THE NAVY NAVIGATION SATELLITE SYSTEM : DESCRIPTION AND STATUS

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The present article was published in *Navigation* — the Journal of the U.S. Institute of Navigation — in 1968 (Vol. 15, No. 3, Fall 1968) after being presented at the Institute's National Marine Navigation Meeting at Annapolis, Maryland, in 1967.

Although, inevitably, progress has been made in this field since the article was originally written it is felt that this article — large extracts of which are here reprinted by kind permission of the Director of the Institute of Navigation — is of present interest.

Mr. STANSELL received the Institute's Burka Award for 1968 for this paper.

ABSTRACT

TRANSIT, the Navy's Navigation Satellite System, has been in continuous operation since January 1964, but only a very limited number of shipboard prototype navigation sets have been available. Production equipment is just now becoming available, both for military and for commercial applications, and the months ahead will see greatly expanded use of the system. This paper describes the overall system, with emphasis on the user's equipment, computation requirements, and accuracy considerations. A look is also taken into the system's future, including expanded applications.

INTRODUCTION

The Navy Navigation Satellite System, perhaps better known as TRANSIT, has been continuously operational since January 1964. The system was initially developed as a very accurate, passive, all-weather, world-wide navigation aid for Polaris submarines. Its usefulness to the surface fleet, however, was effectively and dramatically demonstrated during the summer of 1964 by Project Sea Orbit. A prototype AN/SRN-9 navigation receiver (see figure 1) aboard the nuclear cruiser *Long Beach* reliably provided fixes throughout this around-the-world cruise, often when no other external navigation aids were available because of cloud cover and geographical position.

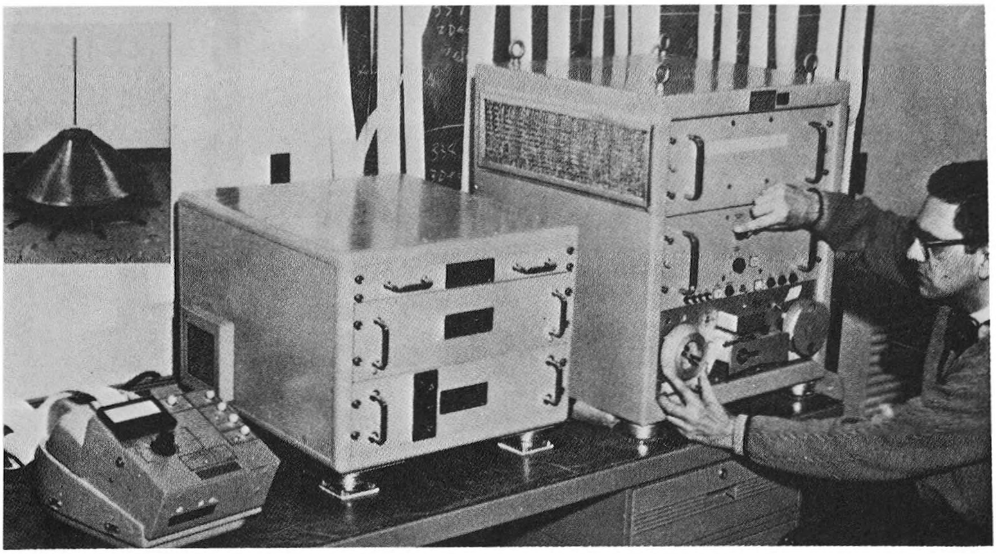


FIG. 1. — Prototype AN/SRN-9 (XN-5) navigation receiver and CP-827 computer.

Based on evaluation of prototype AN/SRN-9 sets, it was decided to procure fully military-approved equipment for fleet use. However, it was not until December 1966 that the Naval Ships Systems Command placed such a contract (with ITT Aerospace Division). In the meantime, the Applied Physics Laboratory at Johns Hopkins University has built a total of 23 prototype sets for interim use.

In other words, TRANSIT, the most accurate world-wide navigation system available, has been in operation for nearly four years, and the only users have been Polaris submarines and a handful of surface ships. This situation is about to end. By early 1968, three different firms will be producing TRANSIT navigation equipment. On 29 July 1967 Vice President HUMPHREY announced that details of the navigation equipment and computational requirements are being released, thus opening the door to extensive commercial use. Four different types of equipment are now being built, and at least three more are on the drawing boards.

Not only will there be a very large increase in the number of TRANSIT users, but the number of applications is increasing. The Applied Physics Laboratory has successfully demonstrated aircraft navigation, geodetic-quality surveying, and rapid precise relative-position determination (translocation). Special equipment for each of these applications is now under development and soon will be available.

TRANSIT SYSTEM DESCRIPTION

Figure 2 is the most basic block diagram of TRANSIT satellites. These satellites transmit two coherent carrier frequencies, one at 150 MHz and the other at 400 MHz. Because they are both derived by direct multiplication of the reference oscillator output frequency, these transmitted frequencies are very stable. In fact, they change no more than about one part in 10^{11} during a satellite pass, and are therefore assumed to be constant with negligible error.

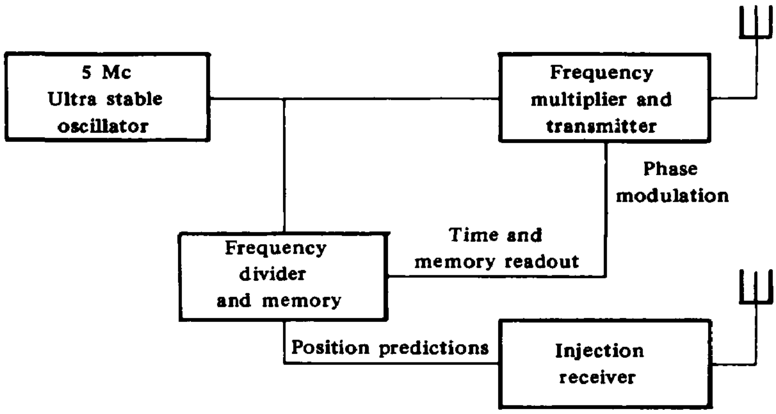


FIG. 2. — Most basic block diagram of Transit satellites.

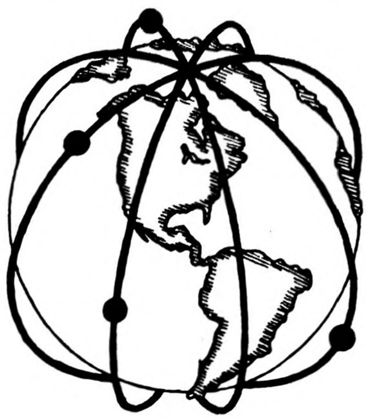
The reference oscillator output is also divided in frequency to drive the memory system. In this way, the navigation message stored there is read out and encoded by phase modulation onto both the 150 MHz and the 400 MHz signals at a constant and carefully controlled rate. Thus, the transmitted signals provide not only a constant reference frequency and a navigation message, but also timing signals, because the navigation message is controlled to begin and to end at the instant of every even minute. An updated navigation message and time corrections are obtained periodically from the ground via the satellite's injection receiver.

Figure 3 shows that the navigation satellites are in circular polar orbits, about 600 nautical miles high forming a "birdcage" of orbits about the revolving earth. Thus, each point on earth passes under every satellite orbit twice in 24 hours. Because the satellites circle the earth in only 1¾ hours, they pass within line of sight of an earth observer at least twice each time he is near an orbit. Therefore, each satellite will provide at least four navigation fixes per 24-hour day. With the three satellites being maintained operational today, one can expect no less than twelve passes per day, averaging two hours between fixes.

Figure 4 is a representation of the overall navigation system, the ground portion of which is operated by the U.S. Navy Astronautics Group, with headquarters at Point Mugu, California. The ground system consists of four tracking stations, a computing centre, and two injection stations. It is an important attribute of TRANSIT that all ground stations are located on U.S. soil.

The tracking stations are located in Maine, Minnesota, California, and Hawaii. Each time a TRANSIT satellite passes within line of sight of a tracking station, it receives the 150 MHz and 400 MHz signals, measures the doppler frequency shift on these signals caused by the satellite's motion,

Navigational Satellite System



Four polar orbits

FIG. 3. — Transit satellites are placed in circular, polar orbits about 600 nautical miles above the earth.

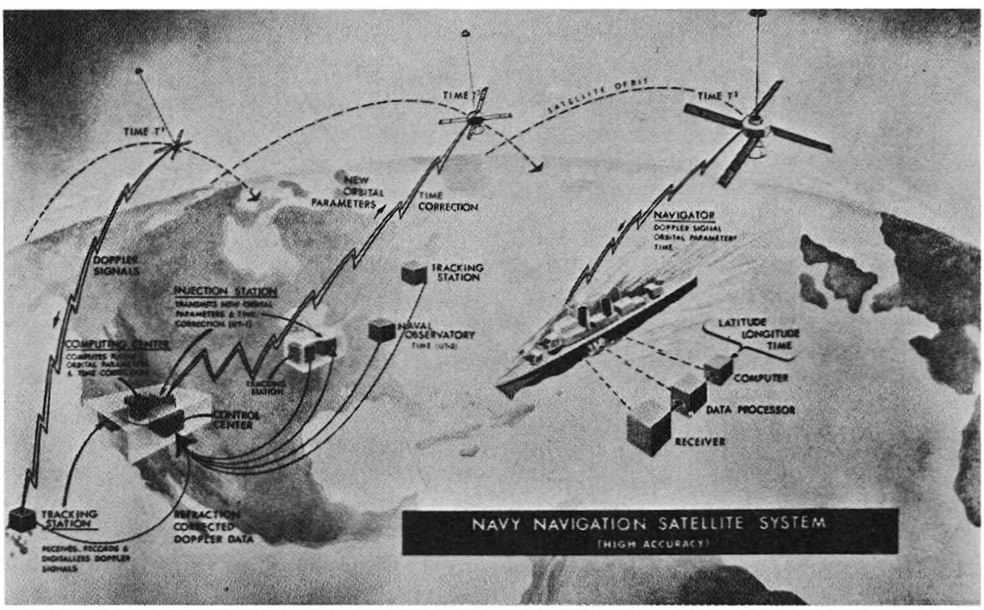


FIG. 4. — Overall schematic drawing of the Navy navigation satellite system.

and records the doppler frequency shift as a function of time. The doppler data then are sent to the Point Mugu computing centre, where they are used to determine each satellite's orbit and to project each orbit many hours into the future.

To digress for a moment, it should be noted that in order to determine a satellite orbit and to project that orbit into the future, one must have an excellent mathematical model of the earth's gravity field. Without an excellent gravity model, it would be impossible to predict accurately where the satellite will go. Determining the gravity field with sufficient accuracy has certainly been the most challenging problem in developing

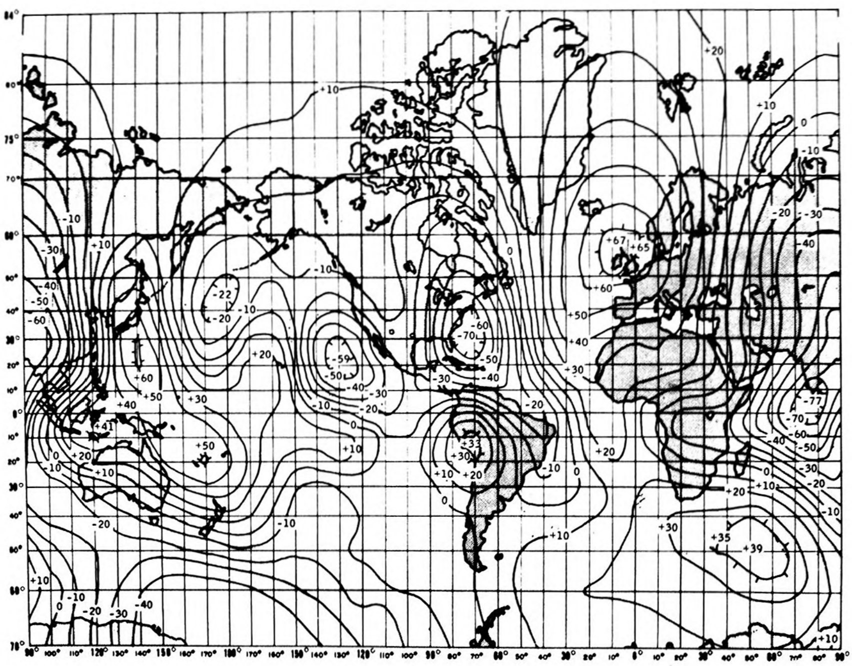


FIG. 5. — Contour plot of mean sea level deviations from a reference ellipsoid, in metres, as defined by the gravity model in operational use since January 1966.

the TRANSIT system. Figure 5 is a contour map showing the deviations of mean sea level (the geoid) from a perfectly elliptical earth as defined by the gravity model which has been in operational use since January 1966.

Returning to figure 4, the computing centre creates a navigation message from the predicted orbit. This navigation message is provided to one of two injection stations, from which it is transmitted to the appropriate satellite. Each satellite receives a new message about once every twelve hours, although the memory can run for sixteen hours without requiring a reload.

As stated earlier, the satellite continuously transmits its navigation message, which lasts exactly two minutes and which begins and ends at the instant of each even minute. Each two-minute message contains two parts, one fixed and one which changes from message to message. The fixed part, defined by figure 6, is a set of parameters describing a perfectly smooth, precessing elliptical orbit. The variable part of the message is a set of corrections which, when added to the smooth orbit, define the actual position of the satellite at eight two-minute time points. This portion of the message is variable because every two minutes a new orbital correction is added and the oldest one is deleted, keeping the message up to date with the changing position of the satellite.

To summarize, the TRANSIT system is designed so that each satellite is a self-contained navigation beacon. It transmits two very stable frequencies, timing marks at two-minute intervals and a navigation message which describes the satellite's position at each timing mark. By receiving these signals during a single pass, the system user can calculate an accurate position fix.

Word number	Symbol	Meaning	Units
56	t_p	Time of perigee	min
62	$\dot{M}$	Rate of change of mean anomaly	deg/min
68	φ	Argument of perigee at t_p	deg
74	$\lvert\dot{\varphi}\rvert$	Rate of change of argument of perigee (Absolute value)	deg/min
80	ε	Eccentricity of orbit	-
86	A_0	Semi-major axis of ellipse	km
92	Ω_N	Right ascension ascending node at t_p	deg
98	$\dot{\Omega}$	Rate of change of Ω_N	deg/min
104	$\cos\psi$	Cosine of orbit inclination	-
110	Ω_G	Right ascension Greenwich	deg
128	$\sin\psi$	Sine of orbit inclination	-

Fig. 6. — Fixed portion of satellite navigation message.

OBTAINING A POSITION FIX

Measurement technique

By receiving the navigation message, the TRANSIT system user learns the position of each passing satellite at the two-minute time marks. Thus, to obtain a fix, he must measure his position relative to the known satellite orbit. This measurement is made by means of the doppler frequency shift on the received signals, which is a unique function of the observer's position (and motion) and the known orbit of the satellite.

Figure 7 illustrates the doppler measurement technique employed by the AN/SRN-9 navigation receiver. The frequency, f_R, being received from the satellite at any time consists of the frequency being transmitted, f_T, plus a doppler frequency shift due to relative motion between the satellite and the receiver. Note that the transmitted frequency is not exactly 400 MHz, but it is offset low by 80 parts per million (32 kHz at 400 MHz).

The navigation receiver has within it a very stable crystal reference oscillator, from which a 400 MHz ground reference frequency, f_G, is derived. Thus, the navigation receiver is able to obtain a relatively low difference frequency (32 kHz ± 8 kHz) between f_G and f_R, which are both near 400 MHz. The doppler measurement is obtained by counting the number of difference frequency cycles which occur between each two-minute timing

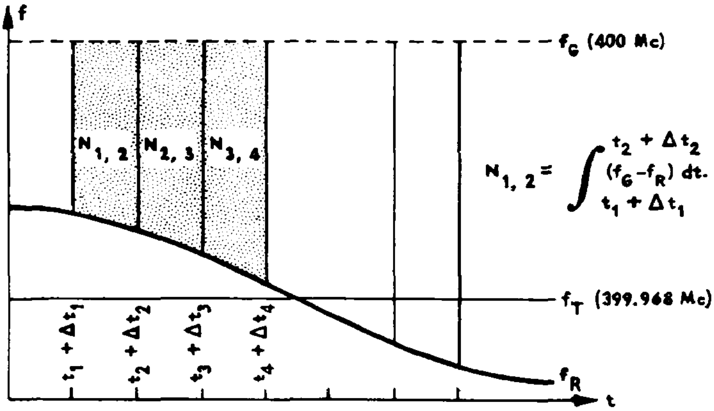


FIG. 7. — Implementation of integrated doppler count.

mark received from the satellite. This process is called the integrated doppler measurement, because the frequency count may be represented mathematically by an integral of the difference frequency over the specified time interval.

Geometric interpretation

The integrated doppler count can be interpreted geometrically. Figure 7 shows that each count, N_{12}, N_{23}, etc., is really the count of a constant difference frequency, $f_G - f_T$, plus a count of the number of doppler frequency cycles received during that time interval. It is the doppler cycle count which is physically meaningful; the count of the difference frequency $f_G - f_T$ is simply an additive constant which, for convenience, will be denoted by ΔF.

The geometric interpretation is aided by figure 8, which illustrates

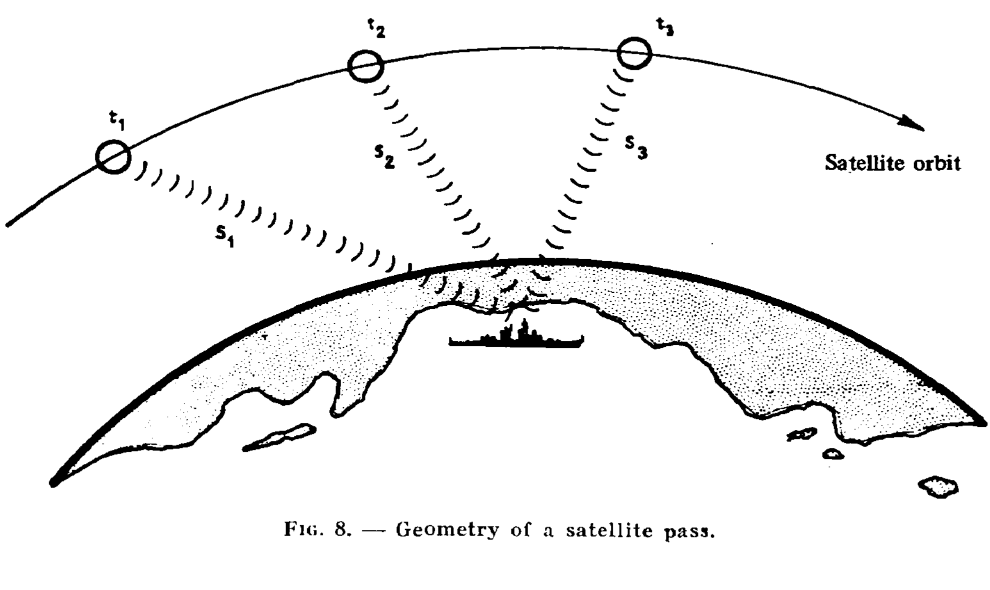


FIG. 8. — Geometry of a satellite pass.

that the distance between the satellite and the observer changes throughout the satellite pass. It is this change, in fact, which causes the doppler frequency shift on the received satellite signals. As the satellite moves closer to the receiver, more cycles per second must be received than were transmitted to account for the shrinking distance. For each wavelength the satellite moves closer to the ship, one additional cycle must be received. Therefore, the doppler frequency count is a direct measure of the change in distance between the receiver and the satellite over the doppler count interval. In other words, the doppler count is a geometric measure of th range difference between the observer and the satellite at two points in space accurately defined by the navigation message. Note also that this is a very sensitive measure of slant range difference; each count represents one wavelength which, at 400 MHz, is only ¾ metre long.

Mathematical interpretation

For those who are interested, the following paragraphs present a somewhat more rigorous mathematical interpretation of the doppler count. Recall that the doppler count is a count of the difference frequency $f_G - f_R$ over the time interval between receipt of two satellite timing marks. The equation defining the doppler count N_{12} is given beside figure 7 and repeated below as equation (1).

$$N_{12} = \int_{t_1 + \Delta t_1}^{t_2 + \Delta t_2} (f_G - f_R)\, dt \tag{1}$$

Note that $t_1 + \Delta t_1$ is the time of *receipt* of the satellite time mark which was transmitted at time t_1. Therefore, Δt_1 and Δt_2 represent the propagation time delay for the time marks to travel the distances S_1 and S_2 from the satellite to the receiver. The propagation delay is defined by the slant range distance divided by the speed of light.

$$\Delta t_j = S_j / c \tag{2}$$

Equation (1) represents the measurement actually made by the receiver, but this expression can be expanded mathematically as given in equation (3).

$$N_{12} = \int_{t_2 + \Delta t_2}^{t_2 + \Delta t_2} f_G\, dt - \int_{t_1 + \Delta t_1}^{t_2 + \Delta t_2} f_R\, dt \tag{3}$$

The first integral in equation (3) is of a constant frequency f_G, so it is easy to integrate, but the second integral is of the changing frequency f_R. However, this second integral represents the number of cycles *received* between the times of *receipt* of two timing marks. By a "conservation of cycles" argument, this quantity must equal identically the number of cycles *transmitted* during the time interval between *transmission* of the timing signals. This identity is indicated by equation (4).

$$\int_{t_1 + \Delta t_1}^{t_2 + \Delta t_2} f_R\, dt \equiv \int_{t_1}^{t_2} f_T\, dt \tag{4}$$

Substituting this expression into equation (3) gives :

$$N_{12} = \int_{t_1 + \Delta t_1}^{t_2 + \Delta t_2} f_G \, dt - \int_{t_1}^{t_2} f_T dt \tag{5}$$

Now, because the frequencies f_G and f_T are assumed constant during a satellite pass, the integrals in equation (5) become trivial, resulting in:

$$N_{12} = f_G \, [(t_2 - t_1) + (\Delta t_2 - \Delta t_1)] - f_T (t_2 - t_1) \tag{6}$$

Rearranging the terms in equation (6) gives:

$$N_{12} = (f_G - f_T) \, (t_2 - t_1) + f_G \, (\Delta t_2 - \Delta t_1) \tag{7}$$

Because $(f_G - f_T)$ also is assumed constant during a satellite pass, and because $(t_2 - t_1)$ is the constant 120 seconds between transmission of the satellite's time marks, their product, which will be denoted $\Delta F \, \Delta T$, is constant. By substituting the definition of Δt_j given in equation (2) and by noting that the wavelength of the frequency f_G is defined by:

$$\lambda_G = c/f_G \tag{8}$$

Equation (7), defining the doppler count, becomes :

$$N_{12} = \Delta F \Delta T + (1/\lambda_G) \, (S_2 - S_1) \tag{9}$$

Therefore, it is evident that each doppler count consists of a constant plus a direct measure of the slant range change between the receiver and the satellite over the designated time interval. It is also convenient to rewrite this equation, solving for ΔS_{12},

$$\Delta S_{12} = (S_2 - S_1) = \lambda_G N_{12} - \lambda_G \Delta F \Delta T \tag{10}$$

Calculating a position fix

Five or six two-minute doppler counts are obtained during a typical satellite pass. Each doppler count consists of a constant plus a measured slant range difference between the receiver and the satellite at positions defined by the navigation message. The measured range differences are truly known only if the constant but unknown frequency difference, ΔF, between the satellite's oscillator and the receiver's reference oscillator can be determined.

To calculate a position fix, the doppler counts and the satellite message are fed to a digital computer. The computer is also provided with an initial estimate of the ship's latitude and longitude and an estimate of the frequency difference ΔF. The computer then compares calculated range differences from the known satellite positions to the estimated ship's position with those measured by the doppler counts, and the navigation fix is obtained by searching for and finding those values of latitude, longitude, and ΔF which make the calculated range differences agree best with the measured range differences. Because the geometry is complicated, only simple, linearized equations are used, and the computations are performed iteratively until the solution converges. No more than three or four iterations are normally required, and a fix is obtained within a minute or less on typical small digital computers.

Motion of the ship

If a ship is underway during a satellite pass, then that motion must be provided to the computer. It may be described in terms of speed and heading, range and bearing to a fixed target, or estimated latitude and longitude at the two-minute time marks. The data may be inserted manually or electrically, and it can come from any available motion sensing device, but it must be provided as an input to the navigation fix computations.

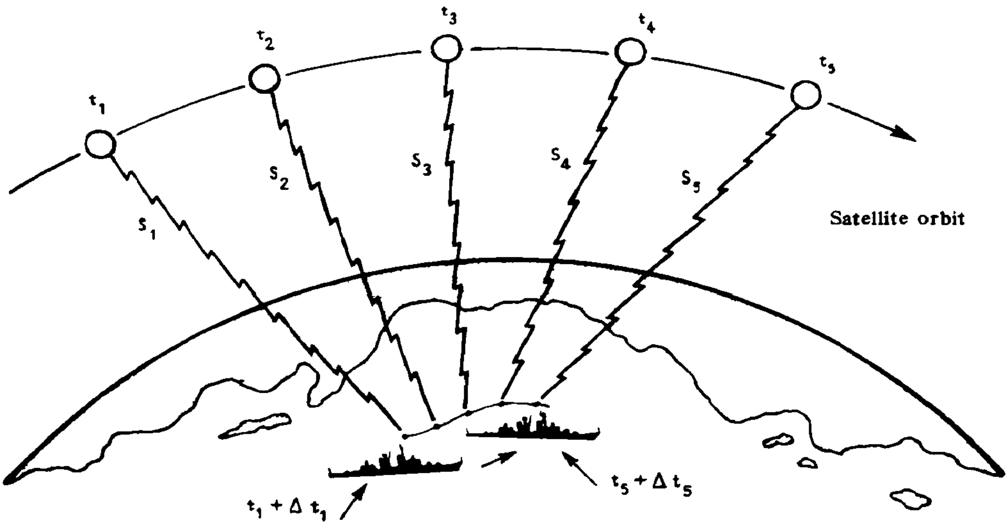


FIG. 9. — When underway, ship's motion must be known so that measured slant range differences to the satellite will be geometrically meaningful.

Figure 9 shows that if ship's motion is accurately known, the calculated range differences from satellite to ship can be compared accurately and correctly with the range differences measured by the doppler counts. In this case, although the navigation fix is expressed as a latitude and longitude at a single time point, the computation is in reality navigating the entire specified path of the ship. In other words, the navigation computation finds where on the earth that path best fits the doppler-measured range differences.

These considerations naturally raise the question of what happens when the ship's motion cannot be determined accurately, e.g., due to an unknown current. This question will be considered further in the next section, but, at least in theory, the navigation computation can also be used to determine such velocity errors. In practice, however, it has been determined that only one component of velocity error, namely the northsouth component, can be determined effectively. Nevertheless, this capability can significantly improve the results to be expected when relatively poor velocity measuring instruments are available.

ACCURACY CONSIDERATIONS

Fixed station accuracy

For a fixed station, there are four basic error sources. These are : (1) instrumentation measurement noise, (2) signal propagation anomalies, (3) antenna height estimate error, and (4) error in the satellite orbit prediction.

Instrumentation measurement noise may be determined by placing two navigation sets side by side and comparing their navigation results. Many such trials have demonstrated that this noise is on the order of 0.005 nautical mile, which is entirely negligible except for the most precise surveying requirements.

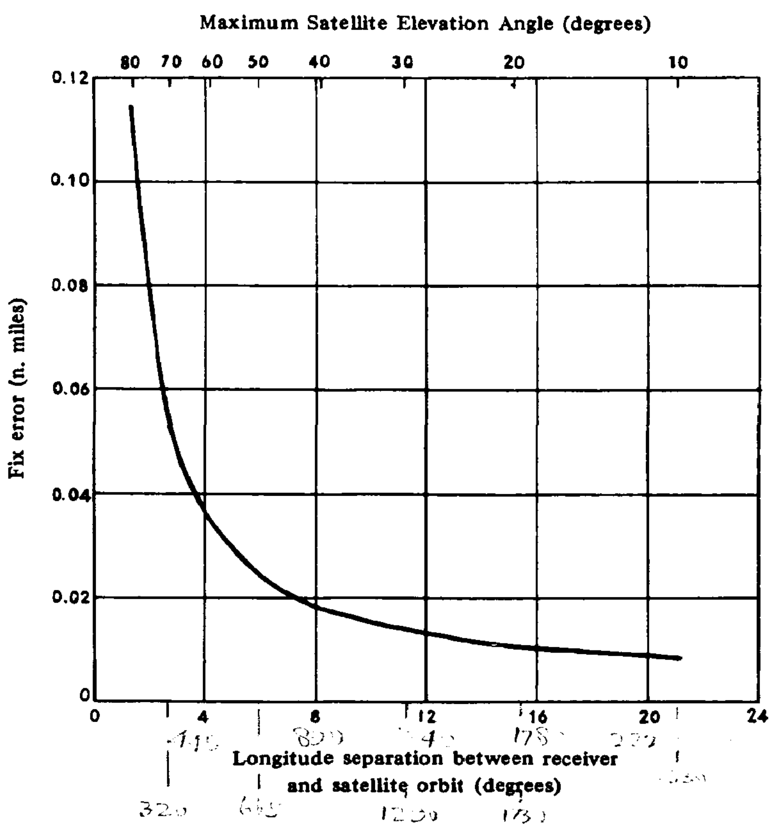


FIG. 10. — Fix error resulting from each 100 feet of antenna height error.

There are two types of signal propagation anomalies. One is ionospheric refraction and the other is tropospheric refraction. Because doppler frequency shift and the tropospheric refraction effect are both directly proportional to transmitted frequency, there is no way for a TRANSIT receiver to measure the tropospheric refraction error. On the other hand, ionospheric refraction is very nearly inversely proportional to frequency, so that a good measure of ionospheric refraction error can be made by comparing the doppler frequency shift at 400 MHz with that at 150 MHz. This is, in fact, the reason two frequencies are transmitted by TRANSIT satellites. The error remaining after this correction is typically less than 0.005 nautical mile. Without this correction, the error will range from negligible to as great as 0.5 nautical mile, depending on time of day and recent sunspot activity. Tropospheric refraction error is typically about 0.02 nautical mile, which can be reduced by an order of magnitude, if desired, with a mathematical tropospheric refraction correction, to which local weather conditions are an input.

If antenna height above local sea level is not well known, e.g., for aircraft navigation, an error will be introduced as indicated by figure 10.

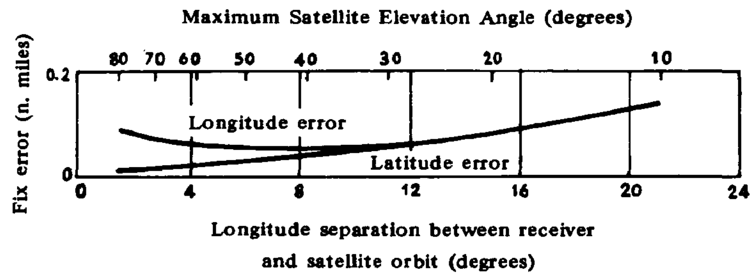


Fig. 11. — Fix error resulting from each knot of velocity east error.

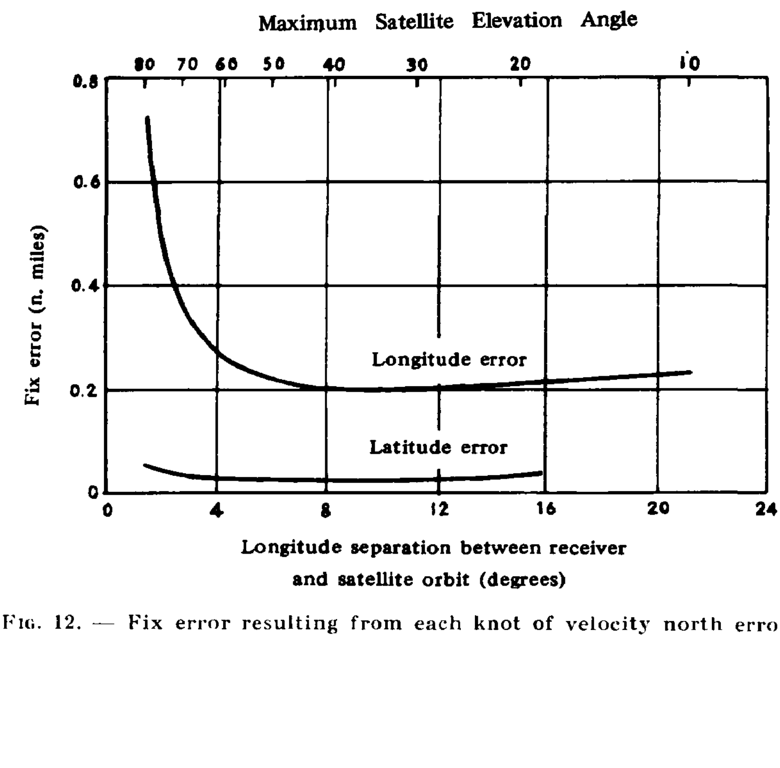


Fig. 12. — Fix error resulting from each knot of velocity north error.

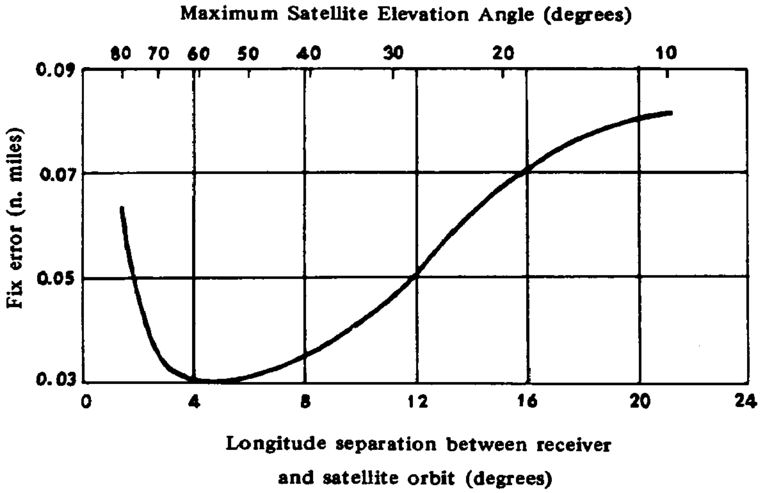


FIG. 13. — Average fix error resulting from random errors of 60 ft RMS in specifying ship's position at two-minute time marks.

Hopefully, shipboard navigation will not be troubled by such an error.

The largest single source of error for a fixed station is the error in satellite orbit prediction. This, in turn, is almost entirely due to the accuracy with which the earth's gravity field is known.

Accuracy when underway

The previous discussion of navigation errors for a fixed receiver applies equally well to one which is moving, as long as that motion over the earth is precisely known. This fact has been firmly established by tests in which a moving ship was accurately tracked by theodolites. However, if the ship's motion is not known accurately, additional error will be introduced into the TRANSIT navigation fix.

If the ship's unknown motion takes the form of a constant velocity error, the resulting position fix error can be expressed quite easily, as indicated by figures 11 and 12. These figures show that, in round numbers, the position fix will be about 0.25 nautical mile for every knot of unknown velocity. These figures also show that a velocity north error typically causes a fix error two or three times greater than a velocity east error.

In many cases, the ship's motion is defined by range and bearing to a fixed target or by latitude and longitude at the two-minute marks. For instance, latitude and longitude are used whenever an inertial navigation system is available. In addition to a constant drift rate or velocity error, there also will be a random error in defining the ship's position at each time mark. This random error can result from a number of sources, including roundoff of the data words, i.e., not having enough significant digits. Figure 13 shows typical fix errors which can result from such random position definition errors.

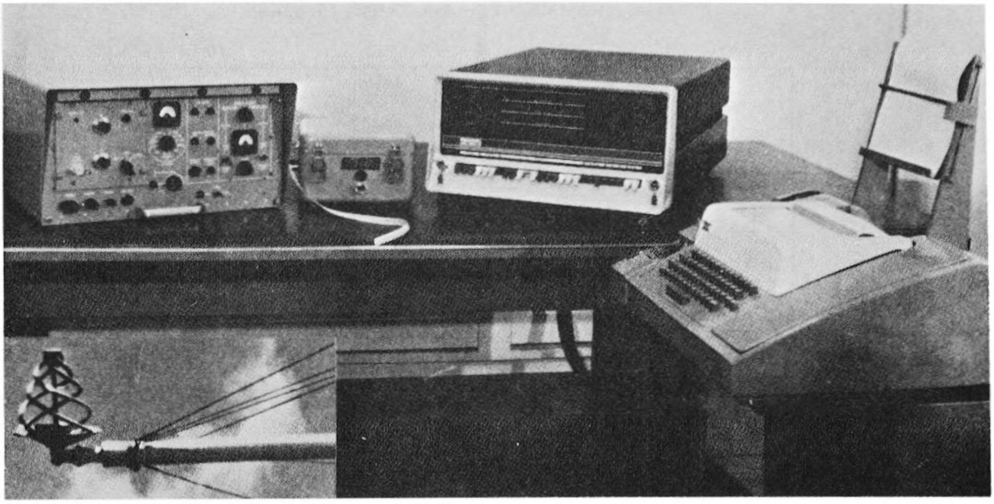


FIG. 14. — Radio navigation set designed by ITT Aerospace Division.
A commercial version, known as Seaway, can be used with commercial computers, such as the PDP-8S shown on its right.
(*Photography courtesy of ITT Aerospace Division*).

Accuracy summary

Because all the errors discussed above are relatively small, it should be evident that TRANSIT is the most accurate, world-wide navigation system available, especially for users having very precise motion measurement equipment. However, fixes with a typical accuracy of 0.25 nautical mile are available to practically every ship. (See, for example, NASA Contractor Report; NASA CR-612n September 1966.)

EQUIPMENT

Figures 14, 15 and 16 give an idea of the design and size of the equipment.

THE FUTURE

Equipment trends

There are three distinct trends in the navigation equipment now becoming available or in design. The first of these trends is toward fully

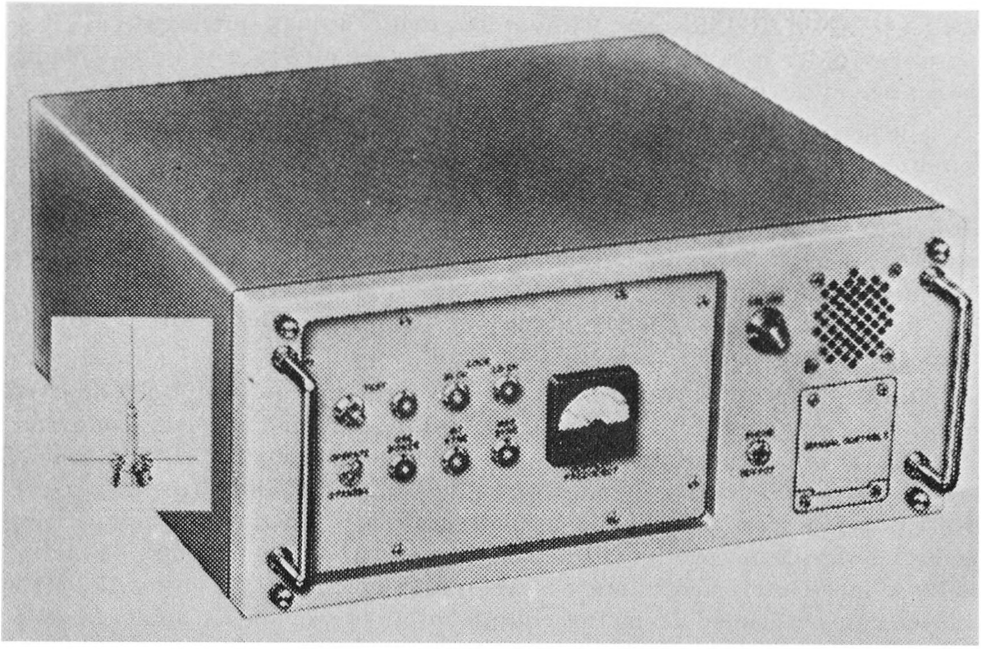


FIG. 15. — 702 CA radio navigation set designed by the Magnavox Company. The set can be used with a wide variety of commercial computers. (*Photograph courtesy of the Magnavox Company*).

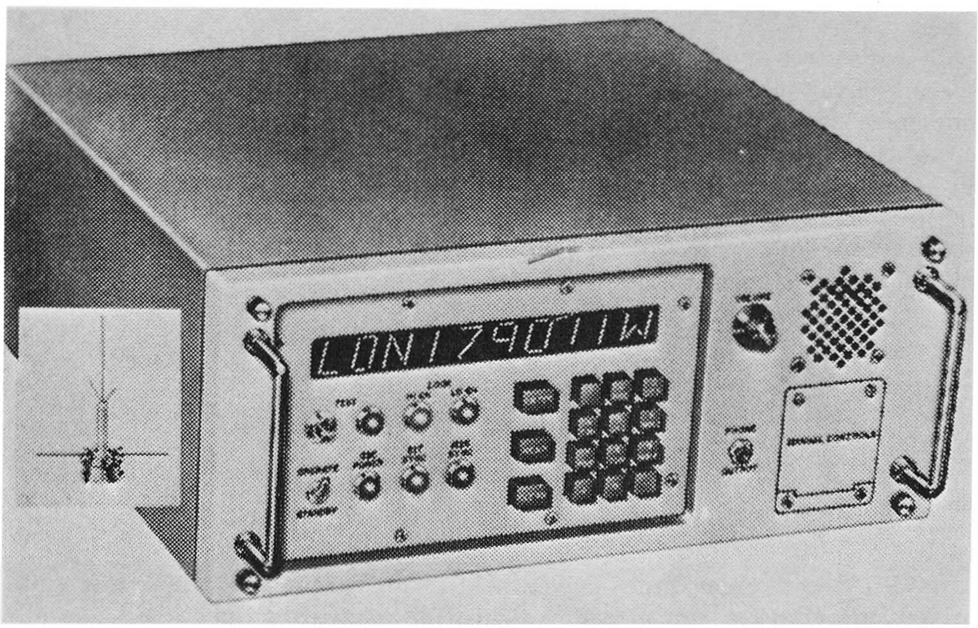


FIG. 16. — 706 CA radio navigation system designed by the Magnavox Company includes both the receiver and the computer in the same size cabinet as the 702 CA receiver shown in figure 15. (*Photograph courtesy of the Magnavox Company*).

automatic operation. Most receivers will search for, acquire, and track every available satellite pass without requiring human intervention. If a digital computer is connected both to the receiver and to a velocity sensing instrument, the entire navigation fix procedure can be automatic.

The second equipment trend is toward combining the receiver and the computer. This technique saves money by permitting the computer to perform some of the functions now implemented in the receiver with hardware. More important, perhaps, is that the computer program is delivered with the equipment, and the problems of hardware interface compatibility and computer program checkout are entirely eliminated. This technique is particularly attractive for those who desire a totally hands-off operation.

The third trend is toward lower cost. Although a TRANSIT receiver now can be obtained for about $30 000 and a combined receiver/computer for about $55 000, these prices can be expected to drop for three reasons. One is that as production volume rises and initial design investments are covered, prices can drop. The second reason is that, in a competitive market, design innovations will be sought to further reduce costs. Finally, for those more interested in low cost than high accuracy, the entire 150 MHz receiver can be deleted from the equipment. This saving is achieved only at the expense of ionospheric refraction correction, which seldom reaches a half mile in magnitude.

Number of satellites

Because reasonably priced navigation equipment is now becoming generally available both for government and commercial uses, both the number of users and the number of TRANSIT system applications are bound to increase substantially. However, many potential applications, e.g., aircraft navigation, often require more frequent fixes than three satellites can provide, and interest is growing in increasing the number to at least four and perhaps as many as twelve to twenty-four satellites, giving essentially continuous coverage.

OTHER SYSTEMS

Omega

With about eight high power VLF transmitting stations, many on foreign soil, OMEGA can provide world-wide navigation coverage. The one significant advantage to OMEGA is continuous coverage, versus a satellite fix about every two hours, assuming no increase in the number of satellites. In all other respects, e.g., accuracy, radio interference, variable propagation effects, and lane ambiguity, TRANSIT had the advantage. It will be very interesting to watch the parallel growth of and uses for these two navigation systems.

One very interesting fact which generally has been overlooked is how well OMEGA and TRANSIT complement each other, much in the same way that TRANSIT aids and complements any other navigation system. Whether it be an inertial navigation system or dead reckoning TRANSIT provides an accurate position fix often enough to keep the continuous navigation aid from drifting too far off course. To provide that fix, the TRANSIT computation must know the ship's motion during the satellite pass, and that data is obtained from the continuous navigation aid. This same complementary arrangement is not only possible between TRANSIT and OMEGA (or any other VLF navigation aid), but it holds substantial promise. Frequent TRANSIT fixes can overcome many typical VLF navigation problems, e.g. lane ambiguity and variable or unknown propagation time delays. (See, for example, J.H. STANBROUGH, Jr., Experimental VLF Relative Navigation on R/V *Atlantis II*, Cruise 15, Woods Hole Oceanographic Institution Reference No. 66-61, November 1966.)

Synchronous satellite navigation system

There continues to be much interest in a navigation system based on synchronously orbiting satellites. The attraction is fourfold. First, at synchronous altitude (19 327 nautical miles above the earth) one satellite can serve a vast portion of the earth. Second, because the satellite appears to be stationary or to move very slowly, continuous navigation would be available. Third, because communication satellites will be at synchronous altitude anyway, it appears convenient to combine the communication and navigation functions in the same satellites. Finally, by a combination communication and navigation satellite, a means of traffic control from a shore station(s) would be available.

The approach which appears most feasible is like a "big LORAN in the sky", i.e., the observer, by receiving signals from three satellites at known positions, would measure the range difference between two pairs of these satellites and determine his location. Thus, to have world-wide coverage will require no less than twelve and perhaps as many as twenty-four satellites, all at synchronous altitude.

Such a system certainly can be built, given enough time and enough money. A number of organizations, both military and civilian, are interested and are studying various proposals for overcoming the technical difficulties. However, at this time, there is no major effort to build such a system, and if an effort is begun, it surely would be many years before the system could be operational.

At much less cost, most of the advantages claimed for the synchronous navigation system can be gained simply by increasing the number of TRANSIT satellites. The ground system is in place and would not have to be expanded. Even the aspect of traffic control can be obtained by providing a suitable communications link. In other words, if by any means, including communication satellites, ships or airplanes can communicate with a shore station, traffic control can be obtained. In fact, given such a communication system, ships and airplanes can obtain TRANSIT navigation fixes *without* having a digital computer. To achieve this, the six or seven 7-digit doppler count numbers obtained by the TRANSIT receiver plus speed and heading information would be sent via the communication channel to a central, shore-based computer. The central computer would calculate the position fix, store it for traffic control, and relay the fix back to the ship or airplane for its use.

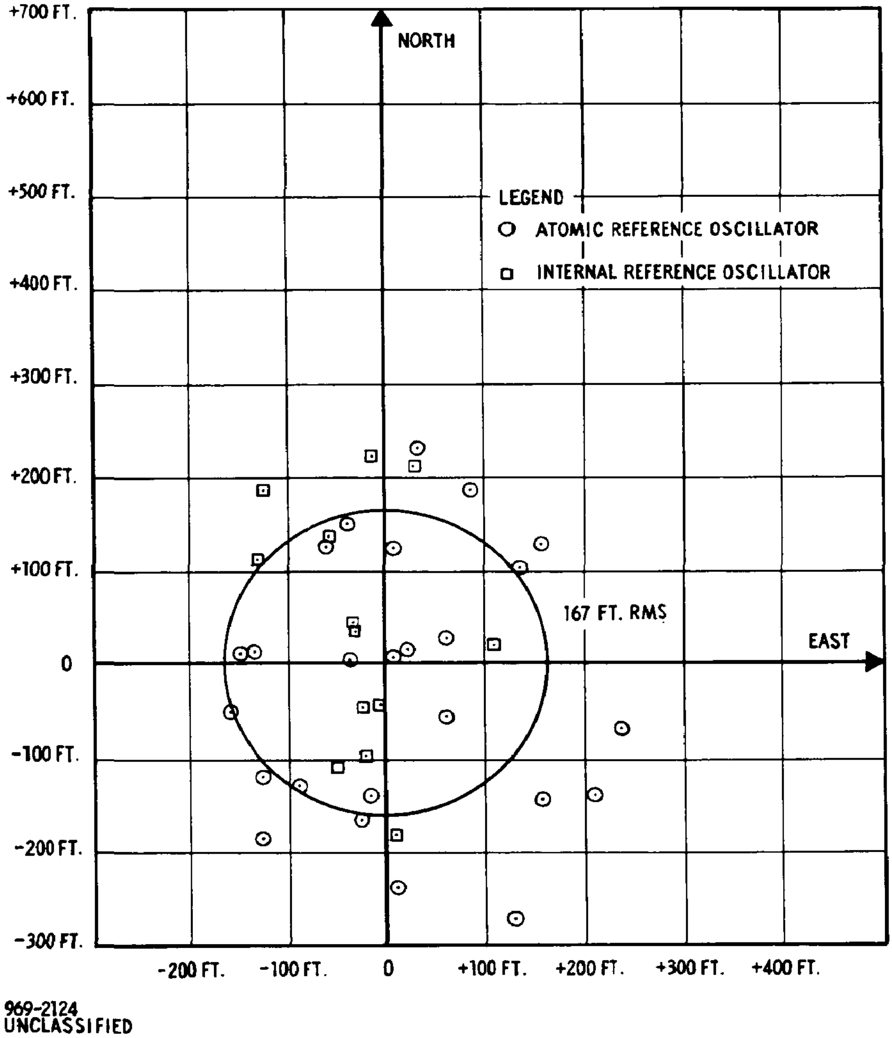
SUMMARY

The TRANSIT satellite system is now operational and has been so for four years, during which time enough experience has been obtained to prove its effectiveness. With reasonably priced navigation equipment now becoming readily available, both for government and for commercial applications, greatly expanded use will be made of this system. It is significant to note that TRANSIT has become a major national asset and a prime example of effective peaceful use of space, although initially it was developed by the Navy to satisfy strictly military requirements.

Editor's Note

The author of this article is continuing his work in the field of Satellite Navigation as a senior staff engineer with the Magnavox Company, Torrance, California. When this reprinted article was already in press for the review, the author commented to the IHB that "description of a navigation system without mention of its inherent accuracy is less than completely satisfactory". Mr. STANSELL *then noted that a more recent paper of his,* entitled "An Integrated Geophysical Navigation System Using Satellite-Derived Position Fixes", provides information on the degree of accuracy that it is possible to obtain with this Navigation Satellite system. This later paper was prepared for presentation at the First Annual Offshore Conference at Houston, Texas, 18-21 May 1969, and is copyrighted by that Conference (paper no. OTC 1102). Although it is not possible to reprint this article here, we may provide the following abstract which will be of interest:

In theory, the position fix accuracy obtainable with the Navy Navigation Satellite System is limited only by error in the satellite's orbit position message and by the user's knowledge of his own ship's motion. In practice, however, accuracy also depends on the sophistication and precision of the computer program which performs the position fix calculation. One commercially developed integrated navigation system of Magnavox manufacture



Actual MX/702/hp Short-Doppler Fix Results.

(designated MX/702/hp), which in particular gives excellent computer inputs of ship's motion using a bottom Doppler sonar and a Sperry Mark 227 gyrocompass, uses a Hewlitt-Packard 2116B digital computer. During a test lasting 62 ½ hours, this combined system produced 30 acceptable fixes, the RMS radial position accuracy of which was 268 feet, while the circle of equal probability (CEP) was 180 feet. Results in Asia or Europe might not be quite as good because of the longer elapsed time following the entry of corrective data to the satellite memory system as it passes over the continental United States. It should be noted that the Doppler sonar limits use of this method to depths of less than 1 000 feet (350 m).

Mr. Stansell has further informed the Bureau than an even later development has been that an experimental "Short Doppler Program" has become operational and has been distributed to users of the Magnavox equipment system. Field results show an accuracy now being achieved with this refinement that is better than 170 feet (52 m) RMS radial, as illustrated in the foregoing graphic plot. (The "Short Doppler Program" acts to interpolate satellite orbit positions to obtain better fix accuracy than the program which used only the normal description of the orbital position provided every two minutes by the satellite — thus using a shorter count.)