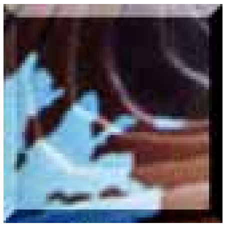

An Overview of Transit Development

Robert J. Danchik

The Transit Navigation System was widely used by the U.S. Navy and the civilian community as an all-weather global navigation system. The Applied Physics Laboratory designed all aspects of Transit, including the spacecraft, user equipment, and ground control system. Several experimental satellites were launched to test key features of the design, after which a series of operational satellites were launched. Transit was continuously improved during its years of operation, resulting in an extremely reliable and accurate navigation system.
(Keywords: Navy Navigation Satellite System, Transit Improvement Program, Transit Navigation System.)

INTRODUCTION

The development of Transit, more formally known as the Navy Navigation Satellite System, was arguably the largest step in navigation since the development of the shipboard chronometer (see Ref. 1 and the article by Dava Sobel in this issue). During its 32 years of operation, Transit was widely used by the U.S. Navy and the civilian community as a highly reliable, precise, all-weather global navigation system. APL designed all aspects of the system, including the spacecraft, user equipment, and ground control system. A comprehensive description of Transit is given in Ref. 2.

Transit fulfilled the Navy's need for a precise navigation system for its nuclear-powered ballistic missile submarines (SSBNs). The fire control system of an SSBN had to know the submarine's position precisely to accurately fire a missile at a target. Initially, the Navy wanted positional fixes for the SSBNs several times a day with an accuracy of 0.1 nmi for each fix. The users were to have passive receivers and obtain data in real time. Later, the Navy Space Command expanded the requirements as follows:

- Coverage: The mean waiting time for a navigation satellite pass (elevation between 15 and 75° at any point on Earth must not be more than 4 h. The percent of time that the waiting interval is more than 8 h must be less than 5%, and the longest interval must be less than 24 h.
- Navigation accuracy: Each satellite must provide navigation fixed-site positional accuracy of 0.042 nmi (3σ) in each direction (0.06 nmi radial).
- Timing accuracy: Transmission at any time from any operational navigation satellite must maintain a precision of 200 μs (3σ) relative to Universal Time.

- Reliability: System reliability must be maintained at 0.97 for any specific satellite and 0.98 for the system (satellite constellation and ground support).

PROGRAM SPONSORSHIP

In the spring of 1958, APL defined and described the essential elements of the Transit Navigation System and then delivered a 50-page proposal to the Navy Bureau of Ordnance. The entire process took about 17 days. (See the article by Guier and Weiffenbach in this issue for a description of the events leading to the genesis of satellite navigation. Also in this issue, see the "Tribute to Frank T. McClure" in V. Pisacane's article.) During the summer of 1958, work on Transit was sponsored by the Polaris program. Formal sponsorship by the Advanced Research Projects Agency (ARPA) began in October 1958 and included authorization for APL to design and build satellites and ground stations.

ARPA sponsorship resulted in part from the Navy's initial reluctance to acknowledge the need for improved navigation. During the first year of ARPA sponsorship, the agency requested an estimate of the mean time to failure (MTTF) of Transit satellites from an independent organization. After the organization considered the general complexity of the electronics and the field experience of similar equipment, it provided an MTTF estimate of only 2 weeks.

Nevertheless, Transit received strong support from the Navy's Strategic Systems Programs Office (which had Polaris submarine oversight) because it offered potential global accuracy that was lacking in competing ground-based systems such as Omega, which was a VLF hyperbolic navigation system. Long-range radio navigation (loran C), limited in coverage, was supported by the Navy as a backup system. Yet, with a good understanding of the physics involved, the Strategic Systems Programs Office was willing to make Transit operational because of the improvements in accuracy and coverage that it offered.

In May 1959, APL issued a program plan identifying an ARPA experimental phase and a Navy operational phase.[3] In the early 1960s, the program became part of the Fleet Ballistic Weapon System under sponsorship of the Strategic Systems Programs Office, which continued to sponsor the program until it was terminated on 31 December 1996. However, after the Navy Space Command was established (about 1985), the Transit system was transferred to it, although the Strategic Systems Program Office continued the day-to-day management.

TRANSIT DESIGN AND MANAGEMENT APPROACH

Richard B. Kershner, a highly respected and successful manager at APL, was given responsibility for managing Transit development. (See Ref. 4 and the "Tribute to Richard B. Kershner" in V. Pisacane's article in this issue.)

Throughout development, Kershner insisted on the simplest design necessary to achieve success. Later, this approach became known as KISS (keep it simple, stupid).

At the time of Transit development, military systems were built for manual servicing and maintenance. Since a satellite in space required remote control and maintenance, it had to be designed with more reliability than was usual at the time. Kershner's solution to this dilemma took two approaches. The first was to use dedicated people and give them responsibility for their design from concept through test and operation in orbit. Kershner believed that although money motivated people to work, a sense of accomplishment was a stronger driving force.[5] Kershner's second approach was the establishment of a parts reliability group. Its mission was to examine component designs in detail and determine which components were well suited for a long orbital life, resulting in a list of flight-qualified components for use on spacecraft.

EXPERIMENTAL SATELLITES

The general plan for the Transit program called for launching a series of experimental satellites, each one going a little farther toward an operational satellite to provide full navigational capability, and each one testing a key feature needed in the final design.[6]

The first Transit satellite, Transit 1A, was launched from Cape Canaveral on 17 September 1959 but failed to achieve orbit. Transit 1B, launched on 13 April 1960, was the first Transit satellite to achieve orbit and operated for 89 days. It transmitted on two frequency pairs to test the technique for refraction correction and to determine if the transmitted frequencies should be close together or far apart. It also included a change concerned with the residual rotation of the satellite after despinning in orbit. In this regard, a large permanent magnet was aligned along the symmetry axis of the satellite, constraining that axis to follow the direction of the Earth's magnetic field. In addition, long slender rods made of a material with high magnetic hysteresis were oriented orthogonal to the magnet. These damped out large deviations of the satellite with respect to the magnetic field, leaving small oscillations. Thus, Transit 1B became the first satellite to use magnetic techniques to maintain attitude control.

Only two types of attitude control had been used previously for artificial satellites. The first and simplest was spin stabilization. However, this was not compatible with Doppler tracking since the frequency it transmitted would be modulated by the angular velocity, creating two sidebands separated from the central frequency by only a small amount. These sidebands, if they were not suppressed in some way, would make it difficult to get an accurate measurement of the central frequency. The second technique was the use of attitude jets to provide appropriate torques to maintain attitude. However, APL felt that the use of these jets on Transit satellites was not compatible with a 5-year lifetime goal established by Kershner and would make difficult the precise prediction of the orbit. Consequently, magnetic stabilization, as described previously, was used on the experimental satellites. Since all tracking stations were in the Northern Hemisphere at the time, where the satellite would generally point down (whereas in the Southern Hemisphere it would point up), this method was useful. However, it would not be acceptable for the operational system, which required full global capability.

Thus, APL then began to examine gravity-gradient stabilization[7] for attitude control. The feasibility of using this technique for artificial satellites was a matter of considerable dispute in 1960. Many felt that the available torques based on the nonlinearity of the Earth's gravitational field were too small to provide a reliable engineering solution to attitude control. A problem in achieving gravity-gradient stabilization was eliminating the initial oscillation about the vertical.

The Transit Research and Attitude Control satellite, which was launched simultaneously with an experimental satellite, demonstrated the principle of gravity-gradient stabilization. Sufficient information was gained from this gravity-gradient experiment to justify using the technique for attitude control on the operational satellites.

Transit 2A, similar to Transit 1B, was launched on 22 June 1960 into an orbit of 66.7° inclination, 626 km perigee, and 1078 km apogee. Transit 2A transmitted until 26 October 1962, giving it a useful lifetime of more than 2 years. A planned Transit 2B was never built.

Transit 3A was launched on 30 November 1960 but failed to achieve orbit. Transit 3B, launched on 21 February 1961, carried a digital clock driven by the same oscillator that drove the transmitters, and it transmitted timing signals governed by the clock and a 384-bit memory. This allowed testing of the techniques for loading the memory from the ground, the ability of the memory to hold a message in orbit, and the ability to encode the memory contents by means of a frequency modulation on one of the main transmitters. It was also shown that ±60° phase modulation could be used to transmit the contents of the satellite memory without degradation of the accuracy of the Doppler signal and Doppler measurements.

Transit 4A was launched on 29 June 1961, followed by Transit 4B on 15 November 1961. Transits 4A and 4B were drum-shaped instead of spherical to provide more space for solar cells. In addition, operational 150- and 400-MHz frequencies were used for the first time. However, transistors operating at 400 MHz were not available, so the final transistor operated at 200 MHz, and a varactor multiplier was used to obtain 400 MHz. Together, Transits 4A and 4B allowed the determination of harmonics in the Earth's gravity field that had not yet been evaluated, and they also allowed firm navigational ties to be established from continent to continent as well as to isolated islands. As a result, it was discovered that the position of Hawaii was incorrect by 1 km.

OPERATIONAL SATELLITES

Prototypes

The next series of satellites were operational prototype satellites. After the launches of the experimental Transit satellites, the Scout rocket was selected as the dedicated launch vehicle for the program because it delivered a payload into orbit for the lowest cost per pound. However, the Scout decision imposed two design constraints. First, the weights of the earlier satellites were about 300 lb each, but the Scout launch capacity to the Transit orbit was about 120 lb (it was later increased significantly). A satellite mass reduction had to be achieved despite a demand for more power than APL had previously designed into a satellite. The second problem concerned the increased vibration that affected the payload during launching because the Scout used solid rocket motors. Thus, electronic equipment that was smaller than before and rugged enough to withstand the increased vibration of launch had to be produced.

Meeting the new demands was more difficult than expected, but it was accomplished. The first prototype operational satellite (Transit 5A-1) was launched into a polar orbit by a Scout rocket on 18 December 1962. The satellite verified a new technique for deploying the solar panels and for separating from the rocket, but otherwise it was not successful because of trouble with the power system. Transit 5A-2, launched on 5 April 1963, failed to achieve orbit. Transit 5A-3, with a redesigned power supply, was launched on 15 June 1963. A malfunction of the memory occurred during powered flight that kept it from accepting and storing the navigation message, and the oscillator stability was degraded during launch. Thus, 5A-3 could not be used for navigation. However, this satellite was the first to achieve gravity-gradient stabilization, and its other subsystems performed well.

Transit 5C-1 was similar to the 5A series but involved some redesign to improve performance. This satellite was launched on 3 June 1964 and operated successfully until 23 August 1965.

From the early stages of the program, it was recognized that nuclear power provided an alternative to solar power for satellites, but it was not clear which would be better for the Transit satellites. Nuclear power, tested on Transit 4A and 4B, showed good results, so it was decided to have two series of prototype operational satellites. The 5A series, which evolved into the 5C-1, had solar power, whereas the 5B series had nuclear power.

Three 5B series satellites were launched by Thor Able-Star rockets with piggyback 5E series satellites. The 5E series were launched to obtain environmental data in the vicinity of the operational orbit of Transit satellites and used solar power.

Transit 5BN-1 was launched on 28 September 1963 into an excellent orbit. Unfortunately, the satellite developed a problem that kept it from being fully useful as an operational satellite for navigation: It achieved gravity-gradient stabilization upside down, and thus the signal level was too low for operational users with low-gain antennas. However, geodetic and navigational evaluation data were obtained.

The Beginning of Operation

Transit 5BN-2 was launched on 5 December 1963 and became the first operational navigation satellite. It was used regularly by both surface and submarine units of the Navy until November 1964. From the time that Transit 5BN-2 became operational, at least one satellite has been operational for routine use by the Navy. Transit 5BN-3 was launched on 12 April 1964 but failed to achieve orbit, after which it was decided that the operational satellites would be solar powered because of the lower cost and the need to obtain special approval to launch each nuclear-powered satellite.

The Oscars

The series of satellites that closely followed the design of Transit 5C-1 were called “Oscars” (Oscar is the phonetic alphabet for “O”, i.e., operational) and had one important change: Hysteresis rods were installed on the solar panels to dampen the residual motion after the satellite despin operation in orbit following launch (Fig. 1).

The original plan was for the Oscar satellites to be built by the Naval Avionics Facility at Indianapolis (NAFI), and NAFI did build Oscars 1, 2, 3, 5, and 7. All except Oscar 3 reached orbit. However, the fabrication of the satellites did not meet specifications, and those that achieved orbit operated only a few weeks.

After Oscars 1 and 2 failed to operate more than a few days, the Navy sponsor decided that APL would refurbish the subsystems built by NAFI for Oscars 4, 6, 8, 9, and 10, and then assemble and launch them. These satellites worked for 7 to 11 months in orbit. APL built Oscars 11 through 17 while the Navy sought a production contractor. Ultimately, RCA was selected and produced all satellites beginning with Oscar 18.

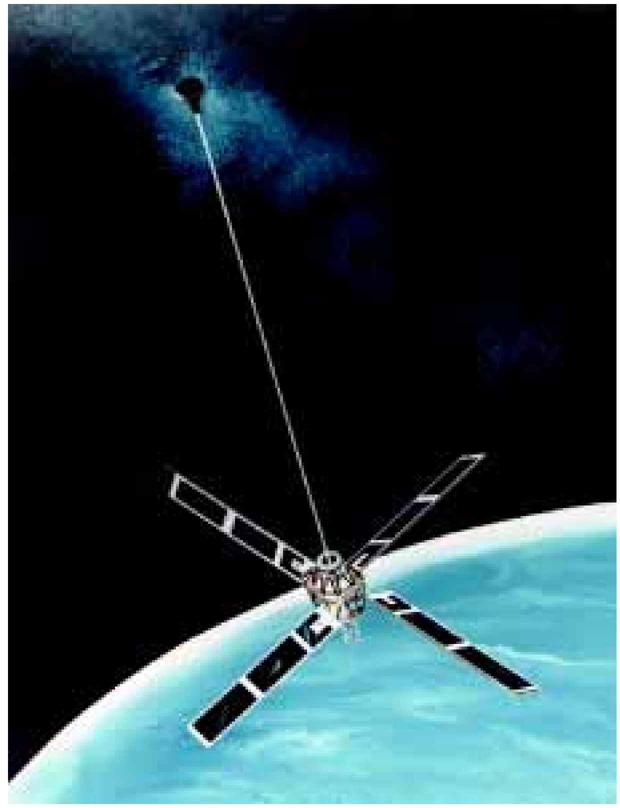

Figure 1. Oscar satellite.

The failures of Oscars 4, 6, 8, and 9 were due to several factors considered to be workmanship-related. For Oscar 10, a decrease in the number of solar cells available for charging the batteries was caused by thermal working of the solar cell interconnections as the satellite passed through the Sun and shade while orbiting the Earth. The problem was fixed on Oscar 12, which was the next operational satellite launched. Oscar 11 was not used at this time. It was later modified and launched as the satellite designated TRANSAT to perform related experiments. Beginning with Oscar 12, the satellites demonstrated an average orbital lifetime of more than 14 years. Two satellites, Oscars 13 and 20, operated for more than 20 years.

Oscar 17 provides an interesting side note in the history of Transit. The satellite was turned over to the National Air and Space Museum in 1976 and was displayed to the public for more than 8 years. In 1984, it was refurbished at APL and launched as the Polar Beacon Experiment and Auroral Research satellite to collect data for studying communications over the Earth’s polar regions.

When the Navy contracted with RCA to build the Oscars, the satellite lifetimes were expected to be about 14 months. After RCA built Oscars 18 through 32, it became clear that the orbital lifetimes were much longer than anticipated so satellite production ceased. All unlaunched satellites were placed in containers for long-term storage at RCA. The row of gray containers became known as “the long gray line.” A review of the system performance is available.[8]

TRANSIT IMPROVEMENT PROGRAM

The Transit Improvement Program (TIP) was established in 1969 to test improvements to the Transit Navigation System with the goal of providing a radiation-hardened satellite. The satellite had a requirement to broadcast ephemerides for 5 days without input from the ground, thereby necessitating the development of a drag-free satellite.

The drag-free technology that was used was the Disturbance Compensation System (DISCOS), which had been under development for several years by a group at Stanford University led by Daniel DeBra.[9] The group had demonstrated the concept with a two-degree-of-freedom system using an air cushion vehicle on a ground plate, but the technique had not been applied to a satellite in orbit.

Disturbance Compensation System

The first of the TIP satellites was a proof-of-concept experiment designated TRIAD, which used a three-body system connected by deployable booms[10] (Fig. 2). The radioisotope thermal generator was on the top of the assembly, the DISCOS was in the center, and the electronics were in the lower section. Although a component in the computer failed two months after launch, many features of the satellite were tested and shown to be successful. In particular, the DISCOS performed well,[11] showing that the orbit could be predicted for up to 60 days. Also, an incremental phase shifter was successfully tested, which provided higher precision timing to navigators.

The next two satellites (TIP-II and TIP-III) had fully redundant subsystems and were radiation-hardened. The main difference in the design between TRIAD and TIP-II and TIP-III was in the DISCOS unit. The DISCOS on TRIAD was a three-dimensional system, compensating for along-track, cross-track, and vertical forces. To reduce the cost and complexity of the operational satellites, the DISCOS units on TIP-II and TIP-III were changed to single-axis correction that corrected the major component of the aerodynamic drag.

Figure 2. TRIAD satellite configuration in orbit.

Transmitters

The TIP 150- and 400-MHz transmitters of the TIP satellites were redesigned with the output power raised to 3 W at 150 MHz and 5 W at 400 MHz. In addition, each TIP satellite was equipped with a minicomputer with 64 KB of memory.[12] Although fully programmable onboard computers are now common, such systems were innovative in 1969 at the start of the TIP design.[13]

Hydrazine Thruster

If a satellite is in an orbit plane other than exactly polar, the plane of the orbit rotates (precesses) in inertial space. The cause of this precession is the oblateness of the Earth (i.e., the Earth’s equatorial bulge). The precession rate of the Oscar satellites varied from about 0.01 to 0.1° per day because of small differences in orbital inclination, which translated to an annual precession rate of about 4 to 40°. This situation created a potential coverage problem for users when orbits overlapped since the MTTF of the satellites was 14 years. The most practical way of achieving the desired orbit with the Scout rocket was by adding a propulsion stage to correct the orbital inclination. Thus, the TIP satellite contained a hydrazine thruster that could be fired by command from the ground or by delayed command stored in the satellite.

Pulsed-Plasma System

It was also necessary to replace the cold-gas jet system used on the proof-of-concept TRIAD, which carried gas for only about 12 months of operation of the DISCOS. Even though the single degree of freedom of the DISCOS cut the fuel requirements by about one-third, it was impossible to carry enough fuel for 10 years without having considerably better specific impulse than was provided by cold gas. After a survey of all possible devices, a pulsed-plasma system developed by Republic Aviation was selected[14] (Fig. 3). This highly ingenious device uses solid Teflon as the fuel. It produces thrust by striking an arc across one face that vaporizes and dissociates the Teflon and partially charges it. Simultaneously, a current loop creates a magnetohydrodynamic bottle to hold the disassociation products and heats them electrically. Then, the collapsing magnetohydrodynamic force field releases the highly energetic disassociation products, which are emitted by the nozzle of the thruster. The accelerating Teflon that is released produces the impulse.

This pulsed-plasma electric propulsion system provided an effective impulse of 500 lb·s; thus, 2.2 lb of Teflon divided between two thrusters could provide a 10-year fuel supply. TIP-II and TIP-III each used two solid-propellant pulsed-plasma thrusters for drag compensation. The forward- and aft-facing thrusters were actuated by an onboard sensor and generated an impulse of roughly 85×10^{-6} lb·s (37.4 dyns) within 1 s of that command. Normally, the DISCOS electronic logic determined which of the two thrusters would produce impulses to keep its proof mass centered in the cavity.

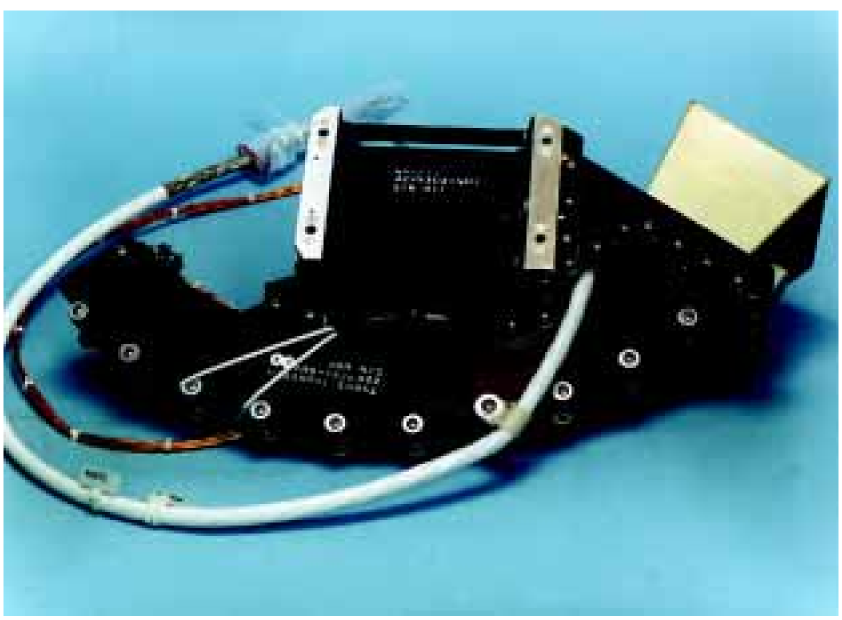

Figure 3. Pulsed-plasma Teflon thruster.

Oscillator

The oscillator developed for the TIP satellites weighed about 2.6 lb and, being of a later design, performed better than those for the Oscars. The remarkable positional accuracy of Transit, especially for the surveying mode, is partly due to the very good short-term stability of the oscillator.[15] An additional satellite subsystem, called the incremental phase shifter, moved the frequency any small desired amount with very great precision in response to a command from the ground.[16] The incremental phase shifter also could continuously move the frequency at a given rate so that once the aging rate was determined, it could eliminate the effect of this aging.

Other Improvements

A major improvement in the TIP satellite design was the introduction of the quadrifilar helix antenna. This antenna has an almost ideal pattern—clean left-hand circular polarization at both 150 and 400 MHz. In addition, all major electronics were made redundant and could be switched into the mainstream of operation of the satellite by signals received through either of two redundant receivers. Furthermore, radiation-hardened (large- and medium-scale) integrated circuits were interconnected on a ceramic substrate to obtain high-density packaging.

NOVA SPACECRAFT

In 1977, the Navy awarded a contract to RCA for the production of three Nova spacecraft (Fig. 4) with the option to build two more. These satellites, launched in the 1980s, were nearly identical to the TIP-IIand TIP-III satellites. Improvements included the addition of magnetic damping to the DISCOS and a stiffening of the lower boom assembly.

STACKED OSCARS ON SCOUT

By the late 1980s, the Scout rocket was able to launch about 260 lb into Transit's operational orbit. After a feasibility investigation by APL, the Navy awarded RCA a contract to launch two Oscar satellites on the same launch vehicle. This dual-launch method was called stacked Oscars on Scout (SOOS).

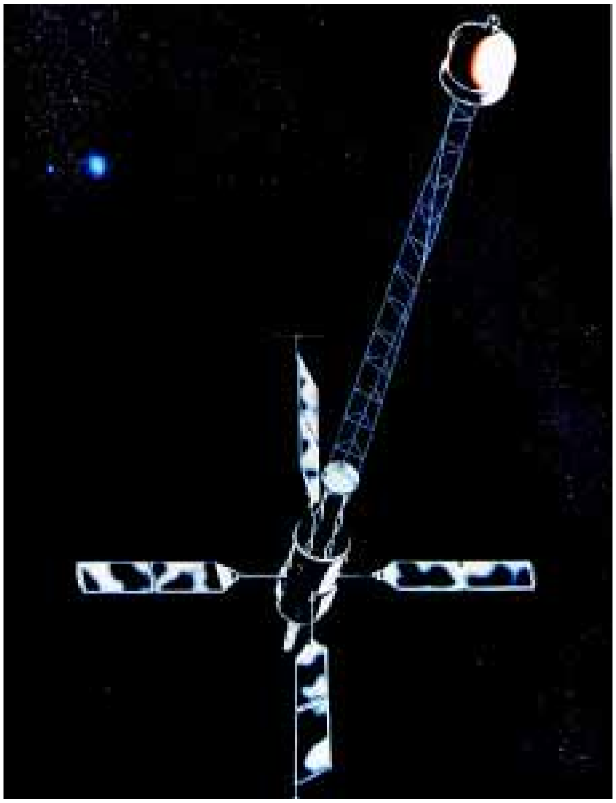

Figure 4. Nova satellite.

The primary purpose of this approach was economics. The Navy could get the remaining satellites into orbit without procuring additional launch vehicles. The first SOOS configuration was launched in 1985. The second SOOS was launched in 1987, and the last two were launched in 1988. This established a constellation of 12 satellites, with 7 or 8 operational, and the remaining ones stored in orbit.

IMPROVING NAVIGATIONAL ACCURACY

The early Transit developers were always looking ahead. For example, they made allowances for Transit to incorporate future advances in geodesy and software without having to change the hardware. Over the years, several changes were made to ground system and flight system software without any effect on the system interface between the satellites and the ground system. Figure 5 shows how the accuracy of Transit improved over time. This accomplishment was due to several factors, which are discussed in the following paragraphs.

Gravity-Field Determination

Transit 1B tracking revealed two crucial facts: (1) Accurate determination, and especially prediction of satellite orbits, required a greatly improved determination of the Earth's gravitational field. (2) The tracking of low-altitude satellites provided an unprecedented and powerful means of making this needed improvement. Although there were several ways to determine the Earth's gravitational field, the use of Doppler tracking proved to be the most powerful. By 1964, APL had developed a sophisticated model of the gravitational field of the Earth in the form of an expansion in spherical harmonics (a three-dimensional analog of a Fourier series) that was sufficiently accurate to make possible the initial goal of better than 0.1 nmi navigational accuracy at sea. Thus, the gravitational field of the Earth was no longer a limiting factor in the navigational accuracy achieved at sea, which instead was dominated by the orbit prediction errors caused by the inherent unpredictability of drag and errors in the estimate of a ship's velocity.

Drag and Solar Radiation

Two forces that are not gravitational in origin affect the motion of a satellite. One is drag produced by the residual atmosphere found at satellite altitudes, and the other is the force produced by the pressure of solar radiation.

The structure of the upper atmosphere is highly complex; it varies drastically with latitude, longitude, altitude, and time. The density of the daytime atmosphere is greater than that of the nighttime atmosphere, and measurements show that the ratio of day to night density at 1000 km may vary by a factor of 2 to 4.[17,18]

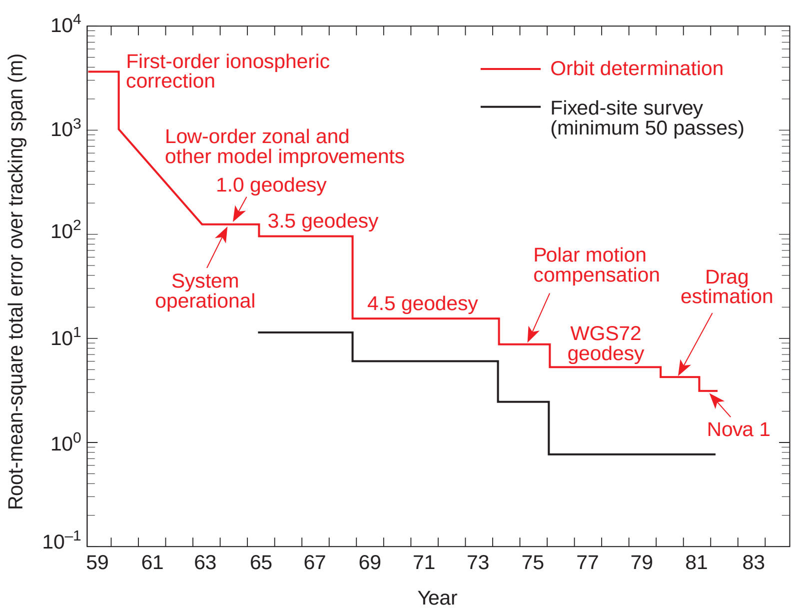

Figure 5. Improvements in Transit orbit determination and surveying accuracy. (WGS72 = World Geodetic Survey, 1972.)

The amount of drag varies from day to day and with the 11-year sunspot cycle. This effect is highly correlated with the solar spectrum in the microwave region (wavelengths of 10 to 20 cm) and with the activity of the Earth's magnetic field, both of which can be monitored on the ground. During intense solar activity, Oscar satellite orbits were computed twice daily because of this effect. The algorithms in the orbit determination program effectively reduced the effect of drag over the years.[19] The Nova spacecraft were not affected by changes in air density.

At an altitude of 1000 km, the electromagnetic pressure exerted by solar radiation is about 10 times the drag pressure exerted by the residual atmosphere.[20] If the forces acted in the same direction, the resulting perturbation would be about 1000 m in a day. Fortunately, radiation pressure tends to average to near zero over one orbit, resulting in an effect over a day of about 10 m.

Van Allen Radiation Belts

One of the earliest discoveries of the space age were belts of electrons, protons, and other ions trapped by the Earth's magnetic field named (for their discoverer) the Van Allen radiation belts. These charged particles are continuously removed by interaction with the atmosphere but are also continuously replenished from the solar wind. A nuclear device detonated outside the atmosphere can greatly increase the density of the charged particles in the Van Allen belts. With sufficiently enhanced radiation belts, the life of satellite solar cells and the electronics could be degraded to the point of inadequate operation. The TIP and Nova satellites were hardened to endure enhanced particle radiation in response to a high-altitude nuclear weapon test in 1962, which caused the failure of all the satellites in orbit.

Ionosphere and Troposphere

The satellite signal, in reaching the observer, travels through the ionosphere and troposphere (the near atmosphere), both of which interact with the transmitted frequency.[21] The largest part of the ionospheric error is resolved by broadcasting the two coherent frequencies of 150 and 400 MHz.

Correction for the tropospheric error, unlike the ionospheric error, is not frequency dependent but rather depends at every point on the pressure, temperature, and humidity. The Transit system user may or may not take into account this effect on the collected Doppler data.[22–24] The tropospheric effect manifests itself as an error in the instantaneous range from the observer (navigator) to the satellite. The error is largest (typically 80 m) at low elevations and smallest (about 2.3 m) when the satellite is directly above the observer. Thus, the system software either processed data at higher elevations or corrected for the tropospheric error at lower elevations.

SYSTEM ACCEPTANCE

Wide acceptance of the Transit Navigation System took some time. SSBNs and aircraft carriers used Transit's precision navigation from the beginning of system operation in 1964. The first civilian users of Transit were oceanographers on research ships in the mid-1960s. They were unstinting in their praise of the system's performance.

In 1967, Vice President Hubert Humphrey released the system for public and commercial use by ships of all friendly nations. However, it took the development of low-cost receivers in the early 1970s and the world oil crisis in mid-1974 before the system received wide use. Oil-drilling platforms at sea were among the first to use Transit because of the need to determine the precise boundaries of oil deposits. Then, within a few years, civilian use far exceeded military use. Oil tankers transporting oil during the embargo established the system's cost-effectiveness. Use quickly expanded within the commercial shipping industry because port arrivals could be predicted with better accuracy. General commercial shipping followed. As the cost of receivers got lower and lower, reaching approximately the $1000 level, pleasure boats began to use Transit.

Gradually, other ocean-going ships that required precise location information acquired Transit receivers. A surprising number of receivers were in use for surveying rather than for navigation. A completely new survey of Western Europe was done using Transit, and international boundary disputes were settled by Transit surveys. For example, the North Sea line separating Norwegian and Scottish waters was positioned by Transit surveys. The position of this line is worth millions of dollars per foot because of the oil deposits at the bottom of the North Sea.

CONCLUSION

During its 32 years of operation, the Transit Navigation System provided an extremely accurate and reliable global navigation system for the U.S. Navy and the civilian community. The system was continuously improved through the years and contributed to numerous advances in space science, engineering, and technology.

REFERENCES

[1]Sobel, D., *Longitude: The True Story of a Lone Genius Who Solved the Greatest Scientific Problem of His Time* (Walker, 1995; Penguin, 1996).
[2]Black, H., "Satellites for Earth Surveying and Ocean Navigating," *Johns Hopkins APL Tech. Dig.* 2(1), 3–13 (1981).

[3]Wyatt, T., "The Gestation of Transit as Perceived by One Participant," *Johns Hopkins APL Tech. Dig.* **2**(1), 32–38 (1981).
[4]Gibson, R. E., "In Memoriam: Richard Brandon Kershner," *Johns Hopkins APL Tech. Dig.* **3**(1), 96–101 (1982).
[5]Kershner, R. B., "The Arcane Art of Research and Development Management," *Johns Hopkins APL Tech. Dig.* **2**(1), 45–49 (1981).
[6]*History of the Space Department at the Applied Physics Laboratory, 1958–1978*, JHU/APL, Laurel, MD (Jan 1979).
[7]Fischell, R. E., *Magnetic and Gravity Attitude Stabilization of Earth Satellites*, CM-996, JHU/APL, Laurel, MD (May 1961).
[8]Pisacane, V. L., Holland, B. B., and Black, H. D., "Recent (1973) Improvements in the Navy Navigation Satellite System," *Navigation. J. Inst. Navig.* **20**(3), 224–229 (Fall 1973).
[9]DeBra, D. B., "Disturbance Compensation System Design," *APL Tech. Dig.* **12**(2), 14–26 (1973).
[10]Dassoulas, J., "The TRIAD Spacecraft," *APL Tech. Dig.* **12**(2), 2–13 (Jun 1973).
[11]Space Department of JHU/APL and Guidance and Control Laboratory of Stanford University, "A Satellite Freed of All But Gravitational Forces: TRIAD 1," AIAA-74-215, AIAA 12th Aerospace Sciences Meeting, Washington, DC (1974).
[12]Perschy, J. A., Elder, B. M., and Utterback, H. K., "TRIAD Programmable Computer," *APL Tech. Dig.* **12**(4), 12–20 (1973).
[13]Jenkins, R. E., "Demonstration of the Value of Spacecraft Computers," *Johns Hopkins APL Tech. Dig.* **5**(3), 225–237 (1984).
[14]Ebert, W. L., Kowal, S. J., and Sloan, R. F., "Operational Nova Spacecraft Teflon Pulsed Plasma Thruster System," AIAA-89-2497, AIAA/ASME/SAE/ASEE 25th Joint Propulsion Conference, Monterey, CA (1989).
[15]Norton, J. R., and Cloeren, J. M., "Brief History of the Development of Ultra-Precise Oscillators for Ground and Space Applications," *Proc. IEEE Int. Frequency Control Symp.* (1996).
[16]McGovern, T. L., and Rueger, L. J., "TRIAD Incremental Phase Shifter," *APL Tech. Dig.* **12**(4), 2–11 (1973).
[17]Eisner, A., and Yionoulis, S. M., *Semi-Annual Variation in the Upper Atmosphere (900–1200 km) at Solar Minimum*, TG 1314, JHU/APL, Laurel, MD (1977).
[18]Eisner, A., and Yionoulis, S. M., *Long-Period Terms in the Neutral Density of the Upper Atmosphere*, CP067, TG 1314, JHU/APL, Laurel, MD (1979).
[19]Eisner, A., *Drag Estimation and Satellite Orbit Determination*, TG 1327, JHU/APL, Laurel, MD (1980).
[20]Newton, R. R., "The Near Earth Potential of Doppler Location," *Johns Hopkins APL Tech. Dig.* **2**(1), 16–31 (1981).
[21]Guier, W. H., and Weiffenbach, G. C., "Theoretical Analysis of Doppler Radio Signals from Earth Satellites" *Nature* **181**, 1525–1526 (1958).
[22]Hopfield, H. S., "Two-Quartic Tropospheric Refractivity Profile for Correcting Satellite Data," *J. Geophys. Res.* **74**(18), 4487–4499 (1969).
[23]Eisner, A., *The Effects of the Troposphere on Doppler Navigation Station Positions*, TG 1323, JHU/APL, Laurel, MD (1978).
[24]Pisacane, V. L., and Feen, M. M., "Potential of the Navy Navigation Satellite System in Predicting Ionospheric Characteristics for High Frequency Sky Wave Telecommunications," *Signal* **27**(3), 14–18 (Nov 1972).

ACKNOWLEDGMENT: In preparing this article, I drew on previously published material listed in the references. In particular, I made extensive use of unpublished documents prepared by Richard B. Kershner entitled "Transit History" and "The Transit System." Along with the referenced articles, discussions with Roy Sloan, Jerry Norton, John Dassoulas, Joe Nagrant, Jim Smola, Henry Elliott, Stan Kowal, Lauren Rueger, and Lee Pryor were very helpful. I also wish to thank Don Tracey, Harold Black, and Vince Pisacane for their assistance in the preparation of this article.

THE AUTHOR

ROBERT J. DANCHIK is a retired member of APL's Principal Professional Staff. He received his B.S.E.E. from The Pennsylvania State University in 1955 and his M.S.E.E. from Drexel University in 1960. After spending 7 years at the Martin Company and the Westinghouse Electric Company, he joined APL and worked in the Space Department for about 33 years. For 16 of those years, he served as the APL Program Manager for Transit. At the time of his retirement, Mr. Danchik was the Space Department's Assistant Head for Operations. His e-mail address is danchikrj@aol.com.