ROBERT J. DANCHIK

# THE NAVY NAVIGATION SATELLITE SYSTEM (TRANSIT)

This article provides an update on the status of the Navy Navigation Satellite System (TRANSIT). Some insights are provided on the evolution of the system into its current configuration, as well as a discussion of future plans.

## BACKGROUND

In 1958, research scientists at APL solved the orbit of the first Russian satellite, Sputnik-1, by analysis of the observed Doppler shift of its transmitted signal. This led immediately to the concept of satellite navigation and the development of the U.S. Navy Navigation Satellite System (TRANSIT) by APL, under the sponsorship of the Navy's Special Projects Office, to provide position fixes for the Fleet Ballistic Missile Weapon System submarines. (The articles in Ref. 1, a previous issue of the *Johns Hopkins APL Technical Digest* devoted to TRANSIT, give the principles of operation and early history of the system.) Now, 26 years after its conception, the system is mature. Beginning with the release of the system to industry in July 1967, it has been used by an ever-increasing number of navigators, both military and civilian, for position fixing and for surveying. The civilian users now far outnumber the military users. Over the years, the U.S. Navy, as the operator, has been sympathetic to accommodating the needs of these users, within the constraints of Navy requirements.

## RELIABILITY

Early system plans called for four satellites in equally spaced polar orbit planes (Fig. 1). However, this design goal was never achieved for long in those early days because the satellites had short operational lifetimes. The failures largely resulted from inadequate component quality and the large number of wiring interconnections. However, after OSCAR[2] 10 and OSCAR 12 were launched in 1966 and 1967, respectively, enough data on the failure mechanisms became available to APL to achieve the desired advances in reliability. The integrated circuit introduced in OSCAR 10 significantly extended the satellite lifetime by improving component reliability and reducing the number of interconnections. Subsequently, the last major design change made to the solar cell interconnections, beginning with OSCAR 13, eliminated the thermal-cycling-induced failures observed in these interconnections on OSCAR 10 and OSCAR 12. Since the launch of OSCAR 13 in May 1967, satellite reliability has far exceeded the early design goal of a five-year operational life. The OSCAR 11 solar panels were retrofitted to the OSCAR 13 configuration; this satellite (OSCAR 11) was placed in dry nitrogen storage until it was launched in October, 1977. Prior to launch, it was modified by the addition of a Global Positioning System satellite translator to support the SATRACK Program while still maintaining the TRANSIT navigation capability as a backup mode of operation.

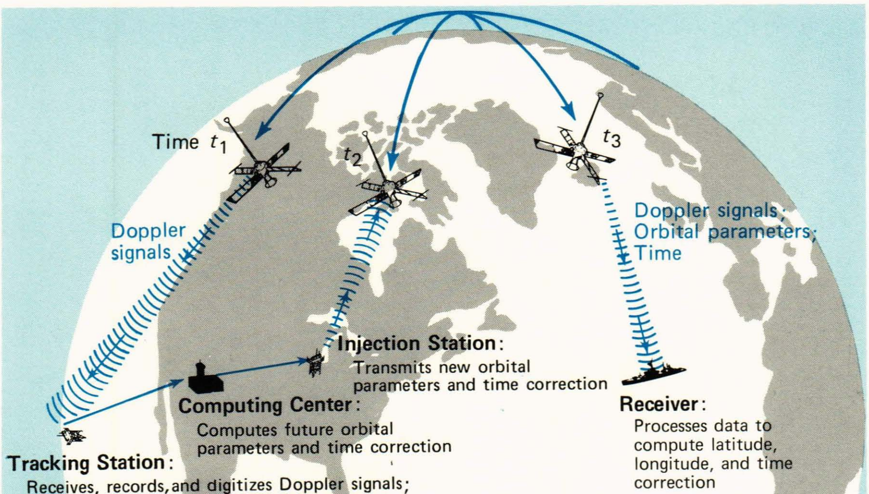


**Figure 1**—TRANSIT concept in the early 1960s.

The calculated mean time to failure of OSCAR satellites since the launch of OSCAR 13 is roughly 14 years.[3] The sample is statistically small. However, there is evidence of an age-dependent failure rate. Table 1 provides a summary of the status of the TRANSIT satellites.

Taking into account past satellite performance and current launch plans, Fig. 2 shows the probability that at least three orbit planes will be available in the satellite constellation from 1985 through 1995. Since the improvements were introduced into OSCAR 13 and subsequent spacecraft, the predominant failure mechanism has been short circuits in the satellite battery. However, there may be other age-induced degradation in other components as well. Because OSCAR spacecraft may be in storage for 15 to 20 years prior to launch, it is difficult to forecast with certainty how long a spacecraft may survive after launch. However, until sensitive components are identified, the current plan is to install a new battery and thoroughly test each stored spacecraft prior to launch.

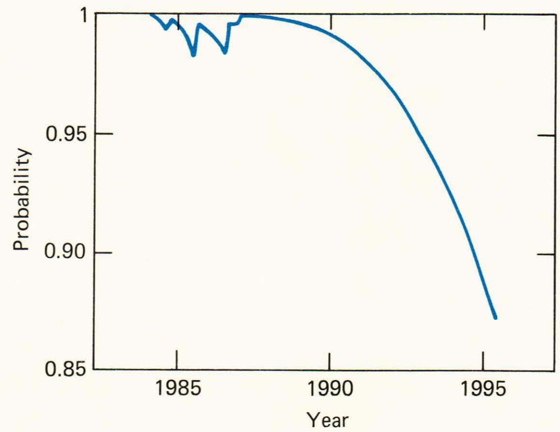


**Figure 2**—Probability that at least three orbit planes will be available in the satellite constellation from 1985 through 1995.

## CONSTELLATION

The early planned constellation was for four equally spaced satellite orbit planes. However, as the system evolved and satellite lifetimes became longer, it became clear that inherent errors in the pointing accuracy of the launch vehicle would result in inclination errors that would make the launch orbit planes precess relative to each other, causing gaps to form in the constellation. These gaps in satellite phasing were referred to as the "streetcar effect" because several satellites would be available for a while, and then a gap in availability would occur. The gaps have been monitored over the years to assure that the gap periods do not become so long as to compromise the system's ability to meet the Navy's needs. Except for a few periods, the satellite orbit planes have drifted relative to each other in such a manner that excessively large gaps have not formed for extended periods of time.

Table 1 indicates which satellites are operational and the status of each; the current constellation of satellites is shown in Fig. 3. As the figure shows, because of the failure of OSCAR 14 we are in one of the rare periods when a large gap has formed in the constellation.

Near-term plans are to reestablish the four-orbit-plane constellation with the launch of a dual OSCAR in 1985. The dotted orbit plane in Fig. 3 shows the planned location for the new spacecraft.

The Navy Astronautics Group maintains the satellite constellation. Through their direction, the system has been operational since 1964 without interruption.

## SPACECRAFT

Currently there are three satellite configurations in the Navy Navigation Satellite System: OSCAR, NOVA, and the dual OSCAR configuration (SOOS, or

**Table 1**—TRANSIT satellite survival data.

| *Satellite* | *Launch* | *Failure* | *In-Service Time (years/months)* | *Availability (%)* | *Status* | *Notes* |
|---|---|---|---|---|---|---|
| OSCAR 13 | May 1967 | | 16/9 | 99.97 | Operational | |
| OSCAR 14 | Sep 1967 | Jan 1984 | 16/4 | | | Battery failed. |
| OSCAR 18 | Mar 1968 | Aug 1976 | 9/4 | | | Battery & boom failed. |
| OSCAR 19 | Aug 1970 | May 1984* | 13/5 | 99.97 | Operational | Intermittent; battery failed. |
| OSCAR 20 | Oct 1973 | | 10/4 | 99.88 | Operational | |
| OSCAR 11† | Oct 1977 | | 0/7 (as a TRANSIT satellite) | 100 | Operational | Intermittent. |
| NOVA 1 | May 1981 | | 2/7 | 98.78 | Operational | |

*Partial failure.
†Operational as a TRANSIT satellite since Jan 1984.

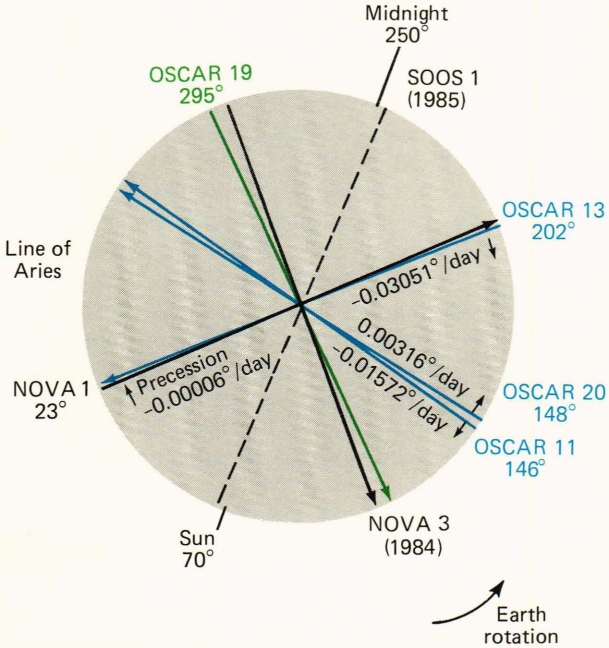


**Figure 3**—View of the operational TRANSIT constellation in October 1984 as seen from a position above the north pole. Because of recent battery cell failures, OSCAR 19 provides service only in full and near-full sun. Planned launch orbits are shown with dotted lines.

Stacked OSCARs on Scout). An artist's concept of the original OSCAR spacecraft (also known as TRANSIT) is shown in Fig. 4a. The OSCAR spacecraft is solar powered, with a command subsystem, an ephemeris storage subsystem, an RF subsystem, a power conversion subsystem, an attitude subsystem, and a telemetry subsystem. OSCAR 13, launched in May 1967 and the oldest of the operational spacecraft in orbit, celebrated its 17th birthday in 1984. OSCAR 14, launched four months after OSCAR 13, lost a second battery cell in January 1984 and was taken out of operational service because the battery voltage could not be maintained during eclipse orbits, causing loss of timekeeping aboard the satellite. After losing a second battery cell, OSCAR 19 continued to operate until May 1984 when the battery no longer could provide enough voltage. In the future, OSCAR 19 will be turned on as power becomes available during semiannual cycles of full exposure of the orbit plane to sunlight, thus precluding the need for battery operation of the satellite.

The NOVA spacecraft was developed to provide hardened spacecraft in the constellation. Figure 4b is an artist's concept of NOVA. The NOVA satellite, designed by APL and manufactured by the RCA Astro-

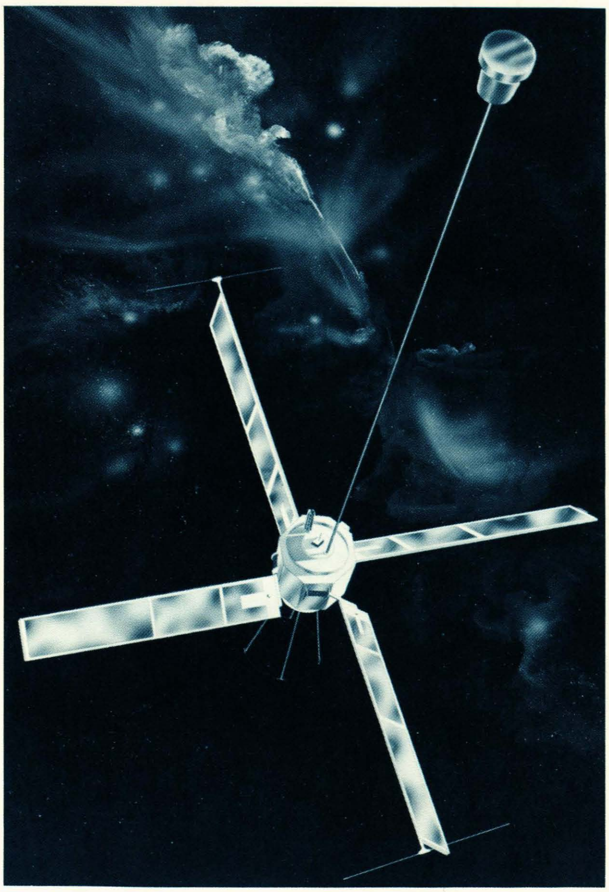

**Figure 4a**—Orbit concept of an OSCAR satellite. The launch weight is 130 pounds and the orbit is 600 nautical miles (nominal).

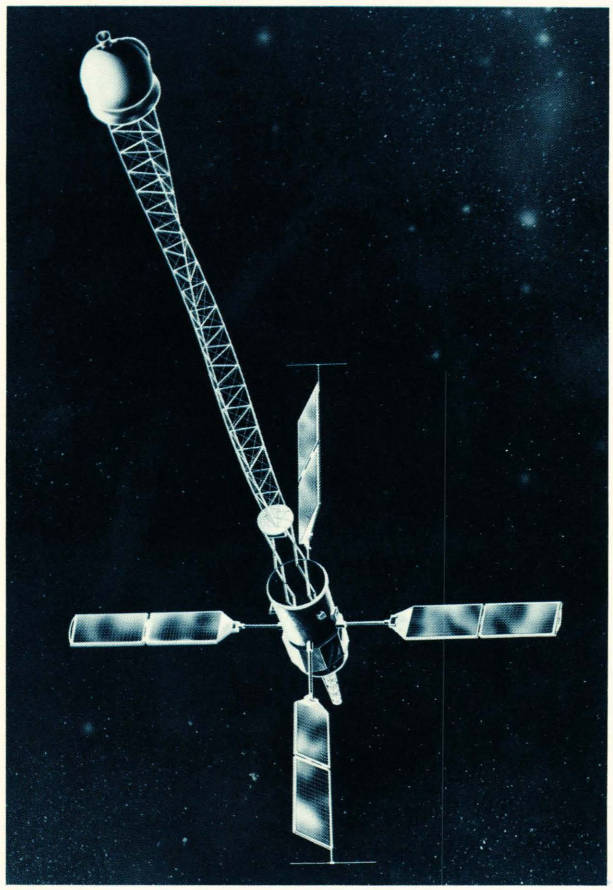

**Figure 4b**—In-orbit concept of a NOVA satellite. The launch weight is 370 pounds and the orbit is 600 nautical miles (nominal). The spacecraft has a DISCOS subsystem to compensate for the variable air drag and plane solar pressure forces acting on the spacecraft.

Electronics Division,[4] has several features not available with the OSCAR spacecraft. These include redundant programmable computers, a single-axis disturbance compensation system (DISCOS), potential for improved time and frequency control, phase control, autonomy, an orbit adjust and transfer system, increased transmitted power, and a three-axis stabilization system. These features have been demonstrated with the NOVA 1 satellite launched in May 1981.[4]

The single-axis DISCOS on NOVA 1 does not approach the precision of the three-axis DISCOS system flown on the TRIAD spacecraft in 1972. An unknown force acting on the proof mass and affecting the performance of the DISCOS was observed immediately after activating the system on NOVA 1. The force was found to be caused by outgassing from materials within the DISCOS cavity. The outgassing had a measurable effect on the ability to accurately predict orbits in the early months and it was observed for approximately one year after launch. Figure 5 shows the decay of the observed force due to outgassing[5] for about 200 days after launch. A method was developed (described in Ref. 5) to change incrementally the DISCOS proof mass bias force under control of the onboard computer to counteract the outgassing forces and thereby provide improved orbit predictability. Current operational procedures at the Navy Astronautics Group, the system operators, provide for injecting ephemeris data into the NOVA satellite that are accurate enough to allow for autonomous operation of the spacecraft for up to 6 days.

Several anomalies have occurred on NOVA 1 that have been traced to electromagnetic interference generated by operation of the Teflon solid-propellant propulsion subsystem. This subsystem uses a high voltage to vaporize the Teflon in order to supply the thrust needed to compensate for drag effects on the DISCOS. An effort is under way at APL to reduce the susceptibility of the NOVA 3 spacecraft to this interference. NOVA 3 was launched in October 1984.

The Navy has a program at the RCA Astro-Electronics Division to modify certain OSCAR spacecraft so that two of them (SOOS) may be launched on one Scout launch vehicle. The development was initiated because the most recent Scout booster configuration can launch a heavier payload into orbit, and because phaseout of the availability of the Scout vehicle is not coincident with system-life requirements. Storage of satellites in orbit is a desirable alternative for meeting system-life requirements; it provides for the most cost-effective use of satellite and booster resources.

Figure 6 is an artist's concept of the SOOS satellites in orbit. In the stacked configuration on the booster, the upper spacecraft (shown in the background) looks like a normal OSCAR. The lower spacecraft (in

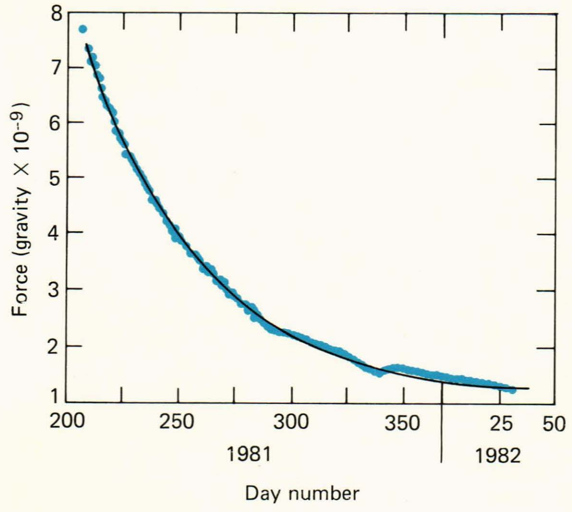


**Figure 5**—Approximately 200 days of decaying force bias on the proof mass caused by outgassing within the proof mass cavity. Measurable force bias changes continued for approximately a year after launch. An opposite-directed force bias under the onboard spacecraft computer control was commanded to the proof mass to counteract the effect on the DISCOS subsystem performance.

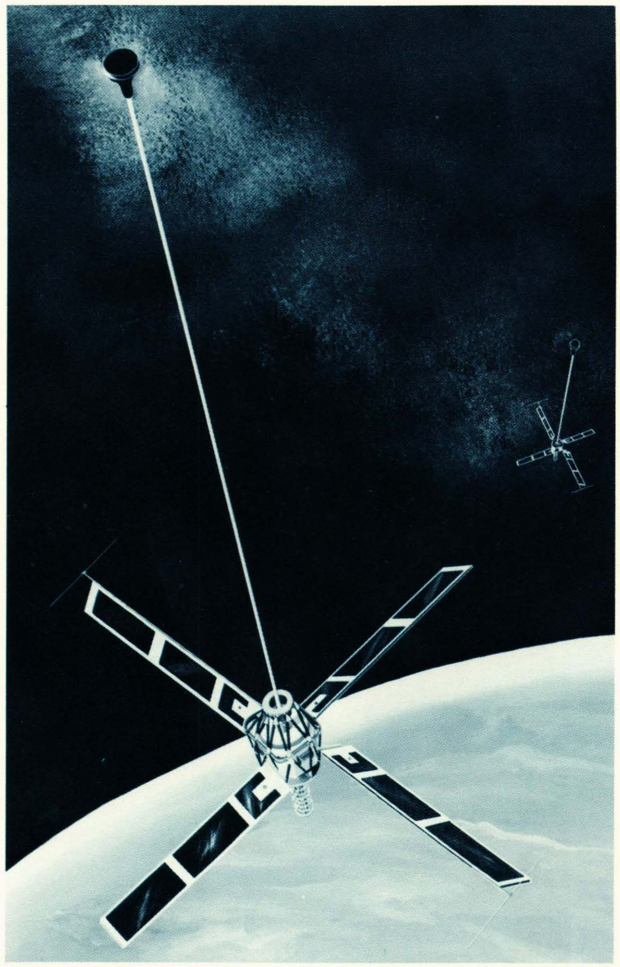

**Figure 6**—Orbit concept of the SOOS satellites. The lower OSCAR spacecraft (in the foreground) retains the graphite epoxy cradle that supports the upper OSCAR spacecraft (in the background) during the launch mode. The spacecraft are separated from the launch vehicle and from each other a short time after launch.

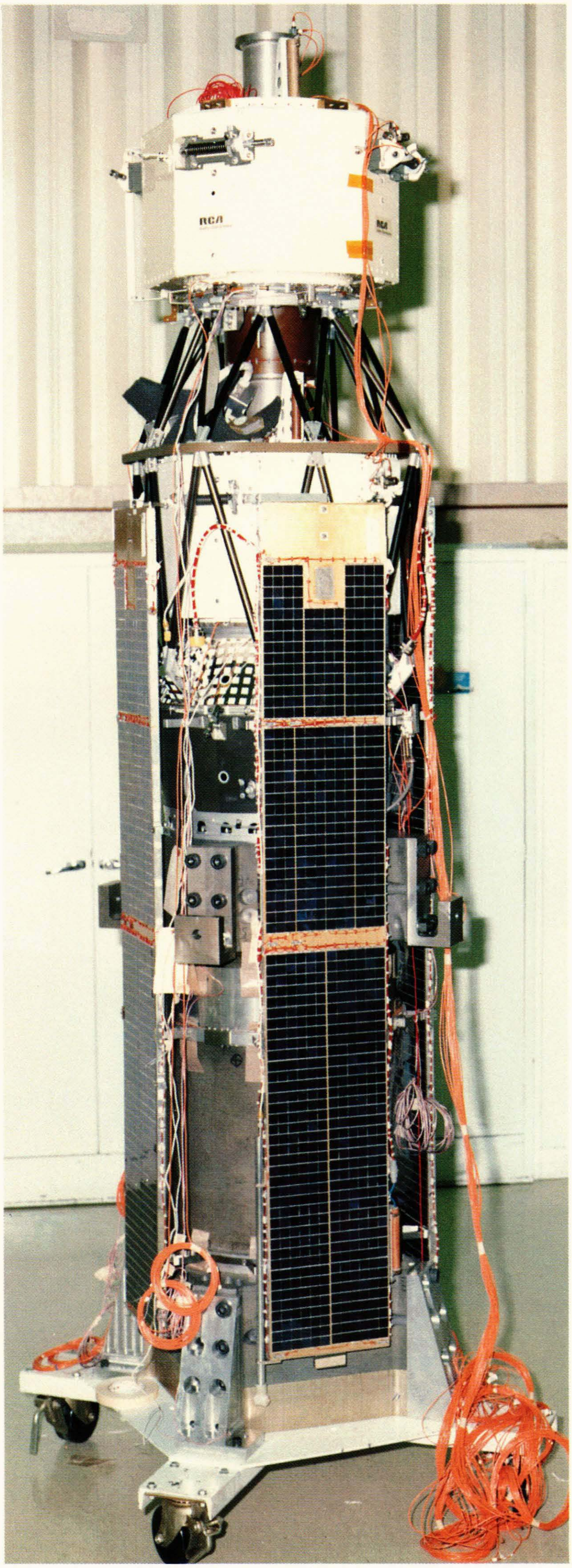

**Figure 7**—SOOS configuration on a simulated Scout rocket fourth stage. The upper spacecraft has the solar panels removed. (The wires are part of the test instrumentation.)

the foreground) is surrounded by a cradle that carries the load of the upper spacecraft during launch. The cradle remains permanently attached to the lower spacecraft as shown. Figure 7 shows the stacked configuration on the booster fourth stage with the solar panels removed from the upper spacecraft. Table 2 compares the major characteristics of the TRANSIT spacecraft.

## USERS

Since its inception, the primary users of the TRANSIT system have been the Fleet Ballistic Missile submarines. However, work was soon initiated at APL to lower the cost of equipment for surface ships. The first of the designs for surface ships and attack submarines produced in the 1960s was designated the AN/SRN-9 (Fig. 8). It is a two-frequency integral Doppler receiver. The functional design concept is replicated today as the method used in precision, two-frequency equipment for position fix and for surveying. In the 1970s, APL initiated the design of a simpler single-frequency unit of somewhat lower accuracy, which was designated the AN/SRN-19. The goal was to develop a model that could be produced in small quantities for less than $20,000. Approximately 250 units have been produced by the Naval Electronics Systems Command. The AN/SRN-19 was the first major step to low-cost receiver designs and has led to a dramatic cost reduction and an equally dramatic increase in the number of TRANSIT system users, equipment manufacturers, and system manufacturers.

The results of a 1982 survey request by the Navy Astronautics Group are shown in Fig. 9. The dramatic increase in the number of user sets produced in the past 10 years is apparent. The manufacturers responding to the survey were

Amex Systems
Brookes & Gatehouse, Ltd.
Canadian Marconi Co.
Electral, Inc.
Frequency and Time Systems, Inc.
Furuno Electric Co., Ltd.
JMR Instrument, Inc.
Magnavox
Motorola
Navidyne Corp.
Navigation Communication Systems
Polytechnic Marine, Ltd.
Racal Decca, Ltd.
Radar Devices, Inc.
Rauff and Sorensen A/S
Raytheon Marine Co.
Rediffusion Radio Systems, Ltd.
Tracor Instruments.

Today, several manufacturers produce single-channel receivers for under $3,000. Figure 10 shows an example.

With these receivers, the users determine navigation fix positions, survey, and recover universal time. The

**Table 2**—Characteristics of TRANSIT satellites.

| *Characteristic* | *OSCAR* | *SOOS* | *NOVA* |
|---|---|---|---|
| Weight (pounds) | 130 | 280 | 370 |
| Ephemeris | 16 hours | 16 hours | 8 days |
| Power output/polarization | | | |
| 400 megahertz | 2 watts/RHC | 2 watts/LHC | 5 watts/LHC |
| 150 megahertz | 1 watt/LHC | 1 watt/LHC | 3 watts/LHC |
| Gravity gradient stabilized | Yes | Yes | Yes |
| Station seeking/orbit adjust | No | No | Yes |
| Station keeping/orbit maintenance | No | No | Yes |
| Drag compensation | No | No | Yes |
| Attitude control | 1 axis | 1 axis | 3 axis |
| Operational frequency offset (parts per million) | ≈ −80 | ≈ −80 | −84.48 |
| Maintenance frequency offset | No | Yes | Yes |
| Programmable computer | No | No | Yes |

RHC = right-hand circular polarization
LHC = left-hand circular polarization

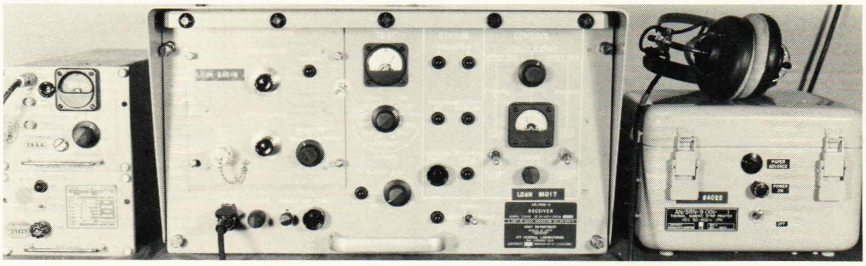

**Figure 8**—The AN/SRN-9 was the first precision operational navigation receiver for surface ships. It is used on some Navy ships.

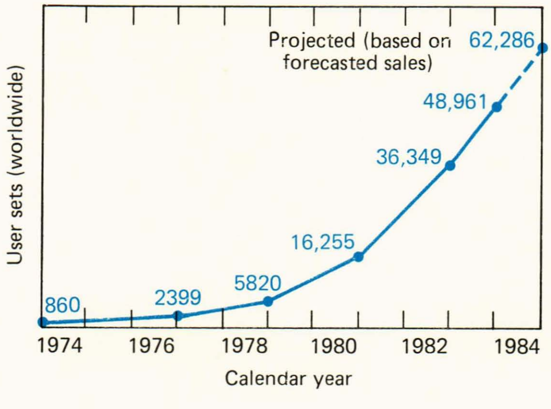


**Figure 9**—Results of a survey of user equipment manufacturers conducted in 1982. The manufacturers responding to the user equipment survey are listed in the text.


**Figure 10**—Example of a low-cost satellite navigation receiver manufactured by Magnavox. (Photograph courtesy of the Magnavox Corporation.)

system is the reference for broad ocean area oil exploration and for Department of Defense global surveying. It is also used in the position determination and the translocation mode to survey international locations and borders in both developed and developing countries. The U.S. Coast Guard requires that ships in U.S. waters have either Loran-C or TRANSIT receivers for position determination. Because of the global nature of TRANSIT, many shipping lines are using TRANSIT receivers.

The system was of particular importance to the oil industry during the oil shortage in 1973-74 in determining accurate locations of shipping so that oil cargos could be diverted to the international port where the best price could be obtained. Using TRANSIT, ships can perform more efficient searches for fish and can return to the same location later. The most recent acceptance of the system has been in the pleasure boat

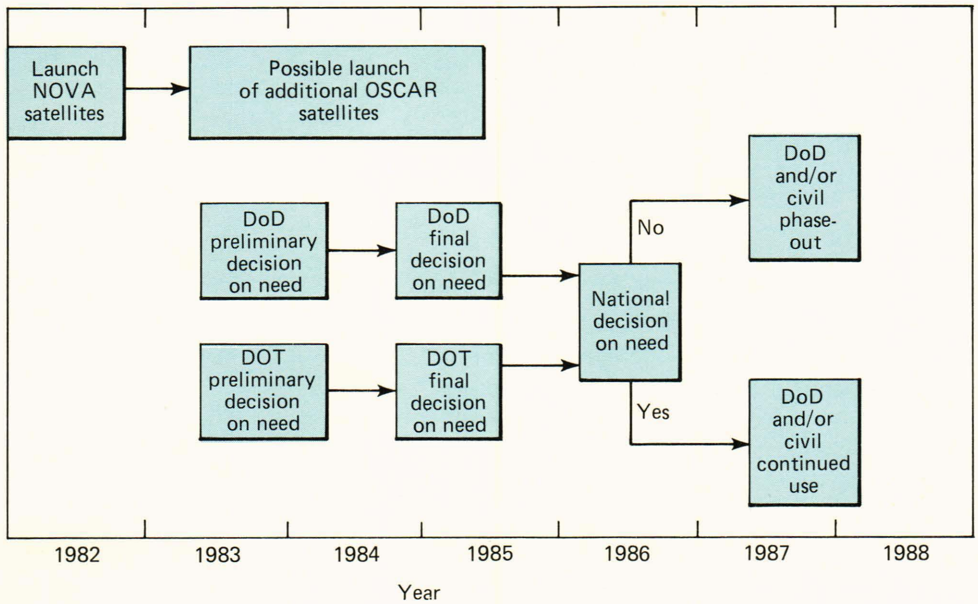


**Figure 11**—Operating plan and time schedule for the TRANSIT system, extracted from the Federal Radio Navigation Plan, 1982.

fleet, thus opening the market to several hundred thousand potential users.

In summary, the TRANSIT system has attained wide international acceptance. Several user conferences are held each year that are attended by hundreds of people representing international users.

## FUTURE

TRANSIT has served the Navy and worldwide civilian users very well over the past 20 and 15 years, respectively. For the next 10 years, TRANSIT service should continue much the same as in the past while a new satellite system, the Global Positioning System, is being developed by the Air Force for the Department of Defense, which plans to continue operation of TRANSIT until 1994. The decision process for TRANSIT, outlined in the Federal Radio Navigation Plan, is shown in Fig. 11. A second factor influencing the future of TRANSIT is the operational support of the Scout launch vehicle, which is planned to end at the end of fiscal year 1989. Between now and then, the Navy plans to maintain the constellation of satellites; planned launches to support the constellation through 1994 are

| | |
|---|---|
| SOOS 1, 1985 | SOOS 3, 1987 |
| SOOS 2, 1986 | SOOS 4, 1988 |
| NOVA 2, 1987 | SOOS 5, 1989 |

REFERENCES and NOTE

[1] *Johns Hopkins APL Tech. Dig.* **2**, 3-44 (1981).
[2] OSCAR is the phonetic alphabet symbol for O, which stands for "operational."
[3] W. L. Ebert, JHU/APL S1A-07-84 (10 Jan 1984).
[4] J. R. Staniszewski, "Expectations Achieved: NOVA I: The Second Generation Navy Navigation Satellite," *RCA Engineer* (Jul/Aug 1982).
[5] A. Eisner and S. M. Yionoulis, "The 'Drag Free' Navigation Satellite," *Proc. National Aerospace Symp.*, The Institute of Navigation, Moffett Field, Calif. (23-25 Mar 1982).

ACKNOWLEDGMENTS—Since its establishment in 1964, operation of the Navy Navigation Satellite System by the Navy Astronautics Group (NAG) has been outstanding. Satellite availability, discussed in this paper, is a tribute to NAG's dedication and determination to maintain the spacecraft in operational use. Recent establishment of the Naval Space Command has provided for the inclusion of all Navy space activities under one command. APL is the Design and Development Agent and provides system support for the Navy Navigation Satellite System. RCA/AED is the spacecraft production contractor for the Navy Navigation Satellite System.