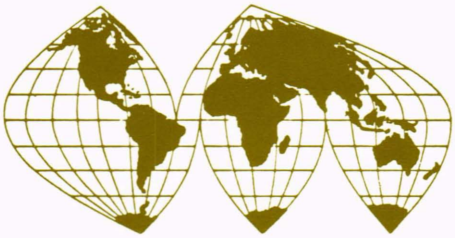

Present State of NAVIGATION BY

R. B. Kershner

A world-wide navigation system, based on the measurement of the doppler shift of stable signals transmitted from orbiting artificial satellites, has been under development for the U. S. Navy by the Applied Physics Laboratory of The Johns Hopkins University for over 5 years. The initial stages of the development have been completed and the system has been in successful use for well over a year.

The purpose of this paper is to describe the most significant features of the system as it has been initially implemented, some of the factors that influence the accuracy that can be achieved by the approach adopted, and some of the potential uses of the system as it presently exists.

Conceptually it is convenient to consider the Navy Navigational Satellite System as being similar to an ordinary hyperbolic radio navigation system but one in which the role of the fixed ground network of transmitting stations is replaced by a sequence of successive positions of a single orbiting satellite. Suppose that at a given time, t_1, the satellite is at a given position, P_1. At a later time, t_2, the satellite has moved to P_2. Then if it were possible to measure the difference in distance from the navigator's (unknown) position to the two points P_1 and P_2, the navigator would be constrained to lie on the surface of a hyperboloid. By choosing the difference in time $t_2 - t_1$ to be about 2 minutes, the difference in position from P_1 to P_2 is about 1000 km which is a reasonable base-line for a hyperbolic system. Waiting another 2 minutes until t_3 gives a third position, P_3, about 1000 km from P_2 and a second base-line for another family of hyperboloids. The intersection of each determined hyperboloid with the surface of the earth gives a line of position, and the two lines of position intersect in a position determination. See Fig. 1.

Actually, as will be seen, the problem is a little more complicated since it is not possible to make an accurate measure of the difference in distance to two points on the satellite orbit to high accuracy in a very simple way. However, the complication only requires using a third base-line and a corresponding fourth position, P_4, at a fourth time, t_4, to resolve the difficulty.

Basic Measurements

The specific technique used can best be understood by going through the very simple underlying mathematics. Let t_1, t_2, t_3, and t_4 be four specific times (in practice exactly 2 minutes apart), and let P_1, P_2, P_3, and P_4 be the positions, in an earth-centered but inertially oriented coordinate system, of an orbiting satellite at the given times (Fig. 2). Suppose the satellite is steadily transmitting a very stable radio frequency, f_T. Suppose that a ground observer is within line of sight of the satellite throughout the time from t_1 to t_4. Suppose further that the ground observer has a stable oscillator producing a reference frequency, f_G, which he uses

The initial stages in the development of a world-wide navigation system have been successfully completed and the system has experienced extensive use for over a year. The operation of the system is based on the measurement of the doppler shift of stable signals transmitted to earth from orbiting artificial satellites. This paper describes the most significant features of the system as initially implemented, some of the factors that influence the system's accuracy, and some of the potential uses of the system.

DOPPLER MEASUREMENT from Near Earth Satellites

to beat against the frequency, f_R, received from the satellite to produce the difference frequency, $f_G - f_R$. It is important that the received frequency, f_R, is not the transmitted frequency, f_T, but is modified by the well-known doppler shift effect. Suppose, still further, that the satellite emits recognizable time markers at the times t_1, t_2, t_3, and t_4 that can be recognized on the ground at the times of arrival $t_1 + \Delta t_1$, $t_2 + \Delta t_2$, $t_3 + \Delta t_3$, and $t_4 + \Delta t_4$, where Δt_1, Δt_2, Δt_3, and Δt_4 are the times of travel of the signal from the positions P_1, P_2, P_3, and P_4 to the ground reception position. Suppose, finally, that the ground receiver is implemented to count the total number of beat cycles (the cycles of $(f_G - f_R)$) between the times of receipt of time markers from the satellite, that is, to compute integrals such as

$$N_{1,2} = \int_{t_1 + \Delta t_1}^{t_2 + \Delta t_2} (f_G - f_R)\, dt. \qquad (1)$$

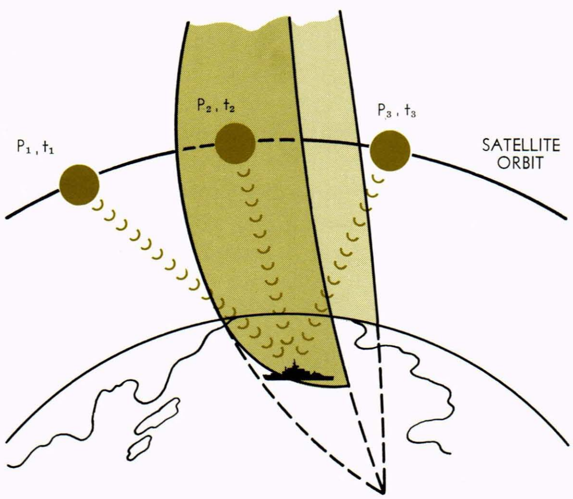

Fig. 1—Operation of Navy Navigational Satellite System presented in a hyperbolic manner.

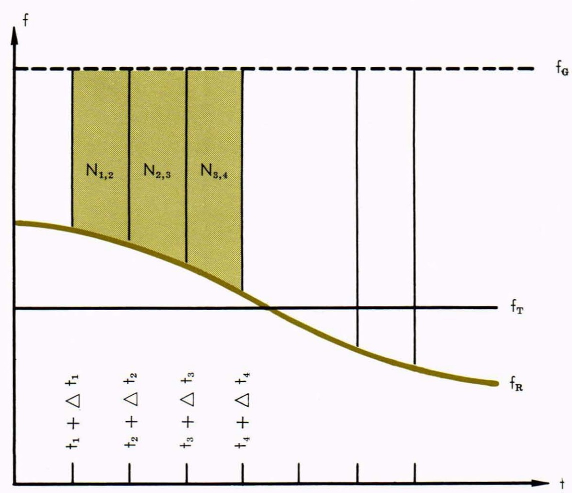

Fig. 2—Mathematical technique to measure difference in distance between two points on satellite orbit.

Now, to the extent that f_G is indeed a constant, we can write

$$N_{1,2} = f_G(t_2 - t_1) + f_G(\Delta t_2 - \Delta t_1) - \int_{t_1 + \Delta t_1}^{t_2 + \Delta t_2} f_R \, dt. \qquad (2)$$

Now comes the crucial piece of skullduggery on which the remarkable accuracy of the system depends. The last term of the above equation

$$\int_{t_1 + \Delta t_1}^{t_2 + \Delta t_2} f_R \, dt$$

represents the total number of cycles *received* from the satellite between the time the t_1 marker is *received* and the time the t_2 marker is *received*. But this is the same as the number of cycles *transmitted* between the time of *transmitting* the t_1 marker and the time of *transmitting* the t_2 marker. Thus,

$$\int_{t_1 + \Delta t_1}^{t_2 + \Delta t_2} f_R \, dt = \int_{t_1}^{t_2} f_T \, dt = f_T \cdot (t_2 - t_1)$$

if f_T is a constant. Using this in Eq. (2) for $N_{1,2}$ gives

$$N_{1,2} = (f_G - f_T)(t_2 - t_1) + f_G(\Delta t_2 - \Delta t_1). \qquad (3)$$

Now, clearly, $\Delta t_2 - \Delta t_1$ is closely related to the difference in distance between the ground point and the points P_1 and P_2. Actually, it is not necessary to assume the ground point is stationary from t_1 to t_2. In fact, if we are working in an inertially oriented coordinate system as suggested above, it is essential to include the motion of the ground station caused by earth rotation even if the ground observer is fixed with respect to the earth. Thus, let p_1, p_2, p_3, and p_4 be the positions of the ground station at the times $t_1 + \Delta t_1$, $t_2 + \Delta t_2$, $t_3 + \Delta t_3$, and $t_4 + \Delta t_4$ respectively. Let $\rho(P_1, p_1)$ be the distance from P_1 to p_1 and C be the speed of light. Then

$$\Delta t_2 - \Delta t_1 = \frac{1}{C}\Big(\rho(P_2, p_2) - \rho(P_1, p_1)\Big).$$

Substituting this in Eq. (3) for $N_{1,2}$ gives

$$\rho(P_2, p_2) - \rho(P_1, p_1) = \frac{C}{f_G} N_{1,2} - C\left(1 - \frac{f_T}{f_G}\right)(t_2 - t_1), \qquad (4)$$

which yields the desired difference in distance to the two satellite positions from the ground observer in terms of the measured quantity $N_{1,2}$ and the design parameters of the system f_G, f_T, $t_2 - t_1$. From this it would appear that combining Eq. (4) with the analogous equation based on P_2, P_3 would yield two equations for the two unknown position coordinates of the ground observer and enable a position fix to be made. However, we must examine the accuracy with which this determination could be made.

The magnitude of the terms involved in Eq. (4) can best be determined for a special geometry. Let us consider the case where the satellite is just above the horizon at t_2 and is essentially retreating from the observing station (the latest portion of an overhead pass). Then, $[\rho(P_2, p_2) - \rho(P_1, p_1)]$ is very nearly the distance the satellite moves during the interval (t_1, t_2). If this time interval is taken as 2 minutes then the distance moved is of the order of 1000 km (since a near-earth satellite travels at about 8 km/sec). If it is desired to determine this distance with an accuracy of about 0.1 km then an accuracy of 1 part in 10^4 is required. For the right hand terms we consider the special case that $f_T \approx f_R$ and we write $f_G = f_T + \Delta f$, where Δf is very small compared to f_G or f_T. From Eq. (4) we have,

$$\rho(P_2, p_2) - \rho(P_1, p_1) = \frac{C}{f_G} N_{1,2} - \frac{C}{f_G} \Delta f (t_2 - t_1). \qquad (5)$$

In order to make the last term small compared to the 0.1 km desired, it should be noted that the multiplier $(t_2 - t_1)C$ is the distance traveled by light in 2 minutes or about 7 x 10^7 km. Therefore, $\Delta f / f_G$ should be less than 10^{-9}. While it is perfectly feasible with modern techniques to make both f_G and f_T constant (stable) to a part in 10^9 over the time of a pass, it is quite difficult to know the calibration (particularly for extended periods at sea) with a comparable accuracy. Accordingly, in the implementation of the Navy Navigational Satellite System the requirement to know the value of $\Delta f / f_G$ has been eliminated. This is readily done simply by using a third base-line interval. Using Eq. (5) together with the two analogous equations based on the intervals (P_2, P_3) and (P_3, P_4), we get

$$\rho(P_2, p_2) - \rho(P_1, p_1) = \frac{C}{f_G} N_{1,2} - \frac{C}{f_G} \Delta f (t_2 - t_1) \qquad (6)$$

$$\rho(P_3, p_3) - \rho(P_2, p_2) = \frac{C}{f_G} N_{2,3} - \frac{C}{f_G} \Delta f (t_3 - t_2) \qquad (7)$$

and

$$\rho(P_4, p_4) - \rho(P_3, p_3) = \frac{C}{f_G} N_{3,4} - \frac{C}{f_G} \Delta f (t_4 - t_3). \quad (8)$$

If we design the satellite to emit time marks at equal (2-minute) time intervals so that $t_2 - t_1 = t_3 - t_2 = t_4 - t_3 = 2$ minutes, then we can eliminate Δf by subtracting Eq. (7) from Eq. (6) and Eq. (8) from Eq. (7), giving

$$-\rho(P_1, p_1) + 2\rho(P_2, p_2) - \rho(P_3, p_3) = \frac{C}{f_G}(N_{1,2} - N_{2,3}), \quad (9)$$

and

$$-\rho(P_2, p_2) + 2\rho(P_3, p_3) - \rho(P_4, p_4) = \frac{C}{f_G}(N_{2,3} - N_{3,4}). \quad (10)$$

This gives two equations for the unknown position coordinates of the ground observer in terms of the known satellite positions at t_1, t_2, t_3, t_4, the measured doppler integrals $N_{1,2}$, $N_{2,3}$, $N_{3,4}$ and the ground reference frequency f_G. This still requires a knowledge of f_G, but an accuracy of one part in 10^5 is quite adequate in this formulation since f_G enters as a straight factor in a term whose overall value is less than 1000 km.

The oscillators used in the program, both in the satellite and in ground (navigating) equipment, have much less than one part in 10^9 variation over the 6-minute time required to measure $N_{1,2}$, $N_{2,3}$, $N_{3,4}$. Hence the errors implicit in the approximations used to derive Eqs. (9) and (10) are very small and are, in fact, measured in meters. Thus, *neither* satellite oscillator (f_T) *nor* ground station oscillator (f_G) stability is a significant factor in navigation system accuracy with the approach used and the stability attained.

Refraction

There is a fundamental assumption in the derivation of the equations in the preceding paragraphs that is erroneous and hence introduces a further error. Specifically, it was assumed that the radio transmissions from the satellite are propagated on straight line paths at the velocity of light, C. This would be true if the propagation medium were a vacuum. Actually, there is a considerable layer of ionized gas, the ionosphere, between the satellite and the ground observer that modifies both the propagation path and the velocity of the transmitted signals. The net result is that the received signal, f_R, is not simply the transmitted signal modified by the doppler shift, $f_T + \Delta f_T$, but rather $f_T + \Delta f_T + \epsilon f_T$ where ϵf_T is an additional apparent frequency variation caused by the ionosphere.

The ionospheric effect is accounted for in the Navy Navigational Satellite program by taking advantage of the fact that the effect of the ionosphere is frequency-dependent. Specifically, if two different frequencies are transmitted, then the doppler effect is directly proportional to frequency but the refraction effect is inversely proportional to frequency, to first order accuracy. Now suppose that two coherent frequencies are transmitted from the satellite, a high frequency, f_H, and a low frequency, f_L, where f_H is some multiple, k, of f_L that is

$$f_H = kf_L, \qquad k > 1.$$

Then the frequency received on the high channel, $f_{R,H}$ will be

$$f_{R,H} = f_H + \Delta f_H + \epsilon f_H, \quad (11)$$

and, on the low channel,

$$f_{R,L} = f_L + \Delta f_L + \epsilon f_L, \quad (12)$$

where

$$f_H = kf_L, \quad \Delta f_H = k\Delta f_L, \quad \epsilon f_H = \frac{1}{k}\epsilon f_L.$$

Then, multiplying Eq. (12) by k and subtracting from Eq. (11) yields

$$f_{R,H} - kf_{R,L} = \epsilon f_H(1 - k^2). \quad (13)$$

Thus, the term ϵf_H in Eq. (11) can be calculated from Eq. (13) as

$$\epsilon f_H = \frac{1}{1 - k^2}(f_{R,H} - kf_{R,L}),$$

and if this correction term is added to the doppler term Δf_H in Eq. (11), we get a corrected doppler term

$$\Delta f_H^* = \Delta f_H + \frac{1}{1 - k^2}(f_{R,H} - kf_{R,L}), \quad (14)$$

that behaves like the ideal vacuum doppler used in the derivations described earlier.

In the Navy Navigational Satellite System, the two frequencies used, f_H and f_L, are approximately 400 Mc/s and 150 Mc/s, respectively, and $k = 8/3$ exactly. Both frequencies are received, and the received frequencies are combined as in Eq. (13) to obtain a refraction correction or "vacuum" doppler in accordance with Eq. (14).

The refraction correction described above is, of course, not perfect. However, the *total* correction due to refraction, at least in the current period of quiet solar activity, is normally only a few tenths of a kilometer with the frequencies used in the system; and the *error* in this correction appears, normally, to be less than a hundredth of a kilometer. It should be mentioned, however, that the next period of high solar activity can be expected to increase not only the size of the correction but also the size of the error in this correction.

Time Accuracy

The time marks, t_1, t_2, t_3, $\cdots$, emitted by the satellite are accurate to about 200 μsec. The method of accomplishing this will be described later in the paper. For the present it is enough to note that the same stable oscillator used to generate the transmitted signals is also used to count the time intervals and control the time markers. Accordingly, although the absolute time accuracy of an individual marker may be no better than 200 μsec, the length of a nominally 2-minute interval between successive markers is accurate to about 10 μsec. Hence, the accuracy of the time marks has a completely negligible effect on system accuracy.

Ship Motion

The basic navigation equations involve the positions p_1, p_2, p_3, and p_4 of the ground station at four successive 2-minute intervals. It is, of course, necessary to express all these positions in terms of two unknowns, namely the latitude and longitude of the ground station at some specific time. For example, the ground coordinates of p_1 can be considered as the unknowns and then p_2, p_3, and p_4 expressed in terms of these unknowns. This requires a knowledge of the motion of the observing station during the 6 minutes of observation. Any error in the estimate of the motion of the observing station during these 6 minutes will lead to an error in the position determination. The amount of this error is a rather complicated function of the geometry of the particular pass (principally of the maximum elevation angle of the satellite) and is also dependent on the direction of the error. An error in velocity in the direction perpendicular to the satellite motion is not as serious as an error in the direction parallel to the satellite motion.

Note that velocity, per se, is not detrimental. As long as the velocity is accurately known there is no problem in allowing for it in the navigation determination. The problem comes from the fact that the velocity required is the true velocity over the earth and not, of course, simply velocity through the water, which is easily measured. Thus the most serious problem comes from the existence of unknown currents. The corresponding problem for aircraft, where unknown winds can be very large, is, of course, much more serious and becomes one of the most difficult problems in extending the usefulness of the Navy Navigational Satellite System to aircraft applications.

Satellite Position and Geodesy

The basic navigation equations also involve the positions P_1, P_2, P_3, and P_4 of the satellite at four successive 2-minute intervals. As the system is implemented these positions are transmitted to the user, in a format which is described below, by a message that is a modulation on the same signals used to generate the doppler shift. The message describing the satellite position is injected into the satellite approximately every 12 hours by either the injection station located in the north central United States or the one on the California coast. Of necessity, the satellite positions are obtained as a computed extrapolation of previous tracking data. Thus, accurate tracking and accurate extrapolation of satellite orbits are crucial to accurate navigation.

The keys to accurate prediction of satellite position are, first, an accurate measurement system and, second, an accurate knowledge of the gravitational forces acting on the satellite. The same doppler measurement technique used for navigation also serves as the appropriately accurate measurement technique for tracking. Thus, the major problem is the determination of a precise model of the earth's gravitational field—a problem in geodesy.

Fortunately, the most powerful means of attacking the difficult problem of measuring the earth's gravitational field has proved to be the accurate observation of the motion of artificial satellites. Tremendous progress, as a result of the extensive tracking of a large number of artificial satellites, has been made in the last few years in improving our model of the gravitational field. Much of this progress has been a part of the development program associated with the Navy Navigational Satellite program, but there have also been special satellites, notably ANNA, with Army, Navy, and Air Force sponsorship, and the recent BE-C launched under NASA sponsorship, whose primary objective was the improvement of geodesy. Finally, a geodetic satellite named GEOS, designed and built by APL for NASA, was orbited on November 6, 1965, and is operating perfectly.

The current status of geodetic research has been reported elsewhere. The model of the gravitational field currently being used in the Navy Navigational Satellite program has been described[1]. It appears that satellite positions based on tracking and extrapolation, using this model of the gravitational field, are accurate to better than 80 meters. Accordingly, geodesy which, for a long time, contributed the major errors in the system, has now been refined to the point that it no longer dominates the accuracy problem.

Air Drag

In addition to gravitational forces there are also small but significant drag forces acting on a near-earth satellite. The operational satellites of the Navy Navigational Satellite program are at an altitude of 600 n.m., and accordingly the drag forces are quite small, particularly in recent years. However, as all other sources of error are brought under control, the problem of predicting drag forces will become more important. It must also be realized that this problem may become much more serious, not only relatively but absolutely, during the next period of high solar activity. It is well known that the density of the very high altitude atmosphere is very strongly influenced by the level of sunspot related activity on the sun. Most of our precision tracking experience has been obtained during the current period of the "quiet sun," and drag prediction may well become a more serious problem if the next period of high solar activity is a very active one.

Colocation and Intervisible Measurements

A simple way to demonstrate the basic measurement capability of the doppler technique is to compare the results obtained with two separate pieces of navigation equipment that are located at essentially the same site. With these "colocation" measurements most of the errors caused by effects other than the basic measurement are eliminated in the comparison since they affect both determinations equally. In particular, errors in the predicted position of the satellite and errors caused by imperfections in the existing first-order refraction correction are almost completely cancelled in this colocation process. Errors caused by unknown velocity of the receiving station are, of course, eliminated if the stations are located at fixed sites on the ground.

Colocation measurements of the type described above have been performed many times, and the results are quite consistent, giving agreement with an RMS of about 10 meters. This experimental result is in agreement with the error analysis described above and shows that the statements made about frequency stability and the like are consistent with the experimental behavior of the equipment.

Actually two pieces of equipment do not have to be located literally side-by-side to obtain results that are remarkably consistent with each other. As long as the distance between ground stations is small enough that they are observing effectively the same portion of the satellite trajectory, it remains true that errors in satellite position and in refraction correction are more or less self-canceling. Tests have been run with equipments separated by various distances up to 1000 miles, with the results shown in Fig. 3.

The ability to get results such as those in Fig. 3 is not only very revealing with regard to the basic source of errors in the system but, in addition, leads to a special mode of use of the system that now appears to have great practical usefulness. Anyone who has a need for very precise navigation in a limited area can accomplish this simply by establishing one fixed station in or near the local area for use as a reference and then consistently correcting his navigation determinations by the error

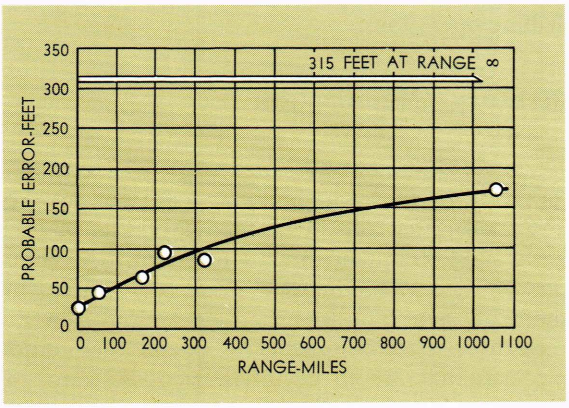

Fig. 3—Probable errors in determining relative position from satellite doppler data.

observed at the reference station. By this means, position determinations with an accuracy given in Fig. 3 are available, where the separation distance is now the distance between the reference station and the navigation station. Of course, if the navigation station is on a moving platform, then velocity errors will cause an additional error. This technique is called the intervisible mode of using the system since it yields greatly increased accuracy only when both ground stations can "see" the satellite simultaneously. An example of an ap-

[1] W. H. Guier and R. R. Newton, "The Earth's Gravity Field Deduced from the Doppler Tracking of Five Satellites," *J. Geophys. Res.* **70**, 1965, 4613-4626.

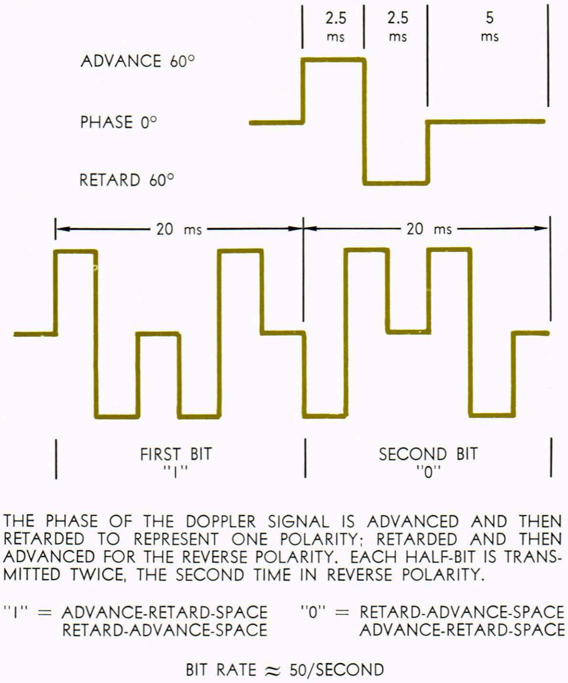

Fig. 4—Communication link modulation waveforms.

plication where the use of intervisible position determinations might be appropriate is off-shore oil drilling operations.

Memory Organization

The information on satellite position required for navigation is stored in a magnetic core memory and transmitted as a phase modulation on the two basic stable frequencies used to generate the doppler shift. The modulation pattern is quite symmetrical so as not to introduce an error in the measurement of doppler. The specific modulation patterns that are to be interpreted as "zero" or "one" are shown in Fig. 4.

The memory, which is read out every 2 minutes, contains 156 words of 39 bits each plus an additional 19 bits (Fig. 5). The great majority of these words are not required for navigation but disseminate information that permits users to determine rise times of other satellites in the system. The first two words are simply a special fixed pattern of "zeros" and "ones" used to recognize the start of a message and to establish synchronization of the ground equipment with the satellite transmissions. Thereafter, the words with specific significance for navigation are a total of 19 words, divided into two sets, an initial set of eight so-called ephemeral words consisting of words 8, 14, 20, 26, 32, 38, 44, 50, and a set of 11 fixed parameters that describe a precessing Kepler ellipse that approximates the satellite orbit. These 11 words are described as follows:

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	$\lvert\dot{\phi}\rvert$	Rate of change of argument of perigee (absolute value)	Deg/Min.
80	ϵ	Eccentricity of orbit	—
86	A_o	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	—

If the orbit were accurately a precessing Kepler ellipse, the position of the satellite at any time could be obtained from these 11 words by the usual formulas. However, because of the departure of the earth's gravitational field from that of a pure oblate spheroid, there are substantial deviations of the actual orbit from the best approximate precessing ellipse. In order to describe the actual, quite complicated, satellite path, values are given for the deviations from the approximate precessing ellipse for every even 2 minutes of universal time. These deviations are given in the eight ephemeral words mentioned above.

The words contained in the satellite memory are inserted by a transmission from a so-called injection station on the ground. Thereafter the main memory is simply read out every 2 minutes until a new injection takes place. All words are read out unchanged during the interval between injections (usually about 12 hours) except for the eight ephemeral words. These special words change on every memory readout and pertain to the particular time of the readout. Specifically, consider the memory readout that lasts from t minutes to $t + 2$ minutes. Then the eight ephemeral words will contain the orbit deviations appropriate to the times $t - 6, t - 4, t - 2, t, t + 2, t + 4, t + 6, t + 8$, respectively. Thus, on each successive readout the ephemeral words are precessed upward so that the word number 8 in the previous readout is discarded and replaced by the previous word 14, the old word 14 is replaced by the old word 20, etc., and finally a new word 50 is transmitted. This new word is transferred from a separate memory in the satellite known as the ephemeral memory, which is filled at the time of injection but which is not read out. Instead, on each memory readout, a single 39-bit word is transferred across to fill word 50 in the main memory. The ephemeral memory contains 480 words and, since a fresh word is used every 2 minutes, the ephemeral memory is used up in 480 x 2 = 960 minutes or 16 hours. Thus, a new injection must be made within 16 hours to prevent the memory from running out. It should be noticed that each word in the ephemeral memory is read out eight successive times, first as word 50, then as word 44, etc., finally as word 8 and then is discarded. Notice also that a single 2-minute memory readout gives orbit information for a full 14-minute interval, spanning the time of readout symmetrically.

Timing

The orbit readout rate is controlled by counting down from the basic stable oscillator and hence is quite uniform. However, in spite of the excellent stability of the satellite oscillator, there are long-term drifts that slowly change the basic oscillator frequency during the life of the satellite. Thus, to keep the memory readout period accurately at 2 minutes, it is necessary to modify the countdown chain on occasion. This is done by using one special bit of each 39-bit word in the memory as a signal to determine whether or not to suppress a single count in the countdown process. This is done at a point where a single count has a value of 10 μsec. Thus a total variation of 156 x 10 μsec = 1.56 Msec in each 2 minutes is available. With this level of adjustment, the time could still be off appreciably at the end of 12 hours. However, a vernier adjustment is available by inserting an appropriate count suppression signal in an ephemeral word. Such a correction bit is used only once and then discarded.

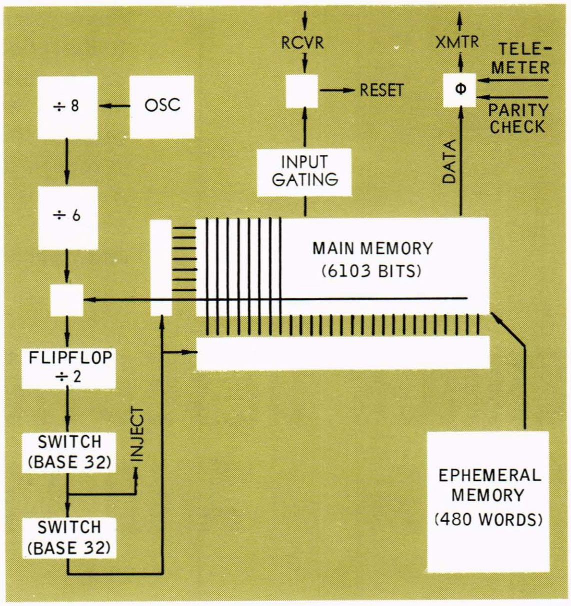

Fig. 5—Memory organization.

This vernier correction can adjust the time to the nearest 10 μsec in a 12-hour period.

Signal Reception

The signals received from the satellite are left circularly polarized so that faraday rotation does not affect signal strength. Also, the signal strength is almost independent of satellite range. These desirable characteristics are obtained by using gravity gradient stabilization in the satellite so that the antenna always points toward the earth, and then by shaping the antenna pattern so that less energy is transmitted straight down, where the range is small, and more at substantial angles, where the range is larger. This approach, together with the use of UHF frequencies, and the attendant absence of propagation anomalies, assures a very reliable signal reception in most cases.

Summary

The Navy Navigational Satellite System, which has been in use for well over a year, has proved to be a very effective, convenient, highly accurate means of world-wide navigation unaffected by weather conditions, ionospheric disturbances or other limitations. For special purposes, used in the intervisible mode, it is competitive in accuracy with the most advanced survey techniques. Its development has made a major contribution to the current developments in geodesy. Finally, as a by-product, it provides the most accurate global timing signals available.