Evaluation of the Geoid Based on the SEASAT Altimetry Data at Sea around Antarctica

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海洋衛星シーサットの高度測定データによる南極周辺海域のジオイドの評価

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要旨： NASA が打ち上げた海洋衛星シーサットのレーダー高度計による海面高の測定が，1978年の6月から9月にかけて行われ，機械精度±10cm という高精度の測定に成功した．このデータを処理することにより，南緯45°から南極大陸の縁辺までの海面トポグラフィの図化を行った．衛星の軌道誤差が大きいため，その機械精度に反して，海面高のデータには ±5m の誤差が含まれることがわかった．しかし，ロス海やウェッデル海などの湾形の地帯でのジオイドの顕著なへこみや，東南極沖合のインド洋におけるジオイドのもり上がりなどが，みごとに測られていることもわかった．

Abstract: The SEASAT radar altimetry data, which were obtained during its operational period from June to September 1978, have been processed, and the sea surface topography and/or the geoid in the area between 45°S and the margin of the Antarctic Continent have been contour-mapped. Mainly because of the uncertainty involved in the satellite altitude the sea surface topography includes maximum errors of ±5 m. However, some significant features such as geoid depressions at the Ross Sea and the Weddell Sea or the regional geoid upheavals over the Indian Ocean off East Antarctica have been clearly displayed.

1. Introduction

SEASAT is a satellite launched in June 1978 by NASA which had a mission of surveying the ocean from geophysical and oceanographic points of view. The satellite was equipped with five geophysical sensors and an assembly of retro-reflectors for laser ranging (NASA, 1977). All of these sensors are thought to have been the devices produced by the highest-class technology of those days. The radar altimeter was the typical of them, which was capable of sensing a ±10 cm change of the sea surface topography from the orbit of 800 km altitude. The development of the satellite altimeter in the United States seems to have followed three steps, the first one was the device mounted on SKYLAB, the second the device mounted on GEOS and the last the device mounted on SEASAT. Sensitivity of these devices rose step by step from 1 m with SKYLAB, and 0.5 m with GEOS to 0.1 m with SEASAT. The sea level coincides with the geoid surface

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in the primary sense. Deviation of the sea surface topography from the geoid shows a quantity of ± 1 m in the largest case. The largest deviation is caused by strong oceanic currents such as the Gulf Stream or the Kuroshio. The deviation smaller than this is due to either weaker oceanic currents, oceanic tides or atmospheric pressure (for instance, refer to MOLINARI, 1980; SCHWIDERSKI, 1980).

The author is interested in the altimetry data not because they show the sea surface topography but because they are regarded as a good approximation of the geoid surface. The geoid is evaluated from gravity anomalies through the Stokes' integral or by other mathematical methods in a very rigorous fashion provided that gravity anomalies over the whole earth are known in detail. Since such is not the case, the present knowledge of the gravimetric geoid all over the earth involves errors much larger than 1 m. The altimetry geoid, on the other hand, can be looked upon as the most reliable information of the geoid available at present, even if it is not corrected for the ocean dynamical or atmospheric effects. In the area near Japan it is possible to apply various corrections to the altimetry data on the basis of the well-known oceanographic and meteorological data sources. In the remote areas such as the polar regions there are few data available. As for the gravity data the situation is as bad as or even worse than with the other data. So the author thinks that it is worth while to evaluate the sea surface topography as a substitute for the geoid particularly in the regions of difficult access. The sea around the Antarctic Continent has been selected for this reason. Some papers were published already, reporting the results of the GEOS-3 altimetry over the oceans of the world (LERCH *et al.*, 1978; BRACE, 1977). However, they did not lay emphasis on the polar regions, hence it is difficult to extract features of the geoid in the Antarctic region from the maps they compiled. In the south polar region the ice pack prevails in winter over the area as far as 55°S. Unfortunately SEASAT flew during the winter season in the south polar region, resulting in that the altimetry data were modulated considerably by ice. Since it is not known how the ice pack affects the altimetry records, the effects of the ice pack on the altimetry data were regarded as random and were removed by using a digital low pass filter. After the above reduction the recorded sea surface heights are plotted on a map of polar projection.

2. SEASAT Altimetry Data

The radar altimeter installed on SEASAT transmits a microwave pulse with a frequency of 13.5 GHz and a beam width of 1.5° perpendicularly to the surface of the reference earth ellipsoid, and measures time interval of the return pulse from the earth surface. After primary processing of the return pulses the altitude data with a rate of 10 per second are obtained and those data are further averaged so as to yield 1 data per second. The SEASAT altimetry data now available are those averaged every one second which are stored in magnetic tapes. The altimetry data have to be corrected from the sensor hard-ware and the geophysical points of view. Geophysical corrections include subtraction of the reference geoid height following the Goddard earth model 10B (GEM 10B) (LERCH *et al.*, 1978), correction

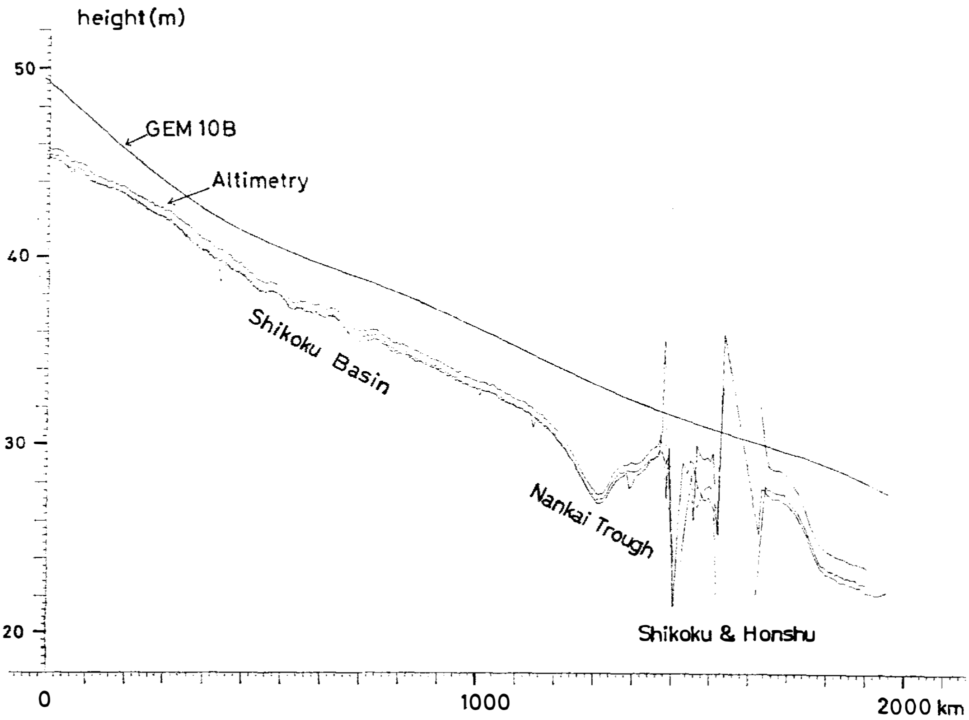

Fig. 1. An example of the SEASAT altimetry data along the orbits across the Shikoku Basin. Left—south, right—north.

for the earth tide after the Melchior model (MELCHIOR, 1978), correction for the oceanic tide after the Estes model (ESTES, 1977), corrections for meteorological and ionospheric effects, and so forth.

Figure 1 shows an example of the SEASAT altimetry which was obtained during the period of the satellite performance test, when the satellite orbit was adjusted so that several successive passes occurred on the same track with respect to the earth. In this figure three successive profiles of the sea surface topography as well as a corresponding profile of the geoid according to the model GEM 10B are shown. It is easily found that the three profiles of the sea surface topography coincide with each other with a maximum difference of 1 meter and that the difference in height between the geoid and the sea surface is approximately 4 m. Since these profiles are obtained in the area extending from the Shikoku Basin northwestwards to Shikoku, Honshu and the Sea of Japan, the SEASAT altimetry shows some features caused by gravity anomalies associated with geological characteristics of the Philippine Sea (*e.g.*, a local sea surface low at the Nankai Trough shown in the middle of Fig. 1). Figure 1 indicates also that a rather large bias error is involved in either the geoid model or the SEASAT altimetry and that the measurements of SEASAT are, in a relative sense, accurate enough to delineate topographic changes of a small scale.

The largest error source in the satellite altimetry is the error in orbital tracking, which amounts to 10 meters or so. SEASAT was rigorously tracked by means of laser ranging in the SEASAT test range near Bermuda in the Atlantic Ocean. Within the test range the orbital height of SEASAT was examined accurately as its uncertainty was less than 3 cm. In the other areas, however, the

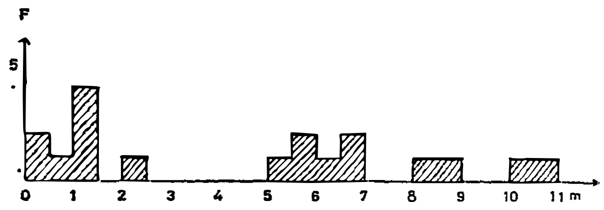

Fig. 2. Distribution of height differences of the SEASAT altimetry at orbital crossings.

orbital information was, in most cases, based on prediction. Figure 2 shows a distribution of height differences at crossings of orbits, which is regarded as an index for estimating the reliability of altimetry data. This distribution was obtained by using 111 passes in 26 days, indicating that the differences scatter from zero to over 10 meters. The results in Fig. 2 suggest that, although the SEASAT altimetry shows in fact a relative accuracy of ± 10 cm, it is deteriorated by the orbital uncertainties, resulting in much worse overall accuracy in height measurements. For this reason, it is necessary to apply adjustments regarding the satellite orbits to the altimetry data before using the data for evaluation of the sea surface topography.

Figure 3 shows an example of GEM 10B and altimetry profiles in the Antarctic region across the Antarctic Continent. In this figure the abscissa shows a distance along the satellite pass, while the ordinate shows heights in meters. The number $T=460$ indicates the number of turns of the satellite. There is a portion of the sea surface topography in the profile of Fig. 3, which scatters with an amplitude of several meters. This portion coincides with the area covered by the ice pack (gentle upheavals of the sea surface observed at the right end of the profile are those caused by gravity highs associated with the oceanic ridges and banks in the Indian Ocean). When such data are used in evaluating the sea sur-

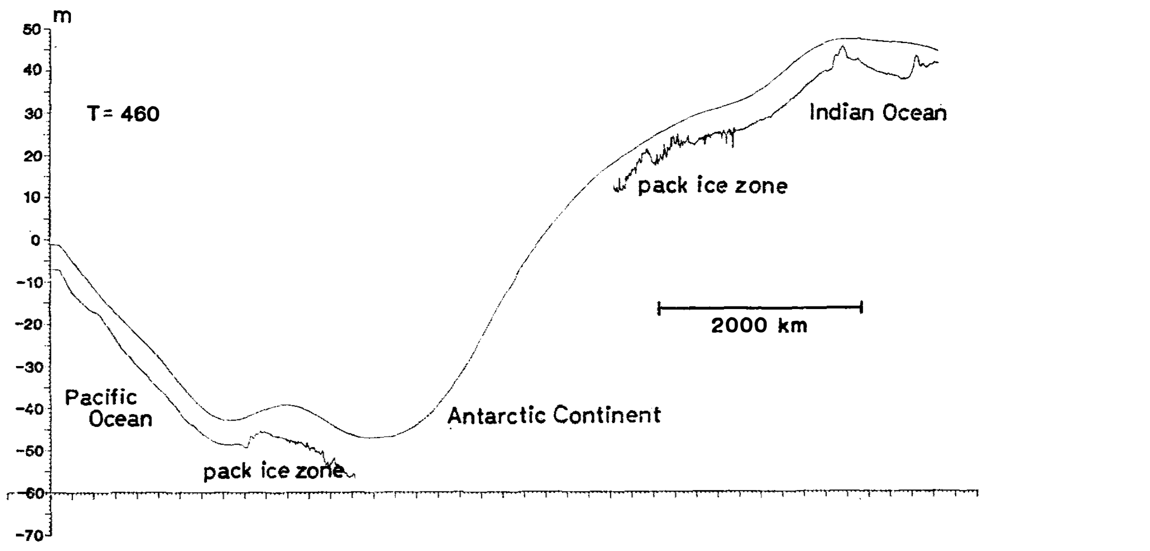

Fig. 3. A profile of the SEASAT altimetry (lower) vs. a corresponding profile of GEM 10B geoid across the Antarctic Continent in the winter season. The profile is along orbit No. 460.

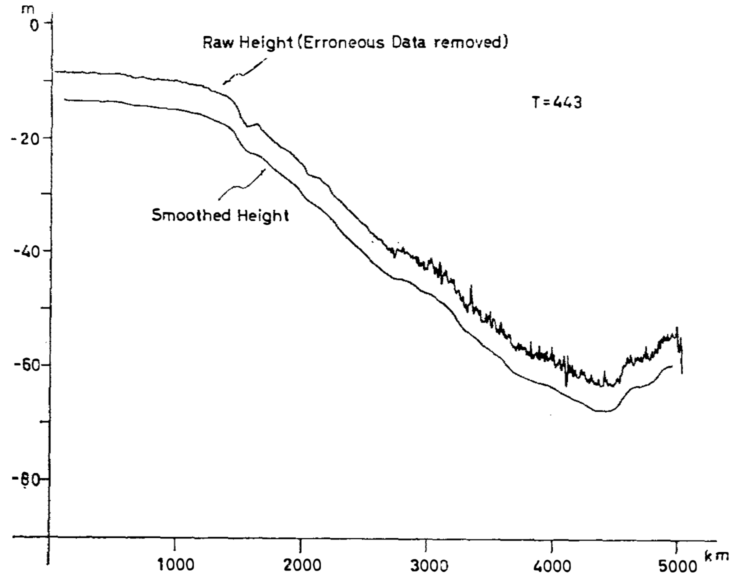

Fig. 4. A profile of raw altimetry data (upper) showing the effect of ice pack in the winter Antarctic sea. The lower profile is a result of smoothing, which is 5 m apart from the profile of the raw data for readability.

face topography with regard to the geoid, the author applies a digital low pass filter by taking a weighted average with a triangular weight function with a spread of 200 km. Figure 4 shows an example of smoothing thus conducted which represents the data from the orbit $T=443$. The smoothed profile is drawn 5 meters below the raw data profile for the sake of readability.

3. Geoid around Antarctica

The SEASAT altimetry data around the Antarctic Continent south of 45°S amount to about 200000 points. Distribution of the SEASAT orbits is shown in Fig. 5, from which it is seen that because of the orbital inclination of 108° with respect to this satellite the southern margin of the orbits is at 72°S, leaving most part of the Antarctic Continent out of range of measurements. Although the SEASAT orbits cover the marine area completely in the eastern side of Antarctica, some part of the western side remains unobserved.

The author used a ready-made computer program provided by the Applications Consultants Incorporated (address; 5555 West Loop, Site 626, Bellaire, Texas 77401) for contouring the altimetry data (subroutine name; SACM: Surface Approximation and Contour Mapping). The computer used was IBM 370-135 with memories of 500 kbytes. Although the contour mapping program seems to be excellent, the data as many as 200000 are too numerous for the computer used to process, resulting in abnormal outputs. Therefore, the data were sampled at every 6 points or about 42 km in terrain distance. Figures 6 and 7 are the contoured sea surface topography and/or the geoid thus calculated. In Fig. 6 the contour interval is 1 m, while in Fig. 7 it is 5 m. As soon found from Fig. 6, when the altimetry data are contoured in detail the satellite orbital lines are delineated more

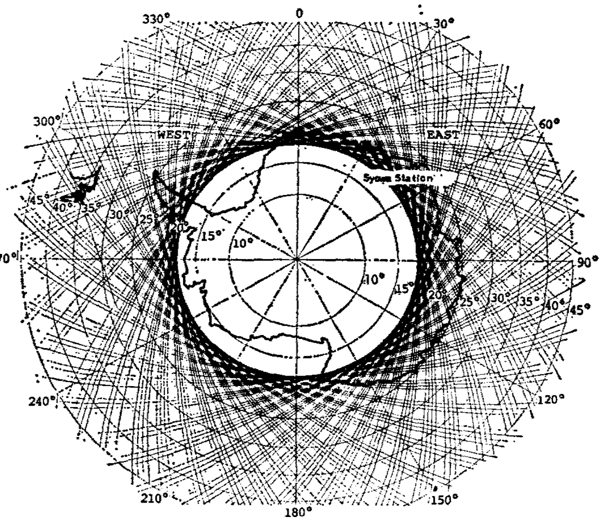

Fig. 5. Orbits of SEASAT around Antarctica south of 45°S.

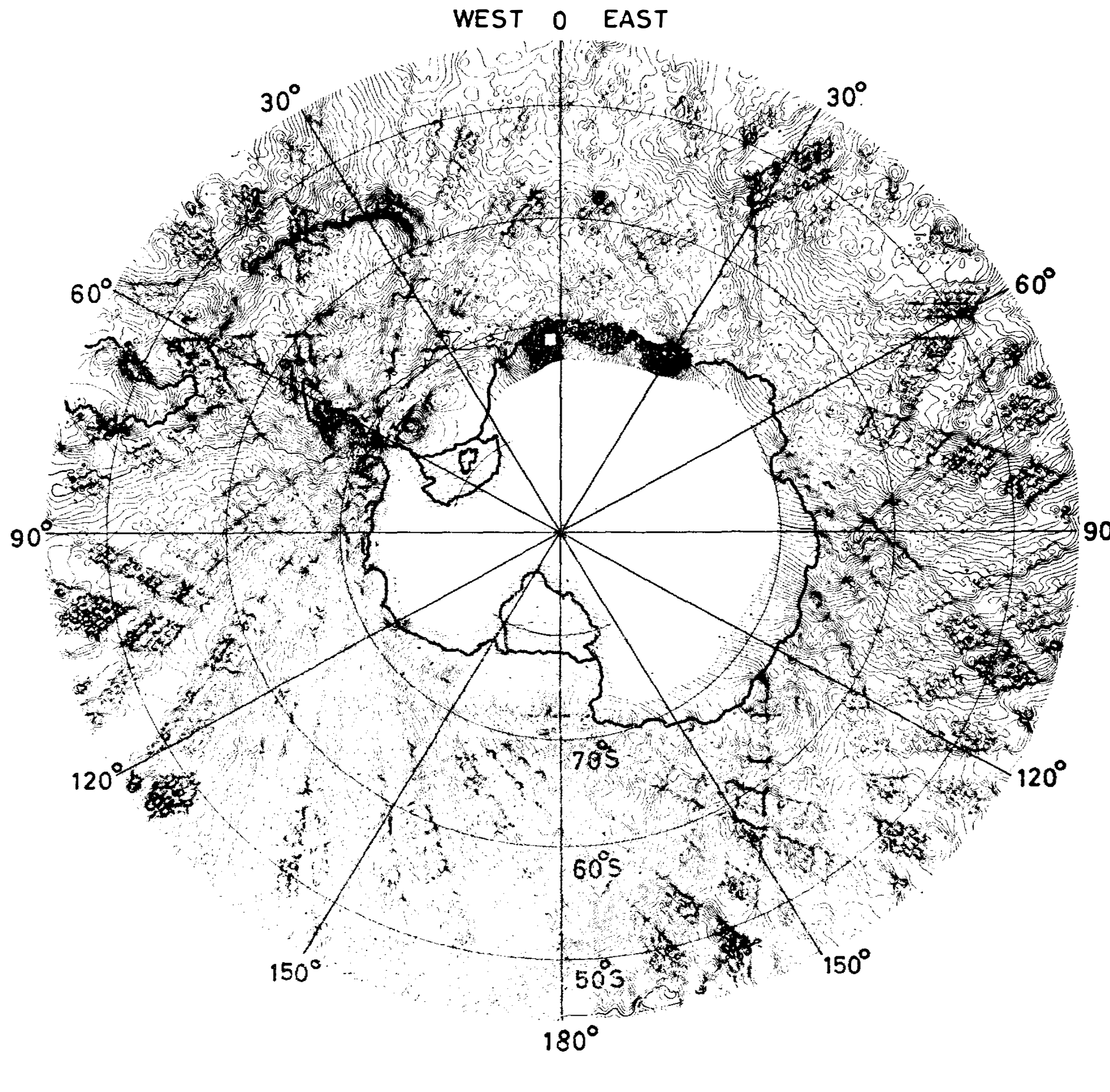

Fig. 6. Contours of sea surface topography with an interval of 1 meter around the Antarctic Continent. Satellite orbits are seen obviously.

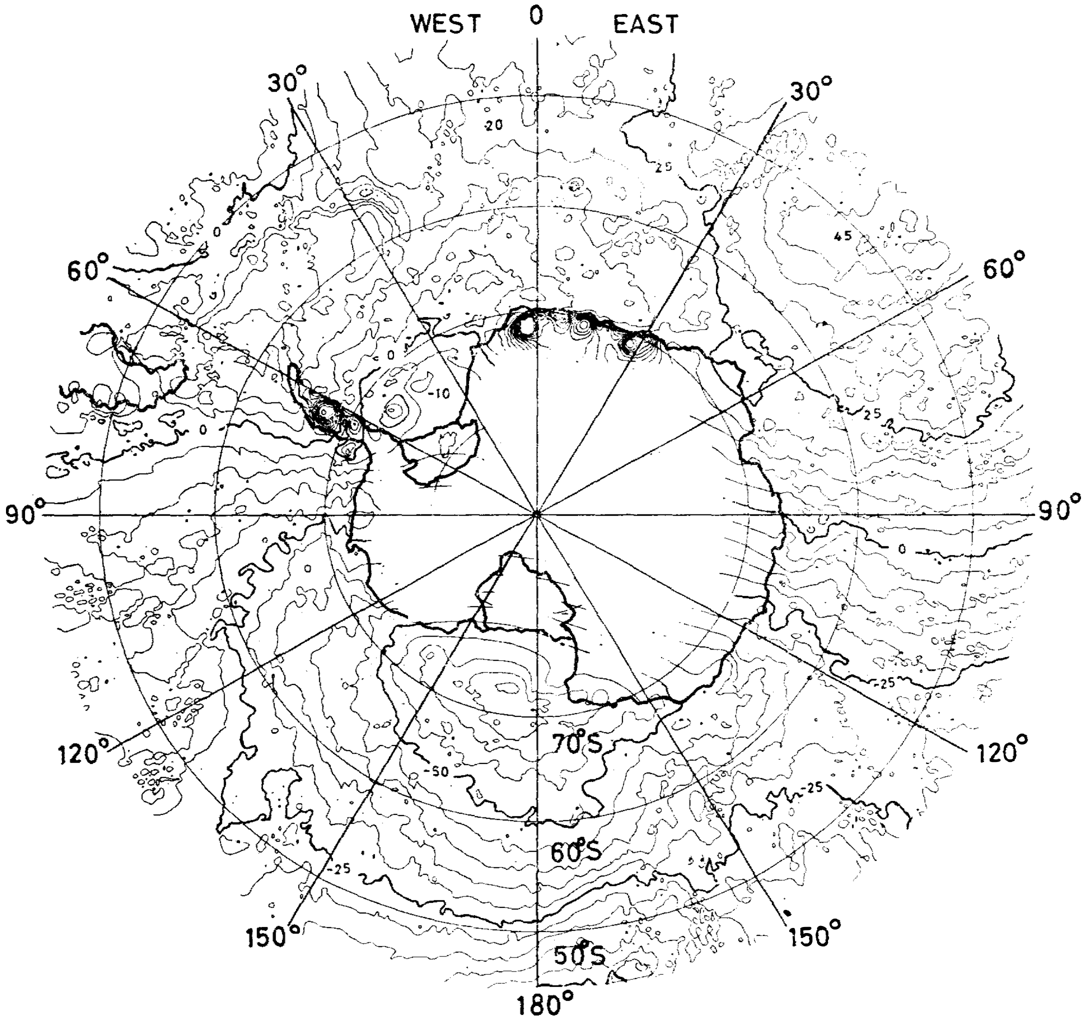

Fig. 7. Contours of sea surface topography with an interval of 5 m.

clearly than the sea surface topography. This happens because of significant errors in prediction of the satellite orbits (the sea surface height is the height of the satellite orbit above the reference ellipsoid minus the satellite altitude above the sea surface which is measured by the radar altimetry). If contours are made more sparse as in Fig. 7 (contour interval is 5 m here) the orbital features are weakened and, instead, the geoidal features become apparent.

If the geoid at sea around Antarctica thus obtained is reviewed, the most significant feature to be pointed out is that the geoid is higher in the regions of the Indian Ocean and the Atlantic Ocean, whereas it is lower in the region of the Pacific Ocean. Within the range from 45° S towards Antarctica the highest geoid is +45 m high, which is at 48° S and 50° E. This geoidal high corresponds to the Rena and Obi banks. In this part of the Indian Ocean lies the southwest Indian ridge which is cut by numerous fracture zones. The area between meridians 120° E and 30° W including West Antarctica and part of East Antarctica is a zone where the geoid is depressed significantly. The lowest geoid which is found in the middle of the Ross Sea is −65 m. The Weddell Sea is also a zone where the geoid sinks to as low as −10 m. In general the geoid is assymmetrically distributed around

Antarctica; the low region at the side of the Pacific Ocean, and the high region at the side of the Indian and the Atlantic Oceans. The transantarctic mountain range, the Ross Sea, the Weddell Sea and the Antarctic Peninsula seem to be tectonic structures that border the areas with the contrasting geoidal and/or gravity features.

4. Discussion

Difficulty in processing the SEASAT altimetry data arises from wrong orbital information. In order to overcome or alleviate the difficulty, two methods may be considered: One is adjustment of the orbits of the satellite so that the long wave length components of the altimetry data coincide with the geoid model *a priori* given, and the other, assuming the disagreements in altimetry at crossings of orbit to be randomly distributed, is application of self-adjustment procedure on the basis of statistical method so that the disagreements at the crossing points are minimized. Since these procedures will take time, the author intends to report the adjusted result in a separate paper.

Acknowledgments

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