



The Transit Satellite Geodesy Program

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The satellite geodesy program at APL began in 1959 and lasted approximately 9 years. It was initiated as part of a major effort by the Laboratory to develop a Doppler navigation satellite system for the U.S. Navy. The concept for this system (described in companion articles) was proposed by Frank T. McClure based on an experiment performed by William H. Guier and George C. Weiffenbach. Richard B. Kershner was appointed the head of the newly formed Space Development Division (now called the Space Department), which was dedicated solely to the development of this satellite navigation system for the Navy. This article addresses the efforts expended in improving the model of the Earth's gravity field, which is the major force acting on near-Earth satellites.

(Keywords: Doppler navigation, Earth gravity field, Navy Navigation Satellite System, Satellite geodesy, Spherical harmonics, Transit Navigation System.)

INTRODUCTION

On October 4, 1957, the Russians launched the Earth's first artificial satellite (*Sputnik I*). From an analysis of the Doppler shift on the transmitted signals from this satellite, Guier and Weiffenbach^{1,2} demonstrated that the satellite's orbit could be determined using data from a single pass of the satellite. During this time, people from several other laboratories were attempting this same experiment. As Robert R. Newton reported,

Every other person who studied the problem of finding the orbit from the Doppler shift solved the theoretical problem wrong and concluded either that the orbit could not be found at all, or that at best it could be found with low accuracy. Only Guier and Weiffenbach solved the problem correctly; they found that the Doppler observations from a single pass gave an orbital determination as good as all data from all other types of tracking up to that time.³

In a recent article, William H. Guier and George C. Weiffenbach⁴ reminisced about those early days after the launch of *Sputnik I*. (Their article is reprinted in this issue.) The article provides an interesting glimpse into the excitement of that time and the working environment of the Applied Physics Laboratory in those days.

After reviewing Guier and Weiffenbach's results, Frank T. McClure realized that if the satellite orbit could be determined from the Doppler shift at stations of known positions, then the inverse problem could also be solved. That is, given knowledge of the satellite trajectory, one could use the Doppler shift at a ground site to determine the ground site's position. McClure⁵ also recognized that this capability could provide the Navy with an all-weather navigation system. His idea led to APL's being given the task of developing the Navy Navigation Satellite System (also known as the Transit Navigation System) (Fig. 1).



Figure 1. William H. Guier, Frank T. McClure, and George C. Weiffenbach (l to r) discuss the principles of the Transit Navigation System (later called the Navy Navigation Satellite System).

By 1959, APL had designed and constructed the first experimental satellite (Transit 1A), developed computer satellite tracking software, and established five tracking stations for collecting data. Even though Transit 1A failed to achieve orbit, enough data were obtained to demonstrate the feasibility of the Transit system.

The Transit development program was officially begun in 1959. The initial navigational accuracy requirement was set at 0.5 nmi (926 m) with an ultimate goal of 0.1 nmi (185 m). It was recognized from the beginning that significant improvement in geodesy would be needed to achieve these accuracies and that the Doppler shift measurements from orbiting near-Earth spacecraft were an excellent source of data to make this improvement. Thus, a worldwide network of tracking stations was established, and a constellation of geodetic satellites was proposed to obtain the necessary Doppler data.⁶

Initial navigation results yielded errors as large as 1 km over 24-h fitted data spans and as much as 2 km from predicted orbits. When navigated positions were compared using different pairs of transmitted frequencies, however, agreement obtained between solutions was better than 10 m. Thus the dominant errors were shown to be geodetic: the largest force affecting the motion of a near-Earth satellite was the Earth's gravity field. Therefore, the major effort of the APL satellite geodesy research program was directed toward modeling the force of this field.

Geodesy is defined as a branch of applied mathematics that determines (1) the exact positions of points on the surface of the Earth, (2) the size and shape of the Earth, and (3) the variations in terrestrial gravity. To

achieve the objectives of the Navy Navigation Satellite System, simultaneous progress was necessary, via an iterative operation, in these three areas. Accurate station coordinates were needed so that the Doppler residuals accurately reflected gravity model errors. As the gravity model was improved, more accurate station coordinates could be determined, and knowledge of the size and shape of the Earth was improved.

Newton was one of the many people who played major roles in the success of the APL geodesy program. He was also the main author of two APL reports that give an excellent chronological history of the Space program at APL during its early years.^{3,7} This article draws heavily from those reports.

In 1964, NASA started its National Geodetic Satellite Program. Although by that time APL's geodetic research efforts were beginning to wind down, APL did build many of the geodetic satellites used by the main participating organizations of the NASA program. In 1977, NASA issued a final report⁸ on the results achieved by the National Geodetic Satellite Program; chapter 2 of this two-part report presents the contributions made by APL to geodesy. It presents the theories used in determinations and describes in detail the geodetic satellites built by APL.

REFRACTION CORRECTIONS

Two significant refraction effects on the transmitted signal are caused by the ionized and un-ionized portions of the Earth's atmosphere. The ionospheric refraction effects on the Doppler signal, caused by the ionized part of the upper atmosphere, are a function of the transmitted frequency. For large (>100 MHz) transmitted frequencies f , Guier⁹ showed that the Doppler shift Δf as measured at the ground site can be written

$$\Delta f = -\frac{f}{c} \frac{dp}{dt} + \frac{a_1}{f} + \frac{a_2}{f^2} + \frac{a_3}{f^3} + \dots, \quad (1)$$

where dp/dt is the geometric range rate; c is the velocity of light; a_1 is proportional to the time derivative of the total electron content along the geometric slant-range vector from station to satellite; a_2 depends on signal polarization and on the magnetic field component in the direction of travel of the signal, typically 1% of a_1 ; and a_3 has several components and involves, among other effects, the difference between the signal path and the slant-range vector. The first-order effect is the largest. By transmitting two phase-coherent signals at different frequencies, this first-order term can be eliminated by combining the signals as follows:

$$\Delta f_1 - \Lambda \Delta f_2 = -\frac{f_1(1 - \Lambda^2)}{c} \frac{dp}{dt}, \quad (2)$$

where

$$\Lambda \equiv \frac{f_2}{f_1} < 1. \quad (3)$$

The term $f_1(1 - \Lambda^2)$ can be interpreted as the effective frequency in the absence of the ionosphere.

The lower, un-ionized part of the atmosphere includes both the troposphere and the stratosphere. However, about 80% of these refraction effects are produced by the troposphere proper, below the tropopause. The index of refraction of un-ionized air is independent of frequency in the radio region, at least below 15 GHz. Therefore, the two-frequency method that corrects the Doppler signal for the ionospheric refraction effects does not remove the contributions from the troposphere.

Tropospheric effects shorten the satellite-to-station range, on average, by 20 m for high-elevation passes and even more for lower-elevation passes (40 m for a pass with maximum elevation of 30° and 100 m for a 10° pass). The major research into modeling of these effects was conducted by Helen S. Hopfield,¹⁰⁻¹⁵ who developed a two-quartic tropospheric refractivity profile for correcting the satellite Doppler data. This model is based theoretically on a troposphere with a constant lapse rate of temperature. It treats the “dry” and “wet” components of the tropospheric refractivity separately and represents each as a fourth-degree function of height above mean sea level. This model corrects for more than 90% of the tropospheric effects on the received signal.

EARTH'S GRAVITY FIELD MODEL

As stated earlier, the main emphasis of the APL satellite geodesy program was to model the Earth's gravity field, since the gravity field was recognized as the largest force affecting the motion of near-Earth satellites. Also, since the Doppler signals on the satellite-transmitted frequency received by the ground stations are strongly dependent on the satellite's motion, these data provided the best source for determining the gravity field.

The Earth's gravitational potential U , from which the gravity forces are computed, is defined in terms of a series expansion in spherical harmonics of the form,

$$U = \frac{\mu}{r} \left\{ 1 + \sum_{n=2}^{\infty} \sum_{m=0}^n \left(\frac{r_e}{r} \right)^n P_n^m(\sin \varphi) \times [C_n^m \cos m(\lambda - \Lambda_G) + S_n^m \sin m(\lambda - \Lambda_G)] \right\}, \quad (4)$$

where

λ, φ	= satellite right ascension, declination angles,
Λ_G	= Greenwich meridian angle,
$P_n^m(\sin \varphi)$	= Legendre polynomial of degree n and order m ,
μ	= gravitational constant for the Earth,
C_n^m, S_n^m	= coefficients associated with the spherical harmonic of degree and order n, m ,
r	= satellite radius, and
r_e	= scale radius, nominally equal to mean equatorial radius of the Earth.

The coefficients C_n^m and S_n^m are determined from an analysis of the Doppler signals received by the ground stations.

Each harmonic can be thought of as defining a global distribution of mass (with zero mean) within the surface of the Earth. Spherical harmonics for which the order m is zero are referred to as zonal harmonics, since the positive and negative distributions vary among horizontal zones from the North Pole to the South Pole. The special cases of $n = m$ are referred to as sectorial harmonics, because the distributions vary in longitudinal sectors around the Earth. For nonzero m , they are called tesseral harmonics, and their mass distribution is a more complicated mixture of zones and sectors. The zero nodal lines between the positive and negative mass distributions for a given harmonic can be described by the number of horizontal and vertical planar slices through the Earth's surface. For a given harmonic of degree and order (n, m) , the number of vertical slices is given by m , and $(n - m)$ defines the number of horizontal slices.

Although each harmonic has a unique effect on the motion of a near-Earth satellite, the main frequency responses (on a given spacecraft), within subgroups of these harmonics, are very similar. The coverage and sensitivity of the data obtained from a single satellite (or satellites in similar orbits) were not sufficient to separate out the contributions of these harmonics within each group. The most effective way of enhancing their separability was to launch satellites into orbits with distinctly different inclinations with respect to the Earth's equatorial plane. This strategy was adopted.

By the time the main effort in geodesy began, a network of 13 tracking stations was established whose sole objective was to collect Doppler data for use in the geodesy improvement program. This network was referred to as the TRANET system, short for Transit Network. The locations of these stations are shown in Table 1. Note that the station numbers are not consecutive. Some sites were seriously considered but never occupied, while others were used early in the program

Table 1. TRANET Network site locations.

Station number	Location
1	APL
3	Las Cruces, New Mexico
6	Lasham, England
8	Sao Paulo, Brazil
10	Wahiawa, Hawaii
11	San Miguel, Republic of the Philippines
12	Smithfield, Australia
13	Misawa, Japan
14	Anchorage, Alaska
15	Pretoria, Union of South Africa
17	American Samoa
18	Thule, Greenland
19	McMurdo Sound, Antarctica

but later abandoned. This network of tracking stations was designed to keep a satellite at 1000-km altitude and at any inclination continuously in view except for a maximum time gap of about 40 min/day.

Before the advent of artificial satellites, the Earth was assumed to be in hydrostatic equilibrium, symmetrical with respect to the axis of rotation and with respect to a plane perpendicular to that axis. Only a measure of the oblateness of the Earth was known (i.e., the polar radius was thought to be about 21 km shorter than the equatorial radius). Three early determinations from satellite data had a major impact on this thinking. First, the flattening of the Earth was determined to be less than had been thought. Second, determination of the coefficient of the harmonic of degree and order (3, 0) indicated that the Northern and Southern hemispheres were not symmetrical (the “pear-shaped effect”).¹⁶ Third, a discovery, made almost simultaneously at the Smithsonian Astrophysical Observatory and independently at APL by Newton,¹⁷ was the (2, 2) harmonic, which implies an elliptical equator. The last two

effects yield significant departures from symmetry of the Earth’s shape; therefore, the Earth cannot be in hydrostatic equilibrium.

By this time (1962) our tracking errors were reduced to about 0.2 nmi (370 m). In 1963, data were available from satellites at inclinations of 62.0°, 73.6°, and 78.1°, and Guier¹⁸ determined the nonzonal harmonics through degree and order 4. The root-mean-squared residual for this set of data was 102 m.

During the early 1960s, the harmonic expansion of the Earth’s gravity potential was expected to be a rapidly converging series, at least for purposes of modeling the motion of near-Earth satellites. As more data were acquired, more gravity coefficients were estimated; with these estimates came the realization that the convergence of the potential expansion would be much slower than anyone had expected. By 1965, sufficient data had been collected from five satellites at four distinct inclinations to warrant a redetermination of the gravity field through degree and order 8 (Fig. 2).

Different data spans and analysis techniques are used in estimating the zonal and nonzonal coefficients. Zonal harmonic contributions are best detected from their secular and long-period (tens of days) effects on

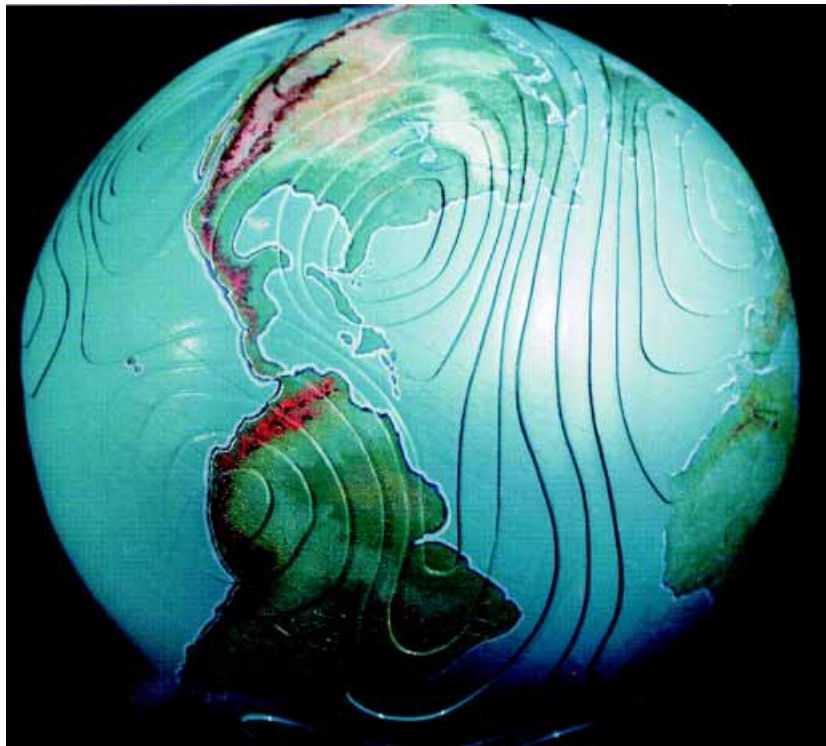


Figure 2. The shape of the Earth (geoid), as determined in 1965 by William H. Guier, Robert R. Newton, and Steve M. Yionoulis of APL’s Space Department using Doppler tracking data from four satellites. The contour interval is 10 m. The picture shows a “low” with its center on the Carolina coast and another low about halfway between California and Hawaii. Other lows are found near the tip of India and in Antarctica. The picture also shows a “high” with its center in Peru. Other highs are found near New Guinea, the Iles Crozet, and Ireland. This globe is on display in APL’s Space Museum. Newer determinations of the geoid show more detail, but the basic picture is unchanged.

the satellite's orbit. Nonzonal contributions are typically at periodicities of less than a day, and their determination is the most computationally time consuming. It should be noted that additional parameters other than the gravity coefficients must be estimated in the fitting process for the nonzonal harmonics. These include coordinates of the tracking sites as well as initial orbit parameters associated with each satellite data span used. Thus between 500 and 600 parameters were being estimated for each complete iteration through the data.

For modern desktop computers with gigabytes of storage, tens of megabytes of random access memory (RAM), and central processing unit speeds exceeding 100 MHz, this task could probably be accomplished in a day. However, in the mid-1960s, computer technology was still in its infancy. The main computer facility for APL was an IBM 7094. Its equivalent RAM, I've been told, was 32 kilowords (where one word is 36 bits), and data storage was on tapes or mechanical disk drives. Even the programming languages were barely beyond the primitive stage (not recommended for the faint of heart). One complete iteration took about 50 h. A backup tape was created at 2-h intervals to guard against a machine failure, and each iteration was repeated to check that the results were valid. The program had to be run at night or on the weekends so that the computer would be available to other users during normal working hours. Several iterations were required for convergence, and the total elapsed time to the final solution was measured in months. Guier¹⁹ was mainly responsible for the theory used and for the design of this fitting program. In its implementation, he had the support of an excellent team of programmers.

When the final results were obtained, improvements in the tracking accuracies were much less than anticipated. In addition, strange and inconsistent behavior was observed in the station along-track residuals (the computed component of station position error in the approximate direction of the satellite's velocity vector) of three Transit satellite tracking residuals. The three satellites, Transit 5BN-2, 5E-1, and 5C-1, were all in polar orbits about the Earth. Transit 5BN-2 exhibited an along-track oscillation with an amplitude of 130 m and a period of 60 h, and Transit 5E-1 showed a similar oscillation with a period of 65 h. No such fluctuation was apparent, however, in the residuals from Transit 5C-1. After some analysis, it was recognized that Transit 5BN-2 and 5E-1 were in near-resonant orbits with the 13th-order harmonics of odd degree, while the orbit of Transit 5C-1 was well removed from this resonance. A resonant condition arises when an integer multiple of the satellite's orbital

frequency becomes commensurate with a frequency generated by one or more nonzonal harmonics in the gravity field. This condition is unstable; the force will eventually move the satellite into a different-period orbit.

From an independent analysis of data from three different polar satellites, coefficients for the harmonics of degree and order (13, 13), (14, 14), and (15, 14) were computed.²⁰ In hindsight, from the amplitudes of the coefficients determined, this was probably the first real clue that convergence of the gravity series expansion would be very slow.

Once these effects were included in our orbit determination programs, the (8, 8) gravity field was redetermined with these resonant terms constrained.²¹ When these results were introduced into the navigation system, the system accuracy improved to 99 m, a factor of almost 2 better than the established goal of 185 m.

By capitalizing on near-resonant conditions in other satellite orbits, additional higher-degree and -order harmonic coefficients were estimated in 1966.^{22,23} Also, by this time, sufficient Doppler data were available from two additional satellites having distinctly different orbits to warrant a redetermination of the geopotential.

The new determination was made using satellite data from seven distinct inclinations.²⁴ It contained coefficients for all harmonics through degree 12 (with the exception of the first- and second-order terms of degree 12), and also 33 additional coefficients of harmonics of degree 13 through 17 that were assumed to be identifiable from the data (Fig. 3). When this new gravity field (called the APL 5.0-1967 model) and the improved station coordinates were introduced into the Transit system, the system accuracy went from 99 to 25 m, exceeding by almost an order of magnitude the accuracy requirements of the Navy Navigation Satellite System. With the success of this gravity model, our efforts in seeking further improvements were no longer justifiable, and this phase of the program was ended.

A recent article by Jerome R. Vetter²⁵ presents a very nice history of the development of Earth gravity models up to the present for those interested in a more comprehensive treatment of the work done in this area. Some other areas of study that were a part of the Transit improvement program included modeling of upper atmospheric density, tidal effects, polar motion, relativistic effects, and the design of more sophisticated satellites. In the remaining references cited at the end of this article, I have listed as many additional published papers as could be found that reflect the work done during the 1960s and 1970s.²⁶⁻⁶⁹ I'm sure that this list is far from complete.

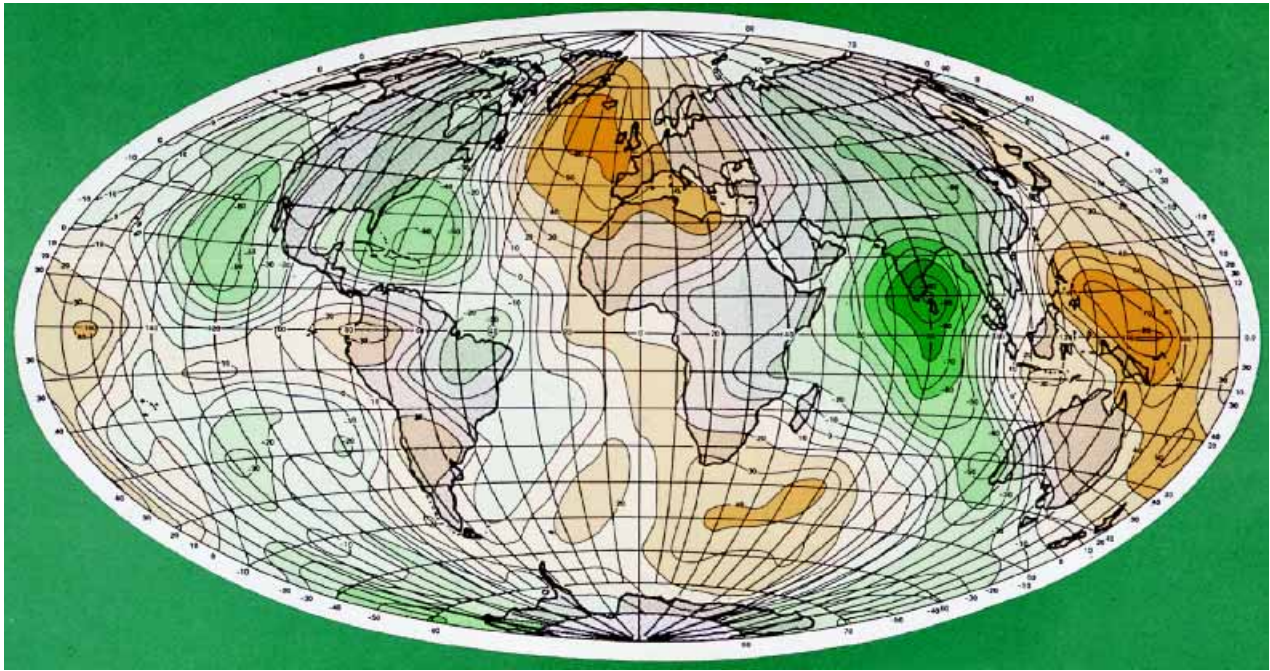


Figure 3. Map of geoidal heights (meters) for the APL 5.0-1967 gravity field relative to a reference ellipsoid with a semi-major axis of 6378.140 km and flattening of 1/298.26.

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