ROBERT J. DANCHIK and L. LEE PRYOR

# THE NAVY NAVIGATION SATELLITE SYSTEM (TRANSIT)

This article provides an update on the current status and future projections for the Navy Navigation Satellite System, also known as Transit.

## INTRODUCTION

The Navy Navigation Satellite System (NNSS), also known as the Transit system, was an APL invention that evolved from the Laboratory's discovery that the Doppler shift on the signal broadcast from the Soviet Sputnik satellite in 1957 could be used to predict when the satellite would be in view from APL.[1-5] Development of the system to provide precision navigation for the Navy's strategic system submarines began in 1958, and the system became operational in 1964.

In 1967, the Transit system was released to industry and became available to civilian ships of all nations. The Transit system became the broad-ocean navigation system, the broad-ocean area oil-survey reference system, the international boundary-survey reference system, the Department of Defense geodetic-survey reference system, and a time distribution system.

The Strategic Systems Programs Office, under a Memorandum of Understanding with the Naval Space Command, provides the life cycle management for Transit. The Navy Astronautics Group is the operational agency for the satellite constellation. Production spacecraft were manufactured by RCA (now the General Electric Astro Space Division). Technical direction and systems engineering for the program are provided by APL. The system concept is shown in Figure 1.

Thirty years after the launch of the first experimental satellite, 25 years after the first operational satellite was placed in orbit, and 22 years after the system was declared operational and released for industrial use, we have a robust constellation consisting of seven operational spacecraft and five spacecraft stored in orbit. The last three planned constellation-replenishment launches placed five new spacecraft in orbit in 1988. The Navy anticipates that these launches will provide sufficient spacecraft to maintain the constellation through the year 2000.

Oscar 13, the last of the operational spacecraft built by APL, was declared nonoperational in January 1989 after 21 years and 8 months of service in space, which may be a record for in-orbit continuous operation. All first-generation operational (Oscar) spacecraft in the NNSS constellation were originally launched one at a time on the Scout launch vehicle. Beginning in 1985, the Oscar spacecraft were designated as Stacked Oscars on Scout (SOOS) spacecraft and were launched two at a time. The second-generation radiation-hardened spacecraft were designated as Nova spacecraft. Over the last eight years, the drag-free concept used on Nova has proved successful in providing long-term on-orbit broadcast ephemeris.

## RELIABILITY

Reliability of the Oscar satellites in the constellation continues to be about 14 years of demonstrated in-orbit life. The oldest spacecraft in orbit (Oscar 20) celebrated its sixteenth year of operational service in October 1989. The other 11 spacecraft (see Table 1) have been in orbit for relatively short times. It is worth noting, however, that the SOOS 1, 2, 3, and 4 spacecraft were stored on the ground in dry nitrogen for 15 to 20 years before launch.

The only known subsystem with a limited lifetime (the battery) was replaced with a new flight-qualified battery just before launch. Since the battery cells launched with SOOS 3 and 4 were not produced in an identical manner as the early flight battery cells, we have initiated a simulated in-orbit test on the ground so that we can closely monitor the new battery cells for any indication of early degradation. Table 2 gives the calculated constellation availability, assuming that the Oscar and Nova spacecraft have a 12-year and 8-year mean time to failure, respectively. Since we do not have sufficient long-term lifetime data for the Nova spacecraft in orbit, we are using the goal of an 8-year lifetime from the production spacecraft contract. The assumed Oscar lifetime is more conservative than the 14-year satellite lifetime demonstrated by the satellites since 1967, to allow for the older spacecraft at launch. The only experience with long-term storage of a spacecraft followed by a launch is with Oscar 11, which was stored for approximately 11 years in dry nitrogen. Before launch, it was modified by adding a Global Positioning System translator. The operational navigation service life of Oscar 11 was about 12 years. The spacecraft translator is still operational.

## CONSTELLATION

Each satellite is monitored to determine any anomalous behavior—for example, solar panel performance, battery voltage, and thermal variations. The operator of the system, the Navy Astronautics Group, monitors all anomalies to prevent loss of service. A Satellite Anomaly

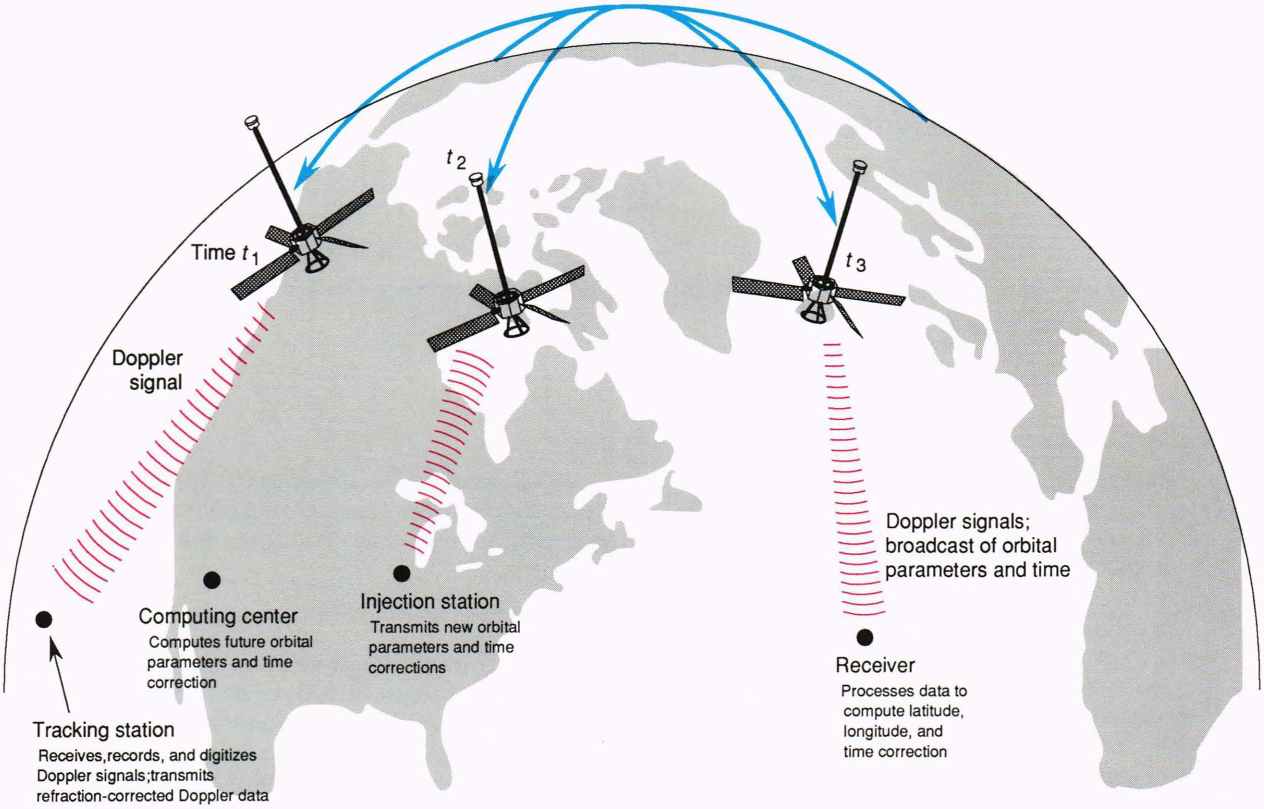


**Figure 1.** The Transit concept in the early 1960s.

**Table 1.** Time in orbit and operational status of Navy Navigation Satellite System constellation as of January 1990.

| | | | Status | |
|---|---|---|---|---|
| Payload | Satellite number | Time in orbit (years:months) | Operational | Stored in orbit |
| Oscar 20 | 20 | 16:2 | X | |
| Nova 1 | 48 | 8:7 | X | |
| Nova 3 | 50 | 5:2 | X | |
| SOOS 1 | 24 | 4:4 | X | |
| | 30 | 4:4 | | X |
| SOOS 2 | 27 | 2:3 | X | |
| | 29 | 2:3 | | X |
| SOOS 3 | 23 | 1:8 | X | |
| | 32 | 1:8 | | X |
| Nova 2 | 49 | 1:6 | X | |
| SOOS 4 | 25 | 1:4 | | X |
| | 31 | 1:4 | | X |

**Table 2.** Calculated Transit constellation availability, assuming an Oscar operating life of 12 years and a Nova operating life of 8 years.

| | Year | | | | |
|---|---|---|---|---|---|
| Probability of having | 1990 | 1993 | 1996 | 1998 | 2000 |
| At least one plane | 1.00 | 1.00 | 1.00 | 1.00 | 0.999 |
| At least two planes | 1.00 | 1.00 | 1.00 | 0.999 | 0.986 |
| At least three planes | 1.00 | 1.00 | 0.998 | 0.984 | 0.902 |
| At least four planes | 1.00 | 0.999 | 0.969 | 0.881 | 0.659 |

Review Board reports and catalogues all satellite anomalies, to provide a synopsis of satellite performance and to provide procedures to eliminate or reduce the impact on the user community. Satellite anomalies also influence the choice between operational and "stored-in-orbit" status for each satellite. All anomalies are analyzed to determine the long-term impact on the spacecraft.

The health of each satellite is determined by routine monitoring. Operational satellites are observed more frequently than are the satellites stored in orbit. The transitions between operation and stored-in-orbit status are kept to a minimum. Periodically, the stored-in-orbit spacecraft are tested operationally.

Currently, the operational SOOS/Oscar satellites have navigation messages injected twice per day. Telemetry is recorded twice per day in conjunction with message injection. Doppler and navigation messages are recorded daily on passes of opportunity. The Nova satellites have navigation messages injected once per day, and telemetry is recorded daily. Doppler and navigation messages are recorded daily on passes of opportunity. The stored-in-orbit SOOS satellites broadcast on a maintenance frequency, and their telemetry is recorded twice per week.

Additional monitoring of the five stored-in-orbit SOOS satellites is conducted according to the following plan: The message readout and operational mode are exercised for one satellite every six months to ensure the serviceability of each particular satellite. A minimum of 72 hours—48 hours to determine the orbit and frequency offset and 24 hours of navigation message testing—is invested. A navigation message is injected twice per day, and telemetry is recorded twice per day. Doppler and navigation messages are recorded daily on passes of opportunity. During the operational period, the clock, carrier stability, carrier signal-to-noise ratio, orbit, and navigation results are monitored in the standard manner for operational satellites.

The sample constellation assignment shown in Figure 2 establishes an overview of the operational status for each satellite. This scenario will vary in accordance with the requirements of the system and the health of the satellites.

## SPACECRAFT

The satellites were placed in orbit (a polar, nominally circular orbit at 600 nmi altitude) by the highly reliable Scout vehicle, but there remained the expected residual inaccuracies in the inclination and eccentricity. These inaccuracies were removed for the Nova series with an orbit-adjustment system, which provided very low nodal precession rates and the bias configuration for the constellation. The SOOS and Oscar satellites have larger node precessions and are, at times, coplanar with other spacecraft in the constellation. Figure 3 shows the orbit plane distribution as viewed from the North Pole on 1 January 1990. Notice that Oscar 20 and SOOS 4 are very nearly coplanar. The three Nova's are separated by about 45°.

A view of the orbit precession over time is presented in Figure 4. There are some intervals when precessions cause orbit planes to cross in late 1989, 1991, and 1996. During these crossing periods, the designated operational spacecraft may change.

The Nova satellites were designed with a disturbance compensation system (DISCOS) for adjusting the along-

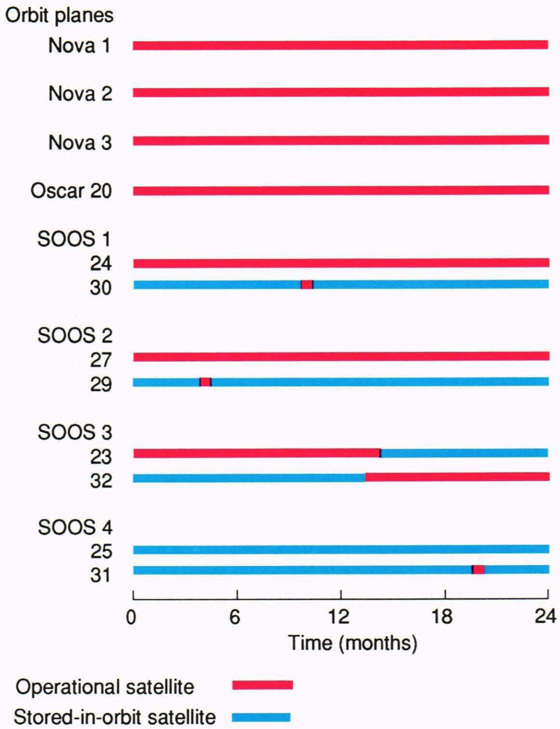


**Figure 2.** Sample constellation assignment, showing distribution choices while keeping seven satellites operational and exercising the operational mode for satellites stored in orbit.

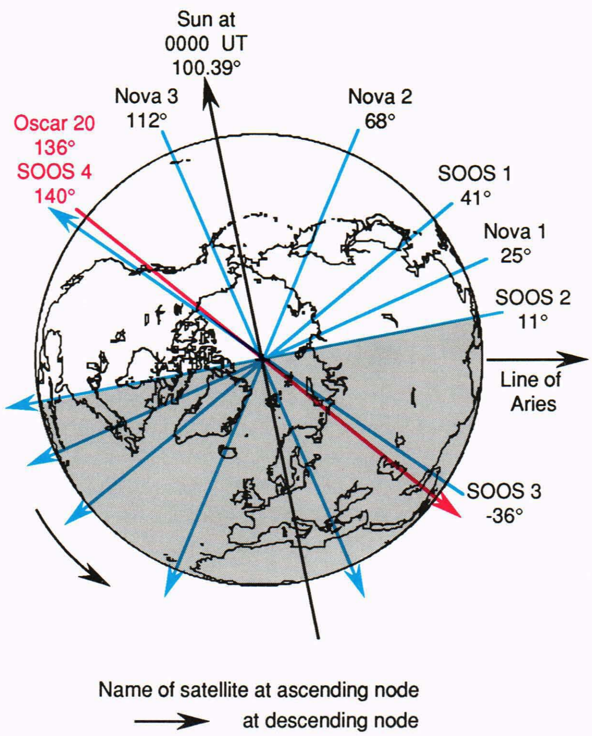


**Figure 3.** View of the Transit constellation in January 1990, as seen from above the North Pole.

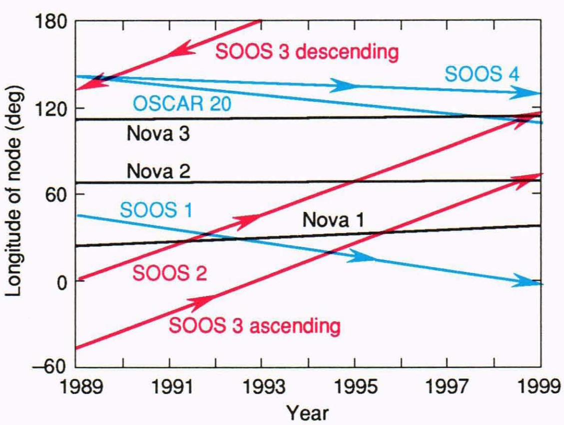


**Figure 4.** Orbit precessions, showing coplanar situations to the year 2000.

track position in their orbits.[5-6] The system automatically compensates for drag and solar pressure uncertainties in orbit prediction. The Navy Astronautics Group commands biases to the DISCOS systems to maintain a phase separation between the Nova satellites. Biasing the DISCOS is accomplished consonant with the orbit tracking and prediction computer program to permit uninterrupted operational service. Acceptable navigation solutions are possible even when orbit planes are nearly coincident if the satellites are separated in phase. The Nova satellites operate with a flight processor (computer) on board, which provides additional flexibility in operations. Delayed commands may be stored and activated in orbit without requiring the satellite to be in view of a station. Data about the orbit may be stored under a variety of programmable criteria.

The DISCOS system required attention to electromagnetic compatibility design criteria. The electric plasma thrusters that compensate for along-track forces introduced electrical noise into other subsystems of the Nova 1 satellite. In particular, the clock and flight computer suffered noise interruptions. Extensive post-launch study of Nova 1 resulted in a rework of Nova 2 and Nova 3 cable harness, filtering, and grounding techniques, which corrected the problem.

## GROUND SYSTEM

The Transit system is operated and maintained by the Navy Astronautics Group from its headquarters at Point Mugu, California. Tracking and injection station detachments are located in Maine, Minnesota, and Hawaii, in addition to the Navy Astronautics Group headquarters in California. This ground network collects Doppler and satellite telemetry data, which is then routed to headquarters for analysis and processing. The computation system at headquarters provides satellite telemetry abstracts to satellite managers and performs the orbit calculations to predict satellite position. Predicted ephemerides are formatted into navigation messages that are returned to the detachments for transmission to the satellites.

The Strategic Systems Programs Office maintains a disaster backup system to use if processing at headquarters is interrupted. Personnel from headquarters have an alternate computer site in the local area where the computational needs can be met. Also, a communication link is maintained between the detachments and APL, where support personnel can assume the computational functions. Part of the continuing refinement of the system includes plans to incorporate additional distributed processing into the ground system at the Minnesota facility.

The drag-compensation algorithm for drag-sensitive satellites is of particular interest. The Navy Astronautics Group predicts the onset of solar storms and their impact on the atmospheric drag by calculating the solar index and magnetic index numbers. When their criteria indicate orbit-prediction problems with the Oscar and SOOS spacecraft that are caused by changes in atmospheric drag, they intervene with the orbit-prediction program and manually establish revised along-track force biases, thus permitting satellites to remain in service when routine procedures would have not kept the satellites' performance within system specifications. The Nova spacecraft have demonstrated their ability to maintain track through abnormal periods of atmospheric drag.

## USERS

The number of system users continues to expand at a slower rate, with many of the new users at the low-cost end of the spectrum, where single-channel receivers are sold to pleasure-craft owners at prices beginning at about $1,000. Two-channel receivers are sold to those requiring precision navigation or survey-quality positioning at prices beginning at $10,000. The last survey indicated that over 80,000 receivers have been manufactured to date.

Figure 5 shows the nominal coverage the system will provide to users over the life of the program with the number of operational satellite planes that are maintained in the constellation. Figure 6 provides the nominal percentage of time that a navigator would have to wait more than eight hours for a navigation fix as the number of satellite planes decreases.

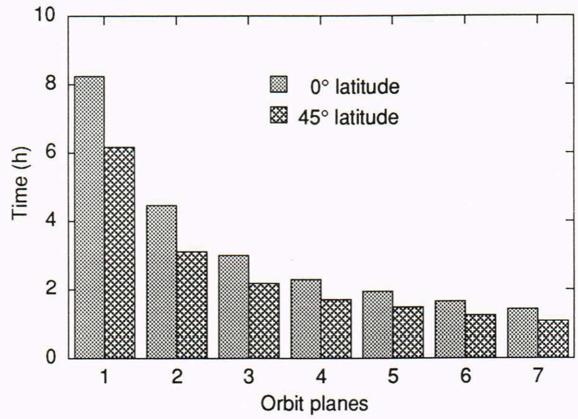


**Figure 5.** Average time between navigation opportunities for various numbers of orbit planes.

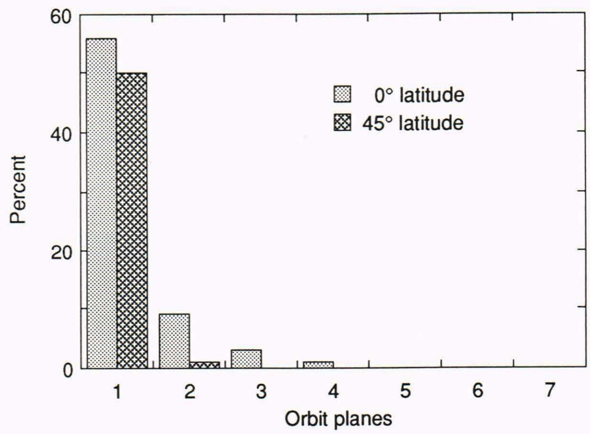


**Figure 6.** Nominal percentage of time a navigator must wait longer than eight hours for various numbers of orbit planes.

## FUTURE PLANS

The Strategic Systems Programs Office plans to continue to operate the system through 1998, with an option to continue operation through 2000. The plan is to operate the Nova and Oscar spacecraft to provide uniform global coverage during the remainder of the program with up to seven operational spacecraft, depending on satellite in-orbit life and orbit dispersion.

The Transit system is healthy, and the plans are to continue to provide high-accuracy outputs and good global Earth coverage through the year 1998.


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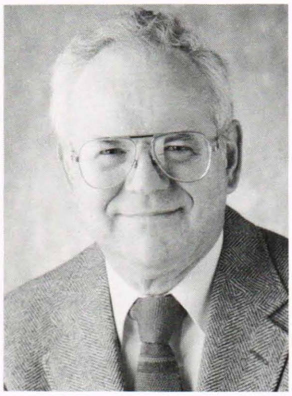
**THE AUTHORS**



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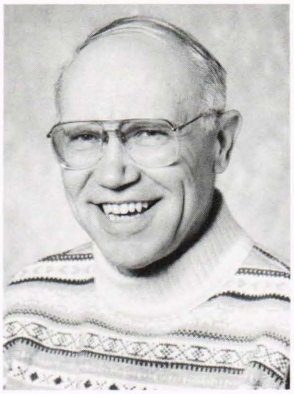

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