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Precise gravity-field modeling in the area of the Japanese Antarctic station Syowa and evaluation of recent EGMs

Yoichi Fukuda [a], [*], Yoshifumi Nogi [b], Kazuya Matsuzaki [c]

[a] Department of Geophysics, Graduate School of Science, Kyoto University, Kitashirakawa Oiwake-cho, Sakyo-ku, Kyoto 606-8502, Japan
[b] National Institute of Polar Research, 10-3 Midoricho, Tachikawa, Tokyo 190-8518, Japan
[c] National Institute of Advanced Industrial Science and Technology, 1-1-1 Umezono, Tsukuba 305-8568, Japan

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ABSTRACT

By combining a Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) Earth Gravity Model (EGM) and in situ gravity data obtained from the Japanese Antarctic Research Expedition (JARE) surveys, we estimated the regional gravity field in the area of Syowa Station, a Japanese research station located in Lützow-Holm Bay, East Antarctica. In situ data sets that were used consisted of land gravity data collected since 1967, shipborne data collected since 1985 and airborne gravity data collected in 2006. The GOCE direct (DIR) solution release 5 (R5) model was used as the long-wavelength reference of the gravity field. Using these data sets, we calculated gravity anomalies and geoid heights at 1-by-1′ grid by means of least-squares collocation.

The resulting geoid height at Syowa Station was compared with a local height based on GPS, spirit leveling and tide gauge data. The result suggests that the sea surface height at Syowa Station is −1.57 m, which is consistent with a dynamic ocean topography model. During this investigation, we also evaluated GOCE EGMs and other recent EGMs by comparing them with the airborne gravity data. The results indicate that the GOCE DIR R5 produced the smallest RMS (Root Mean Square) differences and that the newer models performed nearly as well. These comparisons demonstrate the importance of using reliable in situ data when evaluating satellite-only EGMs.

1. Introduction

Syowa Station, a Japanese Antarctic research station, is located on East Ongul Island in Lützow-Holm Bay, East Antarctic. The area of the station is considered to be key to investigating the formation of Gondwana because reconstructions suggest that a former junction of the continents was located in the area (*e.g.*, Shiraishi et al., 1994; Nogi et al., 2004, 2013). However, the tectonic evolution of the area is not yet fully understood primarily due to the thick ice sheet covering Antarctica and the scarcity of geological and geophysical surveys. Thus, gravity survey data of the area have been sought.

The area is also important for monitoring the ice sheet mass balance. Shirase Glacier, one of the major glaciers in Antarctica, locates there and its subglacial structures may control the ice sheet floor of the area. Recently, extreme snowfall and a consequent mass increase have been reported in the area (*e.g.*, Lenaerts et al., 2013; Shepherd et al., 2012). Understanding the drainage system of Shirase Glacier may be crucial for understanding these mass increases and the future mass balance. Therefore, there have been several attempts to evaluate the velocity and mass discharge of the glacier by means of interferometric synthetic aperture radar (InSAR) (*e.g.*, Rignot, 2002; Pattyn and Derauw, 2002), the SAR image matching technique (*e.g.*, Nakamura et al., 2010), the GPS buoy technique (*e.g.*, Aoyama et al., 2013), and the snow stake and other geodetic methods (*e.g.*, Takahashi et al., 2003). Gravity survey data also provide important basic information about the basement topography and crustal structures.

To contribute to such investigations and establish a gravimetric network for geodetic purposes, the Japanese Antarctic Research Expedition (JARE) team has been conducting in situ gravity measurements in the area for a long time. Land gravity data have been gathered since 1967 and shipborne data since 1985 (*e.g.*, Fukuda et al., 1992; Konishi et al., 2006). The first airborne gravity survey in the area was conducted in 2006 as a part of the Japanese-German collaborative airborne geophysical survey (Nogi et al., 2007).

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[*] Corresponding author.
E-mail address: fukuda@kugi.kyoto-u.ac.jp (Y. Fukuda).

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Despite these efforts, the available surface gravity data in the area are still limited primarily due to the severe conditions in Antarctica. In particular, land gravity data inevitably suffer from instrumental drift and measurement gaps that occur occasionally. The JARE team typically used snow tractors to transport the gravimeters, and strong vibrations from these vehicles adversely affected the precision. Nagao and Kaminuma (1988) evaluated these errors and concluded that the accuracy of the land gravity measurements before 1990 was approximately 10 mGal (10^{-5} m/sec^2). Recent surveys yielded better results. However, the data still include a few mGal of uncertainty (*e.g.,* Toda et al., 2014). Shipborne gravity data onboard the icebreaker Shirase of JARE also suffered from a large instrumental drift. Generally, offsets and drift in the shipborne gravity data can be corrected by comparing the gravity values at ports of call. However, Shirase usually cruised for more than 3 months without calling at a port, which led to large errors. These conditions have been severe obstacles in gravity-field studies in the area. Fukuda (1990) and Fukuda et al. (1990) used an Earth gravity model (EGM) to adjust for drifts and offsets in the early JARE gravity data sets to precisely characterize the local gravity field near Showa Station. However, such adjustments have not been applied to the JARE gravity data sets since then.

Satellite gravity missions in the 21st century have revolutionized gravity-field studies. The Gravity Recovery and Climate Experiment (GRACE) (Tapley et al., 2004) has not only yielded improved models of the static gravity fields but has also revealed ice sheet mass changes in Antarctica via temporal gravity variations (*e.g.*, Yamamoto et al., 2008; Sasgen et al., 2013; Groh et al., 2014) and contributed to studies of glacial isostatic adjustments (GIA) (*e.g.*, Riccardo et al., 2009; Yamamoto et al., 2011; Gunter et al., 2014).

Although GRACE has brought about a revolution in studies of the Earth's gravity field, particularly temporal gravity changes, the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) satellite launched in March 2009 by the European Space Agency (ESA) yielded drastically improved measurements of static gravity fields (*e.g.,* Van der Meijde et al., 2015). Due to its low-altitude orbit (260–224 km) and its sensitive gravity gradiometer, GOCE has achieved accuracies of a few mGal in gravity anomalies and a few cm in the geoid height at a spatial resolution of 100 km (half a wavelength). GOCE completed its mission in November 2013. Using all the available data obtained during the mission, new EGMs have recently been released. GOCE EGMs and other recent EGMs can be used as a long-wavelength reference to reduce errors in in situ gravity data, particularly land and shipborne gravity data, and thereby contribute to highly accurate measurements of the local gravity field. In addition, an airborne gravity survey in 2006 provided homogeneous, high-precision data sets. All of these data sets, although their spatial coverage is limited, are expected to contribute to the evaluations of EGMs in Antarctica where available surface data are limited.

The main purposes of this study, therefore, were to improve the modeling of the gravity field in the area of Syowa Station by combining the JARE gravity data and a recent EGM as a long-wavelength reference and to validate the EGMs by comparing them with the airborne gravity data. We also reviewed the JARE activities in gathering the gravity measurements. We first describe the satellite-only EGMs and in situ gravity data used in the study. Next, we report on details of the gravity-field determination, and discuss the accuracy of the resulting gravity field and the evaluation of the EGMs.

2. GOCE and recent EGMs

GOCE was designed to gain gravity field measurements using an electrostatic gravity gradiometer (EGG) that consisted of three orthogonal pairs of capacitive accelerometers and a high-low satellite-to-satellite tracking instrument (SSTI), which was a state-of-the-art geodetic GPS receiver. Following its launch and a six-month calibration/validation (CAL/VAL) period, GOCE moved to a repeat orbit of 979 cycles in 61 days in September 2009 and began its full-scale measurement mode. Afterward, GOCE observed the Earth's gravity field until the end of its mission in October 2013. Details of the GOCE mission design and the satellite operations are described by Floberghagen et al. (2011).

The ESA has released three solutions of GOCE EGMs: time-wise (TIM), direct (DIR) and space-wise (SPW) solutions. Currently, five releases (R1-R5) of the TIM and DIR solutions and three releases (R1, R2 and R4) of the SPW solutions are available. The primary differences between these solutions are the methods used to calculate the gravity-field coefficients. The DIR and TIM solutions are based on solving the normal equation systems using the along-orbit observations. Among these two solutions, the DIR solutions include data from the Challenging Minisatellite Payload (CHAMP), GRACE and Satellite Laser Ranging (SLR) missions as additional information, whereas the TIM solutions are based solely on GOCE data independent of any other *a priori* information. Contrary to that, the SPW solutions are calculated using the least-squares collocation (LSC) method based on information regarding the spatial correlation of gravity field data. Detailed descriptions of these approaches are presented by Pail et al. (2011). The maximum degrees of the respective harmonic series expansion and the data periods of the models are summarized in Table 1.

We also used a few other recent satellite-only EGMs for comparison, namely, GoGra04s (Yi et al., 2013) and Eigen6s2 (Rudenko et al., 2014). GoGra04s is based on GOCE and GRACE data and is complete up to degree and order 230. In addition to GOCE and GRACE data, Eigen6s2 is based on LAGEOS-1/2 SLR data and is complete up to degree and order 260.

In this study, based on the results of evaluations described later, we finally used GOCE DIR R5 as the reference for the gravity-field estimation. Details of the evaluation are described in Section 4.2.

3. In situ gravity data around Syowa station

In this study, we used airborne gravity data obtained by JARE-47 (Nogi et al., 2013), shipborne gravity data obtained by JARE-27 to −52 (1985–2011), and land gravity data primarily obtained by JARE-9 through −43 (1967–2001). Fig. 1 shows the study area and the distribution of the in situ gravity data. Details of these data are described in the following sections.

3.1. Airborne gravity data

An airborne gravity survey was conducted in January 2006 during JARE-47 as a part of Japanese-German joint airborne geophysical surveys using a Dornier aircraft (Polar-2) of the Alfred Wegener Institute for Polar and Marine Research (AWI). The airborne gravimeter LaCoste & Romberg S99 was used in this survey. The data processing were essentially the same as those described by Riedel (2009) and Riedel et al. (2012). The surveys were conducted along nearly north-south flight lines with a spacing of approximately 20 km in the area of Syowa Station bounded by latitudes 67°S and 73°S and longitudes 35°E and 45°E (Nogi et al., 2013). The flight altitude was approximately 200 m over the sea and approximately 3000 m over the continent. Atmospheric corrections were not applied because the correction for the altitude variation was less than 0.3 mGal. The three-dimensional coordinates of the aircraft trajectory were determined by kinematic GPS observations using two ground reference points. Depending on