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DESIGN OF THE GEOSAT EXACT REPEAT MISSION

The GEOSAT spacecraft was launched into a retrograde orbit from the Western Test Range in March 1985. The first 18 months were dedicated to completing the high-resolution mapping of the marine geoid undertaken by the Seasat mission in 1978 and interrupted by its early demise. In September 1986, the spacecraft was maneuvered into an orbit more suited for oceanography. That phase of the mission is referred to as the GEOSAT Exact Repeat Mission. In order to minimize the effect of geoid uncertainty on the determination of ocean variability derived from GEOSAT altimetry, the ground tracks from each repeat cycle should deviate by no more than 1 kilometer from the mean ground tracks in all other repeat cycles. The origin and planning for the Exact Repeat Mission are described here, together with a discussion of the feasibility of maneuvering and maintaining the spacecraft in an exact repeat orbit.

INTRODUCTION

The GEOSAT spacecraft was launched into orbit from the Western Test Range by an Atlas Agena at 6 PM PST on March 12, 1985. It carried a Seasat-class radar altimeter and a TRANET beacon. GEOSAT's primary mission was to map the marine geoid with a spatial resolution of approximately 15 kilometers. The spacecraft was launched into an orbit similar to that of Seasat, although more eccentric, with an eccentricity of 0.004, a mean semimajor axis of 7168 kilometers, and an inclination of 108.05 degrees. The nodal period for the injection orbit was about 6040 seconds, which corresponds to a near-23-day repeat with closure to within 50 kilometers. The effect of atmospheric drag was such that by fall 1986 GEOSAT was in an almost exact 23-day repeat orbit. The injection orbit was considered acceptable for the geodetic mission, and the spacecraft orbit-adjust system was not exercised. However, the orbit was not ideal for oceanographic applications, and plans were made to maneuver the spacecraft into a 17-day exact repeat and frozen orbit beginning in October 1986.

By "exact repeat" we mean that the ground tracks repeat to within ±1 kilometer for each 17-day repeat cycle. By "frozen" we mean that the argument of perigee and eccentricity of the orbit is chosen so that perturbing forces due to the J_2 and J_3 harmonics of the earth's gravity field cancel one another, resulting in stationary values of the mean argument of perigee and eccentricity.[1] Fixing the mean argument of perigee and eccentricity results in a constant-altitude history from orbit to orbit and eliminates variations in the ground track associated with an eccentric orbit with circulating lines of apsides.

OCEANOGRAPHY AND THE GEOSAT EXACT REPEAT MISSION

Although the primary mission of GEOSAT was to collect altimeter data from a high-density set of ground tracks for computing an oceanic geoid (given approximately by mean sea level), the secondary mission of GEOSAT was designated as mesoscale oceanography after mission planning was well under way. Unfortunately, both the spacecraft and mission design were far from optimal for observing and studying the oceanic mesoscale. (GEOSAT has no boresighted radiometer for water vapor pathlength corrections and was initially in a nonexact repeat orbit.) The long design lifetime of the traveling-wave-tube amplifier used in the GEOSAT altimeter and the maneuverability of the spacecraft (GEOSAT has both velocity and antivelocity cold-gas thrusters) led Mitchell to propose[2] an extension of the nominal 18-month GEOSAT mission, during which the satellite would be placed in an exact repeat or collinear orbit for at least two years. He estimated the conditional probability of successfully achieving the end of the nominal or geodetic phase of the mission as at least 75 percent and of realizing completion of a subsequent two-year extended mission as about 50 percent. Following the proposal, planning began in the Navy for such a mission.

The cross-track spatial separation (i.e., resolution) of the nadir-looking altimeter is determined by the repeat or near-repeat period of the satellite's orbit. Thus, a given temporal sampling frequency results in a specific ground-track separation (as long as the satellite's altitude is allowed to vary only slightly). This relationship is shown in Fig. 1 of Ref. 3 for satellites with altitudes near 800 kilometers (e.g., GEOSAT). Mitchell suggested[2] that sampling frequencies of about 20 days and equatorial ground-track separations of approximately 140 kilometers were nearly optimal for quasisynoptic sampling of the oceanic mesoscale with typical spatial scales of 100 kilometers and time scales of at least 30 days. Later, more quantitative work of Kindle[4] has verified that such orbits might be described as optimum.

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Though much oceanographic research work in the Navy has been possible using GEOSAT data collected from the geodetic mission orbit, the basic limitation was the general lack of adequate independently known geoids in most regions of the ocean.[5] Such independent reference geoids are necessary for nonrepeating ground tracks so that the sea-surface topography associated with mesoscale currents may be computed as the difference between the measured sea level and the reference geoid height. Exact repeat orbits are therefore highly desirable because they allow for the immediate global computation of the sea-surface topography fluctuations associated with the oceanic mesoscale simply by looking at the differences in sea level from one track to the next repeat of that particular track.

A logistical encumbrance on the use of GEOSAT data for oceanographic research has been that the altimeter-measured ranges (distance from the altimeter to the ocean surface) have limited distribution. Such a limitation has been necessary because of the geodetic improvements possible with the extremely dense set of ground tracks collected by GEOSAT during the geodetic mission. Additionally, the mission has resulted in the fill-in of gaps left in the released Seasat data set. Following a suggestion by M. Parke of the Jet Propulsion Laboratory, Mitchell[6] identified a particular choice of 17-day exact repeat orbit whose ground tracks did not allow for any significantly improved geoid recovery beyond that already possible using released Seasat data. This exact repeat orbit also satisfied the quasisynoptic sampling requirements of a near 20-day repeat orbit. While aliasing of the M_2 tidal component is rather severe for a 17-day orbit, it represents no significant encumbrance at the oceanic mesoscale. The unique possibilities offered by the orbit (i.e., that the range data have wider civilian distribution, quasisynoptic at the mesoscale, and require no independently determined geoid for time-dependent mesoscale motions analysis) quickly led to its adoption as nominal for the GEOSAT Exact Repeat Mission. This article presents detailed planning and mission-design considerations for realizing the 17-day exact repeat orbit and for then maintaining the resulting set of ground tracks with a stability of ±1 kilometer.

ORBIT SELECTION

The total effective rms noise floor on the precision of an altimeter range measurement determines the minimum sea-level gradient that can be resolved by the altimeter. At the spatial scale at which the minimum resolvable gradient exceeds the local gradient in the geoid, the altimeter cannot observe any geodetic structure and the altimeter's effective geodetic spatial resolution limit is defined. Brammer and Sailor[7] define the scale to be typically around 30 kilometers for the Seasat altimeter system. The GEOSAT altimeter is somewhat quieter than the Seasat altimeter[2] (also see MacArthur's paper elsewhere in this issue); however, the lack of a radiometer for determining water vapor pathlength corrections on board GEOSAT leads to a degradation of the effective system resolution, so that both systems have effectively the same resolution limit. Figure 1 (from Ref. 6) illustrates the resulting spatial resolution of the GEOSAT altimeter over a very rough geodetic region (a midocean ridge). With a range precision of about 3.5 centimeters, the GEOSAT altimeter noise floor results in a minimum resolvable geoid scale of approximately 32 kilometers. It is important to note that in other regions, where the geoid is typically smoother (e.g., over an abyssal plain), the effective geoid-resolution scale will be even longer than 32 kilometers. Thus, the example shown in Fig. 1 represents an extreme in the geoid-resolution capability of the GEOSAT system. The only regions in which the GEOSAT geoid-resolution limit is likely to be less precise than this value are immediately over trenches and seamounts.

Mitchell[6] identified a particular 17-day repeat orbit with a set of 244 equatorial nodal crossings that began at approximately 1°E longitude and resulted in ground tracks that fell along already released Seasat ground tracks within about one-third of the geoid-resolution limit (i.e., within approximately 10 kilometers of released Seasat tracks) at the equator. Track spacing was much closer than this at higher latitudes. Figure 2 shows the ground tracks of that orbit over the Pacific Ocean. Figure 3 shows the maximum equatorial distance between Seasat and GEOSAT Exact Repeat Mission nodal crossings as a function of the longitude of a reference nodal crossing. Based on Fig. 2, 1°E longitude was chosen as the reference node. The remaining 243 ascending node crossings for the GEOSAT Exact Repeat Mission are equally spaced at 1.4754-degree intervals around the

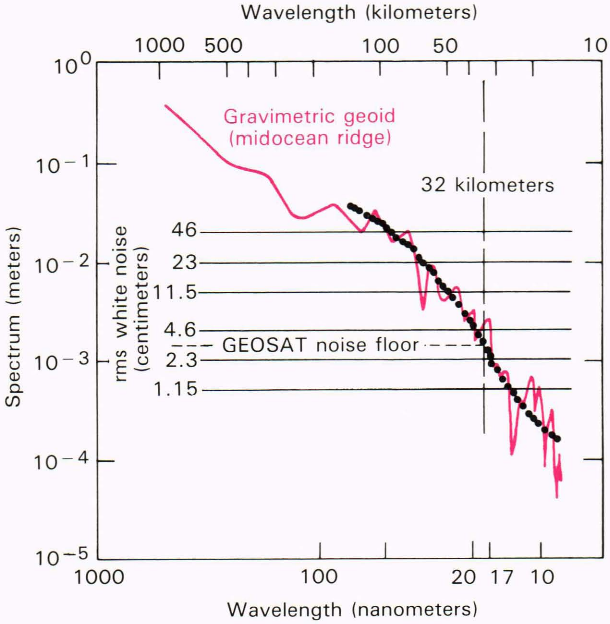

Figure 1—Power spectrum of a geoidal undulation over a midocean ridge. Horizontal lines represent an estimate of the rms white noise floor of the measurement system. For GEOSAT, the noise floor lies between ±2 and ±4 centimeters. The altimeter is essentially incapable of recovering geoidal structure at wavelengths shorter than that wavelength at which the estimated noise floor intersects the geoidal power spectrum. (Figure courtesy of T. Davis, U.S. Naval Oceanographic Office.)

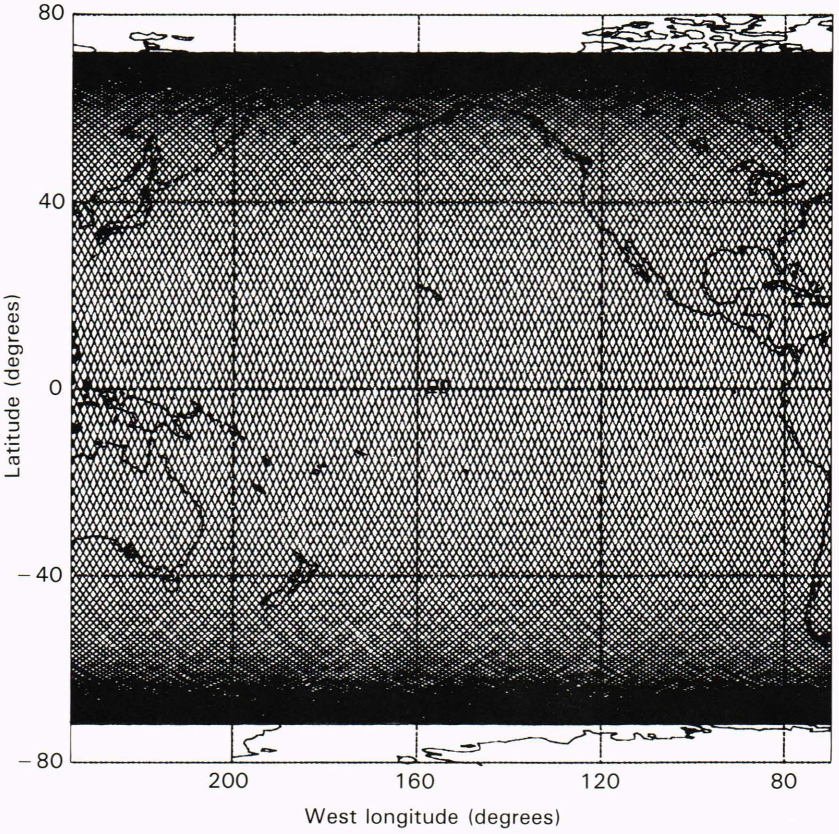

Figure 2—GEOSAT 17-day repeat ground track over the Pacific Ocean.

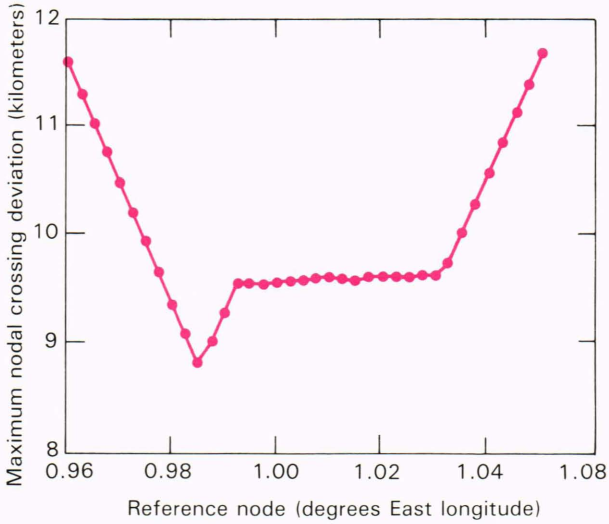

Figure 3—Maximum equatorial distance between Seasat and GEOSAT Exact Repeat Mission nodal crossings as a function of the longitude of a reference node.

equator. Since the orbital inclinations of the two missions are within 0.03 degree of each other, all requirements for an unclassified mission will have been achieved, provided a station-keeping strategy is used periodically to correct the orbit for the effects of atmospheric drag.

NODAL PERIOD

The orbit that minimizes the track spacing between GEOSAT and Seasat is one that completes 244 revolutions in 17 days (14-6/17 revolutions per day). In that context, a day is the time it takes the earth to rotate 360 degrees with respect to the GEOSAT line of nodes. For example, for a 17-day repeat orbit the actual wall clock time required is

$$T = 17 \frac{2\pi}{\dot{\theta} - \dot{\Omega}} ,$$

where $\dot{\theta}$ is the earth's sidereal rotation rate (7.292115×10^{-5} radian per second) and $\dot{\Omega}$ is the precession rate of the GEOSAT ascending node (4.144×10^{-7} radian per second). Hence, T is 17 days, 1 hour, 42 minutes, and 42 seconds. The nodal period required for a 17-day repeat is given by

$$P_n = T/244 = 6037.55 \text{ seconds.}$$

ORBIT PERTURBATIONS

The primary factors that affect the GEOSAT track spacing are atmospheric drag, maneuver errors, and uncertainty in knowledge of the mean orbital period at the time of maneuver. All these factors affect the nodal period of the orbit and, hence, the repeat track spacing.

In addition, there are perturbations to the satellite orbit due to the noncentral gravitational attraction of the earth. These perturbing forces introduce cross-track variations of varying amplitude and frequency in the GEOSAT orbit. Several effects are caused by the oblateness of the earth (described by the geopotential coefficient, J_2) and have magnitudes on the order of 1 kilometer. Fortunately, the perturbations, which have a twice-per-resolution frequency, will always be in phase because they are periodic in the argument of latitude, and there will be no resulting ground-track deviations from orbit to orbit.

Variations in the eccentricity affect the relative location of two satellites in an orbit with the same nodal period. Hence, long-term variations in eccentricity, which are primarily due to J_3, must be considered. The long-period variation in eccentricity is given by[8]

$$\frac{de}{dt} = \frac{-3nJ_3}{2(1-e^2)^2}\left(\frac{R}{a}\right)^3 \sin I \times \left(1 - \frac{5}{4}\sin^2 I\right)\cos\omega \,, \tag{1}$$

where e is the eccentricity, n is the mean motion, a is the semimajor axis, I is the inclination, ω is the argument of perigee, R is the mean radius of the earth, and J_3 is -2.5×10^{-6}. An analytic integration of Eq. 1 yields the following expression, periodic in the argument of perigee, for the variation in e:

$$e(t) = \bar{e} - \frac{3}{2}\,\frac{nJ_3}{(1-e^2)^2}\left(\frac{R}{a}\right)^3 \frac{\sin I}{\dot{\omega}_s} \times \left(1 - \frac{5}{4}\sin^2 I\right)\sin(\omega_0 + \dot{\omega}_s t) \,, \tag{2}$$

where $\dot{\omega}_s$ is the secular rate of ω .

Evaluating Eq. 2 for the GEOSAT orbit elements yields

$$e(t) = \bar{e} + 0.001 \sin(\omega_0 + \dot{\omega}_s t) \,. \tag{3}$$

This variation in eccentricity will have a period of about 210 days. The true anomaly, f, in terms of the mean anomaly, M, is given by

$$f = M + \left(2e - \frac{e^3}{4}\right)\sin M + \ldots . \tag{4}$$

The difference in true anomaly for two satellites with the same mean anomaly is given by

$$\Delta f = 2\Delta e \sin M + O(e^2) \,.$$

For $\Delta e = 0.001$ (from Eq. 3), $\Delta f = 0.002 \sin M$, corresponding to a maximum displacement in time of

$$\Delta t = \frac{\Delta f}{n} = \frac{0.002}{0.00104} = 1.92 \text{ seconds} \,.$$

At the earth equator, this results in a cross-track displacement of almost 1 kilometer. The geodetic phase orbit with mean eccentricity of 0.004 and circulating line of apsides has an additional cross-track deviation of ±4 kilometers from the mean ground track. Consequently, it was important that GEOSAT be placed in a frozen orbit to avoid long-period changes in eccentricity associated with circulation of the line of apsides and the resulting undesirable ground-track deviations.

Figure 4 illustrates the effect of atmospheric drag on the GEOSAT semimajor axis. This is a plot of the Brouwer mean semimajor axis from launch through the first 500 days of the mission. From this figure, it is seen that the daily decrease in semimajor axis has been about 0.45 meter. The F10.7 solar flux (which directly affects atmospheric density) has maintained a value of 70 to 75 during the first 18 months of the mission and should continue near that level for the next year or two. Hence, the decay rate in semimajor axes should remain at about 0.5 meter per day.

The effect of luni-solar perturbations on the GEOSAT orbit inclination is shown in Fig. 5, which is based on an analytical integration of the equations of motion. The primary variation in inclination is the sum of two effects that have amplitudes of 0.004 degree and 0.015 degree and periods of approximately 170 days and 14 years, respectively. Both effects result from the 2:1 commensurability between GEOSAT's node rate (2.05 degrees per day) and the earth's rotation rate about the sun (0.986 degree per day). These inclination changes will introduce small once-per-revolution variations into the cross-track spacing, but they will only be on the order of a few hundred meters. Hence, they will not seri-

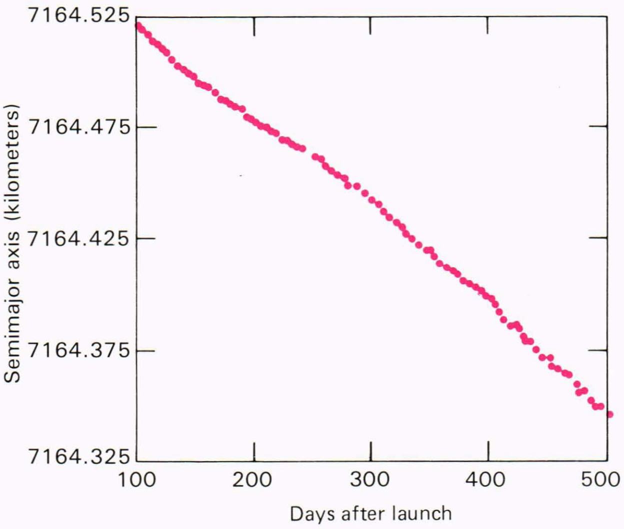

Figure 4—The mean semimajor axis history of GEOSAT.

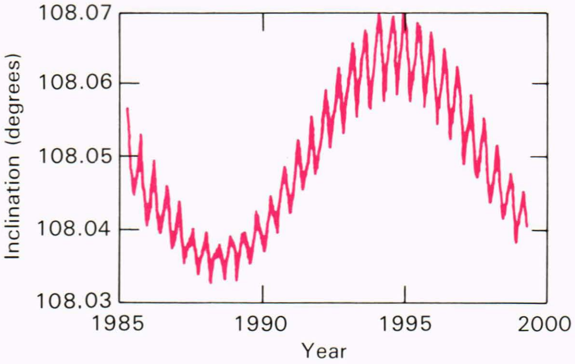

Figure 5—Prediction of GEOSAT orbit inclination.

ously affect the requirement to maintain track spacing within ±1 kilometer.

As indicated in Fig. 4, drag will reduce the semimajor axis of the GEOSAT orbit by about 0.5 meter per day. The effect of drag on the repeat track spacing is easily computed. The partial derivative of orbital period with respect to the semimajor axis is given by

$$\frac{\partial p}{\partial \bar{a}} = 3\pi \sqrt{\frac{\bar{a}}{\mu}} = 1.26 \text{ seconds per kilometer} , \quad (5)$$

where $\bar{a}$, the mean semimajor axis, is 7167.4 kilometers and μ is 398601 cubic kilometers per second per second.

Assume that $\bar{a}$ is reduced linearly by 0.5 meter each day. Hence, the time of arrival of the satellite at the nodal crossing point is decreased by Δt = (1.26 seconds per kilometer × 0.5 × 10^{-3} kilometer per day)/14.3 revolutions per day = 4.4 × 10^{-5} second per revolution.

Since the time of arrival is reduced by an additional 4.4 × 10^{-5} second during each orbit, the total change in arrival time of the satellite at the nodal crossing after N orbits will be

$$\Delta t_N = 4.4 \times 10^{-5} \left[\frac{1}{2} + 1\frac{1}{2} + 2\frac{1}{2} + 3\frac{1}{2} + \ldots + \frac{2N-1}{2} \right]$$

$$= 2.2 \times 10^{-5} [1 + 3 + 5 + 7 + \ldots + 2N - 1] = 2.2 \times 10^{-5} N^2 . \quad (6)$$

The factor of ½ in each term accounts for the fact that the semimajor axis changes linearly over each orbit; hence, the time of nodal crossing change in any given orbit is $\Delta t/2$. We wish to maintain the ground-track repeat distance of GEOSAT to within ±1 kilometer. The velocity of a point at the equator on the earth's surface is 0.465 kilometer per second; therefore, a 1-kilometer shift in track spacing is equivalent to 2.15 seconds of earth rotation. Hence, we must maintain GEOSAT's nodal crossing time to within ±2.15 seconds of the exact repeat period crossing time. According to Eq. 6, which assumes that drag reduces the semimajor axis by 0.5 meter per day, it would take approximately 22 days for the nodal crossing time to change by 2.15 seconds. We can adjust the nodal period at the time of maneuver to overshoot the exact repeat period, thereby causing the ground tracks to displace to the west. Drag would take the orbit through the exact repeat period, and when the ground tracks fall 1 kilometer to the east, another maneuver would be performed. Therefore, maneuvers would be required less frequently than once every 22 days.

Thus far, we have ignored maneuver execution errors, uncertainty in knowledge of the mean nodal period at the time of maneuver, and postmaneuver drag prediction errors. If an orbit using OPNET Doppler data is generated approximately one day before the maneuver, the mean period at the time of maneuver should be known to about 0.001 second (equivalent to 1 meter in knowledge of $\bar{a}$).

The GEOSAT spacecraft weighs about 595 kilograms and carries two 0.044-Newton (0.01 pound-force) thrusters.[9] Hence, an acceleration of 0.044/595 = 7.4 × 10^{-5} meter per second per second will be imparted to the spacecraft. For a circular orbit,

$$\Delta v = \frac{\mu^{1/2}}{2a^{3/2}} \Delta a ,$$

and for the nominal GEOSAT orbit,

$$\Delta v = 5.2 \times 10^{-4} \Delta a . \quad (7)$$

In order to maintain a circular orbit, Δv is applied in two equal burns 180 degrees apart, each imparting a velocity increment of $\Delta v/2$ to the spacecraft. A typical drag makeup maneuver will require a 15- to 25-meter increase in $\bar{a}$. From Eq. 7, a maneuver to increase $\bar{a}$ by 25 meters requires 0.013 meter per second. The corresponding time for each of two burns will be

$$\Delta t = \frac{0.0065}{7.4 \times 10^{-5}} \approx 88 \text{ seconds} . \quad (8)$$

Maneuver execution errors should be less than 10 percent of the total Δv, or about 1 millimeter per second. From Eq. 7, this is equivalent to Δa = 1.9 meters, which, from Eq. 5, yields a period error of 0.0024 second.

The attitude of the GEOSAT spacecraft is expected to be known and stable to 1 or 2 degrees in all three axes during a 3-minute burn. A worst-case situation would be a 5-degree variation. The equation for the rate of change of the semimajor axis expressed in terms of the radial and transverse force can easily be evaluated to show that an attitude variation of 5 degrees will have a negligible influence on the nodal period.

In summary, the nodal period error budget for GEOSAT maneuvers is given by

Orbit knowledge errors	0.001 second
Maneuver execution errors	0.0024 second
rss	0.0026 second

Assuming a postmaneuver nodal period error of 0.0026 second and a change of 0.5 meter per day in semimajor axis due to drag, the equation for the change in time of arrival of GEOSAT at its nodal crossing after k days is given by

$$\Delta t_k = 2.2 \times 10^{-5} (14.3k)^2 + 0.0026 \times 14.3k \, . \qquad (9)$$

Using Eq. 9, it can be shown that if we target for an exact repeat, if drag effects are no greater than 0.5 meter per day, and if maneuver execution errors are in the least favorable direction, we should still have at least 18 days between maneuvers. However, by targeting the nodal period to be slightly greater than that for an exact repeat, the time between maneuvers can be significantly extended by allowing the effects of drag to compensate for the overage in period. Ignoring the effects of orbit determination and execution errors, it is possible to extend the time between maneuvers to about 50 days for a 0.5-meter-per-day drag effect. Considering orbit determination and execution errors as well as a 10 percent error in drag prediction, maneuvers should not be required more than once per month.

As of mid-January 1987, two drag makeup maneuvers had been performed 30 days apart by the GEOSAT spacecraft. However, cross-track deviations between repeat tracks were less than 1 kilometer during this time. Thus, larger burns at less frequent intervals could be used without exceeding the ±1-kilometer track spacing requirement.

MANEUVER PLANS FOR THE EXACT REPEAT MISSION

Maneuvering GEOSAT to the desired Exact Repeat Mission orbit consisted of adjusting perigee and eccentricity to the frozen orbit values, adjusting the semimajor axis to achieve the exact 17-day repeat, and phasing the ground track to within 10.8 kilometers of that of Seasat. Phasing was accomplished in coordination with the semimajor axis trim. These maneuvers took place between October 1 and November 7, 1986, and resulted in GEOSAT being placed almost exactly into the desired orbit.

The frozen orbit values given earlier as 0.001 and 90 degrees for $\bar{e}$ and $\bar{w}$, respectively, are based on analysis of J_2 and J_3 effects. More accurately, higher order zonals also contribute a diminished yet non-negligible effect. To investigate these, an Orbit Determination Program at APL was used to integrate analytically initial conditions for one year using a gravity model with zonal harmonics through J_{29}, drag, radiation pressure, and lunar and solar gravitational perturbations. Initial conditions were adjusted until the "best" long-term frozen orbit was found. Figure 6 shows the one-year trajectory using the initial values for $\bar{e}$ and $\bar{\omega}$ of 0.000805 and 90 degrees, respectively. Perigee excursions are less than 3 degrees. The simulation did not incorporate drag makeup burns; however, they will be relatively small and can be designed to neutralize the excursions. The target orbit values were chosen to be 0.0008 and 90 degrees for mean eccentricity and argument of perigee, respectively.

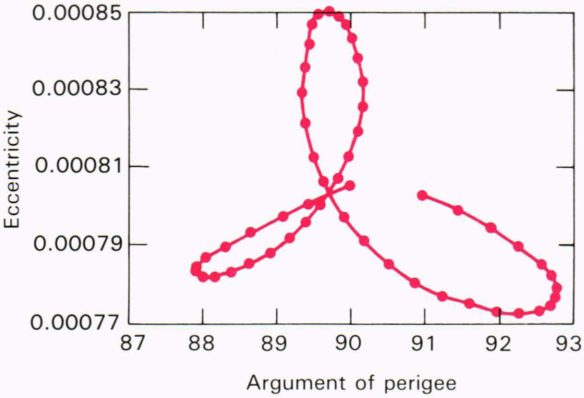

Figure 6—The variation of GEOSAT's mean eccentricity and mean argument of perigee under the influence of zonal harmonics through degree 29.

Because of the small thrusters (0.01 pound-force), a great number of burns were needed. Maneuver simulations showed that approximately 200,000 seconds of thrust time using 55 of the available 84 pounds of fuel would be needed to drive eccentricity and perigee to their frozen values. Actually, 45 pounds of fuel were expended in 239 burns, averaging about 100 seconds each. Drag makeup burns are expected to use only 1 pound of fuel per year; thus fuel is quite abundant.

The maneuvers were planned in two steps. The first step was the adjustment of eccentricity and perigee to near the target values while keeping the period as fixed as possible. A constant period during that time is desirable for two reasons. First, precise antenna pointings are required for S-band communication; maintaining a constant period will simplify antenna alerts and pointing predictions. Second, ground-track drift velocity with respect to the desired fixed ground track should be maintained as high as possible to minimize the time needed for alignment. A single burn will disturb the period; however, a pair of closely timed burns with equal magnitude but opposite sense can essentially keep it constant. Given a thrust in either the plus or minus X direction, there is exactly one true anomaly on the orbit where the desired change to eccentricity and perigee can be realized. For a thrust with the opposite sense, the point of true anomaly is shifted 180 degrees. Thus, the first step of the orbit maneuver consisted of 90 to 95 burn pairs of nearly equal magnitude but opposite sense, separated by 180 degrees. Given a positive thrust and assuming target perigee to be 90 degrees, the position of the burn in the orbit to achieve desired changes to eccentricity and perigee is given by Cutting[1] as

$$\theta = \tan^{-1} \left[\frac{e_1 - e_0 \sin \omega_0}{-e_0 \cos \omega_0} \right] ,$$

where θ is the argument of latitude (the angle from the ascending node), e_1 is the target eccentricity, e_0 is the current eccentricity, and ω_0 is the current argument of perigee.

The point of true anomaly in the orbit is just θ minus the current argument of perigee. That point is defined to be the center of the burn.

The second step of the Exact Repeat Mission maneuver consisted of trimming the period to the 17-day repeat value and simultaneously phasing the ground track with that of Seasat. The actual maneuver sequence deviated slightly from those planned and will be detailed in a future article.

The altimeter was turned off during the orbit adjust period but was turned back on during the last week of maneuvers, which were small period adjustments. The GEOSAT Exact Repeat Mission officially began on November 7, 1986, and the altimeter performance has been nominal to date.

CONCLUSION

The GEOSAT spacecraft has been successfully placed into a 17-day exact repeat frozen orbit. During the GEOSAT Exact Repeat Mission it will be possible to maintain the GEOSAT spacecraft in an orbit that repeats its ground track to within ±1 kilometer with a small orbit-adjust maneuver no more than once a month. Once the thrusters are calibrated and additional experience in performing the maneuvers and predicting drag has been obtained, the maneuver frequency should decrease to well below once per month.

The collection of sea-level data from the 17-day exact repeat orbit maintained during the Exact Repeat Mission will represent an extremely valuable and unique data set for the study of global oceanic mesoscale variability. Experience with the GEOSAT Exact Repeat Mission data will allow us to better use the wealth of oceanographic data from future altimeter missions such as TOPEX/POSEIDON.

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