



# Innovations Derived from the Transit Program

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**O**n 4 October 1957, without warning, the Soviet Union launched *Sputnik I*, and with it the space age. The United States was taken by surprise. We had no receiving equipment to listen to the satellite, and worst of all, we didn't know what the satellite did. This external stimulus led to the Navy Navigation Satellite System, known as Transit, an all-weather satellite navigational system that allowed naval units to pinpoint their positions anywhere on Earth in direct support of the Fleet. This article addresses the largely untold story of Transit operations, including the military importance of Transit, the evolution of the Naval Satellite Operations Center, and the breakthroughs in satellite management resulting from the system.

(Keywords: Naval Aeronautics Group, NAVSOC, NIMS, Transit, TT&C.)

## INTRODUCTION

The Naval Satellite Operations Center (NAVSOC), with facilities stretching from the rock-bound coast of Maine to the Sun-drenched beaches of Hawaii, quietly and competently controlled America's first operational space system, Transit, an all-weather global navigation satellite, for almost 35 years.

Passing unobtrusively 600 nmi overhead every few hours while broadcasting a highly accurate navigation message, Transit required the constant attention of civilian and military personnel at NAVSOC. Whether analyzing orbital parameters, monitoring and directing spacecraft performance, resolving operational computer problems, designing improved software programs or hardware, conducting maintenance, maintaining supply inventories, or planning future space systems, NAVSOC personnel established an unmatched record of success, conquering the space frontier and making it

work for us. The pride and performance of each employee were evident in a record of nearly 100% reliability during the system's years of operational service.

This article is dedicated to the more than 1000 men and women who have worked for NAVSOC since its inception and whose devoted efforts have made Transit an enduring success.

## BACKGROUND

The Transit program was designed to support the Navy's contribution to the nation's strategic nuclear deterrent efforts. Transit provided the accuracy required by Strategic Ballistic Missile submarines (Fig. 1) to fire their missiles on target. This system is recognized by many as the primary deterrent to nuclear war in the



**Figure 1.** Polaris missile submarines were the primary users of Transit in 1965.

1970s and 1980s. Transit enabled the United States to retaliate from unknown locations under the sea.

In July 1967, the vice president of the United States, acting as chair of the National Council for Marine Resources and Engineering Development, made Transit available to commercial and private users and authorized the commercial manufacture and sale of navigation sets to the public. This action resulted in more than 80,000 Transit navigation receivers in use worldwide for pinpoint navigation, surveying, and establishment of critical oil and mineral ownership boundaries. In addition to playing a major role in the nation's nuclear deterrent program and proving to be an invaluable surveying tool, Transit set current standards for cost-effective, robust satellite operations.

NAVSOC headquarters at Point Mugu, California, was established in April 1962 under the name Navy Astronautics Group to operate Transit. Besides the headquarters facility, NAVSOC operates several remote telemetry, tracking, and command (TT&C) facilities. The Laguna Peak Tracking and Injection Facility is about 3 mi from headquarters and currently supports ultrahigh-frequency (UHF) and space ground link system (SGLS) satellite TT&C operations. Detachment Alfa at Prospect Harbor, Maine, supports UHF and SGLS operations in addition to extremely-high-frequency (EHF) operations.

Detachment Bravo was adjacent to the University of Minnesota in Rosemount. This facility closed in August 1997. Detachment Charlie, located at Finegayan, Guam, was established in 1993 in an existing Navy facility, with tracking and telemetry collection capabilities supported by a helix antenna, a 10-m L/S-band dish antenna, and an EHF antenna.

Finally, Detachment Delta was established in 1988 in Colorado Springs, Colorado, within Falcon Air Force Base. Its primary functions are to serve as an alternate to NAVSOC headquarters in the event of a

disaster near Point Mugu and to coordinate scheduling with the Air Force.

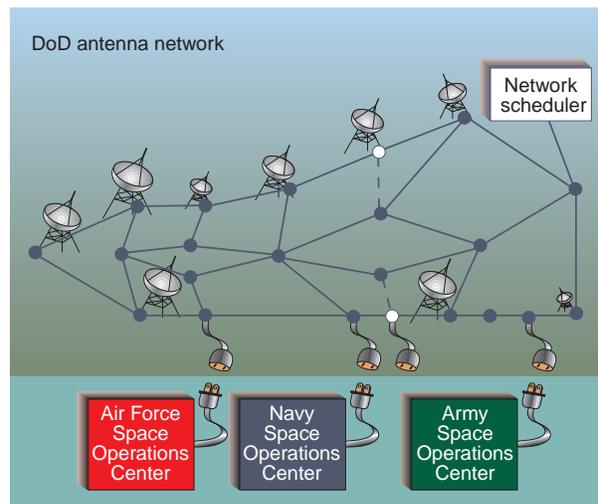
When the Naval Space Command was commissioned in October 1983, the Navy Astronautics Group was transferred to it and assumed the additional responsibilities of operating and maintaining satellite systems for naval space operations. The Navy Astronautics Group was formally redesignated as NAVSOC in June 1990. NAVSOC has continued to modernize and upgrade its facilities; in January 1996, it implemented a cooperative agreement with the Air Force Consolidated Space Operations Center for sharing antenna resources via the “plug n’ use” concept (Fig. 2).

When Transit terminated on 31 December 1996, NAVSOC retained other mission assignments, including operation of the Fleet Satellite Communications System (FLTSATCOM), the FLTSATCOM EHF Package (FEP; Fig. 3), a UHF Follow-On (UFO; Fig. 4), the Geosat Follow-On (Fig. 5), polar EHF satellites, and the Navy Ionospheric Monitoring System known as NIMS.

## SYSTEM PERFORMANCE AND MANAGEMENT BREAKTHROUGHS

### Distributed System

In recent years, the Navy has “flight tested” a distributed satellite control system for Transit. Using the Transit TT&C system as a base, NAVSOC has implemented this state-of-the-art architecture (Figs. 6 and 7). The resulting system has proven to be a flexible, efficient method of spacecraft navigation and has provided the U.S. Space Command a new level of responsive capabilities with demonstrable success in personnel and cost reduction.



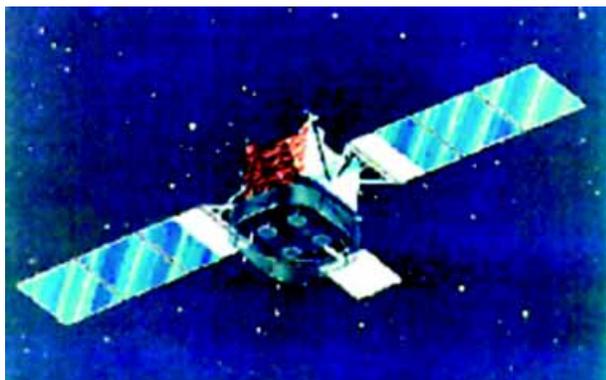
**Figure 2.** Diagram of the “plug n’ use” concept of satellite control. NAVSOC “plugs” into Air Force Satellite Control Network sites via Falcon Air Force Base to control Fleet satellites.



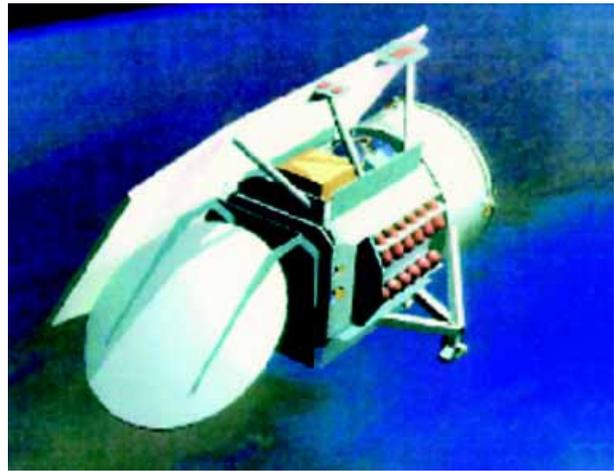
**Figure 3.** Model of the Fleet Satellite Communications System Extremely-High-Frequency Package (FEP).

The distributed system takes advantage of small computers located at each remote antenna/transmitter site. These commercial off-the-shelf computers can be controlled from the site itself or from a remote location. Normally, NAVSOC controls the remote sites and all associated satellites from its Point Mugu headquarters within a single operations center and under the supervision of one duty satellite manager (Fig. 8).

The database-driven distributed approach eliminates the need for most of the overhead software usually associated with the management of multiple functions. System- or satellite-unique data are modularized and loaded from disk as required. This arrangement results in significant economies in software development and maintenance. Since the entire system is based solidly on proven commercial off-the-shelf software, cost and complexity are further reduced. Several simultaneous contacts can be supported easily because much of the data processing is accomplished before transmission. Only the minimum amount of required data is



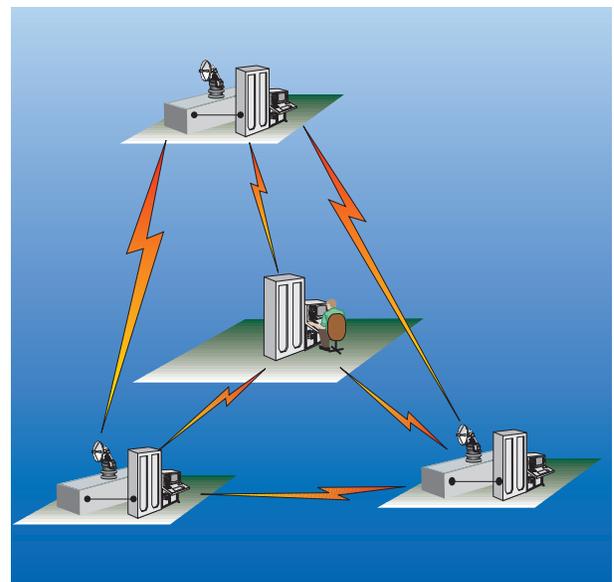
**Figure 4.** The Ultrahigh-Frequency Follow-On (UFO).



**Figure 5.** The Geosat Follow-On (GFO).

transmitted in real time, greatly reducing the size of the interconnecting communications pipelines.

NAVSOC's distributed system has significantly high reliability and survivability because each site can operate independently of the central control site. (Reliability is calculated as time providing valid navigation and timing results divided by the total time as part of the operational constellation.) This independence is critical during disasters or other disturbances. Satellites operated by NAVSOC will therefore continue to run if headquarters becomes disabled. For example, full operations were maintained even when the Laguna Peak facility was isolated because of fires and when headquarters was disrupted during an earthquake. In fact, the combination of this innovative architecture and

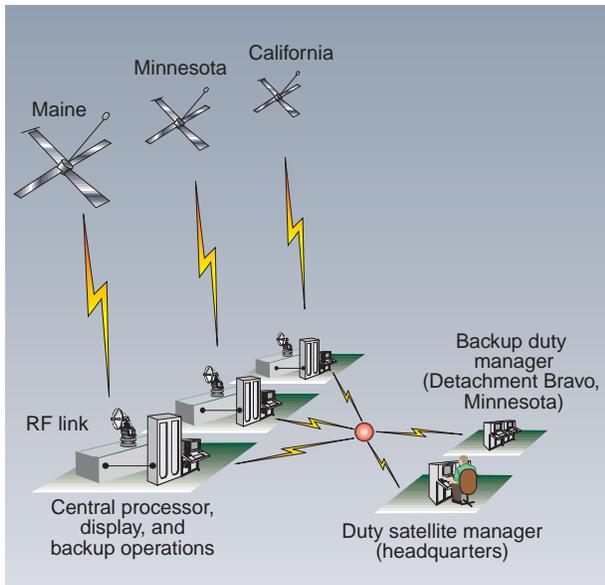


**Figure 6.** Diagram of the NAVSOC distributed architecture. NAVSOC distributes processing by conducting satellite operations with remote site computers.



**Figure 7.** Cartoon of NAVSOC remote site “lights out” telemetry, tracking, and command operations inspired by Transit.

dedicated personnel has enabled NAVSOC to maintain near-perfect reliability to date in direct Fleet support of Transit, FLTSATCOM, UFO, and FEP satellites.



**Figure 8.** The duty satellite manager at headquarters normally controls all operations. A duty manager at the backup site assumes controls if headquarters is disabled.

New satellites can be added to this system at a fraction of the cost required by dedicated systems. As they are added, software modules with unique characteristics are developed and incorporated. This process augments the existing software structure and eliminates the “stovepipe” approach of more traditional satellite control systems.

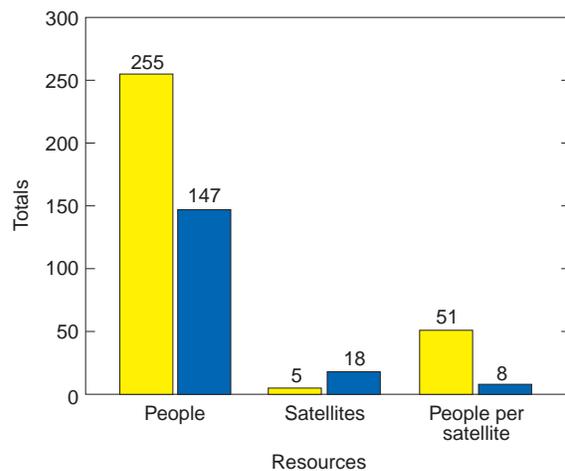
NAVSOC has also implemented a hierarchical interface that is truly user-friendly. The technique layers the level of technical detail so that the operator determines how far to go into any system. Displays range from general “red/yellow/green” overviews to detailed graphical analyses of subsystem performance.

While drastically reducing communication requirements, computer and software complexity, developmental and operational costs, and the required number of operating personnel, the NAVSOC approach has increased reliability and flexibility (Fig. 9). Future DoD satellite control systems will be standardized under the U.S. Space Command to promote complementary component efforts as well as ensure the interoperability and flexibility required of all DoD efforts.

### Satellite Orbit Prediction Capability

As previously noted, the Transit satellite must broadcast precise position and time information for its navigation mission to succeed. Users combine this information with the Doppler shift collected by their receivers to compute current positions.

Satellite broadcast messages were computed at NAVSOC using software developed by APL scientists. NAVSOC orbit analysts and computer operators collaborated to design a set of routine operations and procedures for these activities. These well-documented procedures allowed dedicated computer operations



**Figure 9.** Comparison of NAVSOC personnel and number of satellites in operation between the 1970s (yellow bars) and the end of 1996 (blue bars).

personnel to supply extremely reliable broadcast navigation messages to the satellite TT&C facilities.

The TT&C facilities also provided the raw tracking data that were subsequently incorporated into the Orbit Improvement Program and its successor, the Orbit Determination Program. A major benefit of the latter program was that it was much more analyst-friendly because it was written in PL/I, a higher-level programming language that NAVSOC analysts could easily understand.

NAVSOC ensured the accuracy of the navigation messages by developing a simulated navigation capability to monitor user results. This capability was implemented at headquarters and automatically measured accuracy by “navigating” the tracking data against the broadcast message. If the subsequent navigation error exceeded threshold, NAVSOC personnel warned Fleet users by message that their results were erroneous. Because of the reliability, redundancy, and careful operation of the Transit system by NAVSOC personnel, issuance of such space tracking (SPATRAK) messages was rare.

As Transit developed, scientists learned more about the forces affecting near-Earth satellites. APL physicists and mathematicians incorporated this knowledge into the Transit orbit determination software. NAVSOC implemented this software into daily operations only after extensive testing proved its accuracy and reliability.

In the early days, incomplete knowledge of the Earth’s gravitational forces caused the greatest errors. Table 1

(from Ref. 1) shows the tremendous improvement made in models of the geopotential. With these upgraded models (including ionospheric and tropospheric refraction and radiation pressure) and orbital determination algorithms came improved orbit prediction capabilities, and NAVSOC orbit analysts were able to tackle the long-standing problem of drag uncertainty.

**Drag Compensation**

In the early 1980s the first Nova satellite (Fig. 10) solved the drag problem by compensating for drag with thruster firings. Oscar satellites (Fig. 11) did not have this capability. However, at about the same time, the key elements for an Oscar satellite solution came together: accurate force models, drag tracking techniques, and analyst insight.

As knowledge of the near-Earth forces improved, prediction of satellite position improved. The one area that could not be accurately modeled was atmospheric density (and thus, the drag force). Although the force is small, it is continuous and always in the same satellite along-track direction. Therefore, its cumulative effects become the biggest error source. To solve the problem, APL scientists perfected a drag-tracking technique that consists of modeling and solving for the magnitude of a constant along-track force identified as PHLC(2), i.e., the magnitude of a constant force in the second component of HLC, where H = range, L = along track, and C = coordinate system. This force compensates for

the error in the atmospheric density model and eliminates the need to improve that model. As long as the future reflected the past (i.e., the same average force acted over the prediction span and the tracking span), prediction of satellite position was accurate. However, the future did not always reflect the past. In those situations, NAVSOC had to issue an out-of-service SPATRAK message.

With the advent of a reliable drag-tracking algorithm, NAVSOC orbit analysts could analyze drag errors by comparing PHLC(2) values. They could then apply the standard relation for position error as a function of time and force error after empirically determining when the time of zero position error was in (not at the end of) the tracking span. Finally, they could quantify the PHLC(2) error magnitude that would cause satellite out-of-service time.

**Table 1. Improvement in geopotential model precision as the result of satellite tracking.**

Geopotential model	Orbit precision <sup>a</sup> (m)	Coverage
APL 1.0	100–150	Zonals and sectorials through (4,4) <sup>b</sup> ; December 1963– December 1965
APL 2.0		Zonals and sectorials through (6,6); January 1965– February 1966
APL 3.5	75–110	Zonals and sectorials through (8,8) plus a few resonant terms of order 13 and 14 (Ref. 2); February 1966–June 1968
APL 4.5	15–20	Complete through degree and order (11, 11) plus most terms through (15,15; 226 coefficients; Ref. 3); June 1968 –July 1975
World Geodetic System-72	5–10	Coefficient set complete through (19, 19), zonals through degree 24, and additional resonance terms through order 27 (479 coefficients; Ref. 4)

Note: The table is from Ref. 1.

<sup>a</sup>Satellite altitude = 1100 km.

<sup>b</sup>Numbers in parentheses indicate highest order and degree of sectorial terms.



Figure 10. Drawing of a Nova satellite.

Later, orbit analysts were able to characterize the times when drag errors would be sufficiently large, for example, when solar activity was relatively high and the geomagnetic ( $k_p$ ) index exceeded 6 for two consecutive 3-h periods. Under such conditions, the Orbit Determination Program would characteristically underpredict, then accurately predict, and finally overpredict the drag force. Satellite position errors (and user navigation errors) exceeding specification would occur during both the over- and underprediction periods.

Once this pattern was detected, procedures were developed to compensate for the errors by adding an analyst-determined value to the PHLC(2) used in the prediction span. The magnitude of these drag prediction errors could not be analytically modeled, but depended on geomagnetic activity, solar activity, relation of the satellite orbit plane to the Earth–Sun line, and satellite perigee height. The NAVSOC techniques required application of a combination of analytic algorithms and good judgment and could never be fully automated. However, the judicious application of the technique increased Transit reliability by frequently preventing erroneous navigation results. After the technique was proven, APL scientists modified the program to make the delta PHLC(2) application easier.



Figure 11. Drawing of stacked Oscars on Scout (SOOS).

### Satellite Power Management

Maintaining the health of Oscar and Nova satellites was the primary job of the NAVSOC satellite engineers. The Transit satellites were designed to operate reliably with minimal human intervention. However, because of orbit characteristics, some command and control was required. The typical 600-nmi polar orbit dictated that the satellites be in continuous Sun for about 2 months, followed by 4 months of up to 35-min of shade during every 107-min orbit. Figure 12 is a plot of the percentage of time a typical satellite was in Sun as a function of day of the year. The curve did not change shape from year to year, but rather slid earlier

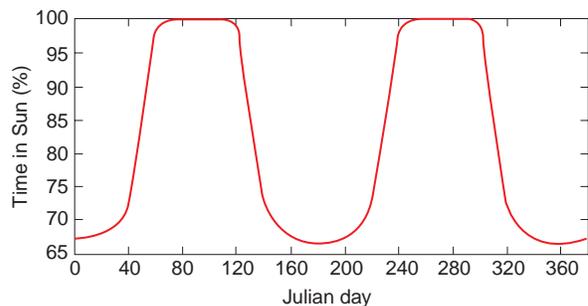


Figure 12. Typical plot of percentage of sunlight as a function of day of the year for a Transit satellite. This plot is for Oscar 20 in 1995.

or later as a function of nodal precession (which is a function of the difference of the inclination from  $90^\circ$ , i.e., a perfectly polar orbit).

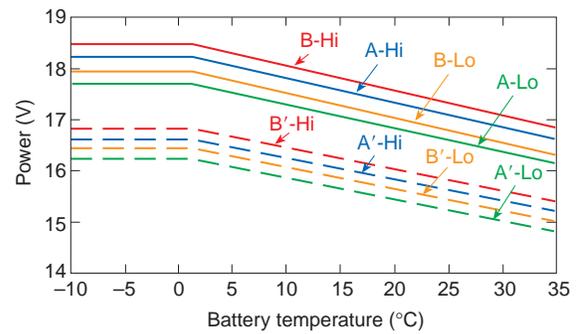
During full-Sun season, the solar cell current is sufficient to operate the satellite. During eclipse season, the batteries must supply the operating power when the satellite is in shade. The solar arrays must then provide enough power to recharge the batteries during the sunlit portion of each orbit. Although the average power required to operate the satellite remains unchanged during eclipse season, the instantaneous power when the satellite is in Sun must be increased to compensate for the (shade) periods of zero solar array power.

NAVSOC satellite engineers managed the Transit satellite power systems to keep the batteries fully charged while minimizing overcharge (which would produce overheating, thereby causing reduced battery lifetime and thus satellite lifetime). They learned that the most significant telemetry parameters were voltage, temperature, and current. By focusing on the values of these parameters, the engineers were able to develop effective power management techniques.

For example, NAVSOC devised a telemetry reduction and monitoring system that provided early warning for satellite problems. Satellite engineers established normal operating ranges for the significant telemetry parameters. These parameters were checked against two sets of thresholds whenever a NAVSOC ground station collected telemetry. Violation of the first set indicated an unexpected condition and caused a warning; violation of the second indicated a serious problem and triggered an alarm. If a parameter exceeded either set of limits, software automatically notified the NAVSOC duty satellite manager. The manager, in turn, would notify an on-call satellite engineer who would start action to investigate and correct the anomaly. By establishing and responding to warning limits, NAVSOC engineers were often able to prevent future out-of-service time.

Available Oscar satellite power could be increased by switching a solar boost array from the automatic temperature control (ATC) circuit to the main bus. Each satellite had one main solar array (permanently wired to the main bus), and most had two boost arrays (separately switchable between the main bus and ATC, one slightly larger than the other). Through experience, NAVSOC engineers learned that it was necessary to switch a boost array to the main bus a few days after entering eclipse season and switch it back to ATC a few days before leaving eclipse season. In this way, they maintained sufficient power to operate and minimized battery overheating. On the few occasions when the power got too low (at the end of a long shade period), a satellite clock would jump out of specification and NAVSOC would notify users via SPATRAK message.

Power for Nova satellites was controlled by selecting an appropriate voltage/temperature curve (Fig. 13).



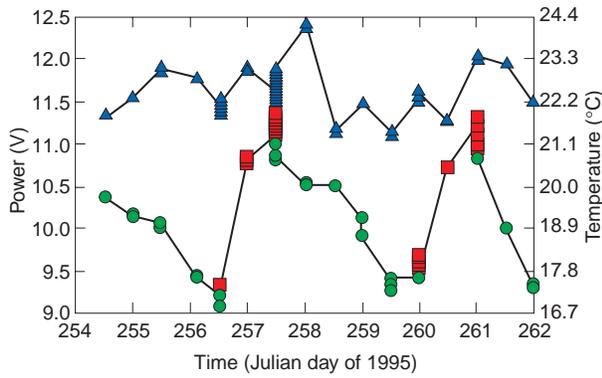
**Figure 13.** Typical plot of Nova voltage/temperature limits. NAVSOC satellite engineers switched among these hardware “curves” to limit battery temperature while maintaining sufficient charge. This plot is for Nova 2. The Nova curves were labeled B-Hi, A-Hi, B-Lo, and A-Lo to identify how to switch among them. There was one command to switch between the 12-cell curves (solid) and the 11-cell curves (dashed). There was another command to switch between A and B curves and a third command to switch between Hi (high) and Lo (low) curves.

During orbits with longer shade times, a higher curve was required to recharge the batteries. However, if the curve selected was too high, the batteries would overcharge and generate heat, which would shorten their lifetime. Battery failure was the failure mode for all three Nova satellites and most Oscar satellites.

Transit satellite power systems were designed to be set once and changed infrequently. Early in life, the minimum power mode was sufficient even in eclipse season. As the solar cells aged, they generated less power. NAVSOC engineers responded to this problem by adjusting the configuration of the satellite power system.

NAVSOC and APL engineers continued their cooperative efforts and developed other innovative techniques that enhanced Transit reliability. For example, by carefully monitoring power system performance and preventing overcharge, NAVSOC engineers were able to successfully operate early Oscar satellites even after one of their eight battery cells failed. A satellite with a second failed cell could operate in full Sun, but not in eclipse season.

As Oscar satellites aged, they required additional power, even during full Sun. NAVSOC engineers designed and implemented a procedure to duty-cycle boost arrays to supply an intermediate amount of power. This procedure switched between slow overcharge and slow undercharge so that the average amount of charge was correct. Figure 14 shows that by daily switching a boost array between main bus and ATC, the battery voltage was kept sufficiently high while preventing damaging temperature increases. The voltage increased when the boost was on main bus (on) and decreased when the boost was on ATC (off). The temperature would increase above acceptable levels if the boost array stayed on much longer.



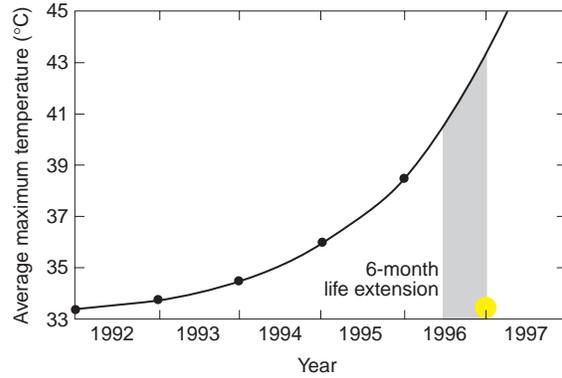
**Figure 14.** Oscar voltage/temperature curves depicting effects of daily switching of boost array between main bus and automatic temperature control circuits. This switching prevented high battery temperatures while maintaining sufficient charge. (Red data points = battery voltage boost on, green = boost off, blue = average battery temperature.)

Changes to Oscars had to be implemented by real-time commands, but the Novas had onboard computers that could execute configuration switches. The NAVSOC engineers were thus able to design and implement a procedure to switch voltage/temperature curves every orbit. This procedure allowed more precise control of battery charging and resulted in the correct amount of charge over each orbit rather than an amount averaged over days as was the case for Oscar satellites.

At the end of service for the last Nova satellite, in full Sun, NAVSOC used a voltage/temperature curve originally designed for a Nova that had lost 1 of its 12 battery cells. This curve greatly reduced the temperature and increased the lifetime. Figure 15 is a plot of maximum Nova 2 battery temperature averaged over the “winter” full-Sun season. It shows a yearly temperature increase until we used the 11-cell curve in 1996. The subsequent temperature reduction (compare actual to projected) added at least 6 months to the life of the last Nova.

## CONCLUSIONS

The power management and drag compensation techniques described in this article greatly contributed to the impressive reliability of Transit, made possible because of dedicated, innovative military and civilian NAVSOC personnel. During its entire operational lifetime—from January 1965 to the end of its navigation service in December 1996—at least one satellite was *always* providing valid navigation messages to the users. The cumulative reliability of individual satellites, at 99.77%, is an extraordinary figure for any system, let alone a space system that cannot be serviced by an on-call repairman. It is significant that the Oscars, with



**Figure 15.** Plot of winter full-Sun seasonal average battery temperature for Nova 2. A significant reduction of battery temperature resulted from using the 11-cell voltage/temperature curve in 1996. The yellow circle indicates the actual temperature point. This temperature reduction increased the satellite lifetime by at least 6 months.

their simple design, were typically more reliable than the Novas. The more complex Nova satellites, although providing important additional capabilities (including the ability to operate for 8 days without ground support), were less reliable partly because more developmental Oscars than Novas were launched before the operational design was finalized. Each Nova satellite was more reliable than its predecessor. The Oscar satellites also had longer lifetimes, typically 10 to 21 years compared with 8 or 9 for Novas.

The other major factor in the admirable success of Transit, besides the devoted NAVSOC staff who took responsibility for the day-to-day operations of Transit and applied innovative techniques, was the APL system design that was so thorough and included valuable operational insights. The combination of good engineering, dedicated personnel, and sufficient fiscal resources created the most reliable system performance imaginable. As the Navy’s satellite operations organization, NAVSOC will continue to apply the lessons learned from Transit operations in the future.

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