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ABSTRACT

The SKYLAB-193 radar altimeter was operated nearly continuously around the world on January 31, 1974. This direct measurement of the sea surface topography provided for the first time an independent basis for the evaluation of global geoids computed from satellite derived gravity models. The models considered were: the Goddard Space Flight Center GEM-6, 7, 8 models; the Smithsonian Astrophysical Observatory M-1 and Standard Earth III models; and the National Oceanic and Atmospheric Administration model. The differences between the altimeter geoid and the satellite geoids were as large as 25 meters with rms values ranging from 8 to 10 meters. These differences also indicated a systematic long wavelength variation (~100°) not related to error in the

SKYLAB orbits. Truncation of the models to degree and order eight did not eliminate the long wavelength variation, but in every case the rms agreement between satellite and altimeter geoids was improved. Orbits computed with the truncated models were in contrast found to be inferior to those computed using the complete models.

CONTENTS

ILLUSTRATIONS

TABLES

1. INTRODUCTION

Before artificial earth satellites existed, geoid models were computed from terrestrial astrogeodetic and gravity observations. Such models were limited in resolution and coverage due to incomplete sampling of the surface of the earth. Earth satellites have however provided a means of deriving at least the long wavelength components of the earth's gravity field because the orbital perturbations caused by the gravity field can be detected with ground based observational systems (e.g., cameras, radars, lasers). Unfortunately there are limitations with this approach. First, since about 70% of the earth's surface is covered with water, ground based tracking stations cannot provide complete orbital coverage and hence satellites may be unobserved for large fractions of an orbital revolution while traversing the open ocean areas. Second, at satellite altitudes (most orbits used for gravity field recovery have perigee heights of 500 to 1100 km) the fine structure of the gravity field is attenuated and the short wavelength features cannot be derived.

As a further refinement to the technique of using artificial satellites to define the global geoid, a new method, radar altimetry, has been developed for directly measuring the distance from the satellite to the ocean surface. The first satellite-borne radar altimeter experiment was carried out during the recent SKYLAB mission. Analyses of the SKYLAB radar altimeter data demonstrated that the instrumentation had the capability for sea surface mapping (McGoogan et al., 1975). Consequently the altimeter data provides an independent standard of comparison for gravimetrically derived geoids. The recent paper of Vonbun et al., 1975 presented a comparison of the "Around the World," pass of SKYLAB altimeter data and the GSFC GEM-6 detailed gravimetric geoid. The rms agreement between the two data types was 8 m. The present paper represents an extension of this work through the use of more recent GSFC gravity models as well as the use of gravity models published by other organizations.

2. COMPARISONS OF THE SATELLITE DERIVED GEOIDS WITH THE SKYLAB ALTIMETER DATA

The results of a previous analysis (Marsh and Vincent, 1974) largely prompted this investigation. The earlier paper presented comparisons of satellite derived geoids along latitude profiles in the northern as well as southern hemispheres. These comparisons revealed generally good geoid height agreement in the northern hemisphere, but differences as large as ±25 meters in the open ocean areas of the southern hemisphere, far larger than the uncertainty estimates associated with the gravity models. Agreement between geoids is generally better in the northern hemisphere because recent satellite-derived gravity models usually incorporate surface gravity data, which is of course relatively abundant in the northern hemisphere.

During the SKYLAB-4 mission, the altimeter was operated over an "around the world" ground track starting off the coast of Brazil and ending in the Caribbean Sea. This revolution covered areas where large differences were observed in the geoid comparisons mentioned above. Figure 1 presents the ground track of the SKYLAB pass superimposed on a contour map of the geoid height differences between two of the gravity models that resulted from the National Geodetic Satellite Program. The differences shown are between the GSFC GEM-6 (Lerch et al., 1975) and the SAO-III (Gaposchkin, 1974) models.

Figure 2 presents a comparison of geoid profiles from the GEM-6, SAO-III and the recent GSFC preliminary GEM-8 model (Lerch, 1975) with the altimeter geoid profile. The GEM-8 model (complete to degree and order 25) is a refinement of the GEM-6 model (complete to degree and order 16) through the addition of 66,000 laser observations recorded during the International Satellite Geodesy Experiment (ISAGEX).

The geoid profile in Figure 2 traverses four significant features: (1) a high in the Indian Ocean southeast of the Republic of South Africa, (2) an extension of the India.. low west of Australia, (3) a high over New Guinea, and (4) the geoidal undulations associated with the Aleutian Islands. As seen in Figure 2, the overall agreement between the altimeter geoid and the others is good. However, significant departures are noted at some points, specifically in the area of the four main features. The following four figures illustrate these departures in more detail.

Figure 3 shows the geoid profiles over the geoid high, southeast of the Republic of South Africa. Whereas the altimeter indicates this feature to be primarily long wavelength ($\sim$10,000 km), the SAO-III geoid shows an oscillation with a wavelength of about 4,000 km and a deviation of over 25 meters from the altimeter geoid. The GEM-6 geoid does not contain the oscillation indicated by the SAO-III model and consequently the agreement with the altimeter data is better except at $15^h 5^m$ where a departure of about 15 m is noted. The GEM-8 geoid profile is relatively smooth in this area and agrees best with the altimeter data.

Figure 4 presents geoid profiles extending from the geoid low approximately 20° west of Australia to the high over New Guinea. The total variation in geoid indicated by the altimeter in this region is 127 meters. This total variation is represented best by the SAO-III model which indicates a variation of 125 meters. The GEM-6 model indicates a variation of 108 meters and GEM-8 shows an improvement over GEM-6 with a variation of 115 meters. A short wavelength (~1000 km) feature with an amplitude of about ten meters was detected by the altimeter at 15^h42^m in the vicinity of Yap Island. Of the three gravity models, only GEM-8 exhibited even a trend in the direction of this feature.

In Figure 5 a comparison in the vicinity of the Aleutian Islands is presented. GEM-8 models the location of this feature most accurately. In the case of the GEM-6 and SAO-III models, a displacement of approximately 10° along track is noted over the high.

Additional geoid comparisons presented by Marsh and Vincent [1974] indicated that better agreement was achieved between the gravity models when they were truncated at (12, 12) and (8, 8). Since independent data were not available at that time it was difficult to assess the accuracy of the geoids derived from the truncated gravity models. Figure 6 presents a comparison between the geoids derived from the SAO-III complete model, the SAO-III (8, 8) model and the altimeter geoid over the geoid high southeast of the Republic of South Africa. Note that the truncated SAO-III model does not contain the short wavelength oscillations exhibited by the complete SAO-III model and agrees significantly better with the altimeter geoid in this area. Thus it is evident that the higher degree and order coefficients are providing more detail in the geoid in this geographic area than is actually present. As an attempt to further investigate these differences, a geoid was derived from the SAO-III model after deleting resonant coefficients of order 11 through 15. Little change was noted in this geographic area between the geoid derived from this model and the one derived from the complete model. Thus resonant coefficient error is not contributing to the large variations.

As another means of analyzing the differences between the satellite geoids and the altimeter data, rms differences were calculated based upon 49 points along the profile. Table 1 presents these rms differences for the complete and the truncated (8, 8) models. (The NOAA model (Koch et al., 1971) was originally represented by 20° x 20° density layer blocks and is thus approximately equivalent to an (8, 8) model.) A plot of the differences displayed a pattern quite similar to the geoid profile with the largest differences being in the vicinity of the first three geoid features noted earlier. Thus the rms computation is dominated by the large differences in these three geographic areas. The significant improvement noted for the (8, 8) SAO-III model is primarily attributed to the improved fit in the South Atlantic and Indian Ocean as shown in Figure 6.

3. ACCURACY OF THE SL-4 ORBIT

Table 2 gives the specifications of the SL-4 orbital arc studied in this paper. The satellite was tracked by NASA Unified S-Band radars at: Goldstone, California; Merritt Island, Florida; Bermuda; Ascension; Carnarvon, Australia; Guam; and Corpus Christi, Texas. The orbital arc length was restricted to a single revolution in order to minimize the effects of model errors, for example, errors due to the effects of uncoupled torques on the satellite from the attitude control system.

A number of error sources in the physical model affect the determination of the SKYLAB-4 orbit. Among these are the earth's gravity model, tracking station coordinates, atmospheric drag, solar radiation pressure and GM. It might be anticipated that atmospheric drag and solar radiation pressure would be serious problems because of the low orbital altitude and large area. However, the area to mass ratio is quite low ($0.03\ cm^2/g$, which is less than for GEOS-I) so that these effects in the radial direction are negligible.

Error propagation studies were carried out for the effects of gravity model and station coordinate errors. The gravity model error was taken as 25% of the difference between the APL 3-5 and SAO 1969 gravity models (Martin and Roy, 1972). Although this error model was established primarily for the GEOS-II satellite orbit, simulations have shown that the SKYLAB range-rate residuals predicted by this model are in good agreement with the residuals actually obtained in the orbit fitting process, providing a check on this error model. Station coordinate errors of 5 meters in each coordinate and an error of 1 part in 10^6 in GM were assumed in these simulations. The rss propagation of the gravity model and station coordinate errors into the radial orbit component is presented in Figure 7. As shown in this figure, the radial orbit uncertainty is predicted to be less than about ±1 meter about the mean value. The station coordinate errors contributed generally less than 50 cm to the radial uncertainty. The GM error produced the mean radial uncertainty of about 2.8 m with a variation of about ±15 cm with a frequency slightly less than the orbital frequency. The mean difference would not be separable from other error sources such as an altimeter calibration error or a scale error in the gravimetric geoid. The ±15 cm variation is small in comparison to the accuracy of the SKYLAB altimeter data, nevertheless it represents an error source which must be considered for future altimeter missions such as SEASAT where 10 cm accuracy is sought.

In addition to these simulations, comparisons have also been made with different gravity models used to determine the SKYLAB orbit. Table 3 presents the range-rate residual rms values obtained with various gravity models. The table presents results for the complete models and in addition, results when the models were truncated at (8, 8). Truncation of the GEM-1, Lerch et al., 1972, GEM-6, GEM-7 and GEM-8 models resulted in an increase of the rms fits. In contrast truncation of the SAO-III model produced a reduction of almost 50% in the rms fit. It is for this reason that SAO-III orbits were not used for geoid comparisons.

4. CONCLUSIONS

Our analysis has revealed that the altimeter vs. gravity model geoid differences were caused by several factors, including differences in the amplitudes of features, dislocation of features (which in turn affects the amplitude of the geoid at a specific point on the surface of the earth) and the presence of

superfluous detail in certain geographic areas. Clearly the altimeter data from GEOS-C will lead to a major refinement of the fine details of the geoid.

ACKNOWLEDGMENT

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Table 1

Rms Differences Between Satellite Geoids and the SKYLAB Round the World Altimeter Pass

GRAVITY MODEL	RMS DIFFERENCE (Meters)	
	COMPLETE MODEL	MODEL TRUNCATED (8,8)
SAO M-1*	8.1	8.2
NOAA	9.1	
GEM-6	8.1	7.4
GEM-7	7.8	7.6
GEM-8 (Prelim.)	7.8	7.3
SAO-III	9.2	7.5

*Lundquist and Veis, 1966

Table 2

Specifications of SKYLAB Orbital Arc

ORBITAL PARAMETER	
SEMIMAJOR AXIS	6808390 METERS
ECCENTRICITY	0.107
INCLINATION	50.028°

ARC LENGTH: 85 MINUTES, 14^h20^m TO 16^h20^m

JANUARY 31, 1974

Table 3

Summary of Unified S-Band Radar Observation Residuals for the SKYLAB Orbit, January 31, 1974, 14^{hr} 20^{m} to 16^{hr} 20^{m}

GRAVITY MODEL	RMS OF FIT	
	COMPLETE MODEL	MODEL TRUNCATED (8,8)
SAO M-1	5.5 cm/s	
GEM-1	3.7	4.7
GEM-6	4.3	4.7
GEM-7	3.3	4.5
GEM-8 (Prelim.)	3.2	4.2
SAO-III	7.5	4.0

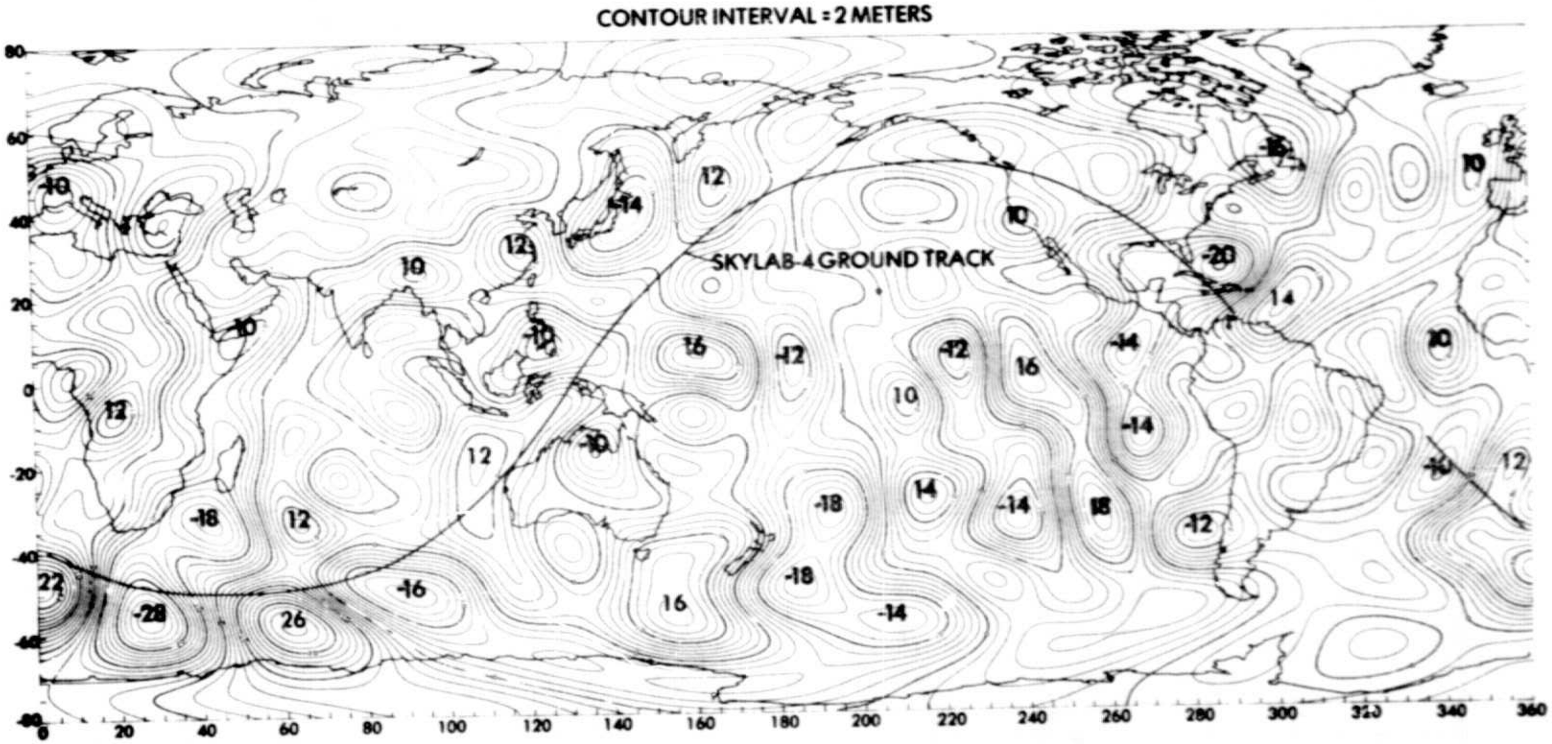

Figure 1. Gravimetric Geoid Height Differences (GEM-6—SAO-III)

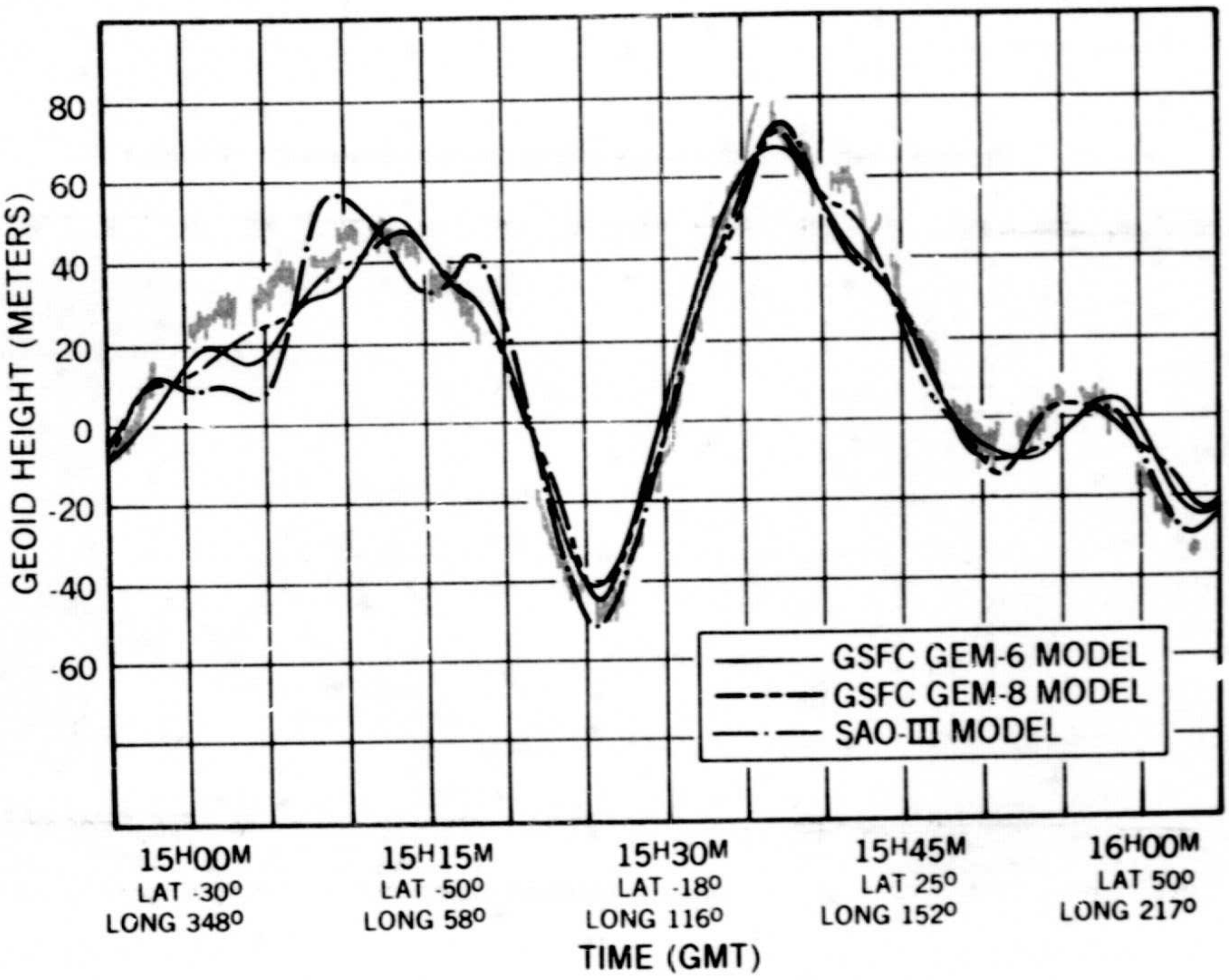

Figure 2. Comparison of Satellite Geoids with SKYLAB Altimeter Data for the "Round the World" Pass

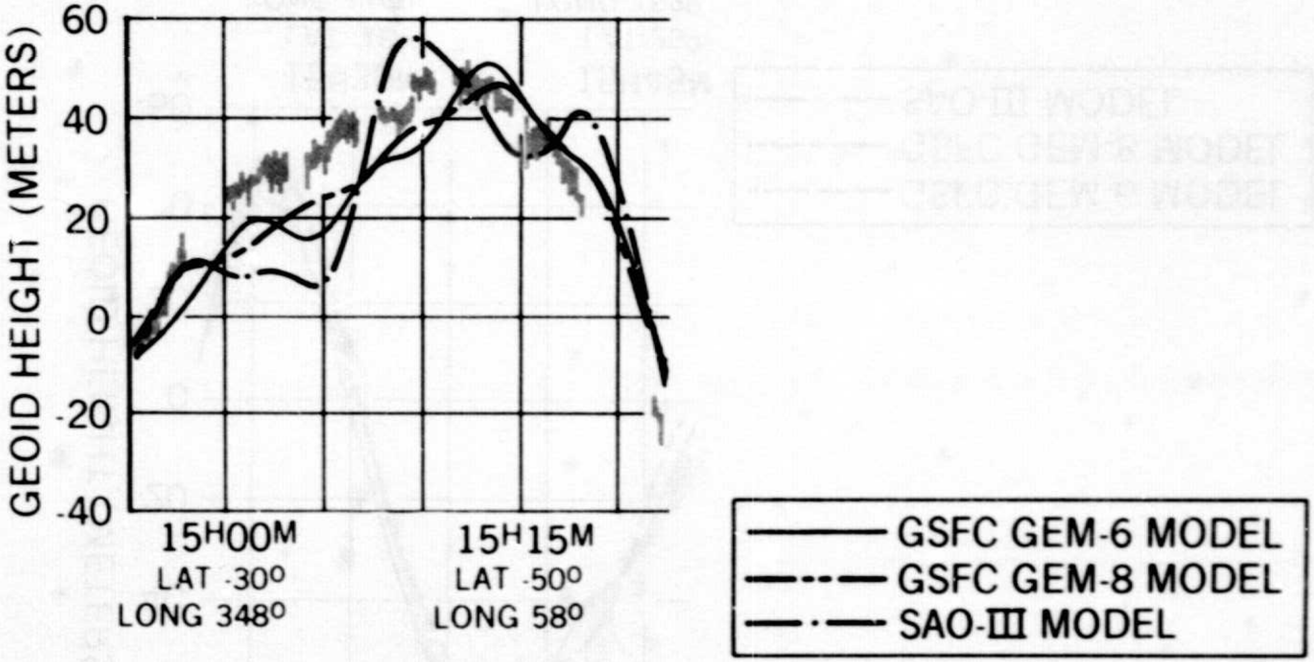

Figure 3. Comparison of Satellite Geoids with SKYLAB Altimeter Data in the South Atlantic and Indian Ocean

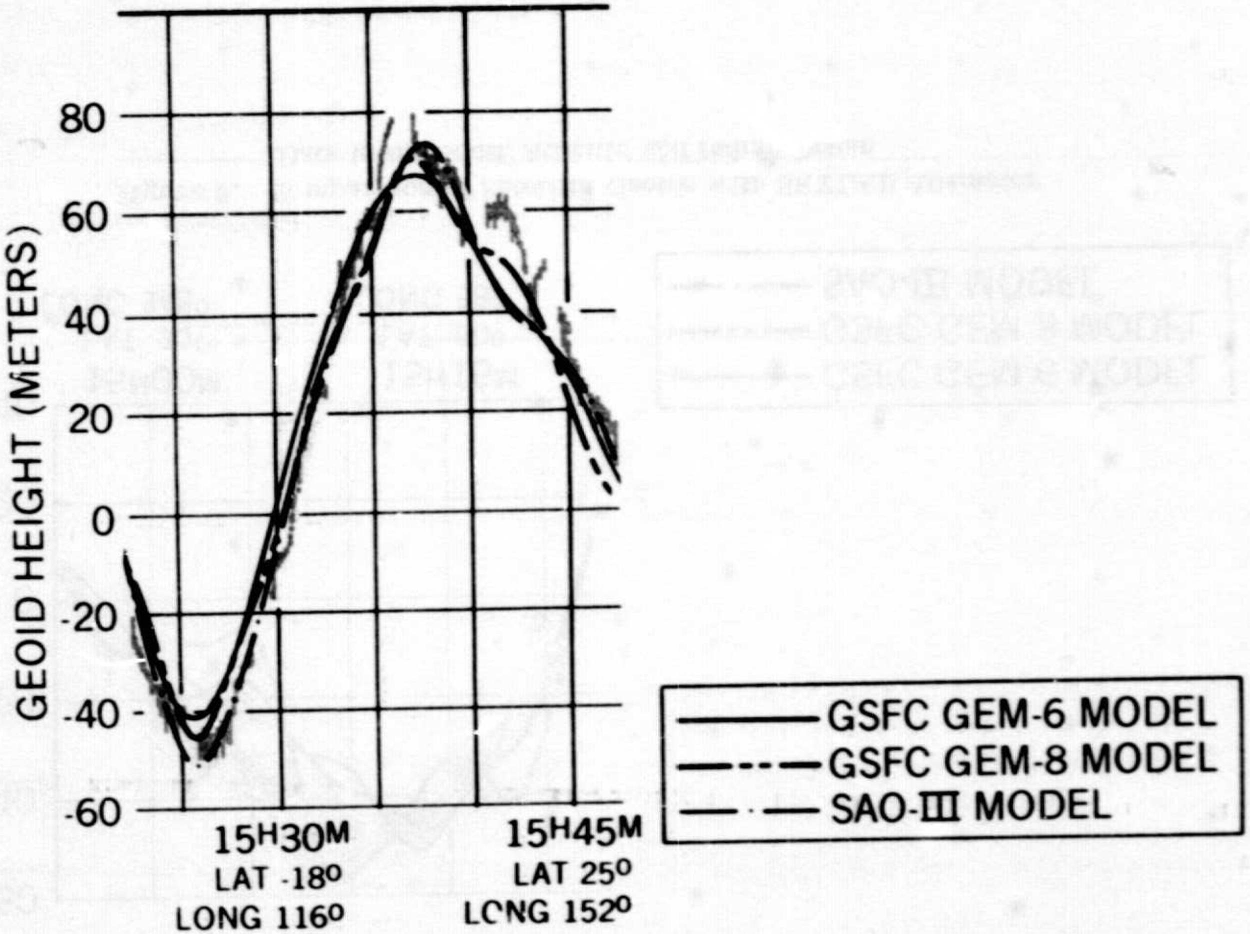

Figure 4. Comparison of Satellite Geoids with SKYLAB Altimeter Data in the Indian Ocean and North of Australia

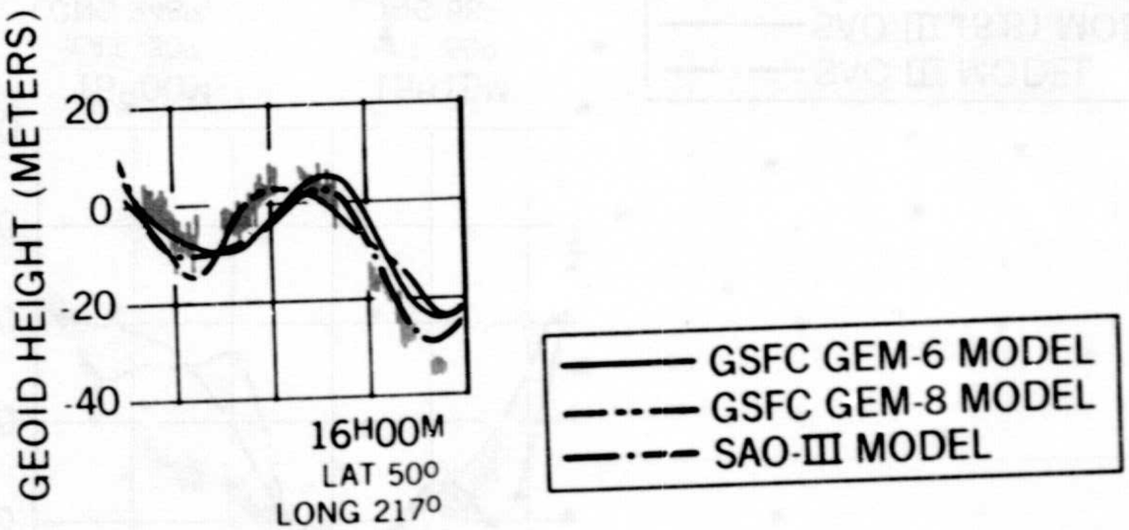

Figure 5. Comparison of Satellite Geoids with SKYLAB Altimeter Data in the North Pacific

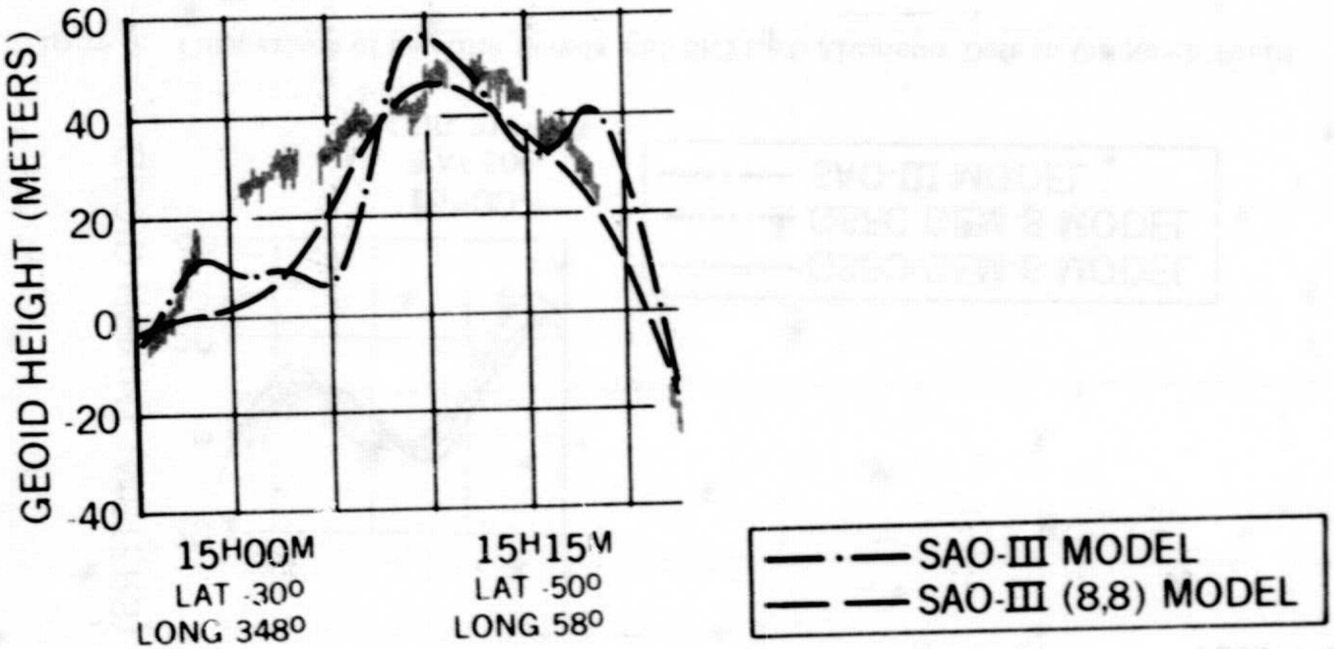

Figure 6. Comparison of SAO–III and SAO–III (8, 8) Geoids with SKYLAB Altimeter Data in the South Atlantic and Indian Ocean

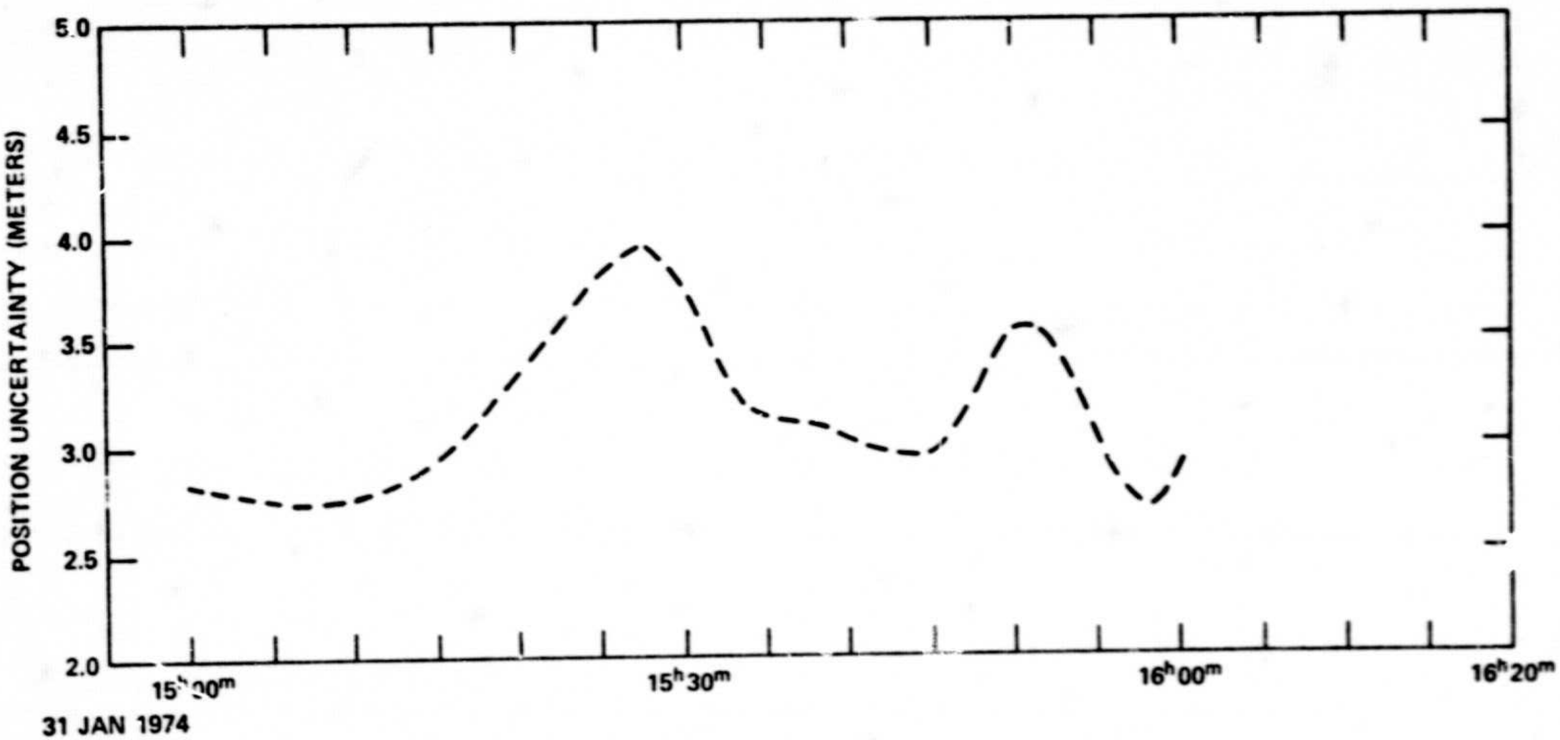

Figure 7. SKYLAB 4 Radial Orbit Uncertainties from Error Analysis