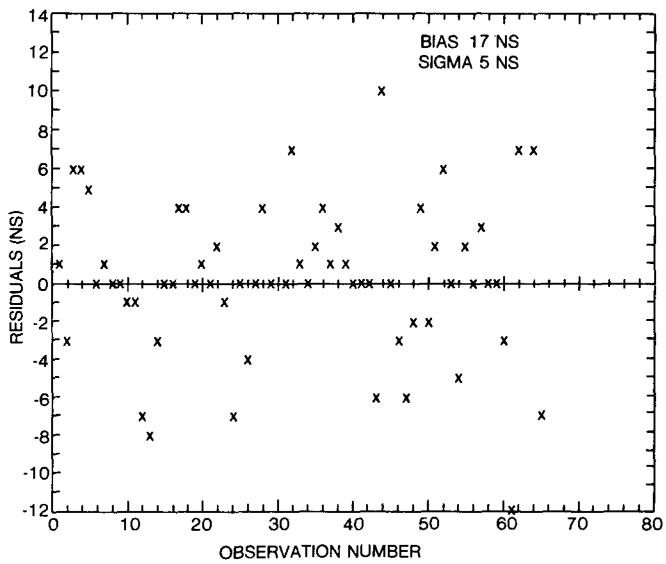

Fig. 27 — Laser-return residuals from the Mt. Hopkins site for day 241, 1977, 0320 to 0338 hours

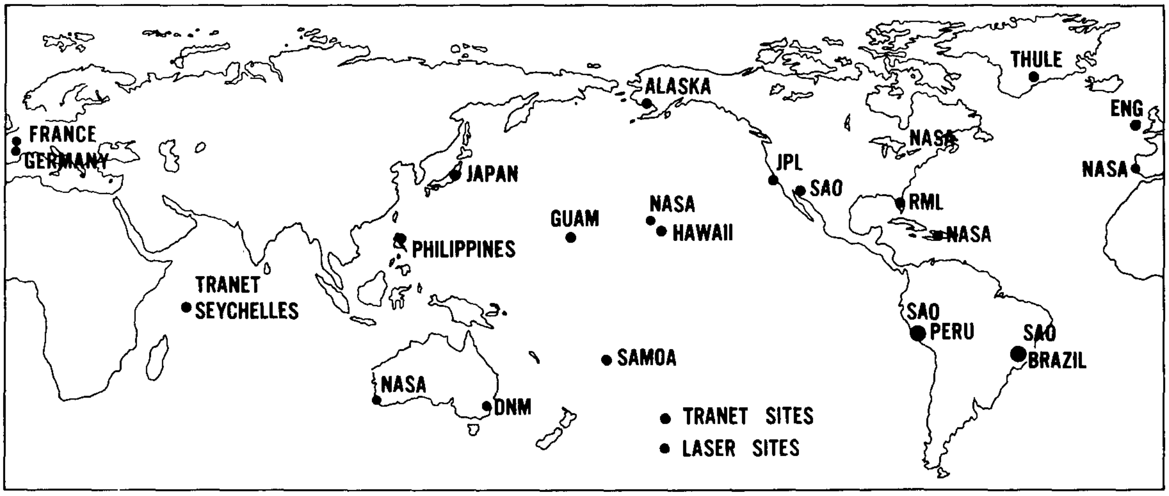

Fig. 28 — Proposed laser network for precise orbit tracking

A proposed laser network for precise orbit tracking is shown in Fig. 28. This proposed network includes possible laser tracking at the operational TRANET sites, which are under the direction of the Defense Mapping Agency.

NTS-2 ACHIEVEMENTS

GPS objectives that have been achieved to date are:

- launch insertion into the GPS constellation position;
- demonstrated orbit stability and controllability;
- first cesium frequency standard in space;
- verification of relativity theory.

Other GPS objectives that are being pursued are:

- satellite clock analysis;
- error budget determination;
- navigation with the Navigation Demonstration System Satellites;
- worldwide timing system synchronization;
- refinement of the coefficients of geopotential;
- measurement of the earth rotation rate.

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