DETERMINATION OF THE GRAVITY FIELD AROUND ANTARCTICA USING SATELLITE ALTIMETER DATA AND SURFACE GRAVITY DATA - A REVIEW OF THE RECENT STUDIES -

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Abstract: Some problems on the simultaneous use of the different kinds of gravity field data for the determination of the gravity field around Antarctica are discussed. Since ground and/or sea truth data in the Antarctic region are limited, the use of remote sensing data is a key for geophysical studies. From this point of view, combined use of satellite altimeter data and surface gravity data by means of a least squares collocation (LSC) method is demonstrated. Recent developments of the space technology provide many different kinds of gravity field data. Thus the studies of the method like LSC should be emphasized to avoid the confusion among the data of different quality and to utilize them effectively.

Key words: gravity field, satellite altimeter, GEOSAT, surface ship gravimeter, least squares collocation

Introduction
During the past few years, we investigated the determination of the gravity field around Antarctica (e.g. Segawa et al., 1988; Fukuda et al., 1988). In spite of many research efforts which are being carried out by many scientists, there remain many areas in the Antarctic region which have been left unexplored. The Japanese Antarctic Research Expedition (JARE), for instance, has carried out gravity surveys since the early stage of the expedition, but the coverage of the gravity data in the region concerned is still insufficient today.

Recent space technology, on the other hand, provides very powerful tools for the studies of gravity field. The gravity anomalies in the Antarctic Ocean, for instance, have been revealed using satellite altimeter data (e.g. Segawa et al., 1984). In particular, the GEOSAT mission provided a high quality data set because GEOSAT is the first satellite which measured the sea surface heights of the Antarctic Ocean during the austral summer season.

The use of this kind of remote sensing data is perhaps a key for the geophysical studies in the Antarctic region. But ground and/or sea surface data also play an important role on the occasions. It is true that the altimeter data are very effective for covering large areas uniformly, but their accuracy and resolution are worse than those of surface ship gravity data. Consequently, combined use of both altimeter data and surface gravity data is inevitable for the precise mapping of the gravity anomalies.

The similar situation will arise more often in the near future because many gravity field observations of different quality are being conducted or in preparation. It is getting more and more important to use different kinds of gravity field data simultaneously. From this point of view, even though there remains some problem in the practical aspects, implementation of the least squares collocation (LSC) method (Moritz, 1980) is an important task to obtain the gravity anomalies. One of the purposes of this paper is to point out the importance of the simultaneous use of the different kinds of data.

In the following chapters, we first review several studies which concern the gravity field determination, and then make some discussion on the problems especially focusing on the combined use of heterogeneous data.

A Brief Biography of the Gravity Measurements around the Japanese Antarctic Stations

Land gravity measurements
The gravity surveys on land around the Japanese Antarctic stations have been carried out by the field parties of JARE. The results of these surveys are summarized in, e.g. Geographical Survey Institute (1986); Nagao and Kaminuma (1988); Nagao et al. (1991). It should be noted that:

1) The values of all the gravity measurements are referred to the base point at Syowa Station, and are converted into the IGSN71 system.

2) The geodetic reference system employed is WGS-72. The positions of some data points were determined by a satellite Doppler positionning system. For those data, the geoid heights were calculated using GEM10B geopotential model to obtain the elevation above sea level. This treatment of the height data will be discussed later.

3) The accuracy of the land gravity anomaly mainly depends on the positioning errors, and is around 10 mgal (Nagao and Kaminuma, 1988).

Surface ship gravity measurements
The first surface ship gravity measurements by JARE were carried out in JARE-8 using a GSI type surface ship gravimeter on board icebreaker Fuji. Afterwards, the measurements by the same system were carried out through JARE-9, JARE-13 and JARE-15. The gravity data obtained,
Table 1. Summary of the surface ship gravity measurements conducted by JARE.

<table>
<thead>
<tr>
<th>JARE</th>
<th>ICE BREAKER</th>
<th>GRAVI-METER</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>-8 (1966)</td>
<td>FUJI</td>
<td>GSI type</td>
<td></td>
</tr>
<tr>
<td>-9 (1967)</td>
<td>FUJI</td>
<td>GSI type</td>
<td></td>
</tr>
<tr>
<td>-13 (1971)</td>
<td>FUJI</td>
<td>GSI type</td>
<td></td>
</tr>
<tr>
<td>-15 (1973)</td>
<td>FUJI</td>
<td>GSI type</td>
<td></td>
</tr>
<tr>
<td>-21 (1979)</td>
<td>FUJI</td>
<td>NIPRORI-I</td>
<td></td>
</tr>
<tr>
<td>-22 (1980)</td>
<td>FUJI</td>
<td>NIPRORI-I</td>
<td>*</td>
</tr>
<tr>
<td>-23 (1981)</td>
<td>FUJI</td>
<td>NIPRORI-I</td>
<td>*</td>
</tr>
<tr>
<td>-25 (1983)</td>
<td>SHIRASE</td>
<td>NIPRORI-I</td>
<td></td>
</tr>
<tr>
<td>-27 (1985)</td>
<td>SHIRASE</td>
<td>NIPRORI-I</td>
<td>*</td>
</tr>
<tr>
<td>-28 (1986)</td>
<td>SHIRASE</td>
<td>NIPRORI-I</td>
<td>*</td>
</tr>
<tr>
<td>-29 (1987)</td>
<td>SHIRASE</td>
<td>NIPRORI-II</td>
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</tr>
<tr>
<td>-30 (1988)</td>
<td>SHIRASE</td>
<td>NIPRORI-II</td>
<td></td>
</tr>
<tr>
<td>-32 (1990)</td>
<td>SHIRASE</td>
<td>NIPRORI-II</td>
<td></td>
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</table>

* Digital data are available.

however, were not so good of quality owing to large instrumental drifts. This large drift is mainly because the ship passing through packed sea ice is subject to strong vibrations and mechanical shocks, which gave rise to malfunctioning of the surface ship gravimeter.

The first successful surface gravity measurements were conducted by JARE-22 (Kasuga et al., 1983). In these measurements, a new surface ship gravimeter NIPRORI-I was employed. The NIPRORI-I surface ship gravimeter was designed to have a strong construction against the mechanical vibrations (Segawa et al., 1981). Since then, the surface ship gravity measurements have been conducted almost every year. They are summarized in Table 1.

All the surface ship gravity data obtained by JARE have been processed into the form of gravity anomaly. In these procedures, we have employed the WGS-72 system for the geodetic reference system and the gravity formula 1967 for the calculation of normal gravity. In particular, the data obtained after JARE-27 have been processed through completely the same procedure, and are ready for distribution (Fukuda, 1990; Fukuda et al., 1991).

Estimation of the overall accuracy of the surface ship gravity data is not an easy task: one way is to get the gravity difference between different data sets. From these gravity differences, we found rather large sensor drifts for the data obtained after JARE-29, though these data contain good signals in short wavelength components (approximately within the time span of one week). The data obtained from JARE-22 to JARE-28 do not contain such a large drift error and the accuracy is estimated as round 5 to 10 mgal.

The Use of Satellite Altimeter Data

Using the SEASAT altimeter data, studies of the gravity fields in the Antarctic Ocean were undertaken by various authors (e.g. Segawa and Asaoka, 1982; Sandwell, 1984). These studies have first revealed the whole view of the gravity anomaly around Antarctica (e.g. Segawa et al., 1984). Although SEASAT have greatly contributed to the improvement on the knowledge of the Antarctic Ocean, the altimeter data, because of only three months of SEASAT life time, were badly affected by the Antarctic sea ice. The sea ice caused not only short wavelength noises but also long wavelength bias in the altimetric measurements, and degraded the reliability of gravity field signals.

GEOSAT, which was launched in March 1985 by the U.S. Navy (Cheney et al., 1986), on the other hand, provided a new data set of altimeter data. GEOSAT was under operation for more than 4 years, and measured the sea surface heights of the Antarctic Ocean during the austral summer for the first time. Thus the data obtained are free from the noise or the bias of sea ice.

The GEOSAT mission was divided into two stages. The first stage called Geodetic Mission (GM) was primarily classified because of their value to the U.S. Military. However, a small portion of the GM data around Antarctica was recently declassified, and using the GM data, a detailed view of the ocean floor has been recovered (Marks et al., 1991).

The second stage of the GEOSAT mission called Exact Repeat Mission (ERM) was aimed to measure sea surface variability, and those data were not classified. We made a preliminary investigation using GEOSAT ERM data (Fukuda and Segawa, 1989), and found that the data are much better than the SEASAT altimeter data. There are several studies which used GEOSAT ERM data for the recovery of the ocean gravity field (e.g. Sandwell and McAdoo, 1988), and these studies clearly show the major features of the ocean floor.

Although the release of the GM data relatively decreased the value of ERM data, ERM data still have several benefits. Repeated measurements of ERM along the same ground track may reduce the measuring errors and also cancel out time variations of the sea surface heights which are considered as noises for the gravity field studies. Thus ERM data should be combined in the processing of GM data to improve the accuracy of gravity field recovery.

Combined Studies of Surface Gravity Data and Satellite Altimeter Data

Segawa et al. (1984) used GEOS-3 and SEASAT altimeter data and surface gravity data to compile a map of free-air gravity anomaly of the Antarctic region. In their study, gravity anomalies converted from the altimeter data and surface gravity data were merged into a single data set by means of a two-dimensional interpolation technique (Segawa et al., 1986).

The same procedure was followed by Fukuda et al. (1988) to compile a more detailed gravity map around the Japanese Antarctic stations. In the study, the satellite altimetric gravity data were carefully calibrated using surface ship gravity data to remove long wavelength discrepancies.

In those studies, altimeter data were converted to gravity anomalies separately, and treated as a new gravity data set. This kind of approach may be practically convenient and might preserve enough accuracy for the mapping of the gravity anomalies. However, it is also true, from both practical and theoretical points of view, that there is no reason to distinguish the gravity data from other converted gravity field data so long as estimate of the gravity field can be described as a harmonic function outside the earth. For this purpose, any quantity of the gravity field data can be
combined directly by means of LSC.

LSC is a method which tries to find a harmonic function which represents the gravity field so as to fit the gravity field data in the least squares sense. Using LSC, we can use various kinds of gravity field data simultaneously regardless of homogeneous data distribution. Afterwards we can compute any kinds of derivatives of gravity field and their formal error estimates. We do not need the separate conversion of the altimeter data anymore, and the data can be used completely same as the gravity data to estimate the gravity field.

As an attempt to practical implementation of LSC, we estimated a geoid and gravity anomalies around the Japanese Antarctic stations using surface gravity data and GEOSAT ERM data (Fukuda, 1990; Fukuda et al., 1990). In the study, the land gravity data described above and the surface ship gravity data from JARE-22 to JARE-28 were employed together with the altimeter data from 38 ERMs of GEOSAT. The results present the most reliable gravity anomalies map and geoidal undulation in the region concerned. Their formal error estimates show the values of 10 mgal for gravity anomaly and 0.2 m for geoidal undulation.

Some Comments on the Simultaneous Use of the Different Kinds of Gravity Field Data

Although LSC has provided us with a powerful tool to estimate gravity fields from heterogeneous data, there remain some problems from practical aspect (Fukuda, 1991). In particular, suitable determination of the covariance function which is necessary in the computation of LSC is rather difficult in the Antarctic region because of sparse data distribution. Fukuda (1990) tried to determine an empirical covariance function using the GEOSAT ERM data, but failed to get a suitable one. This is because the ERM data points are restricted on the fixed ground tracks and not distributed random. For the determination of the covariance function, the GEOSAT GM data should be much appropriate.

The elevation of the gravity points on the land area is somewhat ambiguous. As mentioned above, the positions of some gravity points were determined by a satellite Doppler positioning system. This means that the elevation is given as the height from the ellipsoid and not from the geoid. Thus we can calculate gravity disturbance directly. We made somewhat a priori treatment of geoid height correction for those data. But this kind of correction distorts theoretical consistency because the geoid heights are not known before the estimation of the gravity field. The correction was done only because the accuracy of the land gravity data in Antarctica is within allowance of such an ambiguous treatment. More proper treatment of this problem is that employing gravity disturbance itself as a kind of gravity field data by LSC, and such treatment should be taken in future.

At present GPS takes over the majority of the positioning system in Antarctica, and the same problem occurs more often. Airborne gravimetry, for instance, gives the data of gravity disturbance in this sense. Furthermore, satellite gradiometer will give the completely different kind of gravity field data. Recent developments of the space technology have prevented us from sticking to one kind of data any more. Thus we have to pay much efforts to utilize various kinds of gravity field data effectively.

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