Polar Geosci., **16**, 29–52, 2003

Ten years' progress of Syowa Station, Antarctica, as a global geodesy network site

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(Received April 2, 2003; Accepted July 9, 2003)

Abstract: Progress of geodesy programs at Syowa Station since our former review in 1993 is summarized. As for Very Long Baseline Interferometry (VLBI), Global Positioning System (GPS), and Doppler Orbitography Radiopositioning Integrated by Satellites (DORIS), Syowa Station is a participating station in an international network and has obtained an International Earth Rotation Service (IERS) dome number. Time series of about 5 years show change of position by plate motion. Detection of vertical motion by glacial isostatic adjustment is still under investigation. More than 20000 synthetic aperture radar (SAR) scenes have been received from the European Remote Sensing satellite-1 and -2 (ERS-1/-2) and the Japan Earth Resources satellite-1 (JERS-1) by the Syowa 11-m multipurpose antenna. Several case studies by interferometric SAR analyses have shown characteristic features of the ice grounding zones, ice dynamics and Digital Elevation Model (DEM) estimates. As for absolute gravimeter (AG) measurements, Syowa Station is registered as the International Absolute Gravity Basestation Network (IAGBN) 0417 point. Observations with an FG5 gravimeter were made for two summer seasons 5 years apart, and they showed consistent results within 2 μGal difference. The superconducting gravimeter (SG) observations with a TT70 (#016) produced many scientific results in the two streamlines of tidal bands and normal mode bands. Especially, the first evidence of incessant excitation of the Earth's free oscillations (background free oscillations) is noted as an important contribution from the Syowa SG observations. The Gravity Recovery And Climate Experiment (GRACE) satellite will bring an important advance for the study of ice-water-air mass circulation and its interaction with the solid-earth. The local potential fields calibrated by connecting to the station observatory data should give appropriate ground-truth information for the regional-scale satellite data, which reflects the continuing important role of Syowa Station as a global geodesy network site.

key words: VLBI, GPS, DORIS, SAR, precise gravimetry

1. Introduction

Shibuya (1993) reviewed geodesy programs at Syowa Station (69.0° S, 39.6° E), Antarctica. Most of the recent major space geodesy programs such as Very Long

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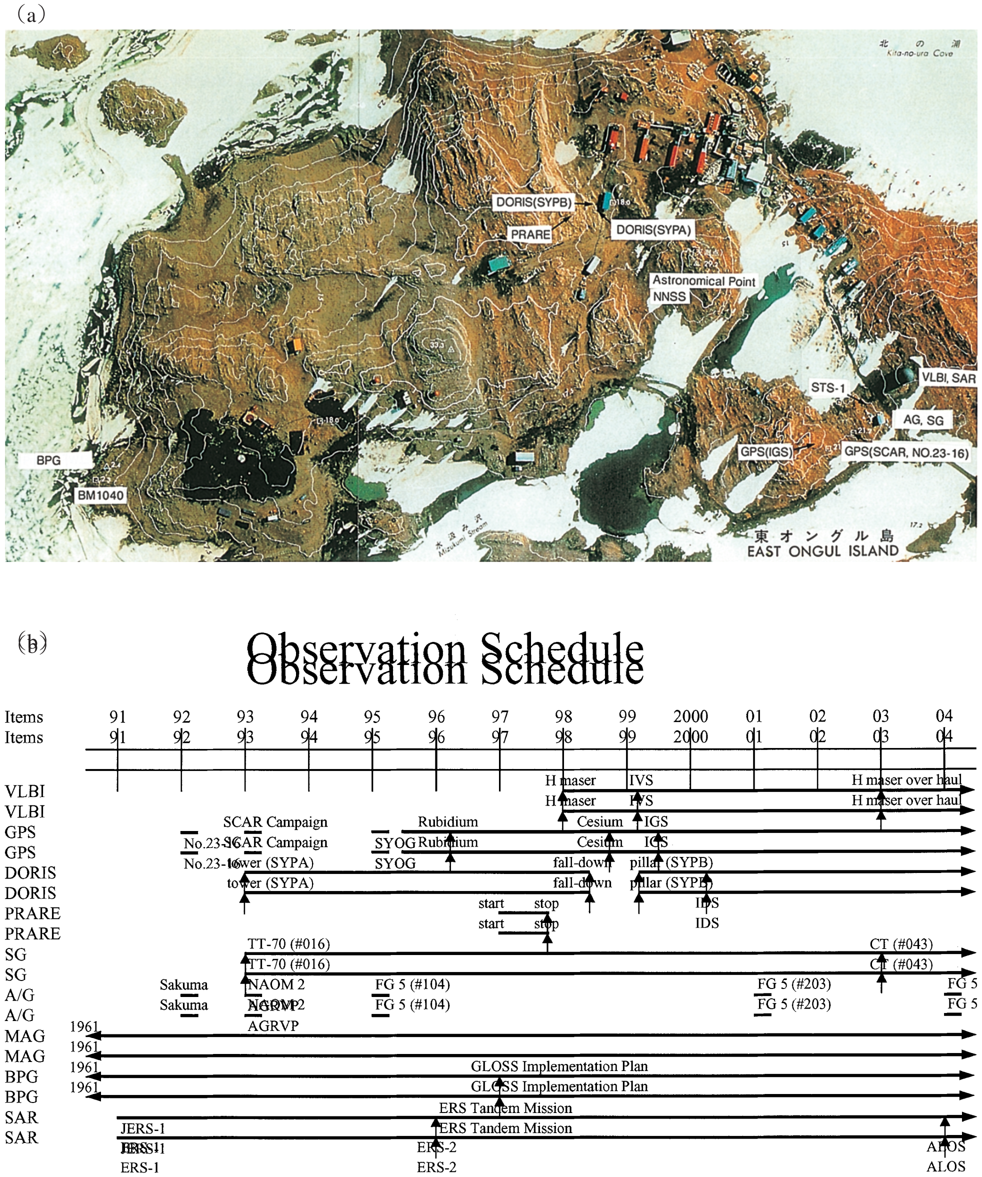


Fig. 1. *(a) Location of geodetic observation sensors superposed onto an orthophotometric map of Syowa Station, East Ongul Island. (b) Brief history of each geodetic observation item is shown by the segment from the start year, where major events are marked by arrows. Planned activities in 2004 are added. For details, see text.*

Baseline Interferometry (VLBI) and the precise gravimetry programs such as superconducting gravimeter (SG) observations were in the planning stage or in the initial stage of installation. The National Institute of Polar Research (NIPR) has been coordinating the geodesy programs of the Japanese Antarctic Research Expeditions

Fig. 2. A summary of geodetic observations carried out at the Antarctic stations. Large alphabetical characters indicate observation items, while small numbers correspond to station names. Their explanations are summarized in the left corner of the figure. Superposed on a RADARSAT image from http://radarsat.space.gc.ca.

(JAREs), and after ten years for the IV-th and V-th five-year programs, Syowa Station has grown to be one of the key stations for the global geodesy network in the southern hemisphere. We briefly review 10 years' progress of each observation item, where the sensor location is marked on the ortho-photometric map of the station area as illustrated in Fig. 1a. The history of each item is shown briefly in Fig. 1b. As compared to other Antarctic stations, activity at Syowa Station is remarkably comprehensive, as shown by the number of observation items in Fig. 2. Acronyms used in this report are summarized in Table 1.

2. VLBI

The status in 1993 was as follows. The 11-m multipurpose S/X-band antenna at Syowa Station (Syowa 11-m antenna) was designed to have capability for the Crustal Dynamics Project (CDP: Ma *et al.*, 1989) based geodetic VLBI observations (*e.g.* Hirasawa *et al.*, 1990). Its capability was proved by the successful test measurement among Kashima (Japan), Tidbinbilla (Australia) and Syowa Station in January 1990 by JARE-30 as described in, *e.g.* Takahashi *et al.* (1997). A cesium frequency standard was used in that experiment.

Table 1a. Acronyms for institutes and organizations.

CNES	Centre National d'Etudes Spatiales, France
CRL	Communications Research Laboratory, Japan
ESA	European Space Agency
GSI	Geographical Survey Institute, Japan
HartRAO	Hartebeesthoek Radioastronomical Observatory, South Africa
IAG	International Association of Geodesy
IAGBN	International Absolute Gravity Basestation Network
ICET	International Center for Earth Tides
IDS	International DORIS Service
IERS	International Earth Rotation Service
IGN	Institut Géographique National, France
IGS	International GPS Service for Geodynamics
IUGG	International Union of Geodesy and Geophysics
IVS	International VLBI Service for Geodesy and Astrometry
JARE	Japanese Antarctic Research Expedition
NAO	National Astronomical Observatory, Japan
NAOM	National Astronomical Observatory of Mizusawa, Japan
NASDA	National Space Development Agency of Japan
NASA	National Aeronautics and Space Administration, USA
NIPR	National Institute of Polar Research, Japan
PSMSL	Permanent Service for Mean Sea Level
SCAR	Scientific Committee on Antarctic Research

Table 1b. Acronyms for project names and technical terms.

ADD	Antarctic Digital Database
AG	Absolute Gravimetry, or Absolute Gravimeter
AGRVP	Absolute Gravimeter with Rotating Vacuum Pipe
ASTER	Advanced Spaceborne Thermal Emission and reflection Radiometer
BPG	Bottom Pressure Gauge
CDP	Crustal Dynamics Project
DEM	Digital Elevation Model
DORIS	Doppler Orbitography Radiopositioning Integrated by Satellites
ERS-1	European Remote Sensing satellite 1
GCP	Ground Control Point
GLOSS	Global Sea Level Observing System
GPS	Global Positioning System
GRACE	Gravity Recovery And Climate Experiment satellite
IGRF	International Geomagnetic Reference Field
IGY	International Geophysical Year
INMARSAT	INternational MARine SATellite
ITRF	International Terrestrial Reference Frame
JERS-1	Japanese Earth Resources Satellite 1
PPP	Precise Point Positioning software in a GIPSY OASYS program
PRARE	Precise Range And Range-rate Equipment
SAR	Synthetic Aperture Radar
SEDI	Study of the Earth's Deep Interior
SG	Superconducting Gravimeter
VLBI	Very Long Baseline Interferometry

After long planning for regular observations (*e.g.* Shibuya, 1995), JARE-39 for the first time installed hydrogen masers and K-4 terminals at Syowa Station, and started regular geodetic observations (4 times a year) from February 1998, with participation of the 26-m University of Tasmania at Hobart, Australia antenna (Hobart) and the 26-m Hartebeesthoek Radioastronomical Observatory antenna (HartRAO) in South Africa (see Fig. 3a). The experiments were coded as JA at first and SYW later. The Syowa 11-m antenna participated also in the OHIG experiments with other additional antennas at O'Higgins Station on the Antarctic Peninsula, Fortaleza in Brazil and Kokee in Hawaii, USA (not shown in Fig. 3a) from 1999.

In the VLBI experiments, far-remotely separated antennas must track the same quasars simultaneously and the recorded data must be correlated off-line at the data center. Therefore, standardized specifications are required for the receiver systems, processing systems, etc. It is not our intention to go into technical details in our review, but we emphasize here that the Syowa 11-m antenna participated in the International VLBI Service for Geodesy and Astrometry (IVS) network from the beginning of its establishment in 1999 (see Fig. 1b). We follow their coordinated observation schedule and technical standards to keep compatibility with the other stations. The allocated International Earth Rotation Service (IERS) Dome Number is 66006S004. Our observation summary including session name, observation date, status of processing, etc., is given in each annual report, such as Shibuya and Doi (1999a) and Shibuya *et al.* (2002).

There are two flowlines of data analyses. As for the SYW experiments, Hobart and HartRAO send the S2 data tapes to the Mitaka FX Correlator of the National Astronomical Observatory (NAO), where S2 to K4 tape copying is done. Then the K4 tapes from Syowa Station are correlated with the thus copied K4 tapes from Hobart and HartRAO by using the K4-K4 correlator at the Geographical Survey Institute (GSI) or at the Communications Research Laboratory (CRL). As for the OHIG experiments, Hobart and HartRAO record the VLBI data on MarkIV tapes and send them to the Bonn Astro/Geo MarkIV Correlator (Müskens and Alef, 2002). K4 tapes from Syowa Station are copied to the MarkIV tapes at GSI and sent to the above Bonn Correlator for MarkIV-MarkIV correlation. The above tape-copying systems accelerated the processing speed as explained by Fukuzaki *et al.* (2002).

The JA984 session was analyzed by Jike *et al.* (2002), and reached the first successful baseline solution. Totally 17 baseline solutions from 1999 through 2002 were obtained by Fukuzaki *et al.* (2002) thereafter. We only give an overview in Fig. 3b, where open circles show the baseline lengths for Syowa-Hobart (top) and Syowa-HartRAO (bottom). Generally the obtained change rate is consistent with the result obtained by the Global Positioning System (GPS) analysis mentioned in the next section 3, as illustrated by solid circles in Fig. 3b. Intraplate deformation across the postulated boundary marked by the dashed curve in Fig. 3a, which may be detected by the change between Syowa (East Antarctica) and O'Higgins (West Antarctica), is under investigation. This deformation must be small or even negligible, and a much longer time span is required to make it clear.

According to Fukuzaki *et al.* (2003), the obtained VLBI coordinates of the antenna reference point in the International Terrestrial Reference Frame 2000 (ITRF2000) system at the epoch 1997.0 were

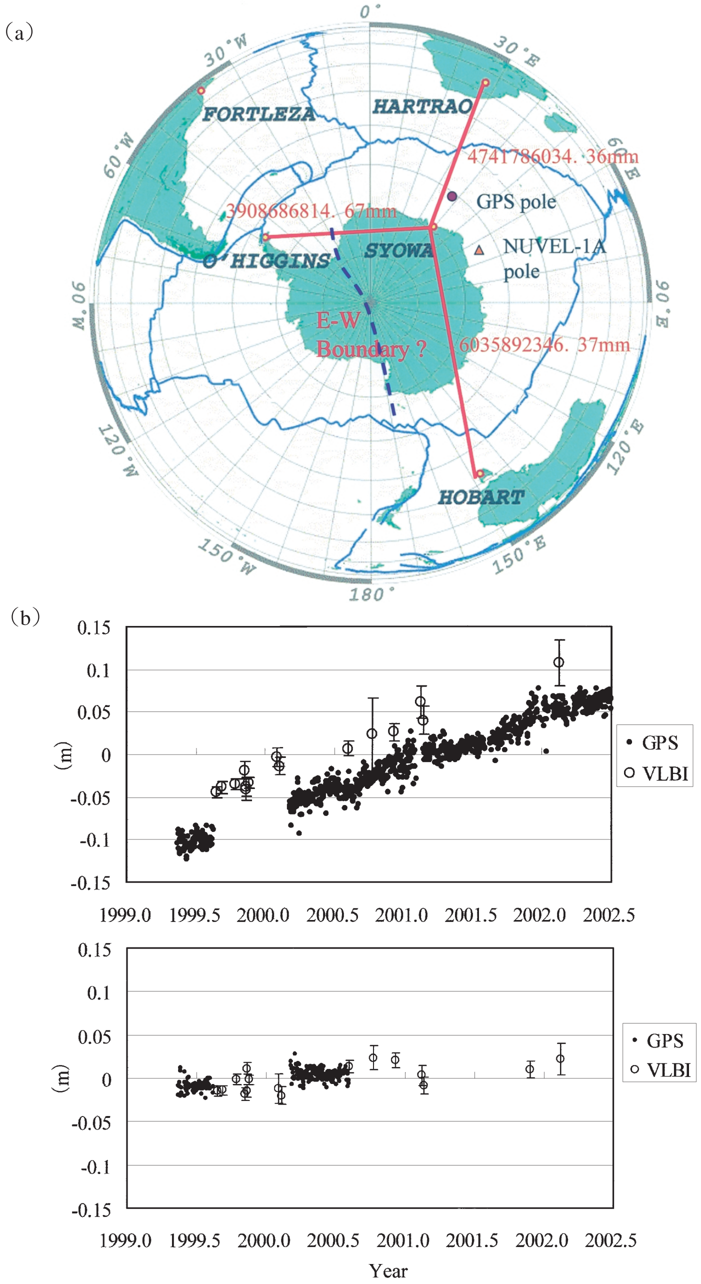


Fig. 3. (a) Antarctic geodetic VLBI network stations for the SYW (Syowa, Hobart, HartRAO) and OHIG (plus O'Higgins, Fortaleza, and Kokee Park which is outside of the figure) sessions. The baseline lengths in mm are the results from the SYW998 solution in Fukuzaki et al. (2002). The solid circle indicates the Euler pole of the Antarctic plate obtained by GPS (Dietrich et al., 2001a), while the solid triangle indicates the Euler pole of the NUVEL-1A model (Argus and Gordon, 1991), respectively. (b) Secular change of baseline lengths for Syowa-Hobart (top) and Syowa-HartRAO (bottom). Open circles with error bars are the results by VLBI, while solid circles are those by GPS. GPS results are offset by 0.05 m against the VLBI results.

$$X=1766194.116\,\mathrm{m},\ Y=1460410.921\,\mathrm{m},\ Z=-5932273.313\,\mathrm{m}, \tag{1}$$

with

$$V_x=0.003\,\mathrm{m/yr},\ V_y=-0.001\,\mathrm{m/yr},\ V_z=0.002\,\mathrm{m/yr}, \tag{1$'$}$$

where V_x, V_y and V_z denote each velocity component.

We plan to continue the observation for, at least 4 more expeditions (JARE-44 through JARE-47).

3. GPS

The description of GPS utilization in Shibuya (1993) was limited to the then near-future prediction, that is, there would be the result of the 1992-year campaign by the Scientific Committee on Antarctic Research (SCAR92), and there would be installation of the permanent GPS pillar site and so on. In 2003, we can say definitely that application of GPS grew faster and wider than we expected, resulting in a large impact on the study of geodesy/geodynamics in Antarctica.

The SCAR GPS point at Syowa Station was selected to be identical to the No. 23–16 geodetic marker (see Fig. 1a). The SCAR GPS campaign continued from 1992 through 1995, and Syowa data were included in the Antarctic solutions by *e.g.* Dietrich *et al.* (2001a) with the other 33 station solution vectors. The estimated Euler pole of the Antarctic plate was located at (60.8±3.0° N, –141.1±7.3° E; solid circle in Fig. 3a for lower-hemisphere projection), and shifted 800 km west from the result of the NUVEL-1A model (solid triangle in Fig. 3a) by Argus and Gordon (1991). The ITRF2000 coordinates of the Syowa SCAR GPS point at the epoch 1997.0, which were converted from the original solution by Dietrich *et al.* (2001a), were

$$X=1766182.582\,\mathrm{m},\ Y=1460336.742\,\mathrm{m},\ Z=-5932285.492\,\mathrm{m}, \tag{2}$$

under the assumption of the same velocity components as in eq. (1)′.

In order to have sub-centimeter stability of the solution, however, a permanent pillar was necessary; it was constructed in January 1995 (see GPS (IGS) in Fig. 1a and the arrow SYOG in Fig. 1b). Participation in the International GPS Service for Geodynamics (IGS) network was delayed until June 1999, because sporadic outliers appeared (Fig. 1 of Yamada *et al.*, 1998) rather frequently in the daily solutions. The reason for this problem was unknown but the daily files during February 1995–May 1999 were archived in GSI and NIPR. This outlier problem was solved during the JARE-40 wintering period (by Y. Fukuzaki), after the replacement of the rubidium frequency standard with the cesium one which was the comparator of the hydrogen maser in the VLBI system (see Fig. 1b).

The allocated IERS Dome Number of the Syowa IGS antenna reference point (code SYOG) is 66006S002. Participation to the IGS network was made possible by a thick INMARSAT uucp link, as constant data transfer of 1 mega-bytes per day was within the capacity of telecommunication.

The obtained ITRF2000 coordinates of SYOG at the epoch 1997.0 were

$$X=1766207.841\,\mathrm{m},\ Y=1460290.350\,\mathrm{m},\ Z=-5932297.680\,\mathrm{m}, \tag{3}$$

with the same velocity components as in eq. (1)′.

Solid circles in Fig. 4 show the secular change of the SYOG coordinates obtained by using the GIPSY OASYS Precise Point Positioning (PPP) software (Zumberge *et al.*, 1997) for the north-south (top), east-west (middle) and up-down (bottom) components, respectively. The uncertainty of the daily solution is 2–3 cm for the NS and EW components, and 3–5 cm for the vertical component, respectively. We can see weak quasi-seasonal variation for the time series of 6 years (1993–1999). It remains for future research to make clear the cause of this variation in relation to the global geodynamics.

Retreat of the ice sheet from the East Ongul Island was estimated as 30000–40000 years before present (bp), while retreat from the southern part of Langhovde (about 25 km south in the coastal outcropped region; see Fig. 5) was estimated as 4000–5000 years bp (Miura *et al.*, 1998). Deduction of the height change rate, that is, tilt by the relative GPS positioning between SYOG and the stable pillar point in Langhovde, may reveal the viscoelastic property of the mantle in relation to the glacial isostatic adjustment in the region concerned. A preliminary study by Kimura and Seo (2001) shows that 9 months' unmanned continuous observation is possible by a hybrid power system of the wind generator with the solar batteries, and accumulated observation data may reveal this property.

4. DORIS

The Doppler Orbitography Radiopositioning Integrated by Satellites (DORIS) beacon was installed in January 1993 in collaboration with the Institut Géographique National (IGN), France. Shibuya (1993) described successful recovery of the Syowa beacon data by the Centre National d'Etudes Spatiales (CNES), but no results were shown in the review.

The beacon was found to be very robust and there has been no problem with the transmitter component for the past 10 years. The problem was the stability of the antenna monument. Though the antenna was first set on a 10 m pylon (code SYPA, see Figs. 1a and 1b) and operated for about 5 years, it gradually inclined west-southwest under the prevailing east-northeast wind. When we plot monthly solutions located in the ftp site,

ftp://cddisa.gsfc.nasa.gov/pub/doris/products/sinex-series/ (4)

by open circles as in Fig. 4, we find that the rate of westward motion is larger by a factor of 4, as compared with the rate estimated by GPS shown by solid circles. Larger error bars (±3 cm) in the east-west component of the monthly solutions than those of the north-south solutions (±0.5 cm) may indicate vibrational instability of the pylon. It broke down in May 1998 and 8 months' interruption occurred before construction of the second-generation antenna on the pillar (code SYPB, see Figs. 1a and 1b) nearby the SYPA. The pillar is 2 m tall and the marker is believed to have 1–2 mm stability. It has a buried attachment to accommodate a GPS antenna to replace the beacon, and the local tie can be checked easily.

The objectives of the Syowa beacon are to determine precisely the orbits of SPOT

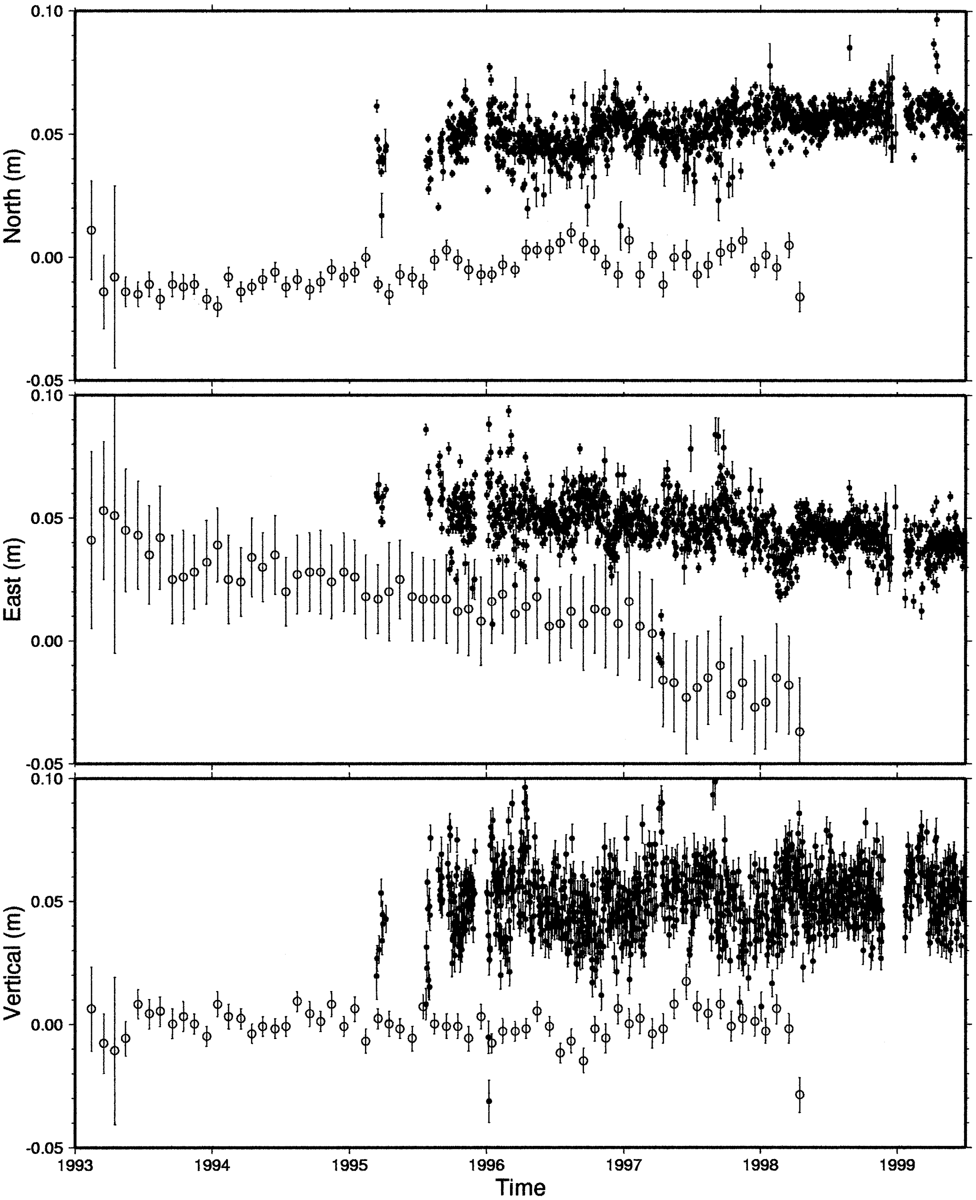


Fig. 4. Daily solutions for the GPS SYOG coordinates are plotted for the 6-year span; (top) north-south, (middle) east-west and (bottom) up-down components, respectively. Solid circles indicate GPS results by the GIPSY OASYS PPP software by Zumberge et al. (1997), while open circles indicate DORIS monthly results from the web site in eq. (4). GPS results are offset by 0.05 m for the positive direction as compared with the DORIS results. Note larger error bars and the faster change rate for the EW component of the DORIS results as compared with those by the GPS results.

and TOPEX/POSEIDON satellites, together with the other 20 globally distributed beacons. We have indirect benefits through distributed radar altimeter data of 1–2 cm accuracy over the Southern Ocean. The IERS Dome Number of SYPB is 66006S003.

Time series analysis of global DORIS coordinates including Syowa data was done by French scientists. Plate motion was studied by *e.g.* Cretaux *et al.* (1998), while vertical crustal motion was studied by *e.g.* Soudarin *et al.* (1999).

The obtained DORIS coordinates of the antenna reference point SYPB in the ITRF2000 system at the epoch 1997.0 were

$$X = 1766505.896\,\mathrm{m},\ Y = 1460266.974\,\mathrm{m},\ Z = -5932207.693\,\mathrm{m}, \tag{5}$$

with the same corresponding velocity components as in eq. (1)′.

In 2000, the International DORIS Service (IDS) was established, and data availability will become higher than before. In order to compare the GPS results with the DORIS results for SYPB after 1999, release of DORIS daily solutions is required.

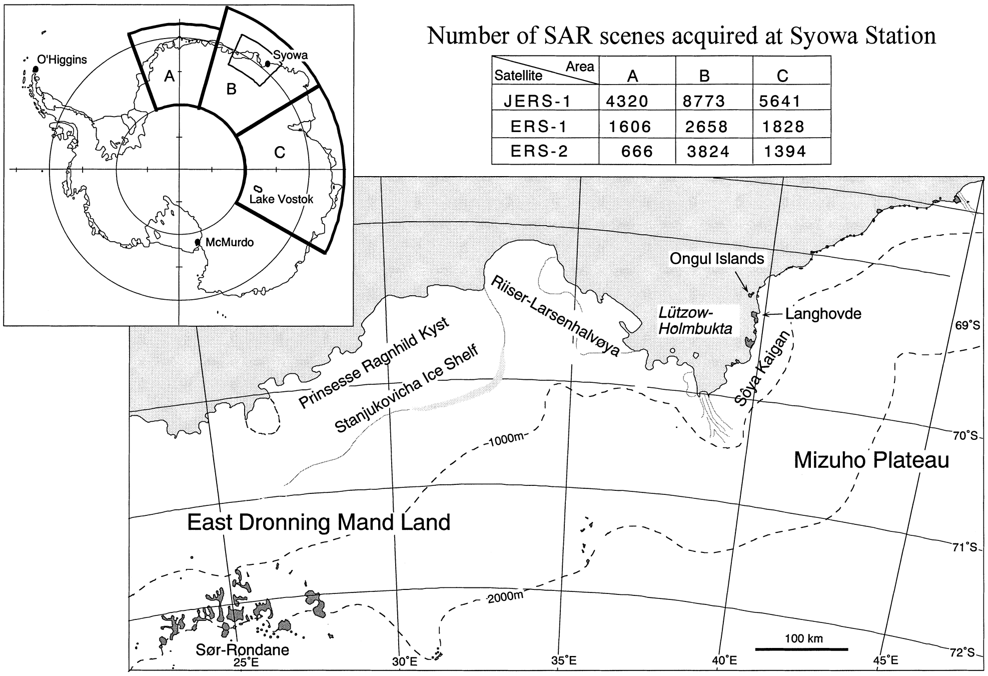
Because eqs. (1), (2), (3) and (5) are expressed at the same epoch 1997.0 in the same ITRF2000 coordinate system, collocation of different space geodetic techniques is possible with the local tie vectors among the related markers. Kanao *et al.* (1995) tried such local ties among several reference markers including the SCAR GPS point and the VLBI reference point, but 5–10 cm uncertainty resulted from the limited surveying instruments and experimental conditions at that time. Geodetic surveying for local ties has been retried among the reference markers for these 5 years, and the preliminary analysis indicates that the offset-corrected coordinates agree among each other within the difference of several centimeters. However, the coordinate values will be described in another report after detailed examination of the surveying results is finished.

5. PRARE and SAR interferometry

In Shibuya (1993), the Precise Range And Range-rate Equipment (PRARE) was described as follows. The malfunctioning of PRARE onboard the European Remote Sensing satellite 1 (ERS-1) delayed installation of the ground antenna at Syowa Station. With the next PRARE onboard ERS-2, precise orbit would be obtained and used for precise radar altimetry and Synthetic Aperture Radar (SAR) interferometry.

The above prediction turned out to be half true and half inaccurate. The ground antenna was installed in May 1997 (see Figs. 1a and 1b). It worked, however, only 7 months, until January 1998, partly because of the difficult maintenance procedure, and partly because of a cabling problem at low temperature, as reported by Shibuya *et al.* (2000). The PRARE turned to be not so important from the viewpoint of SAR interferometry, because the analysis technique developed so fast without PRARE-determined precise orbit data.

Receiving of ERS-1 SAR data by the Syowa 11-m antenna began from 1991 (see Fig. 1b). From 1992 receiving of Japanese Earth Resources Satellite 1 (JERS-1) SAR data followed. An important event was the launch of ERS-2 in 1996, and the operation of the ERS Tandem Mission over Antarctica (see Fig. 1b). With 3 antennas at Syowa Station, O’Higgins Station and McMurdo Station (Fig. 5), ERS-1/-2 SAR data were extensively acquired, covering most of the area with a time spacing of 1 day for the same



Number of SAR scenes acquired at Syowa Station

Satellite \ Area	A	B	C
JERS-1	4320	8773	5641
ERS-1	1606	2658	1828
ERS-2	666	3824	1394

Fig. 5. Syowa, McMurdo and O'Higgins antennas acquired SAR data from the ERS-1/-2 and JERS-1 satellites, covering most of the Antarctic ice sheet. The Syowa 11-m antenna acquired more than 20000 scenes over East Antarctica, where the number for each satellite is given in each major bin area. There are several case studies on the ice surface topography and ice dynamics in the regional map covering the JARE research area.

repeat pass during February–June 1996 (*e.g.* Doi *et al.*, 1998, 1999). This mission was realized under the memorandum of understanding between the European Space Agency (ESA) and the National Space Development Agency of Japan (NASDA), as ERS-2 was not an experimental but an operational satellite.

There have been several case studies in the JARE research area, where SAR interferometry was applied. Ozawa *et al.* (1999a) adopted a three-pass method for the JERS-1 scenes to study the Sôya Coast region (39.5° E–40.5° E, 69.0° S–69.5° S; see Fig. 5) and made a Digital Elevation Model (DEM) of 50 m by 50 m grids. There were 23 suitable ground control points (GCPs), covering the height range from 0 to 600 m, and the obtained DEM grids were shown to have a root-mean-square (rms) error of 15.3 m. As for the GTOPO30 (USGS, 1996) model grids in the region concerned, a similar comparison with the GCP heights resulted in a bias of −66.2 m and rms error of 131.7 m. Ozawa *et al.* (2000) further estimated the flow velocity of the ice sheet under the assumption that the direction of the ice flow was identical to the streamline direction in the intensity image of the Langhovde Glacier (Fig. 5). The estimated velocity was 86.2 m/yr, and the associated flow direction (N86° W) agreed with the maximum gradient direction (N64° W) of the DEM ice sheet surface with a discrepancy of 22°.

The detected ice flow velocity by SAR interferometry was limited to less than 120 m/yr, because of decorrelation of the corresponding pixels at higher velocities.

Sometimes SAR intensity images as well as aerial photographs do not clearly show the grounding zone of the ice shelf (*e.g.*, Ozawa *et al.*, 1999b). SAR interferometry, on the other hand, is useful to detect the accurate location of the grounding zone. Ozawa *et al.* (2002) applied the technique to the ERS tandem data over the Stanjukovicha Ice Shelf in the Princess Ragnhild Coast area (20°E–33°E; Fig. 5). The estimated grounding zone is located several kilometers inland as compared to that of the Antarctic Digital Database (ADD: British Antarctic Survey, 1998); the inconsistency is larger than the delineation accuracy of 20 pixels (600 m) by SAR interferometry. The derived vertical displacements of the ice shelf agreed with the sea surface height changes predicted by the ORI95 ocean-tide model (Matsumoto *et al.*, 1995) within a standard deviation of 5 cm.

Another interesting application of SAR interferometry is the boundary determination of subglacial Lake Vostok (Fig. 5). Using the SAR scenes recorded by the Syowa 11-m antenna, Dietrich *et al.* (2001b) revealed the aerial pattern of vertical motion at the southern lake tip. The obtained pattern was similar to the grounding zone of ice shelves along the marginal (coastal) ice zone.

Figure 5 also shows a number of scenes acquired by the Syowa 11-m antenna. They amount to a total of over 20000 scenes. These scene data will be processed to the 2.1-level or the 0-level data at the Earth Observation Center of NASDA. Because the ERS series SAR uses the C-band (5.3 GHz) with the off-nadir angle of 23°, and because JERS-1 SAR uses the L-band (1.275 GHz) with the different off-nadir angle of 35°, backscattering from the same area must be of different nature. Analysis with both C- and L-band data will elucidate surface/subsurface features related to ice dynamics.

In order to fully utilize ERS/JERS SAR scenes for studying ice dynamics, DEMs from the Advanced Spaceborne Thermal Emission and reflection Radiometer (ASTER) instrument onboard the NASA TERRA satellite should be integrated into interferometric analyses, where available.

6. Absolute gravimeter measurements

The status of absolute gravimeter (AG) measurements described in Shibuya (1993) was as follows. The gravity observation hut (location noted by AG, SG in Fig. 1a) was constructed by JARE-32 during the 1990–91 summer field season. The International Absolute Gravity Basestation Network Category A (IAGBN(A); Boedecker and Fritzer, 1986) Syowa marker (identification number 0417) was installed in the gravity observation hut. A sketch of the gravity observation hut is shown in Fig. 6 (top) with a photo of the IAGBN(A) marker (bottom).

JARE-33 carried out the first AG measurements by using the GSI apparatus (GA 60), and JARE-34 conducted measurements using the second type of National Astronomical Observatory of Mizusawa gravimeter (NAOM2, Tsubokawa and Hanada, 1986), and the Absolute Gravimeter with Rotating Vacuum Pipe (AGRVP) apparatus by Hanada *et al.* (1987). The results of the above measurements were given in the Working Group for Syowa Station Absolute Gravimetry (1994) with detailed site

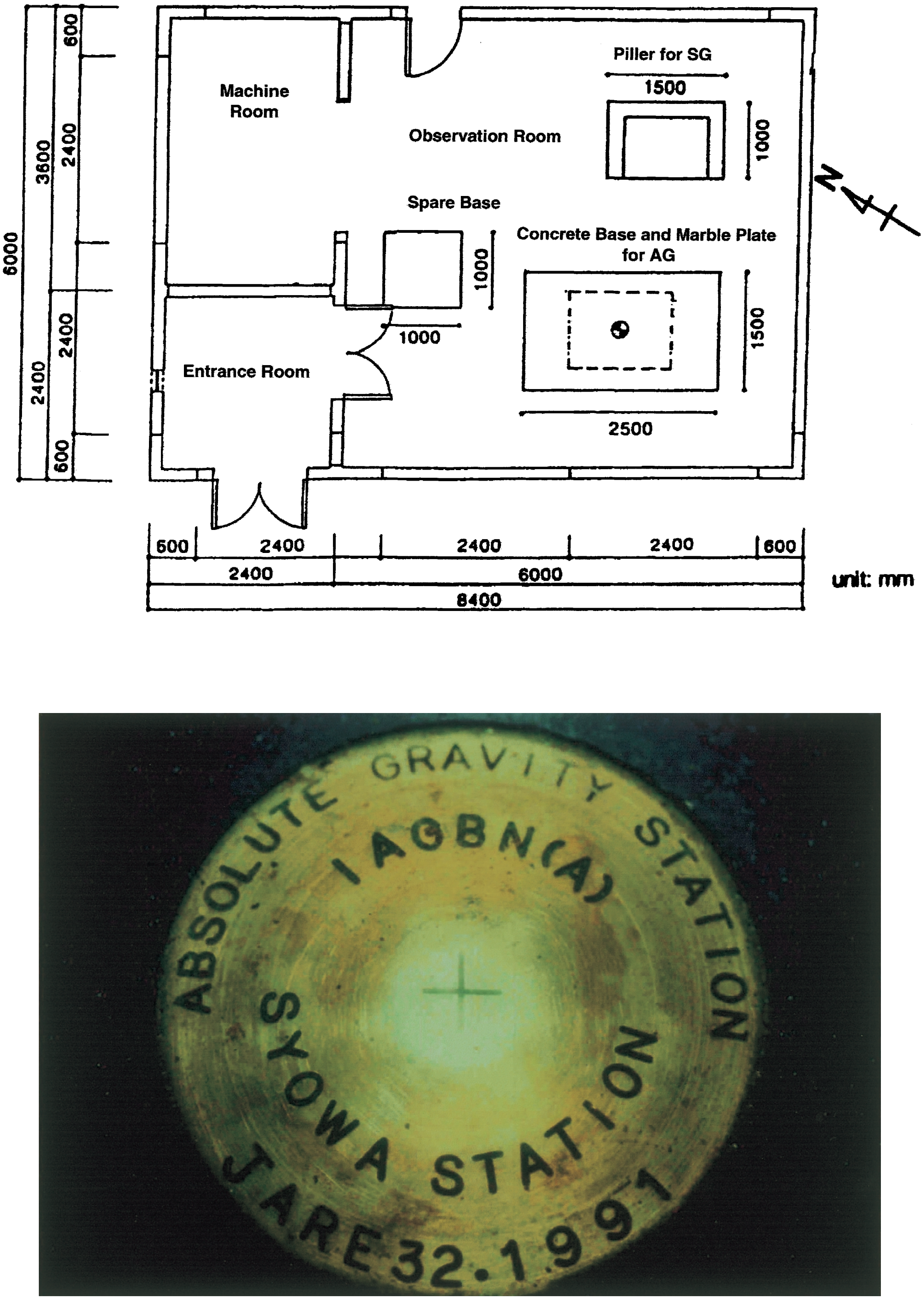


Fig. 6. (Top): Sketch of the gravity observation hut, where the marble plate within the concrete base for AG measurements is installed. The SG TT70 (#016) is hung from the pillar at the northeast corner. (Bottom): The brass disk buried in the marble plate indicates the Syowa IAGBN(A) 0417 marker.

documentation of the station. The measurement data were processed according to the recommendations from the International Association of Geodesy/International Union of Geodesy and Geophysics (IAG/IUGG) resolution described by Boedecker (1988), that is, the gravity values measured had to be corrected for the five effects of light travel time, earth tides, polar motion, atmospheric pressure variations and derivative of gravity along the plumb line.

During the above campaign period, there was no established standard AG. After an international comparative campaign in 1994, an FG5 gravimeter (*e.g.* Niebauer *et al.*, 1986) has been recognized as the global standard AG. Therefore JARE-36 made the measurements at the station marker during 20 January–11 February, 1995, using the FG5 (#104), see Fig. 1b, and obtained the following results (Yamamoto, 1996):

$$\begin{aligned}&\text{Gravity value}=982524.3269\,\text{mGal},\\&(0.0144\,\text{mGal standard error for single measurement})\qquad(6)\\&\text{Number of effective data}=45386,\end{aligned}$$

where $1\,\text{mGal}=10^{-5}\,\text{m/s}^2$.

After a lapse of 5 years, JARE-42 made repeated measurements using the FG5 (#203) during 29 December 2000–26 January 2001, see Fig. 1b. The results (Kimura, 2002) are:

$$\begin{aligned}&\text{Gravity value}=982524.3282\,\text{mGal}\\&(0.0167\,\text{mGal standard error for single measurement})\qquad(7)\\&\text{Number of effective data}=84802.\end{aligned}$$

Both measurements detected several μGal ($1\,\mu\text{Gal}=10^{-8}\,\text{m/s}^2$) variations associated with ocean tide loading. The gravity difference (1.3 μGal) between eqs. (6) and (7) is within the manufacturer-endorsed repeatability (1–2 μGal) of the FG5 gravimeter, and we entered the era of detecting time variable gravity fields associated with the Earth's environmental change.

For the deduction of gravity anomalies in the JARE research area, eq. (6) should be adopted as the standard gravity value with the height datum (elevation above mean sea level) of 21.492 m at the Syowa IAGBN(A) 0417 marker.

7. Superconducting gravimeter observations

Shibuya (1993) plotted the distribution of earth tide stations registered in the International Center for Earth Tides (ICET) data bank (*e.g.* Melchior, 1983). These data obtained by spring-type portable gravimeters, however, do not have enough accuracy or resolution to detect fluid core resonance, core undertones, Slichter mode (Slichter, 1961), etc. Thus SG installation to Syowa Station was planned as part of the Study of the Earth's Deep Interior (SEDI) project, and Fairbanks, Alaska was considered as the conjugate site in the northern high latitudes to have global coverage, together with those in Japan (Esashi, Kakioka and Kyoto) at mid-latitudes.

Sato *et al.* (1993) solved leakage of liquid helium from the SG dewar during the previous (JARE-33) expedition, and gave the initial report of the SG observation which started from March 22, 1993 at the gravity observation hut by JARE-34. After this initial report, SG observations have produced many scientific results in the two streamlines of tidal bands and seismic bands (normal modes).

As for tidal bands, Sato *et al.* (1995) described in detail the installation and startup procedure of the Syowa SG, TT70 (#016), and its system configuration. Subtraction of both short- and long-period tides from the original signals resulted in a fairly small (0.06 μGal/day) trend including instrumental drift. The rms noise level of the data obtained through the MODE filter is estimated as 5–20 nGal ($1\,\mathrm{nGal}=10^{-11}\mathrm{m/s^2}$).

They also showed analysis results of 1-year data (March 22, 1993–March 21, 1994) and confirmed a 10% larger observed M2 gravimetric factor (δ factor) than the theoretical value obtained by Dehant-Wahr (Dehant, 1991). Parallel observation data with a LaCoste-Romberg D73 gravimeter were used to determine the conversion coefficient of the voltage output from the SG to the gravity value. The obtained value was –57.965μGal/V (Kanao and Sato, 1995) and the value has been used throughout the analysis of the Syowa SG data until now.

Though Sato *et al.* (1995) applied the Schwiderski (1980) model for ocean tide correction, Sato *et al.* (1996) recalculated the ocean tide effect by using the ORI95 ocean-tide model (Matsumoto *et al.*, 1995), and with more detailed (including the third-order mesh of 30″ by 45″ and the fourth-order mesh of 7.5″ by 15″) sea-land distribution. The ocean tide corrected δ factors were 1.144, 1.127, 1.157 and 1.111 for O1, K1, M2, and S2 waves, respectively. The discrepancy between the observation and Wahr's (1981) theory was 0.5% for the diurnal waves and about 2% for the semidiurnal waves. It was highly probable that the large discrepancy exceeding 10% in the previous δ factors for the semidiurnal waves at Syowa Station (Ogawa *et al.*, 1991) was caused partly by the inaccurate ocean-tide model of Schwiderski (1980), and partly by coarse modeling of the sea-land distribution.

As for long-period tides (Mf and Mm waves), Sato *et al.* (1997a) showed that the amplitudes, phase lags and δ factors were $11.642\pm0.035\,\mu$Gal, $-0.12\pm0.17^\circ$ and 1.1218 ± 0.0034 for the Mf wave, and $6.143\pm0.058\,\mu$Gal, $0.33\pm0.54^\circ$ and 1.1205 ± 0.0106 for the Mm wave, respectively. Although a detailed explanation is not given here, Sato *et al.* (1997a) tested five global ocean Mf and Mm tide models, and showed that their effects differed by a maximum of 0.104 μGal in amplitude and 18.8° in phase for the Mf wave, and by 0.033 μGal and 6.4° for the Mm wave, respectively, depending on the model. The estimated Mm phases were nearly 180° for the five models, and the variation of their values among the models was relatively small compared with that of the Mf phases, indicating that the Mm wave is much closer to an equilibrium tide than the Mf wave. The ocean-tide corrected δ factors were scattered within the ranges of 1.158 to 1.169 for the Mf wave and of 1.163 to 1.169 for the Mm wave, respectively. The mean δ factors for the five ocean models, 1.162 ± 0.023 for the Mf wave and 1.165 ± 0.014 for the Mm wave, have slightly larger values than those estimated from the theory of the elastic Earth model.

As for the polar motion effect on gravity, Sato *et al.* (1997b) obtained the δ factor of 1.198 ± 0.035 and an apparent time lag of about 20 days against the gravity changes predicted from the IERS polar motion data.

Sato *et al.* (2001) recently showed that the μGal-level annual gravity variation could be detected at Syowa Station as well as Canberra (Australia) in relation to the sea surface height variations associated with non-steric change of ocean circulations.

As for seismic (normal mode) bands, a remarkable discovery was made by analyzing a 3-year duration of Syowa SG data. Nawa *et al.* (1998) produced a frequency-time spectrogram of the SG records after subtracting tidal signals, which showed the stripes of 30 lines at nGal level parallel to the time axis in a frequency range from 0.3 to 5 mHz ($1\,\mathrm{mHz}=10^{-3}\mathrm{s}^{-1}$). Assuming that earthquakes are only the sources for the free oscillations, they calculated the synthetic spectrograms. The resultant spectrograms have not shown such series of parallel lines as observed. This study gave the first evidence of incessant excitation of the Earth's free oscillations (background free oscillations), mainly the fundamental spheroidal modes.

Search for incessant excitation was further extended to other SG data recorded at Canberra, Esashi, Metsähovi (Finland) as given by Nawa *et al.* (2000). Spectrograms for 1-year period and averaged power spectra for seismically quiet periods were obtained for each of the stations, together with Syowa Station. The above background free oscillations were detected most consistently and distinctly at Canberra, while that at Syowa Station was close to the critical limit for detection. There were anomalous but characteristic strong stripes at frequencies between 3 and 4 mHz only at Syowa Station, and they were found to be explained basically by the seiche of Lützow-Holm Bay (see Fig. 5) as described later.

Recently Iwano *et al.* (2003) analyzed parallel observation data for the TT70 (#016) SG and the FG5 (#203) AG described in Section 6. They obtained the sensitivity factor of SG as -58.165μGal/V with an accuracy of 0.1%; this value should replace the previous value of -57.965μGal/V with 1.0% accuracy. With this revised sensitivity factor, ten years' SG data should be analyzed in detail for tidal and non-tidal bands.

It is not easy to maintain the SG year-round because we have to liquefy the gas helium into liquid helium and refill the SG dewar at least twice a year. This inevitably introduces artificial noise twice a year, affecting the analysis of annual variations. A second-generation SG, typed CT by the manufacturer, has a cryo-cooler to keep the liquid helium year-round. In March 2003 during the writing of this manuscript, JARE-44 wintering staff members are working to initiate this new SG CT (#043) (see pinup photo of Fig. 7) in the gravity observation hut. We will replace the current TT70 (#016) SG at the end of 2003 after 6 months' parallel observations.

8. Geomagnetic variometer observations

Shibuya (1993) has pointed out the difficulty of continuing geomagnetic variometer observations in Antarctica, although the data give fundamental information on secular variation of the Earth's geomagnetic field. Ten years ago 10 stations were conducting the observations, including Novolazarevskaya, Syowa, Molodezhnaya, Mawson, Davis, Mirny, Casey, Dumont d'Urville, Arctowski and Vostok (see Fig. 2). In 2003, there remained 6 stations: Syowa, Mawson, Davis, Casey, Dumont d'Urville and Arctowski, as the 4 stations of the former Soviet Union ceased the observations.

There is little progress in the analysis of geomagnetic variometer observations. We only revise here Fig. 7 of Shibuya (1993), and illustrate the variation of residual geomagnetic intensity values from 1968 through 2002. The residuals were calculated

Fig. 7. The new SG CT (#043) is being installed in the gravity observation hut. Instead of the current pillar (left end of the photo), the tripod will support the 4K cryo-cooler, which is tentatively hung by the light-blue belt from the ceiling. The new CT (#043) will be moved to the pillar site after performance test. The photo was taken and sent by H. Ikeda (JARE-44).

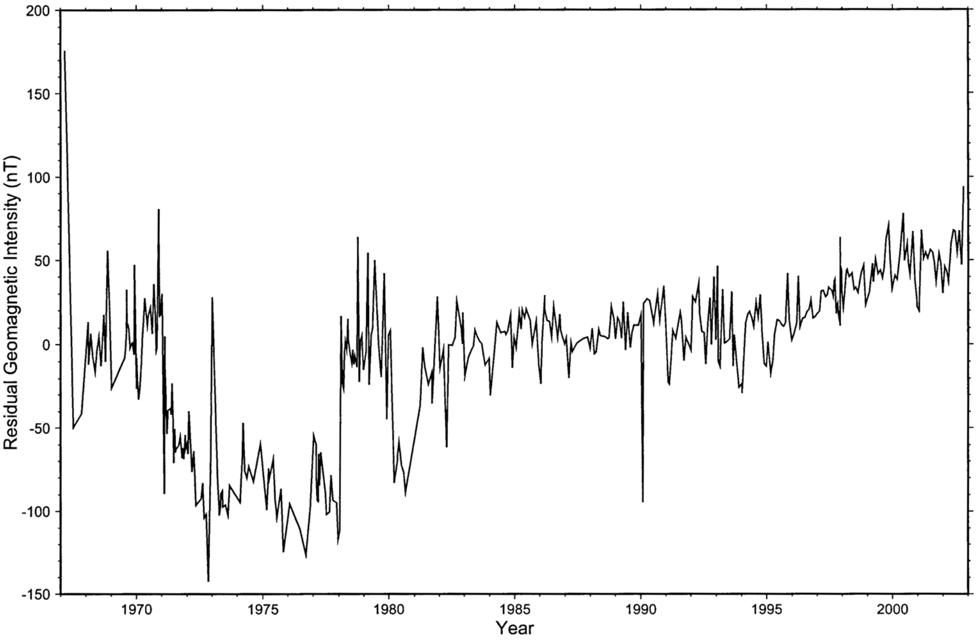


Fig. 8. The residual geomagnetic intensity values were calculated by subtracting the synthetic IGRF model value of eq. (8)′ from the observed value in eq. (8).

from the observed values of the absolute geomagnetic field at Syowa Station, which are listed in

http://aurora1.nipr.ac.jp/wdcc2/syowa.magne/abs/list.all, (8)

together with the synthetic International Geomagnetic Reference Field (IGRF) values calculated by using the IGRF & T89 model and the software in

http://aurora1.nipr.ac.jp/wdcc2/igrf/igrf.html. (8)′

Figure 8 illustrates the thus calculated residual geomagnetic intensity (observed minus IGRF) values in the ordinate as a function of the calendar year as the abscissa. The variation during 1982–2002, ±30 nT, is smaller than that from −140 to 80 nT during 1968–1981. The apparently smaller variation range during 1982–2002 as compared with that during 1968–1981, may partially be explained by reduced measurement noise with the more sophisticated absolute fluxgate magnetometer than the classic hand-generator-GSI-type absolute magnetometer for geomagnetic baseline determination.

9. Sea level observations

Because tidal observations were then made mainly for hydrographic and navigational purposes, most of the Antarctic expeditions made the ocean tide observations only for several years at the early stage from the International Geophysical Year (IGY), that is, during 1960–1965. Shibuya (1993) briefly described tidal observations from the viewpoint of long-term monitoring of sea level change.

As for Syowa Station, recording of sea level variation has been continuing since 1976 at Nisi-no-ura Cove using the bottom pressure gauge (BPG) located at a depth of 10–15 m (left-end of Fig. 1a). Analyzing these observation data, Odamaki *et al.* (1991) reported an apparent sea level fall of 0.95 cm/yr during 1979–1988.

The global sea level rise predicted by the National Research Council (1990) is 1–3 mm/yr, and the Global Sea Level Observing System (GLOSS) implementation plan was organized in 1997 (see Fig. 1b), which is explained in *e.g.*

http://www.pol.ac.uk/psmsl/programmes/gloss.info.html, (9)

where Syowa Station is positioned as a global core network station (GLOSS identification number 95), together with the other 9 Antarctic sites. They send tide data to the Permanent Service for Mean Sea Level (PSMSL).

In order to detect signals of the global warming effect, both precise calibration of the sensor amplification factor and a precise local tie to the bench mark (BM1040 in Fig. 1a) are required. According to Odamaki *et al.* (1991), the calibration of the BPG was based on staff readings of sea level at 10 min intervals for 25 hours' duration once per year in the austral summer. As the quartz sensor drifts, and as sea level around Syowa Station has 25–30 cm seasonal variation (Nagata *et al.*, 1993), more precise and frequent calibration was definitely required.

Aoki *et al.* (2000, 2001) made differential GPS observations on the fast ice at Nisi-no-ura Cove between April and December 1998. The vertical displacement was shown to consist of oceanic tidal variation and high-frequency variation of several minutes' period. This high-frequency fluctuation of about 1 cm was supported by simultaneous 8 hours' video monitoring of sea level variation, and has been partially explained by a seiche in Lützow-Holm Bay (Nawa *et al.*, 2003), as the resultant frequency-spectra were very similar among BPG, GPS sea-level and SG.

The low-pass filtered variations agreed well with a standard deviation of 1.7 cm on the daily time scale. Tidal constituents derived from the 8 months' GPS observations showed good agreement with those from the seven years of BPG observations (*e.g.* Odamaki and Kuramoto, 1989). Moreover, GPS was shown to have 2 cm accuracy for observations of the seasonal and intra-seasonal variation of sea level. The GPS-derived sea level, combined with observed sea ice thickness, supported the BPG result with an rms error of 0.7 cm (Aoki *et al.*, 2002).

Aoki *et al.* (2002) further suggested that the BPG-derived sea level had a seasonal variation of about 13 cm for the 1990s, much smaller than 25–30 cm for 1979–1988 which was indicated by Nagata *et al.* (1993), with a high in April-June and a low in November-December.

As GPS technique is free from drift, frequent calibration of BPG by GPS may lead to sub-cm accurate year-round observation of sea level variations in ice-covered oceans, and may give a more reliable rate of sea-level change. However, local sea level observations cannot separate sea level rise/fall from crustal subsidence/uplift. Therefore, AG and space geodetic results must be integrated in the interpretation.

In application to ocean dynamics, GPS observations on fast sea ice will play an important role in the determination of dynamic sea surface height with accuracy better than 10 cm, as shown by Doi *et al.* (2002).

10. Concluding remarks

Ten years' progress of geodesy programs at Syowa Station has clearly indicated two important facts: (1) each observation component must be included in a corresponding global network according to a standardized instrumentation system and data archiving method, and (2) parallel observations give us clues to find overlooked or unidentified phenomena and detect signals which are at the threshold level of noise.

Launch of the Gravity Recovery And Climate Experiment (GRACE) satellite will be an important development in the study of Antarctic environments, especially in the JARE research area (Fukuda *et al.*, 2002). The low-low (500 km height) satellite-to-satellite laser tracking system (*e.g.* Jekeli, 1999) will give us temporal change (time constant of about 1 month) of the Earth's gravitational fields in terms of geoid height, where the temporal change is highly related to the ice-water-air mass circulation. Because of basal sliding of the ice sheet over Mizuho Plateau (*e.g.* Mae and Naruse, 1978; Shibuya, 1986), a 3-year trace of the temporal change may detect the thinning rate of the ice sheet.

Although station observatory data cannot constrain satellite-derived data by themselves, oversnow-traverse and airborne geophysical data (gravity, magnetics, ice thickness, surface topography) must be calibrated by connecting to the station observatory data. To date, 20-mGal contouring of the free-air gravity anomalies (Fig. 5 of Shibuya *et al.*, 1999b) and 50-nT contouring of the crustal magnetic anomalies (Fig. 2 of Golynsky *et al.*, 1996) are still sparse and we require updated maps with new flights. The local potential fields calibrated by connecting to the station observatory standard, in turn, should give ground-truth information for the regional-scale satellite data. Syowa Station geodetic data will continue to play an important role in the study of global geodynamics, especially in the study of ice-water-air mass circulation in the Antarctic region.

Acknowledgments

Geodetic observations at Syowa Station are basically maintained by successively changing JARE wintering-over members, and we express sincere thanks for their contributions. In the period covered by this report, 22 members in Table 2 from JARE-34 through JARE-43 took care of the related facility and instruments. We are also grateful to the colleagues from NAO, Kyoto University, GSI and CRL for their support in training the JARE members, and also to the personnel at the international global network sites listed in Table 1.

Table 2. JARE wintering-over members. They maintained facility and instruments for geodesy and solid-earth geophysics at Syowa Station from JARE-34 to JARE-43 on a yearly basis.

JARE-34	1992–94	Tadahiro Sato (NAO), Kenta Okano* (Tokyo Univ.)
JARE-35	1993–95	Kazunari Nawa* (Tokyo Univ.), Naoto Ishikawa (Kyoto Univ.)
JARE-36	1994–96	Yuichi Aoyama* (NAO), Toshiyuki Tanaka* (Kanazawa Univ.) Kazushi Maruyama (GSI)
JARE-37	1995–97	Hiroaki Negishi* (Kyoto Univ.), Yoshifumi Nogi (NIPR)
JARE-38	1996–98	Toshihiro Higashi (Kyoto Univ.), Masaki Kanao (NIPR)
JARE-39	1997–99	Shigeru Aoki (NIPR), Takaaki Jike* (Sokendai†), Yoko Tono* (Kyoto Univ.)
JARE-40	1998–00	Yoshihiro Fukuzaki (GSI), Takashi Nakanishi* (Kyoto Univ.)
JARE-41	1999–01	Koichiro Doi (NIPR), Noritsune Seo (JHD‡)
JARE-42	2000–02	Sachiko Iwano* (Kyoto Univ.), Yoshihiro Ito* (Tohoku Univ.)
JARE-43	2001–03	Katsumi Sakura (Hokkaido Univ.), Koji Yoshii* (Kyoto Univ.)

* Master-course or doctor-course student.

† Sokendai (The Graduate University for Advanced Studies).

‡ JHD (Japan Hydrographic Department).

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