N6?-30340

NAVIGATION SATELLITES

RICHARD B. KERSHNER
Applied Physics Laboratory
The Johns Hopkins University

One of the earliest suggestions for a practical operating satellite system to accomplish a practical terrestrial objective to receive financial support was a system for global navigation. The system, supported initially by the Department of Defense's Advanced Research Projects Agency, was the outgrowth of work done by William Guier and George Weiffenbach at the Applied Physics Laboratory of The Johns Hopkins University in the very sophisticated analysis of the doppler shift from the first Sputnik. The specific suggestion for a possible navigation system, based on a similar precise analysis of the doppler shift resulting from the relative motion of an artificial satellite and a ground observing station to yield an accurate determination of the position of the ground station from a knowledge of the satellite orbit, was due to Frank McClure of the Applied Physics Laboratory, and the first special NASA award for contribution to space technology was given to Dr. McClure for this concept.

The detailed system to accomplish global navigation with the aid of special artificial satellites was embodied in a program under the code name of Transit in 1959, and responsibility for the development was transferred from ARPA to the Navy in 1960. The proposed system concept, as widely described at that time, is shown in figure 1. It includes a constellation of four satellites in polar orbits, with orbital planes at 45° intervals, which transmit two coherent stable frequencies. Also, modulations are imposed on these frequencies which signify the contents of a satellite memory which can be loaded from the ground. This transmission is a simple communication channel which makes available to the user a recent determination of the satellite orbit. In addition to obtaining the orbit information, the user also measures the doppler shift exhibited on the received frequency from the stable satellite oscillator because of the relative motion of the transmitter (satellite) and receiver (ground point fixed on a rotating earth). Because of the transmission and reception of two coherent frequencies, it is possible to make a good approximate correction for the major ionospheric refraction effect.

Progress on this system, as reported in the open literature up to 1963, was very encouraging. In particular, enough was published during this period to establish the fact that the limitation on accuracy for the system would be determined by the knowledge of geodesy since the largest uncertainty would result from the knowledge of the satellite orbit which, in turn, was limited by our knowledge of the force field which controls the satellite orbit. Unfortunately, in March 1963, a change in policy resulted in the classification of this project so that we can not report in an unclassified manner the current status of this specific program.

NASA has been observing the progress of this program to determine whether or not it would meet general civilian and commercial needs for a global navigation system. It has tentatively determined that the program has certain disadvantages, as far as general purpose, nonmilitary use is concerned, that are sufficiently restrictive to warrant a serious search for alternative systems. Quite recently there has been announced the results of a study program, carried out by General Electric (GE) that proposes an alternative system that is believed, by some, to more nearly meet the needs of a general-purpose civilian system.

The general concept of the GE system is to establish a system of a large number of satellites distributed with random phase about four different orbits at an altitude of some 6,000 miles. In addition, the system has six ground stations strategically located about the globe. It can be shown that with an appropriate,

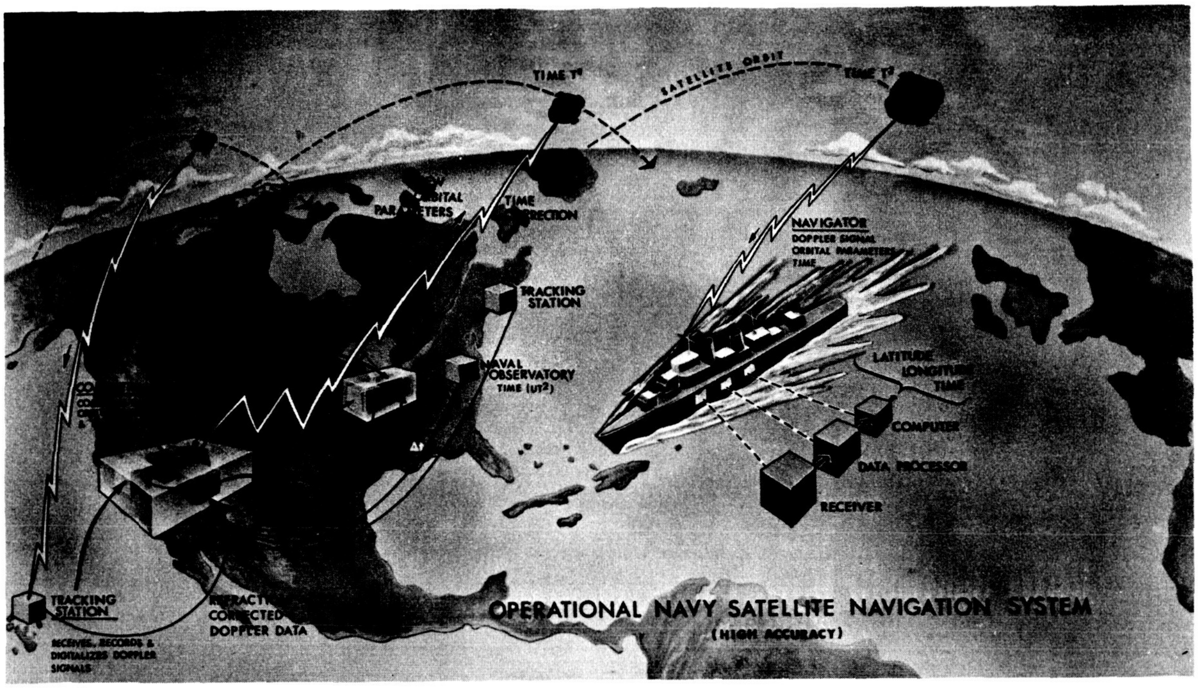

FIGURE 1.—*Operational Navy satellite navigation system.*

relatively large, number of satellites there will always be essentially, for any potential user, two satellites which are simultaneously within his line of sight and within the line of sight of one of the six ground stations. When a user desires his position he sends out a simple signal which is relayed by all satellites within line of sight. A ground station which receives this request for position from two separate satellites responds by sending out a time impulse. This time impulse is relayed by the two satellites from which the request was received on to the user and is simply echoed back by the user via the same two satellites to the ground station. By measurement of the time difference in these paths, the ground station, which, of course, knows the satellite position, can compute a triangulation for the user and establish his position, or at least two alternative positions. This information is then sent to the user, again by a satellite as a relay point. The user generally can readily select the correct one between the two possible positions since they usually differ quite widely.

The considerations which lead to this system proposal were, of course, quite different from those which dictated the system selection of the Navy. In the case of the Navy's system, the entire cost of establishing and maintaining the system and paying for user equipment is all carried by the same organization, and the proper consideration is to meet the objectives with a minimum overall cost of system plus user equipments. There also are a relatively small number of user equipments, so that it is quite reasonable to pay a substantial amount for user equipment if by so doing the system establishment and maintenance costs can be reduced. For a general-purpose civilian system, however, in which user equipment cost must be paid by the private shipowners, the system will attract users only if shipboard equipment cost can be held quite low. Thus, in principle, it is reasonable to consider systems which are appreciably more expensive to establish and maintain if this more complex system can result in greatly reduced user-equipment cost. But, of course, the deeper question of whether it is appropriate for the Government to provide such a service as a subsidy or whether, alternatively, the economic considerations should provide for eventual amortization of the system costs by charges to the user must, of course, be decided ultimately by the Congress or the President.

The purpose for raising this issue, at this time, is simply to take the opportunity to suggest to all within earshot that the economic considerations will, or at least should be, very important in the decision-making process to come, and that it may not be too late to consider alternatives which could make an exceedingly large effect on the outcome of these economic considerations.

First, it is apparent that NASA, in making a determination of the suitability of the Navy's navigation approach for civilian needs, simply considered the system as proposed and did not investigate the question as to whether it was possible to modify or augment the system to meet the requirements of civilian use for considerably less money than would be required by the development of a totally new system. Secondly, and perhaps more important, if the pattern established in the past is followed, the decision with regard to implementing a civilian navigation system will be made on the premise that a satellite system as a navigation aid will have to justify itself economically on the assumption that it accomplishes nothing else. Now the fact is that the satellite system required to implement the GE navigation proposal is to all intents and purposes simply another intermediate altitude, random-orbit communication system. It may have rather specific requirements with regard to reproducibility of time delay but this is a minor technical detail. If the United States does establish, through the ComSat Corp., or in any other way, a midaltitude, random-orbit communication satellite system, adding to these satellites the requirement that they be able to accept and relay the signals and messages required for a navigation system of the GE type might make very little difference in the design and costs of the satellite. In this case, the economic consideration involved becomes markedly different.

It is granted that the exceedingly complex governmental and industrial boundary conditions that exist in the communication satellite area make this suggestion very difficult to implement, but surely somewhere there is a big enough system.

Whatever system is used to establish navigation on a worldwide basis with the aid of artificial satellites, it is clear that the accuracy of the system is dependent, among other things, on the accuracy with which the satellites can be tracked. And this, in turn, is dependent on the precision with which the forces, primarily gravitation, which act on the satellite, are known. In short, an accurate description of the gravitational force field is a prerequisite to accurate navigation by satellites.

Although it is not quite so obvious, actually the same information is required to establish an Earth-based global navigation system. In fact, since the Earth is largely water covered and elevations, even on land, are based on "sea level," the "shape" of the Earth is controlled by the gravitational field; that is, the liquid surface of the Earth will form an equipotential surface in the gravitational field (with proper allowance for the effect of rotation). Thus, knowing the gravity field is equivalent to knowing the shape of geoid, i.e., the equipotential surface. And knowing the shape of the Earth is obviously necessary to provide accurate global navigation even by Earth-based systems such as Omega.

In summary, progress in global navigation accuracy, with or without satellites, is dependent on progress in geodesy. For this reason, it seems appropriate to indicate here the current status of geodesy. It is particularly appropriate to discuss this matter since geodesy constitutes another of the practical applications of artificial satellites for accomplishing a terrestrial objective.

Before the advent of artificial satellites, the Earth was considered to be an oblate spheroid, that is, an ellipsoid of revolution with a circular equator but a polar flattening. The first major departure from this shape was the determination by O'Keefe that there was an appreciable peaking at the north pole and flattening at the south pole which constituted a north-south dissymmetry. This fact, referred to in the press by the phrase "pear-shaped" (figure 2), was deduced

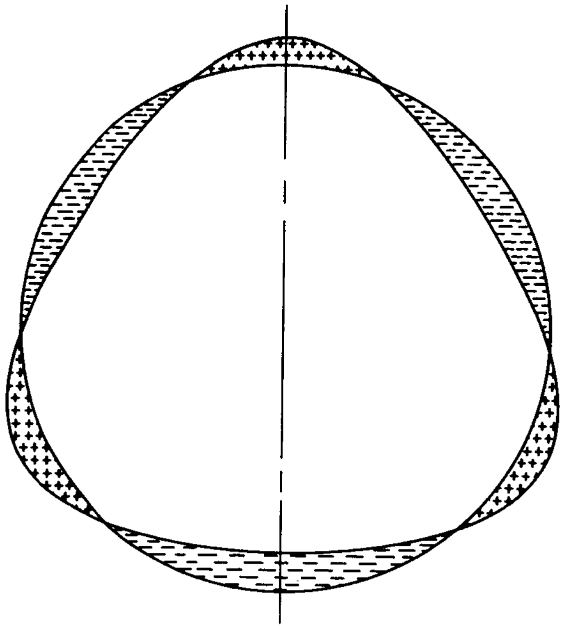

FIGURE 2.—Pear-shaped Earth.

from satellite tracking. The next major announced departure from the earlier model was given by Izsak with the statement that optical satellite tracking clearly indicated that the earth's equator was elliptical. This fact has been determined independently by Newton at the Applied Physics Laboratory, based on doppler tracking results.

It is customary, in geodetic research, to express the gravitation field in terms of a series expansion in spherical harmonics:

$$V(r, \varphi, \lambda) = -\frac{K}{r}\left[1 + \sum_{l=2}^{\infty} \sum_{m=-l}^{l} \frac{J_{l_m}}{r^l} Y_l^m(\varphi, \lambda)\right]$$

$J_{2,0}$ = 1st oblateness term[4,5]
$J_{4,0}$ = 2nd oblateness term[4,5,7]
$J_{3,0}$ = Pear-shaped term[4,5,6]
$J_{5,0}; J_{7,0}$ = Higher order odd-harmonics[4,5,6]
J_6 = Higher order even harmonics[7]
$J_{2,2}; J_{2,-2}$ = 1st elliptic equator term[8,9,10]

In this expansion, the terms which are longitude independent are called zonal harmonics and those which depend on longitude (like the elliptic equator term, $J_{2,2}$) are nonzonal harmonics. The announcement of the pear shape of the Earth and of the elliptic equator corresponded to an approximate determination of $J_{3,0}$ and $J_{2,2}$, respectively.

In 1963, Guier, of the Applied Physics Laboratory, used data from the doppler tracking of three satellites at different inclinations to make a determination of all nonzonal harmonics through the fourth order. Table I summarizes the data used, and table II indicates the data fit obtained with this determination. It is of interest that the overall data consistency of about 0.06 nm (nautical mile) is contrasted with about 0.2 (nm) 1 year earlier and something like 1 nm 4 years earlier.

At about the same time, Cohen (at Dahlgren), Kaula, and Izsak also made determinations of some or all of these harmonic coefficients. The results are shown in tables III, IV, and V.

TABLE I.—*Summary of doppler data used.*

Satellite designation	Inclination, deg	Semi-major axis, km	Eccentricity	No. of individual satellite passes	No. of distinct station location	No. data groups, satellite orbits	Av. no. of passes per group	Av. time span per group (hr)
1961αη1	32.4	7410	0.010	87	9	8	11	15.9
1962βμ1	50.1	7510	.007	199	15	9	22	22.7
1961o1	66.8	7320	.008	155	13	10	16	23.3
Totals				441	18	27		

TABLE II.—*Final data root-mean-square residuals*

Satellite	Symmetric component (along-track),	Antisymmetric component (slant range),	Total residuals	
	Miles	Miles	Miles	Nautical miles
1961αη1	78.1	81.9	113.2	= 0.061
1962βμ1	62.0	60.7	86.8	= 0.047
1961o1	73.6	84.6	112.3	= 0.061
		RMS total	102.3	= 0.055

Shortly after this determination of the harmonic coefficients through the fourth order, a polar satellite, which could be tracked accurately with doppler, became available. The results were quite surprising; namely, that the same geodetic coefficients which made possible the tracking of three separate satellites to a consistency of about 0.06 nm could allow no better than about 0.15 nm in tracking a polar satellite. At this point Newton made a new determination of the

TABLE III.—*Nonzonal harmonic coefficients of the geopotential, n = 2*
Value (x 10⁶)

Coefficient	Guier	Cohen	Kaula	Izsak
C_2^1 ---	*(0.0178)	....	....	....
S_2^1 ---	*(—0.0348)	....	....	....
C_2^2 ---	1.680	1.836	1.19	0.968
S_2^2 ---	—0.638	—0.987	—1.10	—0.400

*C_2^1 and S_2^1 should be negligible. They are listed in this table as one indication of the accuracy of the results.

TABLE IV.—*Nonzonal harmonic coefficients of the geopotential, n = 3*
Value (x 10⁶)

Coefficient	Guier	Cohen et al.	Kaula	Izsak
C_3^1 ---	1.768	....	1.10	1.12
S_3^1 ---	0.194	....	—0.12	0.06
C_3^2 ---	0.2858	....	0.115	0.091
S_3^2 ---	—0.025	....	0.027	—0.183
C_3^3 ---	0.1480	....	—0.043	0.071
S_3^3 ---	0.1410	....	0.102	0.124

zonal harmonics (which were not well determined by Guier's approach) and improved the tracking of the polar satellite to about 0.1 nm without hurting the tracking of the lower inclination satellites (table VI).

The geoid that results from these investigations is shown in figure 3. We are approaching the point of being able to make a new determination, based on very high-quality data from four satellite inclinations, including one in polar orbit, of all coefficients through sixth order. However, it is clear that the needs of the geodesy program can only be met by firing still more satellites, specifically instrumented to enable precision tracking, in a variety of orbits.

TABLE V.—*Nonzonal harmonic coefficients of the geopotential, n = 4*
Value (x 10⁶)

Coefficient	Guier	Cohen et al.	Kaula	Izsak
C_4^1 ---	—0.5688	—0.6785	—0.199	—0.288
S_4^1 ---	— .4597	— .3757	+ .436	— .321
C_4^2 ---	.05987	.1011	— .0067	.035
S_4^2 ---	.2661	.2688	.0755	.123
C_4^3 ---	.0790	.1580	.0299	.0215
S_4^3 ---	— .0028	—0.036	.0096	.0148
C_4^4 ---	— .00785	....	— .0051	.0097
S_4^4 ---	0.00656	....	0.0116	0.0163

TABLE VI.—*Determinations of the odd harmonics units of 10⁻⁶*

Harmonic	1	2	3	Kozai
J_3 ---	—2.673 ± .059	—2.676 ± .055	—2.703 ± .27	—2.562 ± .007
J_5 ---	—0.088 ± .038	—0.086 ± .035	—0.052 ± .34	—0.064 ± .007
J_7 ---	—0.439 ± .042	—0.442 ± .044	—0.507 ± .63	—0.470 ± .010
J_9 ---	....	....	+0.055 ± .51	+0.117 ± .001

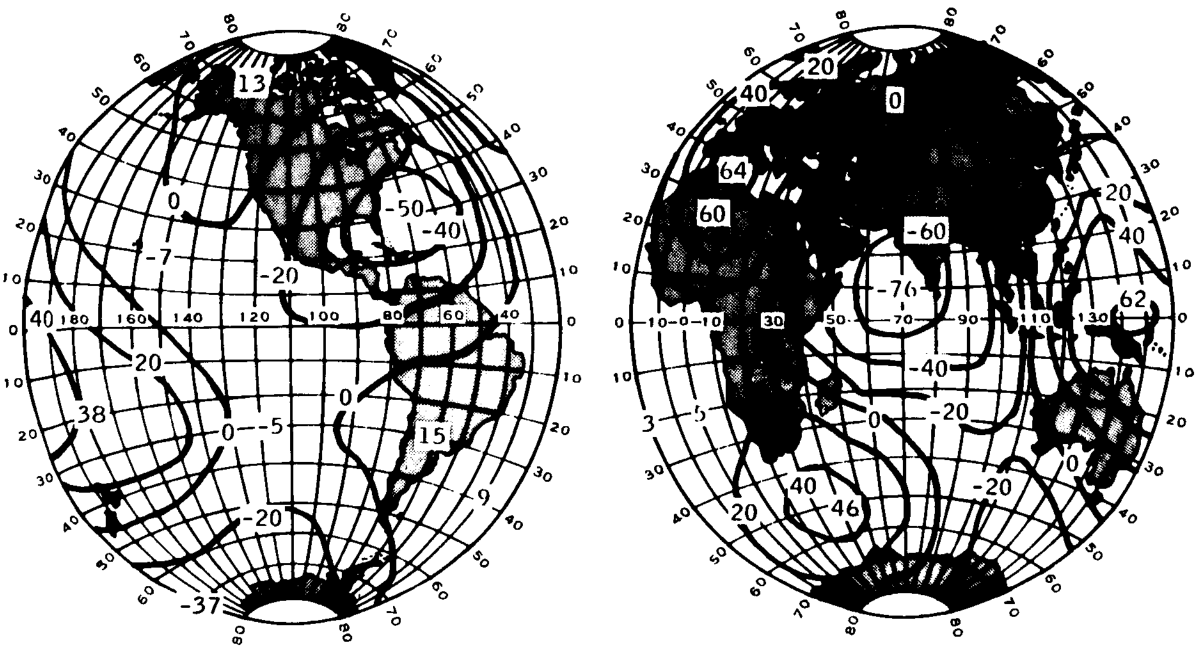

FIGURE 3.—Doppler geiod of satellite (Guier, 1963).