GEOID DETERMINATION OVER BASIN-WIDE SCALES USING A COMBINATION OF SATELLITE TRACKING, SURFACE GRAVITY AND ALTIMETER OBSERVATIONS

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ABSTRACT

A spherical harmonic model of the Earth's gravitational field has been developed using tracking data of 31 satellites, surface gravimetry, and satellite radar altimetry. The model is complete to degree and order 50 and provides a simultaneous recovery for invariant and tidally induced gravitational effects. The ocean tidal model consists of 600 background tidal terms with 90 coefficients being adjusted. The altimeter data are utilized as tracking observations of the ocean surface and provide for a simultaneous recovery of a model describing the stationary sea surface topography complete to degree and order 10 in spherical harmonics. Comparisons between satellite-only models and those obtained with the addition of altimetry/gravimetry find an improvement in geoid representation of more than a factor of two, extending even to the model's longest wavelengths. The stability of the geoid recovery has been assessed using subset solutions. For wavelengths of 2000 km or longer, the combination model provides geoid definition of 6 cm rms accuracy.

INTRODUCTION

One of the major goals of satellite oceanography is to determine the ocean circulation patterns on a global basis. This includes (1) the mean circulation over the broad ocean basins; (2) fluctuations about the mean which reveal phenomenon like seasonal mass transport and climatological changes like the "el Nino"; and (3) long term secular changes in the sea surface which can be used to detect worldwide changes in climate such as the "greenhouse" effect. Altimeter satellites are extremely valuable for supporting the acquisition of global data for ocean monitoring which are well resolved temporally. For investigating cases (1) and (3), the surface mapping provided by altimetry must be supplemented by accurate knowledge of the earth's gravitational field in order to isolate the oceanographic signals present in the sea surface.

Improved gravitational models are important for oceanographic investigations using spaceborne altimeter systems. Accurate geopotential models (both static and temporally resolved) are required to compute the satellite ephemeris. Knowledge of the satellite's height is indispensable for determining the absolute location of the ocean surface with respect to the geocenter. The sea surface height is dominated by the geoid; again accurate gravitational and tidal models are required to determine the departure of the ocean surface attributable to geostrophic flow from that of the equipotential surface. The direct inclusion of altimeter data in the definition of the gravitational field provides a new and important resource for the improvement of orbit and gravitational modeling effects. However, the utilization of these observations in geopotential solutions is complicated by the need to successfully accommodate the non-geoidal and incompatible bandwidth signals contained in the altimetry.

Significant progress has been made in developing models of the terrestrial gravity field using satellite data. With the advent of improved satellite tracking technologies like satellite laser ranging, space-based laser targets like the Lageos and Starlette satellites, and the deployment of a global network of tracking systems, these "satellite-only" models are now capable of defining the long wavelength geoid to near-decimeter levels. Combination models have been developed which augment tracking data with surface information which improves the modeling of the short wavelength geoidal features which are not well sensed by the attenuated gravitational effects at satellite altitude. These models have employed global gravimetry which has been reduced to form mean gravity anomalies blocks; these mean anomalies have been used to compute normal equations for the recovery of spherical harmonic gravity fields (Pavlis, 1988). Satellite altimetry has also been used directly in these combination models to better resolve the geoid and the radial evolution of satellite orbits as they overfly the ocean surface. This paper reviews the progress being made at NASA/Goddard Space Flight Center (GSFC) in the modeling of the terrestrial gravity field from both satellite and surface information.

GEM-T2: A MODEL DEVELOPED FROM TRACKING OBSERVATIONS

Goddard Earth Model (GEM)-T2 (Marsh et al., 1989b) has been computed using satellite tracking observations acquired on 31 different satellite orbits. This solution is compared to its predecessor, GEM-T1 (Marsh et al., 1988) in Table 1. GEM-T2 contains terms in the spherical harmonic expansion which are complete to degree and order 36, with selected orders containing adjusted values out to degree 50. This model now nearly exhausts the historical satellite data set available for gravitational field development; it includes laser, optical, Doppler, satellite-to-satellite range-rate, and S-Band average range-rate observations. While additional observations are available on the satellites represented within the model, all existing important satellites for geodetic evaluation are now incorporated. The accuracy of this model obtained from its calibrated error covariance is shown in Figure 1 and is compared with GEM-T1. Figure 1 displays the accuracy assessment in terms of the RMS coefficient uncertainty by degree. The calibration procedure used to obtain realistic error estimates for the GEM models is fully described in Lerch et al., (1988). The development of an automated procedure for determining optimal data weights simultaneously with a properly calibrated field (which has been used for the first time in the determination of GEM-T2) is presented in Lerch (1989).

Orbital accuracies are a central concern and one which motivates the development of improved gravitational models. One of the best ways for assessing the performance of these models is testing them against a broad spectrum of satellite orbits. Table 2. compares the performance of recent GEM models based on the RMS of fit they yield when computing orbital ephemerides. The progress is quite notable. However it is increasingly more difficult to improve these RMS values as gravity field modeling is diminished as the overwhelming contributor to the misclosure of model and observations in these orbital computations. Many additional force model, environmental, and tracking station motion effects require improved modeling to accomplish this objective.

PGS-3520: A COMBINATION MODEL WITH GEM-T2, SURFACE GRAVIMETRY AND SEASAT ALTIMETRY

The gravitational information sensed by satellite tracking systems is complemented by that obtained from surface gravimetry and satellite altimetry. While the earlier has a reduced sensitivity to short wavelength geoid features due to attenuation, the surface data and altimetry contain a rich spectrum of short wavelength geopotential information. In addition, when altimetry is used to monitor the radial component of the orbit trajectory, it provides information which is complementary to the largely along track sensitivity found with traditional ground-based tracking systems. Figure 4 compares the gravity model uncertainties obtained from the "satellite-only" GEM-T2 model, and a model computed using only altimetry and surface gravimetry.

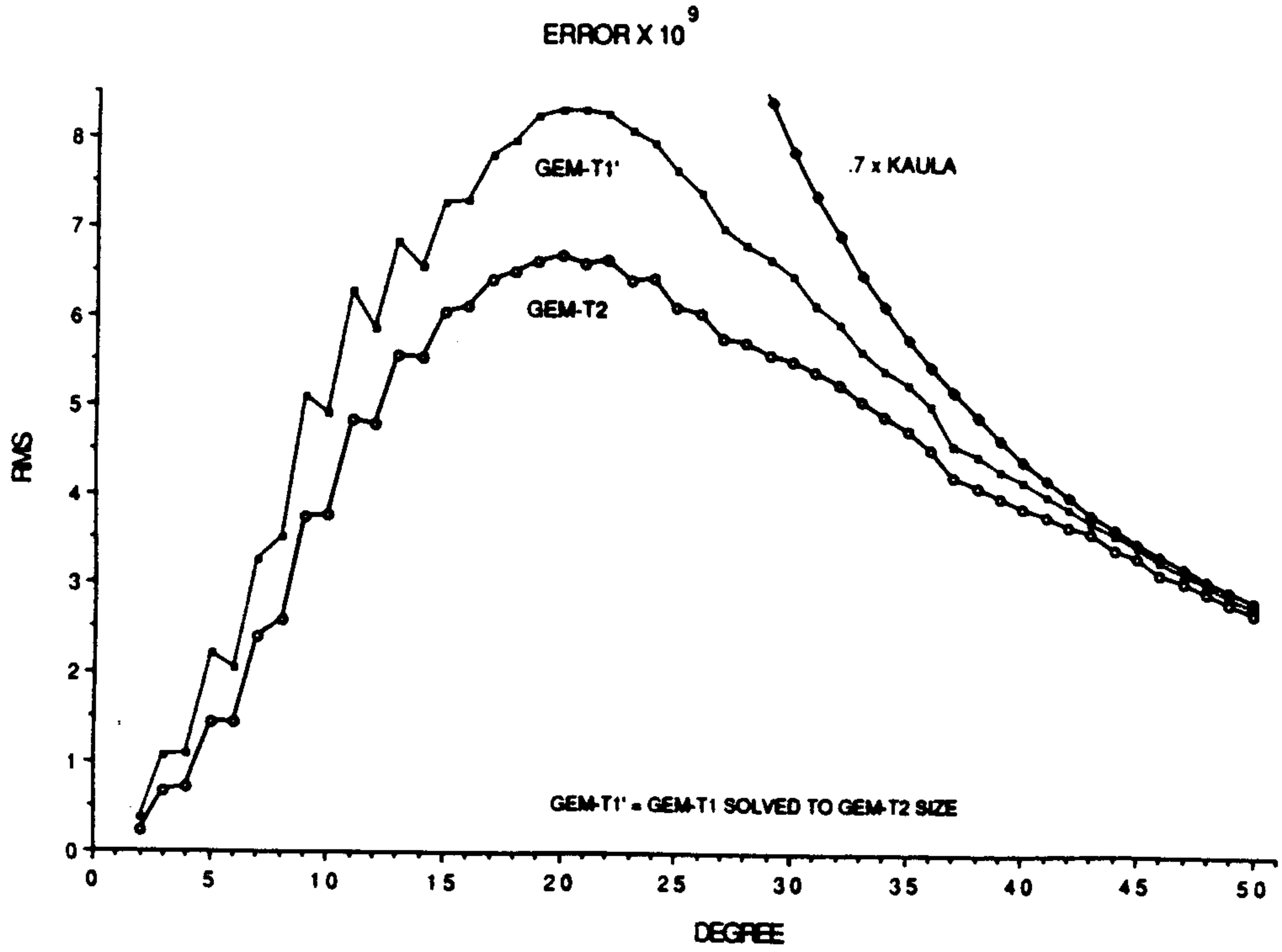
Table 1.

Improvements in GSFC "Satellite Only" Gravitational Models

Data	GEM-T1 (1987)	GEM-T2 (1989)
No. of Observations	792k	2386k
No. of Arcs	581	1132
No. of Satellites	17	31
Amount of LAGEOS data	4.8 years	7.2 years
Size of static gravitational model	36 x 36 complete	36 x 36 complete with 600 additional terms to (50,43)
Size of adjusting tide model	66 coeffs.	90 coeffs.
RMS geoid error		
• at 36 x 36	155 cm	105 cm
• complete model	--	141 cm

Figure 1.

RMS OF COEFFICIENT ERRORS PER DEGREE



When altimetry is utilized directly in geopotential solutions, provision must be made for the long wavelength departure of the ocean surface from the geoid due to the quasi-stationary nature of the sea surface topography over basin-wide scales. PGS-3520 is a combination model based on GEM-T2, global surface gravimetry and SEASAT altimetry. It is complete to degree and order 50. In forming a combination solution containing altimetry, we simultaneously solved for a spherical harmonic model for the stationary dynamic height field complete to degree and order 10. We also extensively masked, corrected and optimally subsampled the altimetry as described in Marsh et al., (1989a) for the PGS-3337 solution, before these data were included in the PGS-3520 field. The result of combining these data are shown in Figure 4 where the RMS coefficient uncertainty by degree is also shown for PGS-3520.

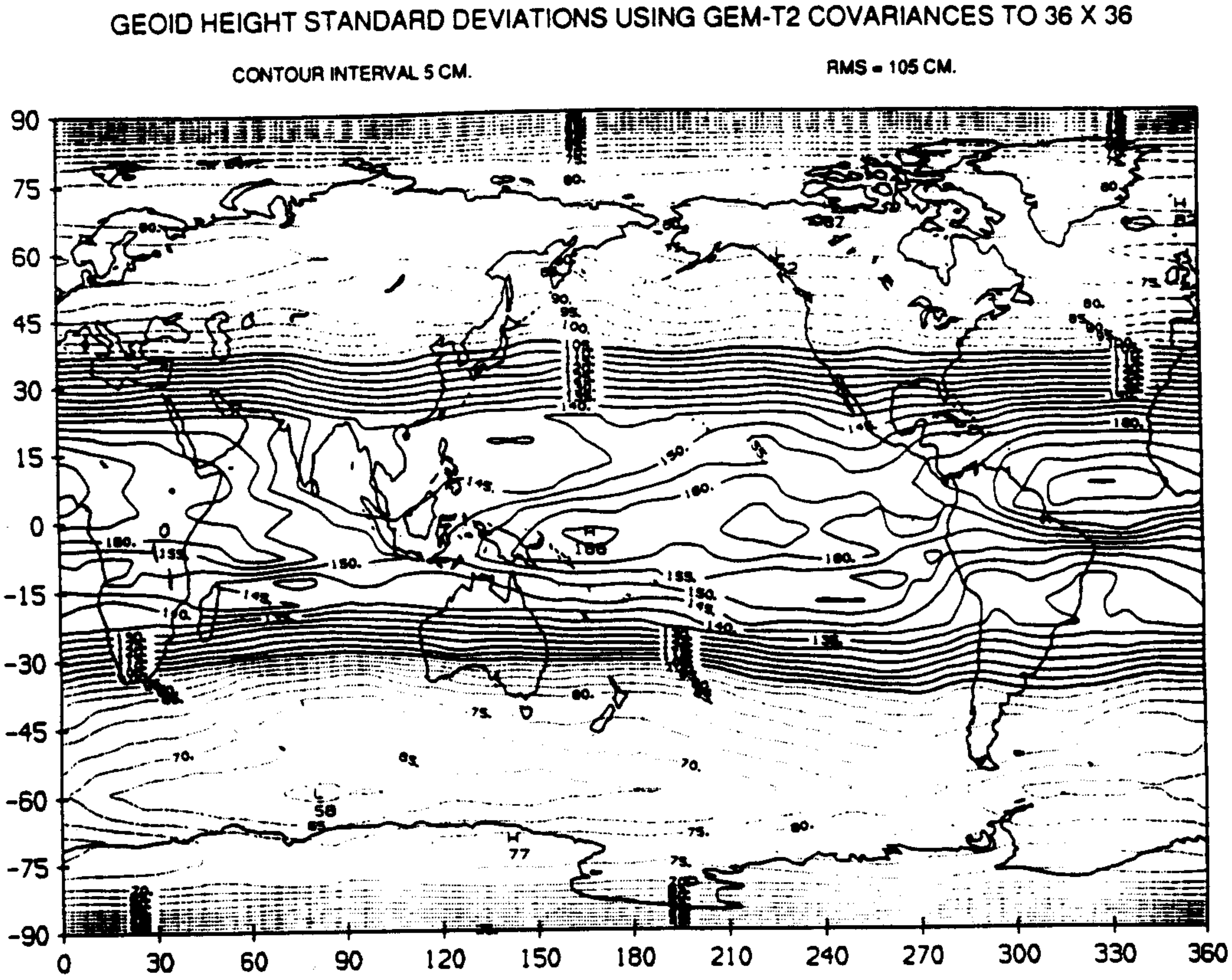
The improvement in geoid accuracy from recent gravitational models is quite significant and is especially important for applications requiring accurate geoid modeling at long and intermediate wavelengths over the oceans. Figures 2a and 2b present the estimated geoid uncertainty obtained from a covariance propagation of model errors. These figures show the estimate of the commission error in the GEM-T2 and PGS-3520 solutions complete to degree and order 36 (which is the level at which GEM-T2 is complete). This truncation represents approximately 500 km surface wavelengths. The uncertainties shown for GEM-T2 (while significantly improved over the 160 cm RMS value obtained for GEM-T1), are zonally banded indicating that there is not a high level of geographic discrimination obtained in gravitational solutions dependent on satellite tracking observations. The orbit perturbations which are predominantly sensed by tracking data are the m-daily and resonance perturbations, and these are globally sampled gravitational effects arising from the earth's rotation and the satellite's mean motion. This situation changes both in modeling accuracy and also in character as surface/altimeter data are added to the solution. In Figure 2b, the geoid uncertainty over the ocean areas which are mapped by the altimeter is found to be minimized. And it is now the regions where the surface representation is poorest (e.g. Asia, the USSR, the poles) that one finds the largest geoid uncertainties. The characteristic of the error is also changed in altimeter mapped regions, where the uncertainty is seen to have little structure.

Figures 3a and 3b compare the geoid uncertainty for the longest wavelength 10x10 portion of these fields. Again, GEM-T2 is a significant improvement over earlier satellite only gravity models. At the indicated 10-20 cm level of geoid uncertainty, there is now a favorable basis for resolving the dynamic height field over similar wavelengths which has a signal strength of approximately 1m. The combination model, PGS-3520, shows significant improvement over GEM-T2, even at these long wavelengths. This is a product of the strength of the altimetry for improving the orbits; there is dramatic decorrelation in the model when altimetry is used which penetrates down to the longest wavelength terms; and these data directly contribute by mapping the shape of the surface across the ocean basins. The simultaneous adjustment of a 10 x 10 degree model for dynamic height in PGS-3520 has not significantly dampened the strength and importance which altimetry adds to the solution. By using the strength of the geoid determination found in our combination models, the dynamic height recovery has been extended to degree 20 in test GSFC solutions.

Earth modeling along the lines of PGS-3520 will be pursued with the addition of altimeter data from GEOSAT and GEOS-3 to produce GEM-T3. This work is expected to be completed in early 1990.

MODEL CALIBRATION

The GEM models are now subjected to a comprehensive calibration procedure. This now automated approach yields a well calibrated solution through the optimal weighting of the observation subsets. This calibration and data weighting system is based on a method which tests the model against solutions lacking specific data subsets. Through the comparison of the differences in the coefficients (ΔC) obtained between the subset and complete solution

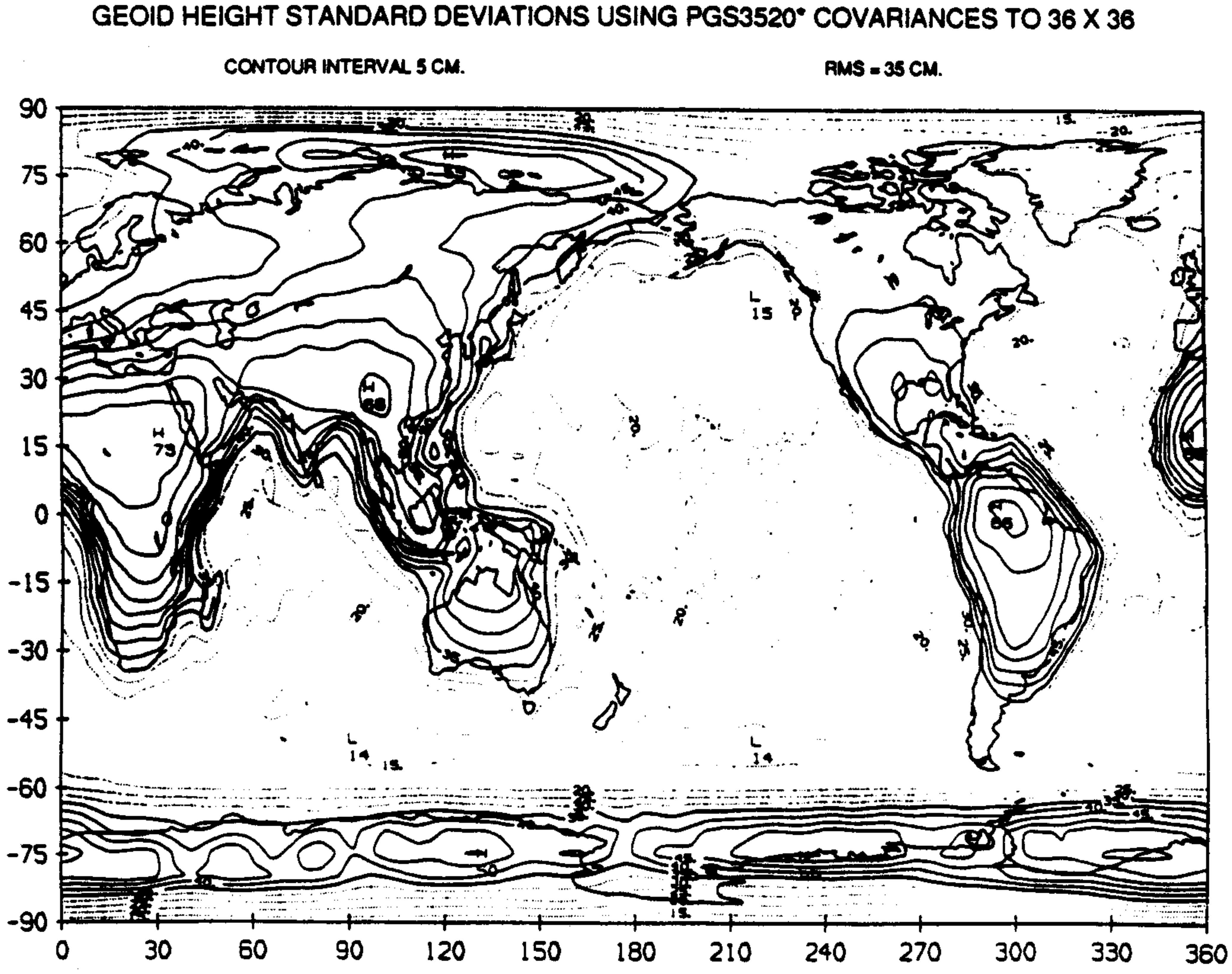


GEOID HEIGHT STANDARD DEVIATIONS USING GEM-T2 COVARIANCES TO 36 X 36

CONTOUR INTERVAL 5 CM.

RMS = 105 CM.

Figure 2a.



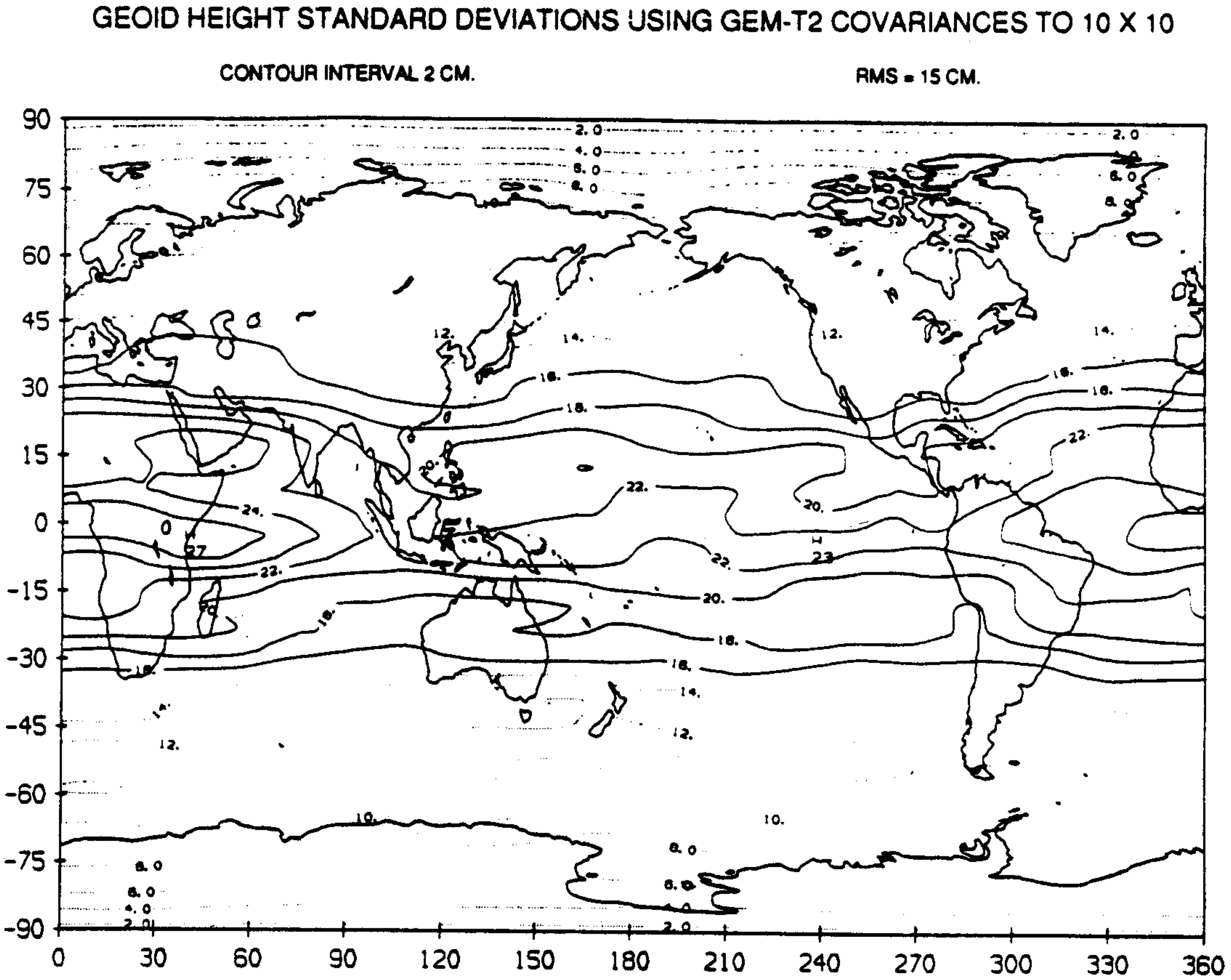
GEOID HEIGHT STANDARD DEVIATIONS USING PGS3520* COVARIANCES TO 36 X 36

CONTOUR INTERVAL 5 CM.

RMS = 35 CM.

* PGS3520 = GEM-T2 + SURFACE GRAVITY + SEASAT ALTIMETER

Figure 2b.

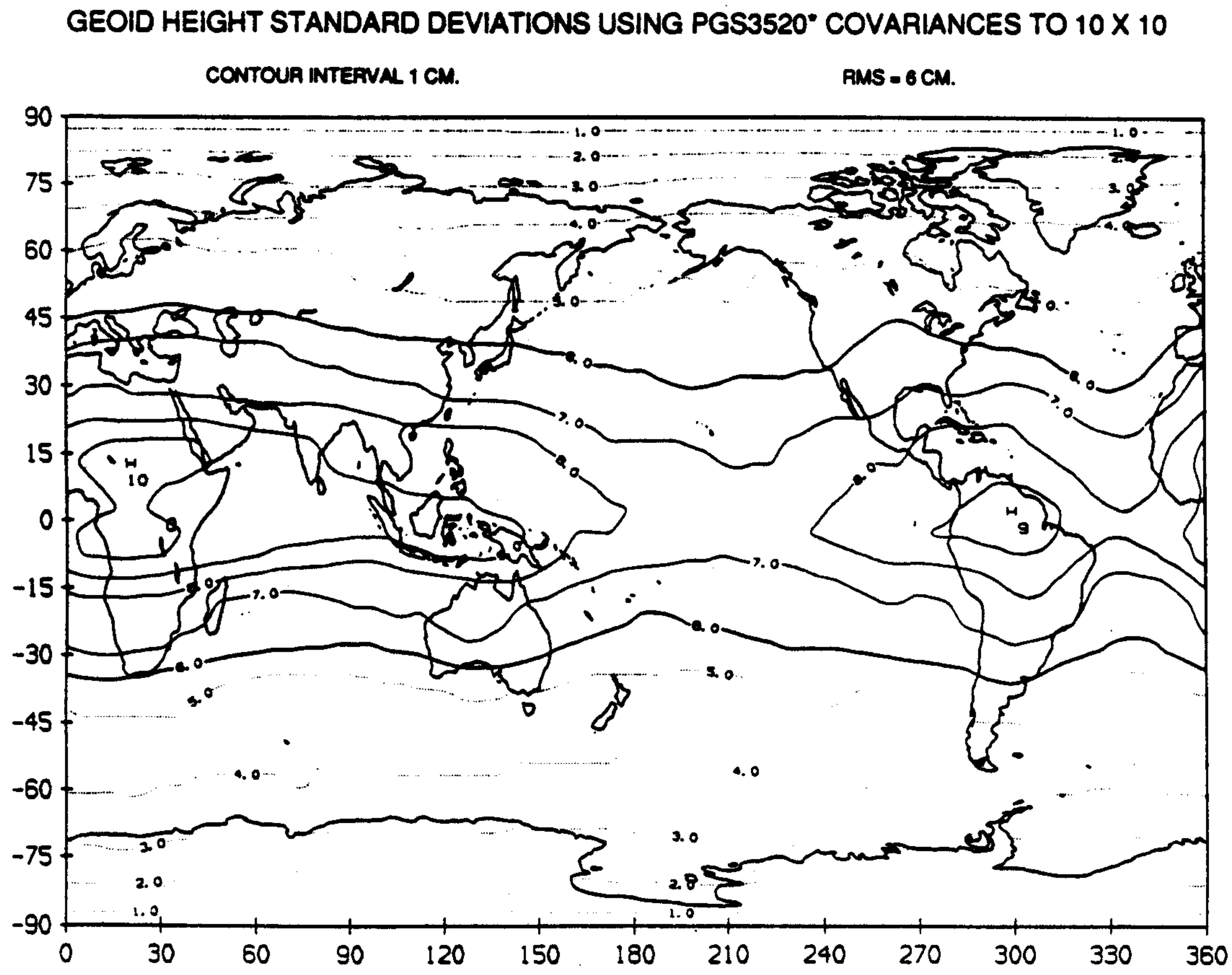


GEOID HEIGHT STANDARD DEVIATIONS USING GEM-T2 COVARIANCES TO 10 X 10

CONTOUR INTERVAL 2 CM.

RMS = 15 CM.

Figure 3a.



GEOID HEIGHT STANDARD DEVIATIONS USING PGS3520* COVARIANCES TO 10 X 10

CONTOUR INTERVAL 1 CM.

RMS = 6 CM.

Figure 3b.

* PGS3520 = GEM-T2 + SURFACE GRAVITY + SEASAT ALTIMETER

Table 2.

Orbit Accuracy Assessments of Satellite Fields Using Test Arcs

(rms of fit)

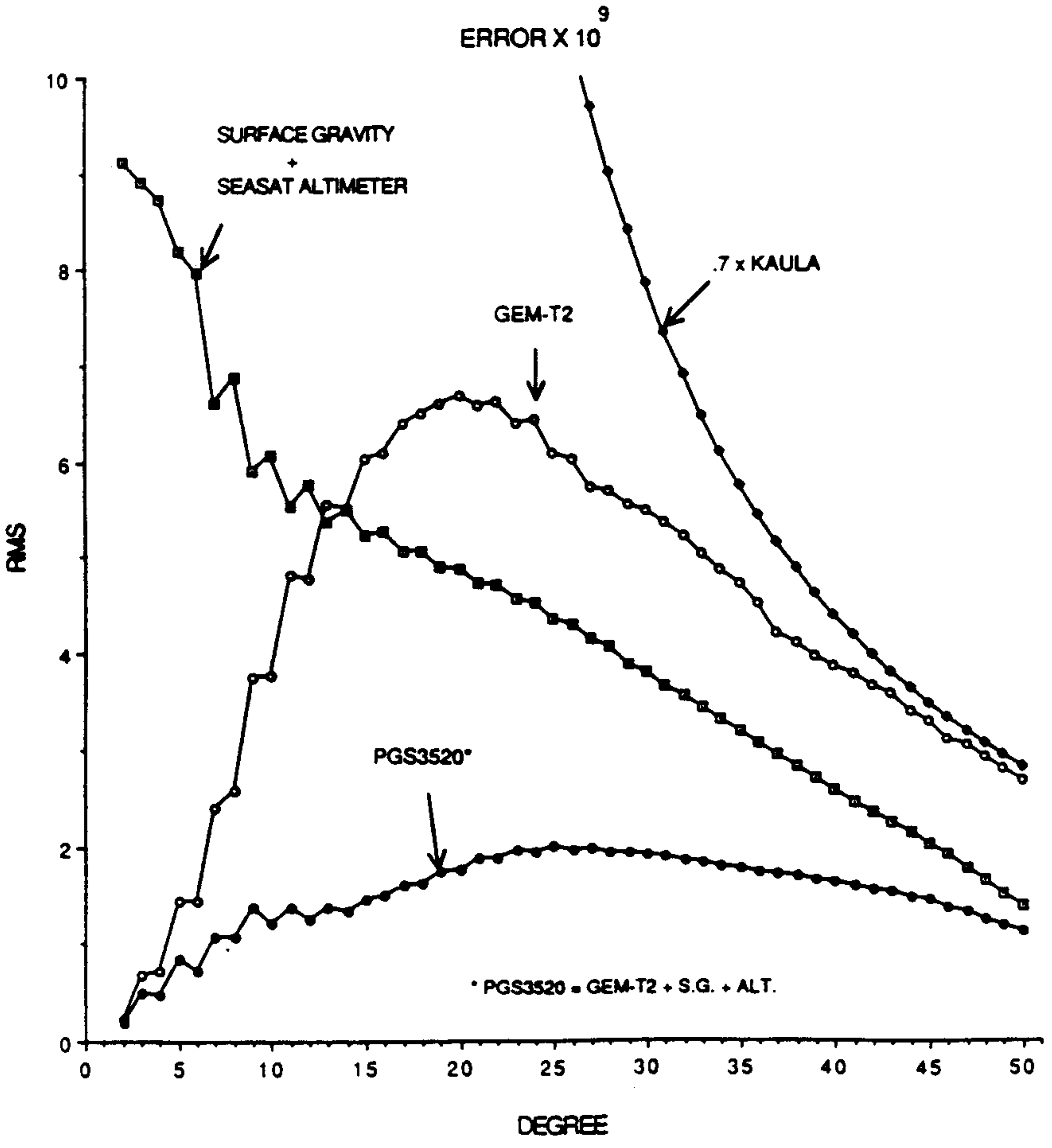
Gravity Field	LAGEOS (m)	AJISAI (m)	STRLT (m)	BE-C (m)	GEOS1 (m)	GEOS2 (m)	GEOS3 (m)	NOVA (cm/s)	ALTIM X-OVER (m)
GEM-9 (1979)	.333	.951	1.16	.873	1.26	1.18	1.72	0.95	3.65
GEM-L2 (1981)	.199	.797	1.00	.893	1.07	1.09	1.87	0.79	6.42
GEM-T1 (1987)	.069	.181	.172	.396	.387	.655	.693	0.44	0.65
GEM-T2 (1989)	.066	.151*	.102	.334	.316	.667	.249	0.37*	0.57
NOISE FLOOR	.038	.038	.040	.102	.206	.343	.101	.335	----

* Satellite now in model

Figure 4.

RMS OF COEFFICIENT ERROR PER DEGREE

SATELLITE TRACKING DATA SOLUTION
VS.
ALTIMETER + SURFACE GRAVITY SOLUTION



* PGS3520 = GEM-T2 + S.G. + ALT.

Table 3.

Summary of Calibration Factors k for GEM-T2 Using Subset Solutions and Other Measures of Subset Field Performance

Data Subset Omitted from GEM-T2	k (Overall Calib.) Factor	Estimated Geoid Ht. Error (m)	Comparison with Altim Grav. Anom. (mgals**2)
none	----	140.5	12.5
Ajisai	0.79	141.3	12.6
GEOSAT	0.81	145.8	12.9
NOVA	0.90	146.2	12.9
Peole, D1D, D1C	0.87	159.0	12.8
Lageos	0.87	141.4	12.6
pre-1980 GEOS 1,2,3, BEC	1.01	146.2	13.6
Oscar	1.13	141.1	12.6
Starlette	0.96	150.2	14.1
SEASAT	0.94	141.1	12.7
Landsat	0.92	142.8	12.7
1980 GEOS-1	1.05	141.3	12.5
1980 GEOS-3	0.96	143.2	12.6
Optical Data	0.92	147.1	13.5
GEOS-3/ATS-6 SST	0.66	140.7	12.5

compared with an error projection of the expected size of the coefficient differences $\sigma(\Delta C)$ obtained from the respective solution covariances, a calibration factor is determined by:

$$|\Delta C| = k\,\sigma(\Delta C)$$

where ideally the calibration factor, $k = 1$. All of the major data subsets are tested and the solution data weights are iterated until a calibration factor near unity is obtained for each. Table 3 reviews the calibration factors obtained in GEM-T2. In the unique case of the GEOS-3/ATS-6 data set, the calibration factor (data weight) was deliberately permitted to deviate from unity reflecting our desire to downweight these data. This decision was based upon test against independently derived gravity anomaly blocks developed from altimeter data (Rapp, 1985). The comparison of the subset models with these surface anomalies is also shown in Table 3. as the residual (in mgal^2) between the model and the surface data. Note, in all cases, the GEM-T2 model outperforms the subset models indicating that each data set is contributing to the overall accuracy of the field.

SUMMARY

Improvements in gravity modeling have been derived through the combination of satellite tracking, altimetry and surface gravimetry observations. The long wavelength geoid now has sub-decimeter accuracy levels and supports the long wavelength separation of geoidal and oceanographic signals sensed by altimeter systems. These models also yield improved capabilities for determining the satellite ephemerides which has wide ranging implications for all aspects of satellite geodesy. The models are still limited by missing local data over large, mostly continental, geographical areas. Areas lacking surface coverage in the solution now are most uncertain for geoid modeling at all wavelengths. The historical satellite tracking data set still lacks optimal distribution of satellite orbital characteristics; especially lacking are laser tracked satellites at low inclination. Also improvements in many areas of force and measurement modeling are required to fully exploit precise laser tracking for geopotential modeling improvements. Without a dedicated geopotential mission, global model accuracies are not likely to improve by more than an additional factor of 3 or 4 beyond present knowledge of the fields at long and intermediate wavelengths. It is hoped that new technologies, like the nearly continuous tracking possible for lower satellites using GPS, or the space-based gradiometer flown on Aristoteles, will significantly improve this prospect.

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