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A SUMMARY OF PRECISE ORBIT COMPUTATION FOR THE GEOSAT EXACT REPEAT MISSION

Recent efforts to recompute orbits for the Geosat Exact Repeat Mission have resulted in a substantial reduction in the satellite's orbit error. The improved orbits are based on Doppler tracking and on the new Earth gravity models being developed at the Goddard Space Flight Center in support of requirements for the TOPEX/Poseidon mission. The first set of orbit solutions based on the Goddard Earth Model (GEM-T1) gravity model and tracking data from the U.S. Navy's Operational Network system are accurate to about 85 cm root mean square (rms) in height. Preliminary tests of orbits computed with the GEM-T2 model, along with tracking data from an augmented network consisting of the Navy's Operational Network and selected Tracking Network sites, indicate that radial accuracies of 35 cm rms can be achieved.

INTRODUCTION

The U.S. Navy Geodetic Satellite (Geosat), carrying a Seasat-class radar altimeter and a Doppler beacon, was launched into a retrograde orbit by an Atlas Agena rocket from the Western Test Range on 12 March 1985. Geosat's primary mission was to provide a dense global altimeter database for determining the marine geoid with a 15-km spatial resolution. The satellite ground tracks were nonrepeating during the primary (geodetic) 18-month mission; thus, that phase of the mission was not well suited for determining sea-level variability.

The long lifetime of the Geosat altimeter and the maneuverability of the spacecraft permitted a secondary mission, the Exact Repeat Mission (ERM), in which the satellite was maneuvered into a 17-nodal-day repeat and frozen orbit.[1] (A nodal day is one revolution of the Earth with respect to the line of nodes of the Geosat orbit.) The ERM became operational on 8 November 1986. Modeled after the Seasat 17-day repeat orbit, the orbit is well suited for monitoring the variability of the ocean mesoscale. For Geosat, the ground track repeats to within 1 km every 17 nodal days. An exact repeat orbit allows the direct computation of sea-level variability by examining an ensemble of repeating ground tracks. No reference geoid is necessary, since the geoid height is common to the repeating tracks. "Frozen" implies that the orbit has nearly stationary values for the mean argument of perigee and eccentricity[2] because the parameters of the orbit are selected so that the perturbing forces caused by the Earth's oblateness and higher-order zonals of the Earth's gravity field approximately cancel one another.

The operational orbits provided with the Geosat geophysical data records[3] are based on the Goddard Earth Model (GEM-10, Ref. 4) and on Doppler tracking data from the Navy's Operational Network (OPNET), which consists of tracking stations in Maine, Minnesota, California, and Hawaii. Born et al.[5] estimated that the radial component of these orbits is accurate to about 3 m root mean square (rms). Fortunately, the largest component of error occurs at a wavelength equal to the orbital circumference, and a large percentage of the error can be removed on a regional basis by using simple adjustment techniques in which the error is modeled as a low-order polynomial.[6] Nonetheless, significant benefit can be derived from using precise orbits. Higher accuracies reduce the amount of orbit error remaining after adjustment and permit the separation of ocean signal and ephemeris errors over a wider variety of spatial scales.

This potential benefit has motivated a joint research venture by the Colorado Center for Astrodynamics Research and NASA Goddard Space Flight Center. Their objective is to establish optimal geodetic parameters and procedures for the computation of the most accurate Geosat orbits possible during the ERM to (1) enhance the value of the Geosat oceanographic investigations by providing the user community with improved ephemerides, and (2) develop orbit determination techniques for the NASA Ocean Topography Experiment (TOPEX)/Poseidon. Scheduled for launch in 1992, this joint altimetric mission by the United States and France will require decimeter-level orbit accuracy to achieve its scientific objectives.

To that end, we have recomputed more than a year's worth of orbits for the mission using the GEODYN II precise orbit determination and parameter estimation software system[7] at Goddard. Although the new orbits are derived from the same OPNET Doppler tracking used to compute the operational orbits, they are based on new models and constants, most notably the GEM-T1 gravity model,[8,9] that have been developed as part of the recent Earth gravity model improvement effort under way at Goddard in support of the TOPEX/Poseidon mission. The improved orbits have been made available to altimeter data users.

Our ability to compute orbits for the Geosat mission has improved since the release of GEM-T1 in 1987 because of the use of GEM-T2 (Ref. 10), the latest gravity model from the TOPEX/Poseidon effort. We have also acquired additional Doppler tracking data from Tracking Network (TRANET-2) sites overseen by the French Space Agency, the Geologic Survey of Canada, and the Royal Observatory of Belgium. We plan to compute orbits for the first two years of the mission by using new strategies that reflect the improvements. Preliminary results are presented in this article, but further analysis is pending and will be published upon the release of the GEM-T2 orbits.

Other investigations have demonstrated that the use of direct or crossing arc altimeter data in the computation of orbits and gravity fields yields highly precise Geosat orbits,[11-13] but there is concern that some of the oceanographic signal may be convolved with errors in the ephemeris by this approach. Consequently, the research described here focuses on the use of Doppler tracking of the Geosat spacecraft and gravity models based solely on satellite tracking data to compute orbits for the mission.

TRACKING DATA

Regular releases of the Doppler tracking data from the OPNET system have been secured from the Naval Astronautics Group to support precise orbit determination activities for Geosat. The OPNET data, used exclusively in computing the GEM-T1 orbits, formed the basis of our efforts to improve orbits for the mission before the TRANET-2 data were acquired.

The French stations in Kerguelen, Kourou, and Tahiti, the Canadian stations in Ottawa and Calgary, and the Belgian station in Brussels form an international network that is better globally distributed than the OPNET network, which was used to produce our first solutions (Fig. 1). Moreover, the error characteristics of the TRANET-2 stations are better understood because of the historical analysis of TRANET data from other satellites.

An additional source of Doppler data for the Geosat mission is the Defense Mapping Agency, which collects and records tracking data from more than 40 globally distributed TRANET-2 and portable TRANET sites as part of its Special Mission Tracking Program. Geosat tracking data from this complete network have not been made available to us on a regular basis, but an 80-day sample of TRANET data from the beginning of the ERM has been released by the Defense Mapping Agency. We have used this database mainly to study station coordinates and to refine precise orbit determination techniques.

Regardless of the tracking network, the processing of the signal at the Doppler ground sites is similar.[14] Station hardware combines the perturbed signal from the satellite beacon with the nominal signal generated by the ground oscillator. The signal is broadcast on two frequencies, thus allowing removal of the ionospheric refraction effect to first order when the signals are combined at the ground site.

For the OPNET sites, the receiver records the time to count a predetermined number of cycles in the differenced signal. Observations begin approximately every

Navy OPNET
Prospect Heights, Maine
Rosemount, Minn.
Point Mugu, Calif.
Wahiawa, Hawaii

Belgian TRANET-2
Brussels, Belgium

French TRANET-2
Kerguelen Island
Kourou, French Guiana
Papeete, Tahiti

Canadian TRANET-2
Calgary, Canada
Ottawa, Canada

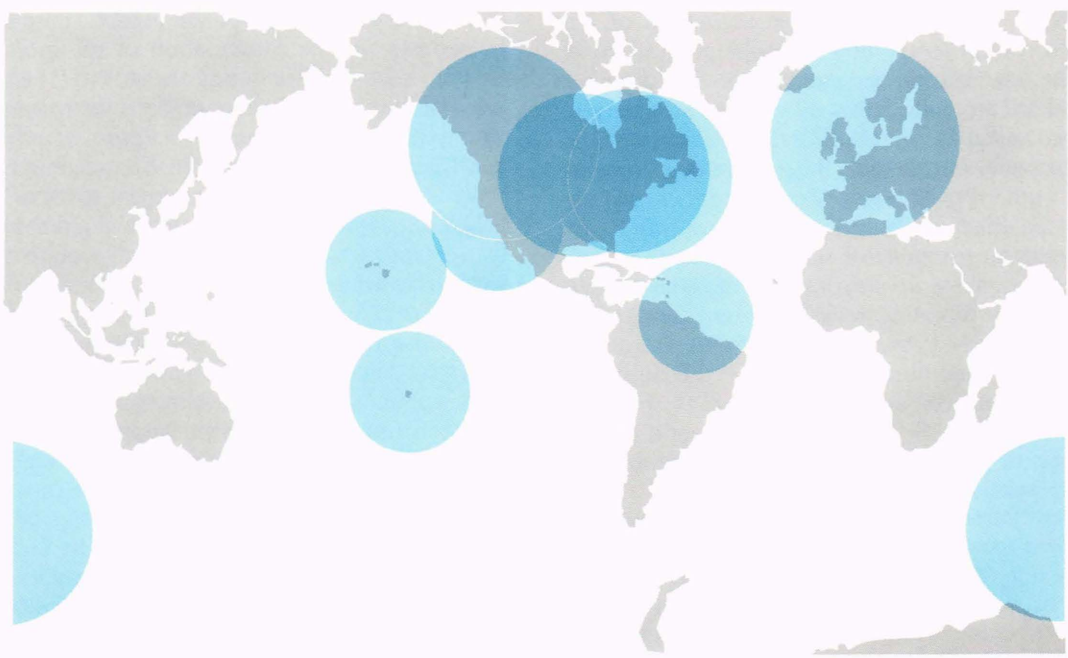

Figure 1. Map of the augmented Geosat tracking network: Navy OPNET, along with French, Canadian, and Belgian TRANET-2 sites.

four seconds and are separated by more than three seconds. For the TRANET-2 sites, the receiver records the number of counts in the differenced signal over a series of nearly constant time intervals. The receivers operate in "nondestruct" mode, each observation beginning immediately after the termination of the previous one, thereby allowing continuous monitoring of the cycle count for the duration of the pass. For this study, the raw cycle counts from both systems were converted into one-way averaged range-rate observations for processing in GEODYN II.

Unlike the TRANET sites, the OPNET sites are not equipped to record meteorological information. In its absence, GEODYN II assumes nominal values for the pressure, humidity, and temperature, an approach that introduces an unmodeled error into the computation of the wet and dry tropospheric refraction corrections to the OPNET data, particularly for low-elevation observations.

GEM-T1 ORBITS

Solution Strategy

The first recomputation of orbits for the Geosat ERM used the GEM-T1 gravity field with tracking data from the OPNET system. Arc lengths of 17 days were selected, a natural choice since 17 days corresponds to the exact repeat period for Geosat, and arcs of that length would allow investigators to recover oceanographic signals over an entire cycle without having to deal with discontinuities in the orbit. More importantly, by relying on the dynamic strength of the force models, longer arcs tend to reduce the effects of sparse, poorly distributed tracking observations. The GEM-T1 orbits for the first year of the mission were established by twenty-five 17-day solutions. Time spans were selected so as to avoid attempting any solutions during the 10 orbit-adjustment manuevers that occurred during the first year.

The GEM-T1 gravity model is the first in a series of advanced models being developed at Goddard to satisfy the requirements of future geodetic and oceanographic missions. It is complete to degree and order 36 and is derived exclusively from direct satellite tracking data from 17 spacecraft with inclinations ranging from 15° to polar. In all, nearly 800,000 observations were used, over half coming from highly precise third-generation laser systems.

With GEM-T1, an internal consistency unsurpassed by any previous GEM models has been achieved. The solution used the latest International Association of Geodesy Reference Constants and other standards adopted for the Project Merit campaign.[15] In addition to the spherical harmonic representation of the time invariant geopotential, the solution contains a subset of 66 ocean tidal coefficients and 5-day averaged Earth rotation parameters. The entire solution was made in the presence of 550 other ocean tidal terms and the Wahr frequency-dependent solid Earth tidal model.[16]

Calibration tests have shown that GEM-T1 is significantly better for modeling the motion of a wide variety of Earth-orbiting spacecraft than any previous satellite-only GEM models. Of particular importance for this study, more than 150,000 observations from the Seasat mission are included in the solution. Because the orbit for the mission was similar to the orbit used in the 17-day repeat portion of the Seasat mission, the GEM-T1 solution should be particularly well suited for computing Geosat orbits. Using analytic perturbations given by Rosborough,[17] we determined the spectrum of the Geosat radial orbit error on the basis of calibrated errors in the GEM-T1 geopotential coefficients (Fig. 2). The overall radial rms error of 45 cm may be somewhat optimistic because of inaccuracies associated with the calibration of the GEM-T1 covariance. The calibration typically is performed by applying a single scaling factor to the formal covariance matrix of the solution. The scaling factor is determined by comparisons with independent databases, such as gravity anomaly and altimetry observations. Marsh et al.[9] point out that, although this method is generally satisfactory, the lowest degree and order of the field is somewhat optimistically evaluated. More importantly, the estimate ignores the errors from the omission in GEM-T1 of the geopotential coefficients above degree and order 36, which can be significant. Haines et al.,[18] for example, showed that the radial perturbations originating from the order 43 coefficients in the GEM-T2 model approach 68 cm rms as a result of a deep secondary resonance related to the near repeat of the Geosat ground track after 43 revolutions of the satellite.

The primary models and constants associated with the GEM-T1 orbit solutions are shown in Table 1. The station coordinates used in the computations are approximately referred to the TOPEX/Poseidon terrestrial coordinate system,[8,9] in which the GEM-T1 gravity model is implicitly defined. The positions were computed using transformations derived from station sites common to the various *a priori* coordinate systems represented.[18] Comparisons demonstrated that any errors were not much more than 1 m.

Orbit Fits

The software used to make the fits for these orbits was the GEODYN II system at Goddard.[7] Given an estimate of the satellite state at some initial epoch,

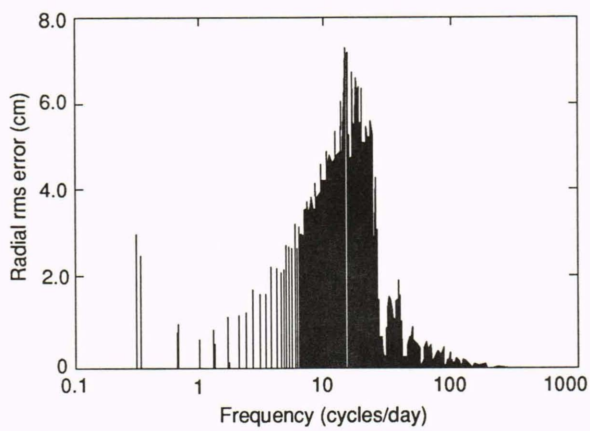

Figure 2. Standard deviation of the Geosat radial orbit error as a function of frequency, based on GEM-T1 model covariance. The overall error is 45 cm rms.

GEODYN II subsequently computes numerically the spacecraft's Cartesian state and force model partial derivatives by using a high-order Cowell integrator. The tracking observations are fit in a least-squares sense by adjusting the satellite state at initial epoch. Dynamic data editing is performed as the least-squares estimator is iterated to convergence. In addition to satellite state, estimable parameters include tracking-station coordinates, force-model parameters, and measurement and timing biases.

By means of the following strategy, the twenty-five 17-day arcs of tracking data were processed. Certain force model parameters were allowed to adjust within each orbit solution, including 17 piecewise daily drag coefficients, one solar radiation pressure coefficient, and pass-by-pass range-rate biases, in addition to the satellite Cartesian position and velocity at epoch. The range-rate biases had to be estimated to account for the relative offset of the ground and spacecraft oscillators. Because of the limited geographic coverage of the OPNET stations as well as the lack of meteorological data, station coordinates were not adjusted. Approximately 35% of the OPNET observations were edited from the original data set, low elevation being the predominant reason.

Table 1. Force and observation models for GEM-T1 orbits.

Force models and constants	
Product of Earth's gravitational constant (g) and Earth's mass (m)	$gm = 398{,}600.436$ km^3/s^2
Earth's gravitational potential	GEM-T1 (36 × 36)
Solid Earth and ocean tide potential due to Sun and Moon	GEM-T1
Atmospheric density model	Jacchia 1971
Third-body perturbations due to Sun, Moon, and all planets except Pluto	Lunar–solar and planetary ephemerides from JPL DE-200
Measurement model constants	
Earth's semimajor axis	$a_e = 6378.137$ km
Earth's inverse flättening	$1/f = 298.257$
Tracking station coordinates	TOPEX/Poseidon system
Love numbers for elastic station dispacements due to second-order solid-Earth tide potential	MERIT values[a] ($h_2 = 0.609$, $l_2 = 0.0852$)
Earth orientation and coordinate system	
Polar motion and length-of-day variations	TOPEX (Bureau International de l'Heure values adjusted to reflect mean pole)
Inertial coordinate system	J2000
Geosat parameters	
Spacecraft mass	618.244 kg
Cross-sectional area	4.651 m^2

[a]From Project MERIT.[15]

The overall fit of the remaining OPNET range-rate data to the computed orbits was typically about 1.5 cm/s rms.

Accuracy Assessment

The following methods were used to assess the accuracy of the GEM-T1 orbits: (1) comparison of overlapping 17-day trajectories, (2) evaluation of crossover residuals, (3) evaluation of direct altimeter fits, (4) evaluation of trajectories with respect to TRANET "benchmarks," and (5) comparison of operational (Naval Astronautics Group) and GEM-T1 orbits. The results from each method follow.

One consequence of the placement scheme for the twenty-five 17-day arcs was the occurrence of 14 periods when neighboring trajectories overlapped. These overlap periods provide a way to assess relative orbit accuracy by differencing the neighboring trajectories over the time period they share. The difference is a measure of the nongeographically correlated orbit error attributable to errors in both the gravity model and the estimated initial conditions. Table 2 gives the statistics of the trajectory differences. Most of the overlap periods were long enough (3 to 4 days) so that a healthy cross section of the error spectrum could be examined. Since the radial component of the orbit error is the critical component for altimeter applications, it received the most scrutiny. The average of the 14 rms radial differences is 1.27 m, but the individual rms values range from 0.30 to 2.45 m. A likely explanation for this phenomenon is related to the phasing of the radial error signals from the two orbits contributing to the overlap. The orbit error is long wavelength in nature, with a dominant frequency of one cycle per orbital revolution. The phase and magnitude of this once-per-revolution component depend on errors in the estimated initial conditions, which are governed primarily by variations in the distribution of the tracking data in different arcs. Gravity errors, particularly

Table 2. Statistics of GEM-T1 overlapping orbit differences.

Overlap No.	Start time: Date	Start time: Time	Duration: Days	Duration: Time	Radial rms difference (m)
1	20 Nov 86	1905:00	4	0608:00	1.91
2	21 Dec 86	2127:00	3	0046:00	0.61
3	21 Jan 87	0416:00	3	2020:00	0.89
4	3 Feb 87	0908:00	3	2021:00	1.20
5	6 Mar 87	0618:00	3	0558:00	1.87
6	20 Mar 87	0132:00	3	0558:00	0.44
7	2 Apr 87	2047:00	3	0559:00	0.30
8	16 Apr 87	1600:00	3	0600:00	1.21
9	19 May 87	1716:00	1	0152:00	1.91
10	9 Jul 87	1117:00	0	0947:00	1.10
11	8 Aug 87	1404:00	4	0021:00	1.41
12	7 Sep 87	1501:00	4	0210:00	2.45
13	7 Oct 87	1755:00	4	0013:00	1.53
14	31 Oct 87	2304:00	9	0200:00	0.94
				Average	1.27

those due to the coefficients that are nearly resonant for Geosat, also contribute to the error signal. Finally, the overlaps tend to reflect the consistency of the orbits at the extremes of the arcs, where the ephemeris errors are larger because of the growth of low-frequency dynamic model errors.

Another tool for analyzing the radial orbit uncertainty is altimeter crossover analysis. Two implied sea-surface–height measurements at the crossing point of a descending and an ascending track are differenced. The residual contains the combined effects of nongeographically correlated orbit error and the time-varying media and ocean signals (e.g., tides, mesoscale variability). Uncertainties in the geoid, the quasi-stationary component of the dynamic sea-surface topography, and the geographically correlated portion of the orbit error are absent from the residual since they are common to both measurements.

Because Geosat is in a repeating orbit, one repeat cycle defines a complete set of geographic locations for the crossover points (for perfectly repeating ground tracks). Thus, the crossover points from one repeat cycle served as a master set of locations, applicable to all repeat cycles. The suitability of this method is discussed more completely by Brenner et al.[19]

Using the GEM-T1 orbits, crossover statistics were computed for the full year (8 November 1986 to 18 November 1987)—more than 8 million individual crossovers. The global rms crossover residual is 118 cm, with a mean of −20 cm. Figure 3 shows the breakdown of the rms differences by geographic area, along with the number of crossovers (in thousands) in each bin. Color images of the crossover residuals also have been generated. Figure 4A shows the rms crossover residuals (mean removed) in 2° square bins. The horizontal banding of the rms differences is attributable to the once-per-revolution orbit error, which is unobservable at extreme latitudes where the crossovers are formed from crossing arcs that lag by almost exact multiples of the orbital period.[20] The image of the mean crossover residuals (Fig. 4B) contains patterns indicating that a systematic bias exists between the ascending and descending tracks over certain regions. These patterns may be related to the limited tracking used in the GEM-T1 solutions. Note, for example, the positive bias in the Indian Ocean where the tracks are far displaced from any active tracking by the OPNET system.

To serve as a basis for measuring improvement, the same crossover differences were calculated by using the Naval Astronautics Group orbits that are contained in the geophysical data records. Figure 5 shows the results. The global rms difference of 365 cm is a factor of 3 greater than the corresponding 118 cm for the GEM-T1 orbits.

Another way to assess radial orbit accuracy is by analyzing direct altimeter data. Whereas crossovers and overlaps provide, in the strictest sense, only a check of orbit consistency, this method provides a strong measure of the orbit accuracy, albeit contaminated by other errors. The approach has evolved from recent research efforts in which altimeter data are used to complement traditional forms of satellite tracking data in computing gravity fields.[21,22] The procedure used to assess the quality of the Geosat trajectories was to pass the converged orbits through the altimeter data using GEODYN II and examine the residuals of the fit. The GEM-T1 orbits were fixed at their Doppler-determined values, and the only estimated parameter in each data arc was a global bias. This bias, referred to loosely as an altimeter bias, accounts primarily for instrument bias and the error in the adopted value of the Earth's semimajor axis.

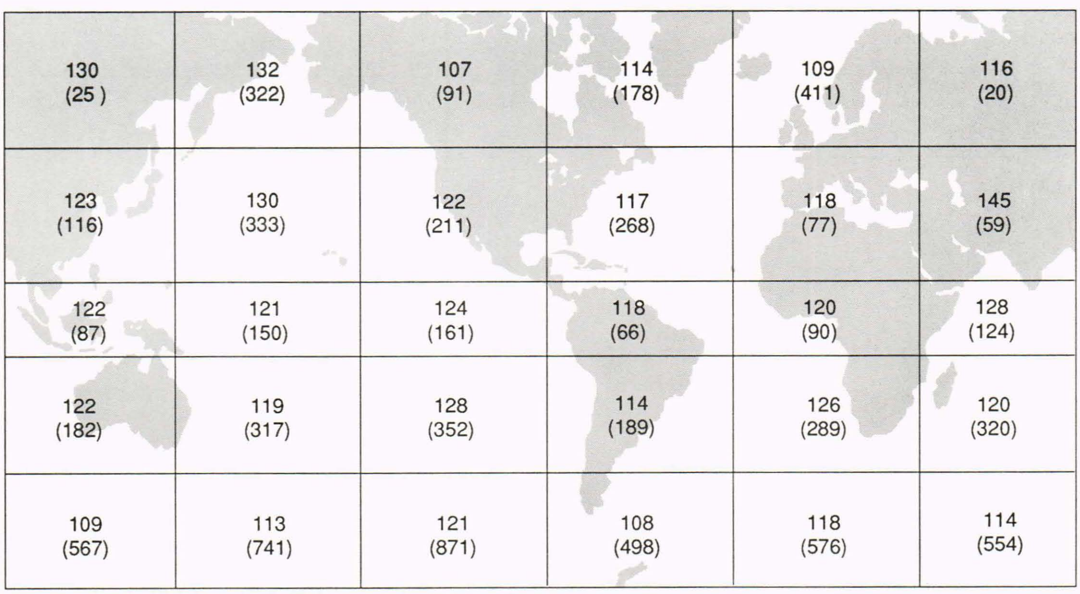

Figure 3. Root mean square altimeter crossover residuals for the first 22 repeat cycles, based on GEM-T1 orbits. The global rms difference is 118 cm. The value in parentheses is the number of crossovers, in thousands.

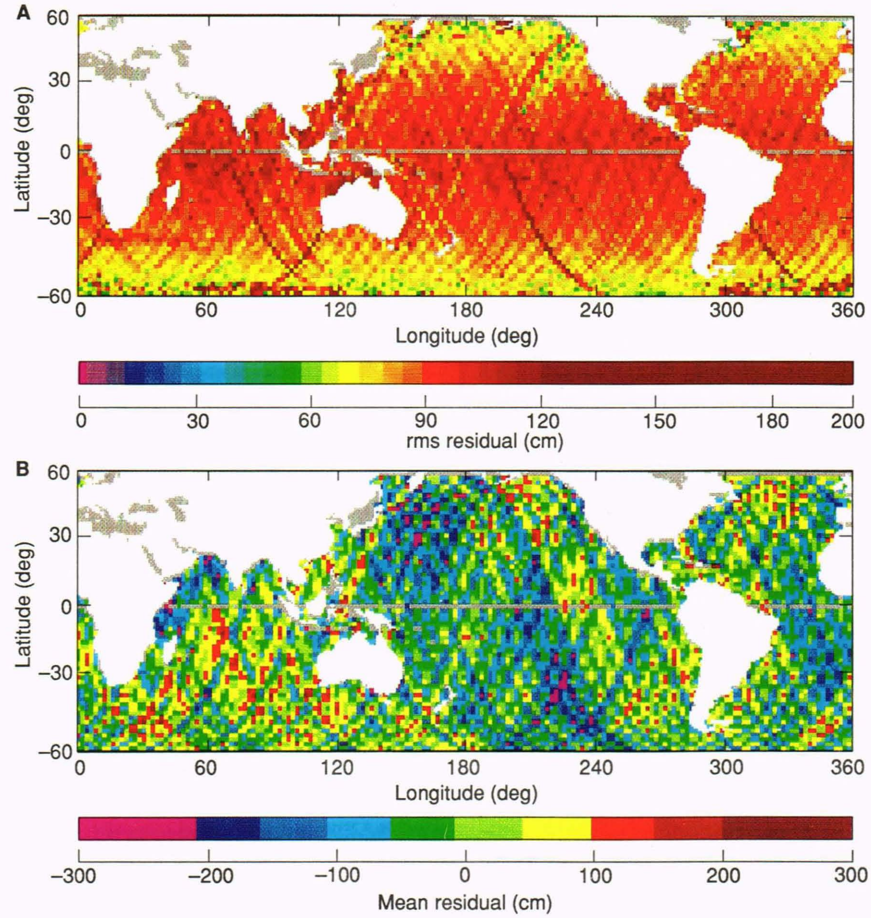

Figure 4. Altimeter crossover residuals in 2° square bins for the first 22 repeat cycles, based on GEM-T1 orbits. A. Root mean square of the residuals (mean removed). B. Mean of the residuals.

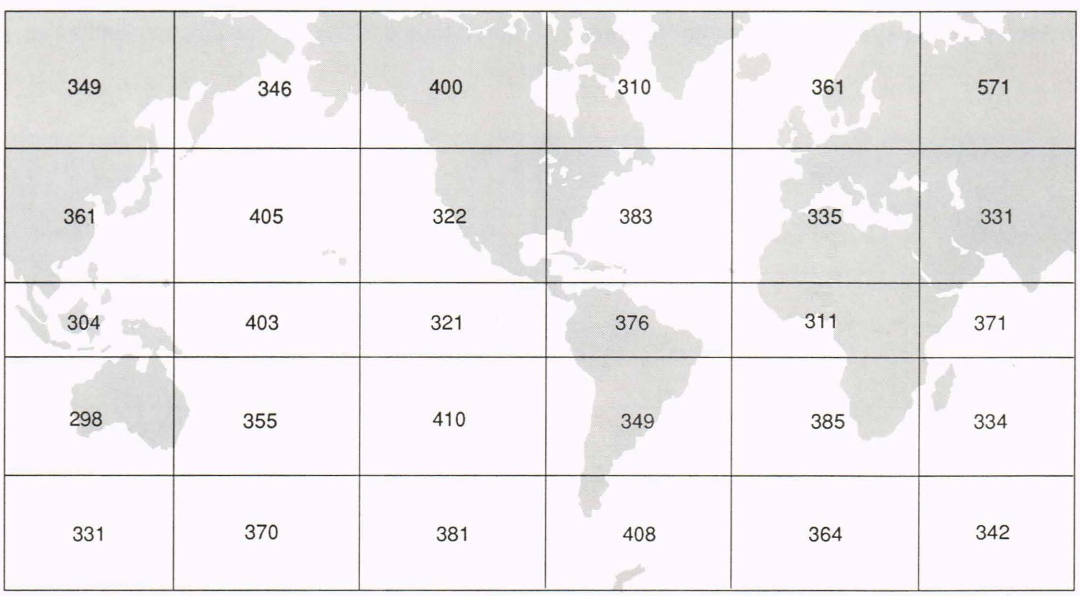

Figure 5. Root mean square altimeter crossover residuals for the first 22 repeat cycles, based on Naval Astronautics Group (GEM-10) orbits. The global rms difference is 365 cm rms.

Compiling the altimeter data into a form suitable for use in GEODYN II requires a rigorous treatment of the many phenomena that affect the altimeter range measurement. Following Marsh et al.,[21] various *a priori* corrections and editing criteria were applied to the altimeter data. A complete description is beyond the scope of this article, but, to summarize, data were eliminated over shallow seas, in regions with sizable short-wavelength geoid signals, and in regions where ocean tide models are not well known. The remaining data were sampled every 15 s to make the computations more manageable. Corrections applied to the altimeter data included those for media, solid Earth and ocean tides, sea state, off-nadir effects, and geoid height. The quasi-steady portion of the dynamic sea-surface topography derived from a recent Goddard preliminary gravity solution (PGS-3337)[21] was also applied in fitting the altimetry. The GEM-T1 geoid was chosen for modeling the geoid to degree and order 36, since the GEM-T1 gravity model was used in computing the orbits. We note that this model is derived only from satellite tracking data and cannot properly resolve many of the high degree and order coefficients of the geoid. Fortunately, the Geosat altimeter data used in this study were corrected to account for the high degree and order geoid contribution (degrees 51 through 300) according to the detailed Ohio State University model (OSU86).[23] The absolute orbit error would have been characterized better if a more rigorous approach had been taken in modeling the geoid. Our intention was not to establish the absolute radial error for Geosat, but rather to derive an estimate of the combined error that was consistent with the known commission error of the chosen geoid model and our estimates of the Geosat radial orbit error derived from other techniques.

Table 3 summarizes the results of the altimeter fits. The residuals contain the combined effects of nongeographically and geographically correlated orbit error, geoid commission and omission error, errors in the dynamic topography and tidal models, and errors in the various other corrections made to the altimeter data. The average of the rms residuals for the 25 arcs is 1.59 m. The commission error in the GEM-T1 global geoid is about 1.6 m rms, based on formal covariance analysis.[9] The tests show that the combined error in our modeling of the Geosat altimetry and orbit is dominated by the geoid error. Orbit error would have to be significantly greater than 1 m rms to show up in these tabulations.

Also in Table 3 are the estimated global altimeter biases for the 25 arcs. The bias in each arc is approximately 65.4 ± 4.4 cm. Assuming that this entire bias accounts for the error in the adopted value of the Earth's semimajor axis (6,378,137.0 m), an improved estimate of the value would be 6,378,136.3 m. This assumption is somewhat unrealistic since other errors, such as instrument bias, contribute to the discrepancy. Nonetheless, it agrees closely with the estimate of 6,378,136.2 m made by Rapp[24] on the basis of Doppler tracking station positions and a spherical harmonic expansion of the Earth's gravity field through degree and order 360.

A comparison of orbits generated independently with the OPNET and TRANET systems over identical time periods supplies another useful indicator of the relative orbit accuracy. Whereas TRANET is a global network of more than 40 stations, the OPNET system consists of only four sites, all in the United States. One would expect that orbits derived from the global TRANET data would approximate the actual orbits more closely. Such a global network reduces the errors in the estimated initial conditions and ensures that the computed orbits will not diverge significantly over regions with no tracking coverage. The comparison was performed for the first 17-day arc (8 November 1986 epoch), and the rms difference of the two orbits in the radial sense was only 18 cm. Most of the signal is at a frequency of once per orbit revolution and results from slight differences in the estimated initial conditions.

Global differences between the precise orbits and the operational orbits were generated for two full repeat cycles in late 1986 and early 1987 (Fig. 6). The residuals exhibit a strong latitude dependency. Most of them, particularly those over the middle and high latitudes, fall between −5 and +2 m, but there are differences of 10 m and greater in the extreme southern latitudes. The altimeter fits described previously suggest that the sea-surface heights derived from the precise orbits agree globally with the marine geoid at the rms level of about 1 m. Thus, the operational orbits appear to diverge over the southern latitudes.

Table 3. Direct altimeter residual statistics for GEM-T1 orbits.[a]

Arc epoch date	No. of altimeter observations	rms residual (m)	Altimeter bias (cm)
8 Nov 86	31,655	1.59	67.1
20 Nov 86	32,419	1.68	70.8
7 Dec 86	32,369	1.52	70.7
21 Dec 86	32,109	1.48	73.6
7 Jan 87	31,843	1.55	70.3
21 Jan 87	31,903	1.52	60.8
3 Feb 87	30,998	1.73	61.4
20 Feb 87	30,806	1.77	61.2
6 Mar 87	30,361	1.48	67.3
20 Mar 87	30,344	1.51	65.1
2 Apr 87	30,524	1.49	66.6
16 Apr 87	29,682	1.48	70.1
3 May 87	30,922	1.51	65.8
19 May 87	26,610	1.55	66.2
5 Jun 87	29,348	1.52	67.2
22 Jun 87	29,493	1.58	65.0
9 Jul 87	27,633	1.62	62.6
26 Jul 87	31,377	1.57	62.0
8 Aug 87	31,657	1.55	63.6
25 Aug 87	30,326	1.74	55.4
7 Sep 87	30,096	2.01	60.3
24 Sep 87	30,979	1.78	58.9
7 Oct 87	29,301	1.54	64.0
24 Oct 87	31,583	1.48	69.9
31 Oct 87	29,405	1.64	69.9
	Average	1.59	65.4 ± 4.4

[a]GEM-T1 geoid used, with high degree and order corrections ($50 < l,m < 300$) according to OSU86 model.[23] l,m = the degree and order of the geoid.

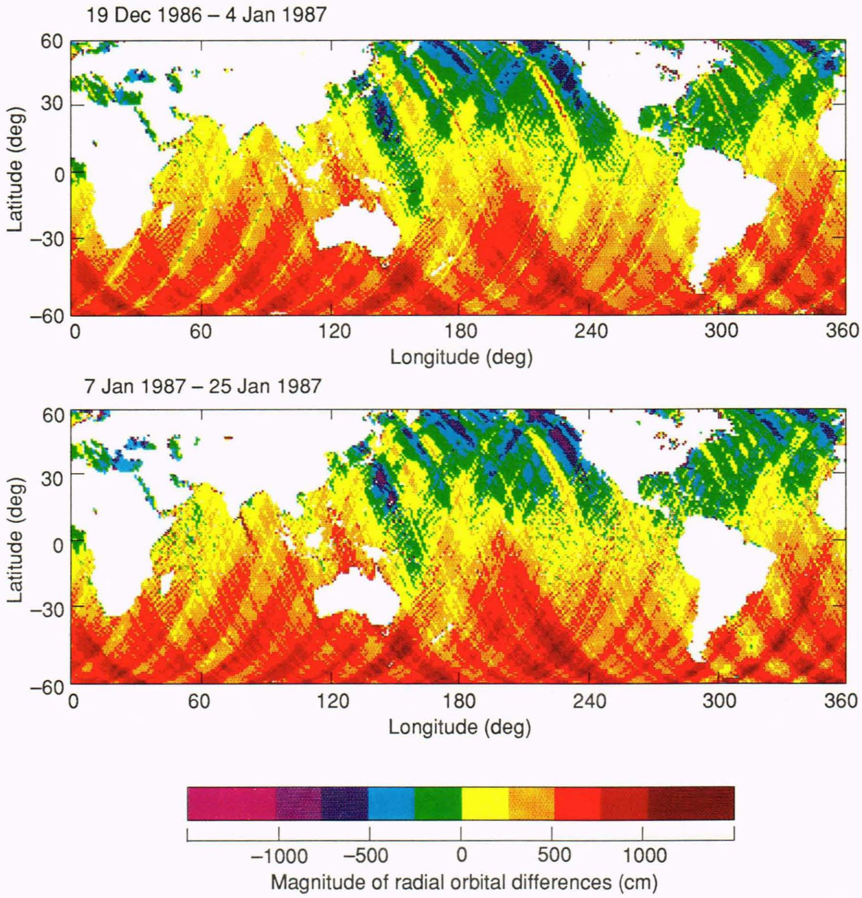

Figure 6. Radial differences between GEM-T1 and Naval Astronautics Group (GEM-10) orbits over two repeat cycles.

This phenomenon is not completely understood. Some of the systematic behavior of these residuals could be explained by a large once-per-orbital-revolution radial error attributable to the different gravity models used in the two procedures. Another area to explore is the effect of the sparse tracking in solutions of various arc lengths. The operational orbits computed by the Naval Astronautics Group fit the OPNET tracking data in 2-day arcs. Although the precise orbits originate from the same tracking data, they are computed from 17-day arcs. Longer arcs rely heavily on the strength of the force models, and the effects of limited tracking are lessened. Conversely, shorter arcs rely more on strong global tracking, implying that the short-arc approach used to generate the operational orbits is probably not optimal for fixing the satellite position over the southern latitudes, where there are no tracking stations.

Another possible contributor to the latitudinal bias is differences in coordinate systems. Procedurally, the Naval Astronautics Group uses the World Geodetic System (WGS) 1972 station coordinates, together with the GEM-10 gravity model, to compute the operational orbits. The ephemerides are then assumed to be consistent with WGS-72, and are subsequently transformed into WGS-84 by applying a center offset, a scale adjustment, and a longitudinal rotation.[5] The transformation is applied to account for a known 4.5-m offset between the origin of WGS-72 and the Earth center of mass along the body-fixed z-axis. Because of the 4.5-m shift, WGS-72 is not geocentric and, hence, is not consistent with the coordinate system implicitly defined by the GEM-10 gravity model. We suspect that the application of this transformation also contributes to the latitudinal bias.

In summary, the radial accuracy of the GEM-T1 orbits has been evaluated by using various measures. The rms altimeter crossover residual was 1.2 m. Dividing this value by the square root of 2 yields a good approximation of the total radial orbit error, if the geopotential can be considered the dominant error source and if the portion of the error that is observable in the crossover differences (nongeographically correlated) is approximately equal to the portion that is unobservable (geographically correlated). This approximation suggests that the overall radial orbit error is 85 cm rms. Examination of the radial differences of the overlapping trajectories, however, revealed that the orbit error exceeds 1 m rms at the extremes of the solutions where dynamic-force-model errors, particularly those resulting from gravity resonance, tend to grow. An analysis of the direct altimeter residuals indicated that the total rms residual of 1.6 m is dominated by geoid error and that it is unlikely that the total radial orbit error exceeds 1 m rms. Finally, the Geosat radial orbit error predicted from the GEM-T1 covariance is 45 cm rms. If this prediction is augmented by a reasonable estimate of the error caused by the omission of the 43rd-order terms in the GEM-T1 solutions, the total predicted error from geopotential sources (omission plus commission) exceeds 80 cm rms, consistent with the estimate of 85 cm rms inferred from the crossover analysis. All things considered, the best estimate of the radial orbit error for the GEM-T1 orbits is about 85 cm rms.

GEM-T2 ORBITS

Solution Strategy

At this writing, we are recomputing Geosat orbits for the first two years of the ERM using the GEM-T2 gravity model,[10] an enhanced satellite-only model containing selected terms to degree and order 50. Like GEM-T1, it is complete to degree and order 36, but it also contains more than 600 coefficients above degree and order 36. In all, more than 2.4 million observations from 31 satellites were used in determining the model. In addition to observations originating from ground-based tracking systems, the model contains satellite-to-satellite tracking observations from ATS-6 to Geos 3.

Of special interest for this study, GEM-T2 contains Geosat TRANET Doppler data from the global network for the first 80 days of the mission. We previously argued that GEM-T1, which contains no Geosat data, is well suited for use in computing Geosat orbits, owing to the significant amount of Seasat tracking data used in the solution. Although that is true, Geosat and Seasat are, physically, two very different spacecraft. It follows that their reactions to nonconservative forces such as air drag and solar radiation pressure may be quite different, implying that each spacecraft may be causing a different aliasing of low-frequency resonant gravity errors into the nongravitational force parameters during the least-squares adjustment. Thus, we believe that some benefit is being derived from incorporating new tracking information into the solution, particularly for accommodating the resonant gravity errors that we will describe.

We have estimated the Geosat radial orbit error resulting from the GEM-T2 geopotential error by using the calibrated model covariance. Following Rosborough,[17] we grouped the radial orbit errors from GEM-T2 by coefficient order and plotted them against those from GEM-T1 (Fig. 7). Formally, the common commission error (through order 36) is significantly less in GEM-T2 than in GEM-T1. In fact, even including the large error for GEM-T2 from the 43rd-order resonance, its overall commission error of 20 cm rms is substantially better than the corresponding commission error of 45 cm rms for GEM-T1.

If the perturbations are grouped according to frequency, their behavior is better characterized. Two of the largest spikes in the radial orbit error spectrum shown in Figure 8 are a result of the order 43 terms. Most of the resonant perturbations at this order are being mapped into radial perturbations of once-per-orbit revolution (the largest spike), although there is some residual effect on the radial component at the resonance frequency of 0.058 cycle per day.

As discussed earlier, additional TRANET-2 tracking data have recently been made available to augment the OPNET tracking data in our new solutions. The improved global coverage (Fig. 1) is intended to result in smaller errors in the estimated initial conditions while preventing the computed orbits from diverging over the Southern Hemisphere.

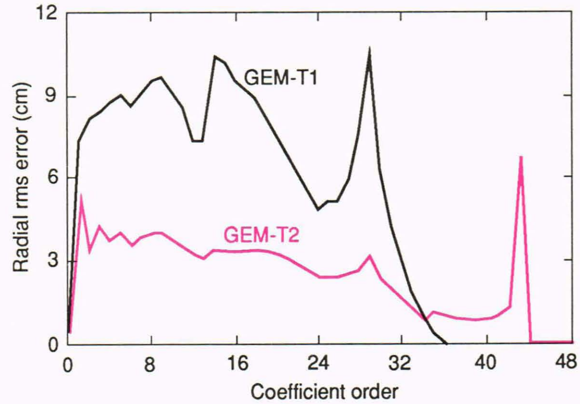

Figure 7. Standard deviation of the Geosat radial orbit error as a function of coefficient order, based on GEM-T1 and GEM-T2 covariances. The GEM-T1 error is 45 cm rms. The GEM-T2 error is 20 cm rms.

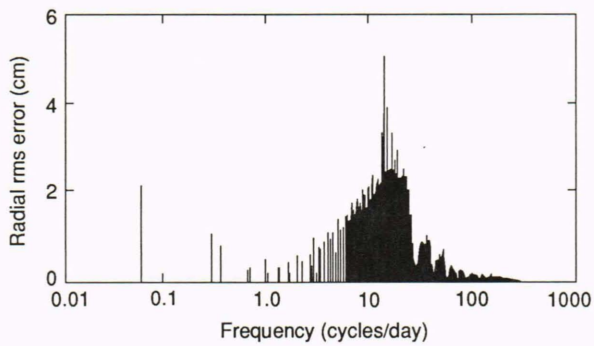

Figure 8. Standard deviation of the Geosat radial orbit error as a function of frequency, based on GEM-T2 model covariance. The overall error is 20 cm rms.

Progress has also been made in the area of station coordinates. Preliminary solutions were performed in which the tracking station coordinates used in the GEM-T1 orbit solutions were allowed to adjust. In many cases, the adjustments were large enough to lend suspicion to the transformations that were used for deriving the station coordinates in the TOPEX/Poseidon reference frame. Improved station coordinates are being used in our new solutions; they are derived from the GEM-T2 gravity model adjustment and thus are consistent with the GEM-T2 geodetic system. The heritage of these coordinates is described by Haines et al.[18]

We have noticed improvements in orbit accuracy using 6-day arcs of tracking data as opposed to the 17-day arcs used for the GEM-T1 orbits.[18] We believe the improvement is attributable to the increased sensitivity to low-frequency dynamic model errors, particularly those of gravity resonance, in the longer arcs. Moreover, there are several periods in the second year of the mission when there is insufficient time between orbit adjustment maneuvers to use 17-day arcs. Therefore, we have selected shorter arc lengths, nominally 6 days, for the GEM-T2 orbits. Although there will be more discontinuities in the satellite ephemerides with this approach, the orbit accuracies should improve. The arc placement scheme will be similar to the one used for the GEM-T1 orbits, with the arcs overlapping between maneuvers. We plan to use nominal overlaps of 1 day.

Orbit Fits

Preliminary orbit fits incorporating the new strategy have been made. Except as noted, the procedure followed was identical to the one outlined previously for the GEM-T1 orbits. One difference is the incorporation of the two different types of Doppler data, OPNET and TRANET-2. When weighted equally, the post-processed fits of these range-rate data are typically 1.5 and 0.5 cm/s rms, respectively. The difference reflects a real difference in both data quality and our ability to model effects at the station, such as troposphere error and antenna tracking point corrections. Since the overall fit of the OPNET data is generally a factor of 3 worse than the fit of the TRANET data, the OPNET data were downweighted with respect to the TRANET data.

Using this approach, three 6-day arcs of the combined tracking data from May 1987 were fit using the GEODYN software; a 17-day arc over the same time period was also fit. The weighted rms fit of the range-rate data was about 0.5 cm/s, which reflects the lower noise of the TRANET-2 data and the downweighting of the OPNET data, in addition to the actual improvement in modeling the orbit. A slightly higher percentage of edited observations was used and is attributable to the introduction of the TRANET-2 data into the solution. Since the TRANET-2 antennas are omnidirectional, they collect more low-elevation data than do the OPNET antennas.

Accuracy Assessment

Because our preliminary GEM-T2 solutions do not overlap, crossover and altimeter residuals were the primary tools used to assess radial accuracy. Crossovers were calculated for the entire repeat cycle represented by the three arcs. Figure 9 gives the breakdown of the rms differences by geographic area; the global rms crossover difference of 49 cm is a substantial improvement over our original GEM-T1 solutions. When the tracking data over the same period were fit as one 17-day arc, the rms crossover residual was 58 cm.

An extensive analysis of the direct altimeter residuals was also undertaken. As was the case for similar tests described earlier, the converged orbits were passed through the altimeter data to determine a global bias and the rms residual about that bias. The same models and corrections were applied to the altimeter data, except that the GEM-T2 expansion was used to generate the marine geoid through degree and order 50 for the cases in which the GEM-T2 model was used to integrate the orbit.

For this study, improvements (i.e., gravity model, tracking data, station coordinates) were added one by one to the solutions so that we were able to determine the relative effect of each improvement on the radial orbit accuracy. The results (see Table 4) must be interpreted in the context that the overall rms residual is dominated by the geoid error resulting from not properly modeling many of the high degree and order coefficients of the satellite-only gravity models. Because of the large geoid error, relatively large improvements in the radial position of the satellite may cause only a slight improvement in the overall fit to the altimeter data.

The first row of Table 4 represents the results from our original GEM-T1 17-day solution that used only the OPNET data. (The original 17-day arc has been separated into three 6-day time spans so that it can be compared

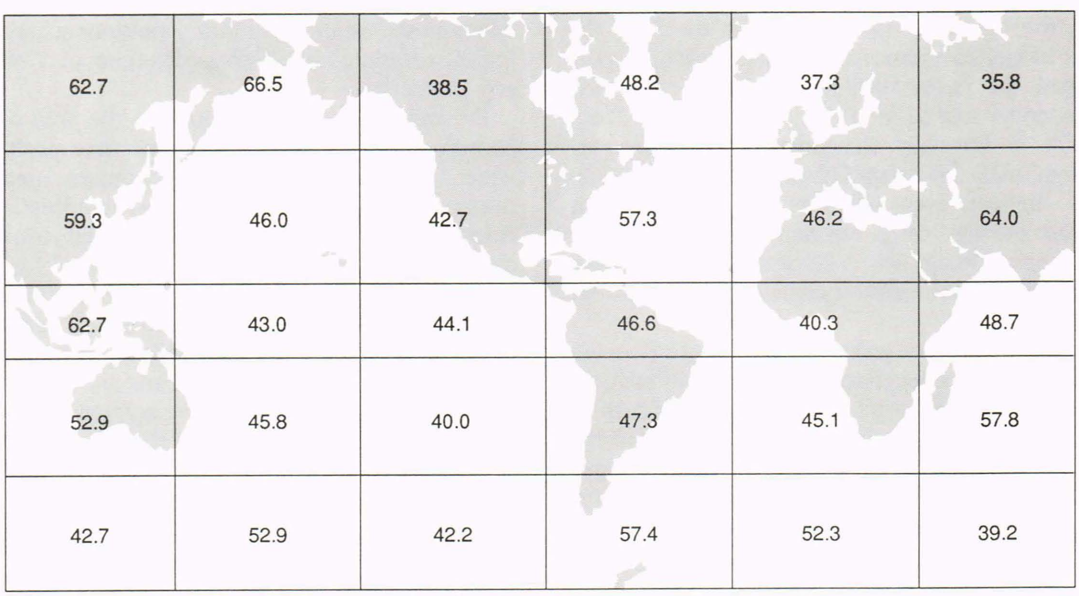

Figure 9. Root mean square altimeter crossover residuals for one repeat cycle (3 May 1987), based on GEM-T2 orbits. The global rms difference is 49 cm rms.

Table 4. Direct altimeter residuals for Doppler solution strategies, from three 6-day arcs beginning 3 May 1987, 1755:00 UT.

Arc length (days)	Tracking network	Gravity and geoid[a]	rms residual (bias) (m)			
			3 May	9 May	15 May	Average
17[b]	OPNET	GEM-T1	1.58 (0.55)	1.45 (0.74)	1.47 (0.71)	1.50 (0.66)
6	OPNET	GEM-T1	1.46 (0.64)	1.51 (0.68)	1.43 (0.69)	1.47 (0.67)
6	OPNET	GEM-T2	1.32 (0.60)	1.32 (0.67)	1.29 (0.64)	1.31 (0.63)
6	OPNET + FCB[c]	GEM-T2	1.27 (0.63)	1.29 (0.67)	1.28 (0.63)	1.28 (0.64)
6	OPNET + FCB[d]	GEM-T2	1.26 (0.68)	1.28 (0.71)	1.28 (0.67)	1.27 (0.69)

[a]The OSU86 model[23] was used to correct for the high degree and order contribution ($50 < l,m < 300$), where l,m = the degree and order of the geoid.
[b]One 17-day arc broken into three 6-day intervals.
[c]FCB = French, Canadian, and Belgian TRANET-2 stations.
[d]FCB plus improved station coordinates.

directly with the new 6-day solutions.) Shortening the solution length to 6 days improves the overall fit from 1.50 to 1.47 m rms. Moreover, the recovered altimeter biases become more consistent. When the GEM-T2 model is used, the fit is improved to 1.31 m rms, although some of this improvement can be attributed to the better modeling of the marine geoid. (The global commission error for the GEM-T2 geoid is estimated to be about 1.4 m rms versus 1.6 m rms for GEM-T1.) The consistency among the individual arcs is also better. Incorporation of additional tracking data from the six TRANET-2 stations reduces the average fit to 1.28 m rms, a substantial reduction in the presence of a geoid error that dominates the altimeter residuals. Finally, the improved station coordinates further decrease the overall fit to 1.27 m rms.

In summary, the use of the GEM-T2 gravity model and the addition of the TRANET-2 Doppler data result in substantial reductions in the Geosat radial orbit error. The rms altimeter crossover residual determined from the preliminary GEM-T2 orbits is 49 cm, suggesting that the actual Geosat radial orbit error is about 35 cm rms. The predicted Geosat radial orbit error from the GEM-T2 model covariance is 20 cm rms. Assuming that the covariance matrix predicts realistic errors, the radial errors due to the GEM-T2 geopotential seem to be somewhat less than the combined radial errors from other sources.

CONCLUSIONS

The heritage of the first full-scale release of precise Geosat orbits for the ERM has been described. One year's worth of precise orbits has been generated by using the GEODYN software at Goddard and applying the GEM-T1 gravity model and OPNET tracking data to arc lengths of 17 days. Our best estimate of the radial error associated with these orbits is about 85 cm rms. The ephemerides have been made available to the altimeter data user community, along with a package for merging them with the Geosat geophysical data records.

Preliminary efforts aimed at computing Geosat orbits with the new GEM-T2 satellite-only gravity model and additional TRANET-2 Doppler tracking data suggest that the Geosat radial orbit can be further reduced to 35 cm rms. Orbits for the first two years of the mission are currently being computed and will be made available to interested altimeter data users.

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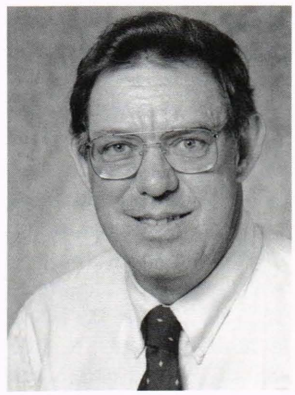

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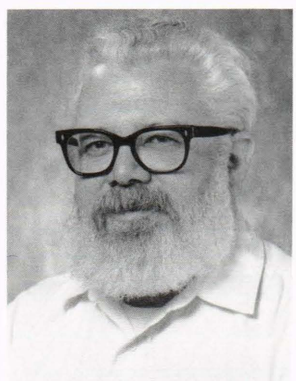

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