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Sea surface height determination by GPS in sea ice region of Lützow-Holm Bay, Antarctica

Koichiro Doi[1], Noritsune Seo[2], Shigeru Aoki[1] and Kazuo Shibuya[1]

[1]*National Institute of Polar Research, Kaga 1-chome, Itabashi-ku, Tokyo 173-8515*
[2]*Hydrographic and Oceanographic Department, Japan Coast Guard, 5-3-1 Tsukiji, Chuo-ku, Tokyo 104-0045*

Abstract: Global Positioning System (GPS) measurements were conducted at five sites on sea ice in Lutzow-Holm Bay, Antarctica. We determined sea surface height (SSH) at each point after correcting for ocean tides, atmospheric pressure and vertical distance from sea surface to ice surface. The overall error of the obtained SSH is estimated as smaller than 10 cm. We also obtained sea surface dynamic height (SSDT) by subtracting synthetic geoidal height from the observed SSH.

The obtained SSDT values show good agreement with those calculated from the fine resolution Antarctic model (FRAM). After taking temporal variations of SSH into consideration the values took higher values at the southern end of the bay than at the northern end of the bay. This spatial feature corresponds to the southward increase of SSDT across the continental slope.

key words: Lutzow-Holm Bay, sea ice, GPS, sea surface height

1. Introduction

The Japanese Antarctic Research Expeditions (JARE) have conducted observations on sea ice and bare rock along the Sôya Coast of Lutzow-Holm Bay at about 69°S and 40°E. Global Positioning System (GPS) measurements were carried out on sea ice in Nisi-no-ura Cove to observe sea level variations in JARE-39 (February 1998 to January 1999) (Aoki *et al.*, 2000). They detected for the first time the vertical displacements of the sea ice due to tidal variations and high frequency variations of 3–6 min period.

During the wintering of JARE-41 (February 1, 2000 to January 31, 2001), GPS measurements were also conducted at five sites on sea ice in Lutzow-Holm Bay to determine sea surface height (SSH) within accuracy of better than 10 cm. There are few SSH observations on sea ice. Precisely determined SSH provides significant knowledge on geoid and/or ocean current.

Radar altimetry is one method to measure sea level variations. Since the target area is located at latitude higher than 65°S, only European Remote Sensing Satellite-1 (ERS-1) and ERS-2 radar altimetry data were available for determining SSH. However, these altimetry data do not have sufficient accuracy because of the surface roughness in marginal sea ice area. Therefore the GPS-derived observations are the only available observations that give reliable SSHs in the area.

2. GPS measurements and their analysis

Two of the authors were members of JARE-41 and they placed observation sites along the sea-ice traverse routes that were set by JARE-41. The five observation sites were named K2, L46, HG20, KZ18, and SV57 from north to south after the names of the nearest route flag numbers. Their locations are shown in Fig. 1. All the observation points were several hundred meters away from the coastline on floating sea.

We put a plane antenna on a tripod, which was fixed to an ice anchor with a nylon wire. The tripod was placed near a heat-retaining plastic case, which contained an

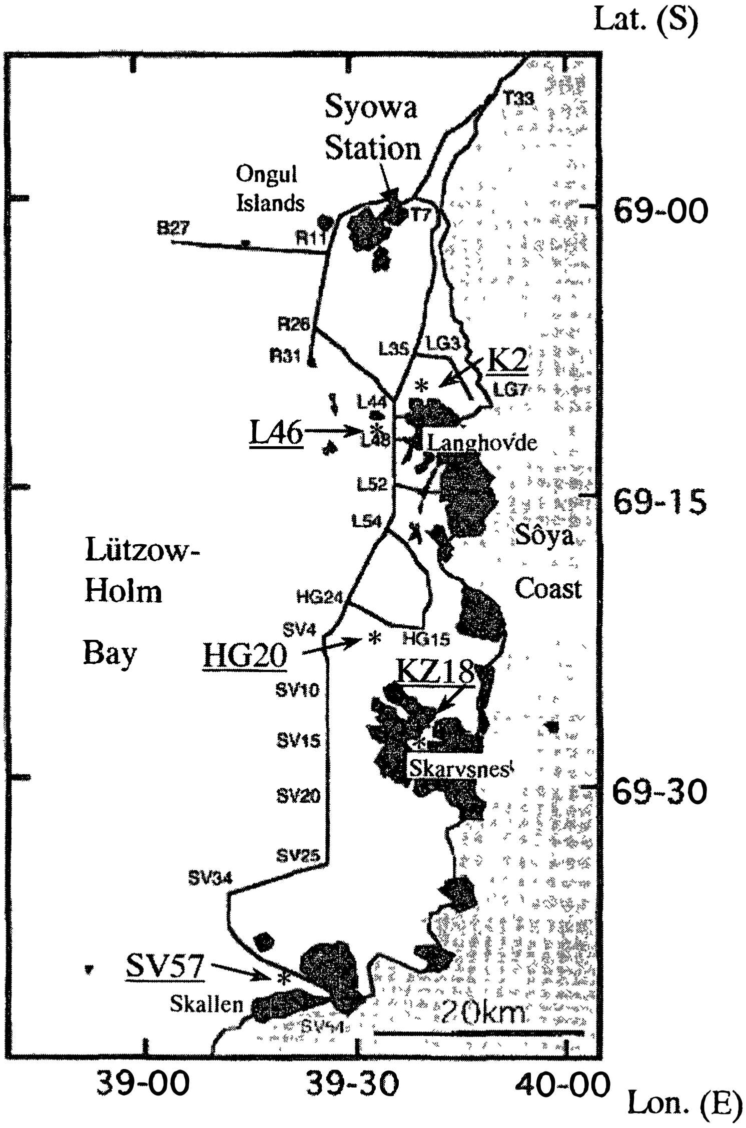

Fig. 1. Observation sites. Observation sites are denoted by asterisks, and the names are underlined. The solid lines show the sea ice traverse routes. The black areas and the gray areas indicate bare rock areas and continental ice sheet areas, respectively.

Table 1 Observation sites

Observation site	Latitude (S)	Longitude (E)	Observation date	Observation period (hour)
K2	69° 09′ 56″	39° 38′ 41″	2000 11 8–11 9	13
L46	69° 11′ 11″	39° 35′ 32″	2000 11 4–11 5	23
HG20	69° 21′ 56″	39° 34′ 21″	2000 10 21	6
KZ18	69° 27′ 48″	39° 37′ 08″	2000 10 20–10 21	19
SV57	69° 40′ 17″	39° 21′ 53″	2000 10 17	12

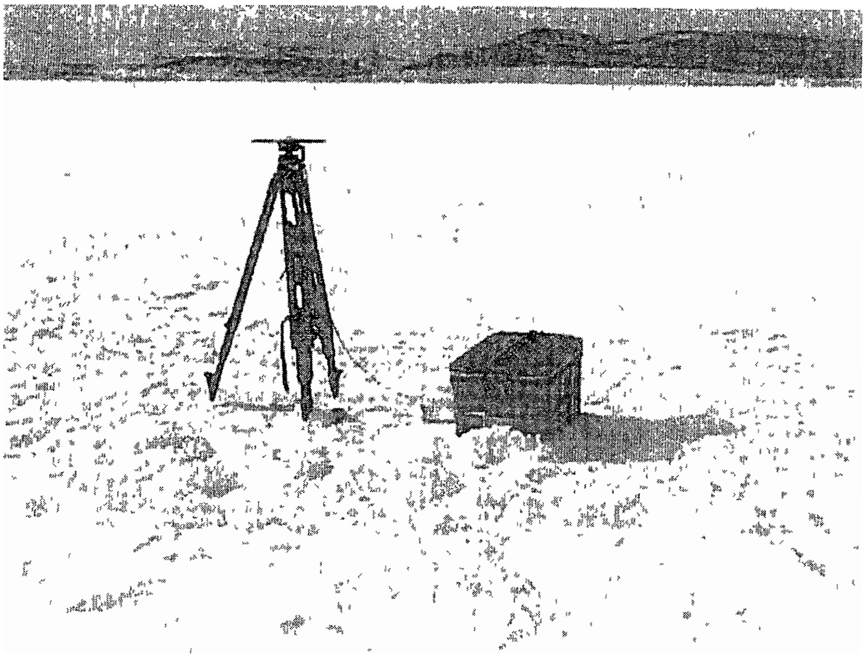

Fig 2 Observation at K2

Ashtech Z-FX GPS receiver and a large capacity battery (120 Ah)

The locations, observation dates and observation durations at each site are listed in Table 1 The observation duration was less than 24 hours at every point Figure 2 shows a photo of an observation in progress at K2

At every point, we drilled a hole in the sea ice and measured both the thickness of the sea ice and the distance between the ice surface and the seawater surface, the data are given in Table 2 The depths of the water surface from the ice surface seem reasonable, because they are one tenth of the ice thickness A schematic of the GPS observation setup is shown in Fig 3

In the baseline analysis, we employed the Syowa International GPS Service for Geodesy and Geophysics (IGS) site as a reference station The IGS site named SYOG has been operating since 1995 (Yamada *et al*, 1998) Baseline lengths from SYOG to each observation point are less than 80 km We analyzed GPS baselines using the GPS baseline analysis software GPSurvey and obtained hourly positions

Table 2 Observed height of sea ice surface and SSH

Observation site	Ellipsoidal height of sea ice surface (m)	R M S (m)	Distance from ice surface to sea surface (m)	Ice thickness (m)	SSH (m)
K2	20 53	0 060	0 18	1 94	20 34
L46	20 36	0 045	0 17	1 62	20 19
HG20	20 10	0 069	0 21	2 11	19 89
KZ18	20 12	0 081	0 17	1 64	19 95
SV57	19 35	0 058	0 08	1 76	19 27

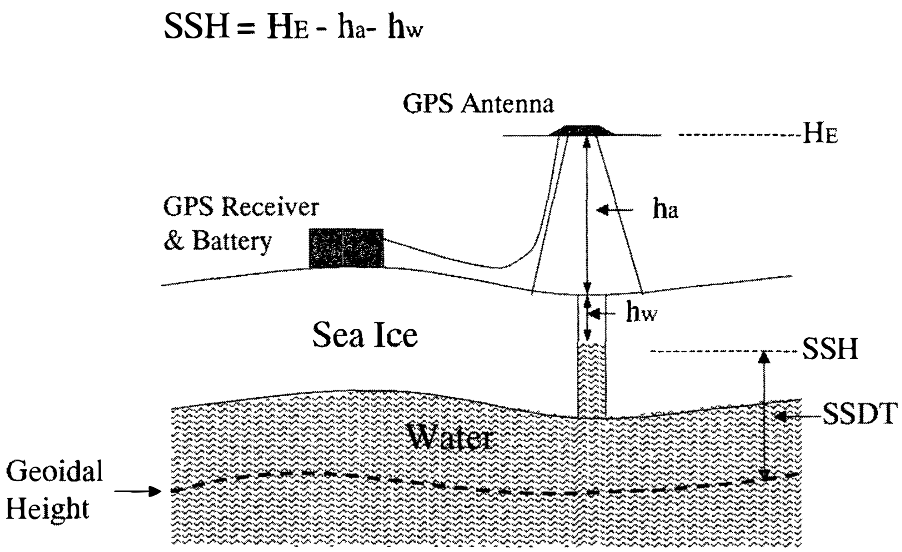

Fig 3 Schematic of observation of sea surface height (SSH) and sea surface dynamic topography (SSDT) on sea ice H_E means GPS antenna height from the WGS84 ellipsoid h_a is antenna height from the ice surface and h_w is distance between the sea water surface and the sea ice surface

3. Estimation of sea surface height

The tidal motion is dominant among the vertical displacements of sea ice on a time scale shorter than one day To remove the ocean tide variations, we used the ORI96 global ocean tide model (Matsumoto *et al*, 1996) as an analytic model

To correct for the atmospheric pressure effect, we assumed the inverse barometer hypothesis of ocean response to atmospheric pressure and used the following equation to calculate the atmospheric pressure effect Δh_p in meters,

$$\Delta h_p = -0\ 009948\ (P - 1013\ 25)$$

We assumed here that the pressure at each site was the same as that measured at Syowa Station P is the sea level pressure at Syowa Station and the unit is hectopascals

After applying these corrections to the hourly GPS solutions, we took the mean of the heights at each site An example of the processing for SV57 is shown in Fig 4 In this figure, the original height components of the hourly GPS solutions are denoted by rectangles and the heights after the corrections are indicated by inverted triangles Note that the curves except for those of ocean tides and the pressure effects are given on a relative

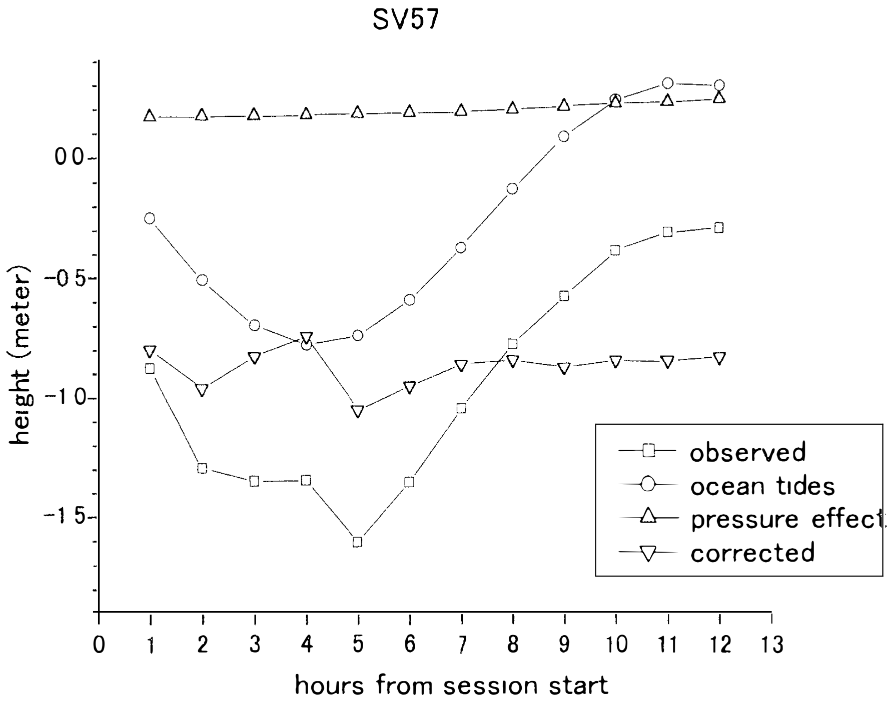

Fig 4 An example of corrections for ocean tides and the atmospheric pressure effect for SV57 Hourly determined heights are denoted by rectangles and corrected SSH relative values are indicated by inverted triangles

scale

Finally, we estimated SSH at each point by correcting for the antenna height and the distance between the ice surface and the seawater surface on the World Geodetic System 1984 (WGS84) ellipsoid The results are summarized in Table 2

The obtained SSHs are around 20 m and their r m s errors are less than 10 cm Since the uncertainty in the measurement of distances from the water surface to the ice surface is at most a few centimeters and as that in the antenna height measurements is less than several millimeters, the overall accuracy of the estimated SSHs is considered to be better than 10 cm

4. Discussion

Temporal SSH variations such as seasonal variations and higher frequency variations also exist (Aoki *et al*, 2002, Nagata *et al*, 1993) The observed SSH must contain these temporal variations of several tens of centimeters The temporal variations can be evaluated from tidal observations conducted at Syowa Station We assume that sea level changes occur simultaneously in Lutzow-Holm Bay and the amplitude at each site is the same as that observed at Syowa Station Thus we estimated the temporal variations at each site from the corresponding observation time The estimated variations at each site and the corrected SSHs are indicated in Table 3

We compared the SSHs with geoidal heights calculated from the Earth Gravitational Model 1996 (EGM96) (Lemoine *et al*, 1996) on the WGS84 ellipsoid The EGM96 geoidal heights are also given in Table 3 As can be seen in Table 3, the differences are

Table 3 Corrected SSH and obtained SSDT

Observation point	Temporal SSH variation (m)	Corrected SSH (m)	Geoidal undulation (m)(EGM96)	SSDT (m)
K2	−0 07	20 41	21 77	−1 36
L46	−0 05	20 24	21 63	−1 39
HG20	0 06	19 83	21 24	−1 41
KZ18	0 02	19 93	21 18	−1 25
SV57	−0 20	19 47	20 35	−0 88

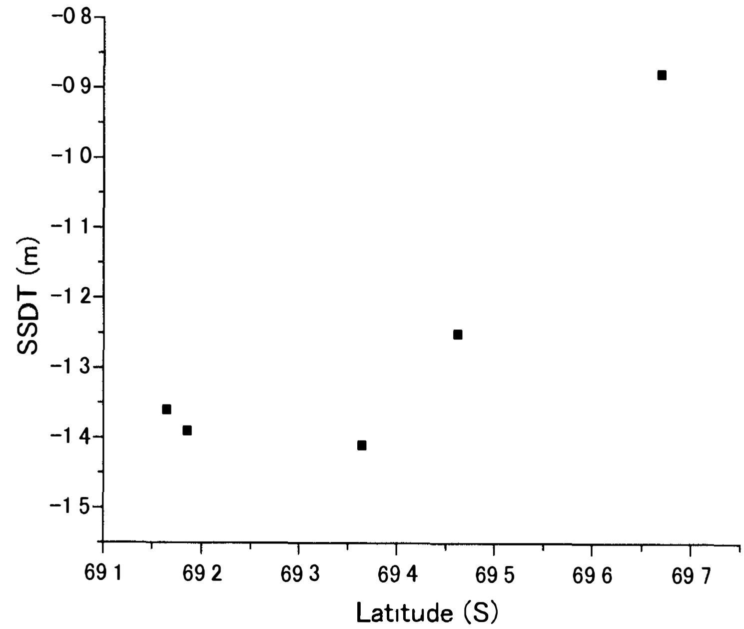

Fig 5 SSDT plotted from north to south

about 1 m The difference between SSH and geoidal height is called sea surface dynamic topography (SSDT) SSDT is known to be induced by surface geostropic current and the speed and direction can be inferred from it The derived SSDTs in Lutzow-Holm Bay are also plotted in Fig 5 according to the latitude They are less than −0 8 m and take lower values in the northern part of the bay

Mean sea surface dynamic topography for the Southern Ocean was estimated from the fine resolution Antarctic model (FRAM) (Webb *et al* , 1991) and historical hydrographic data by Park and Gambéroni (1995) Figure 6 shows the mean SSDT from the FRAM surrounded by 20 and 95°E in longitude and 70 and 55°S in latitude after Fig 6 of Park and Gambéroni (1995) The inferred SSDT from the FRAM around Lützow-Holm bay is about −1 3 m, as can be seen in Fig 6

The SSDTs obtained in this study agree well with those from the FRAM, while they are not consistent with those from hydrographic data (see also Fig 7 in Park and Gambéroni 1995).

The spatial slope, which shows higher SSDT at the southern end of the bay and lower SSDT in the northern part, can be seen in the SSDTs derived in this study This fact corresponds to southward increase of SSDT across the continental slope The maximum

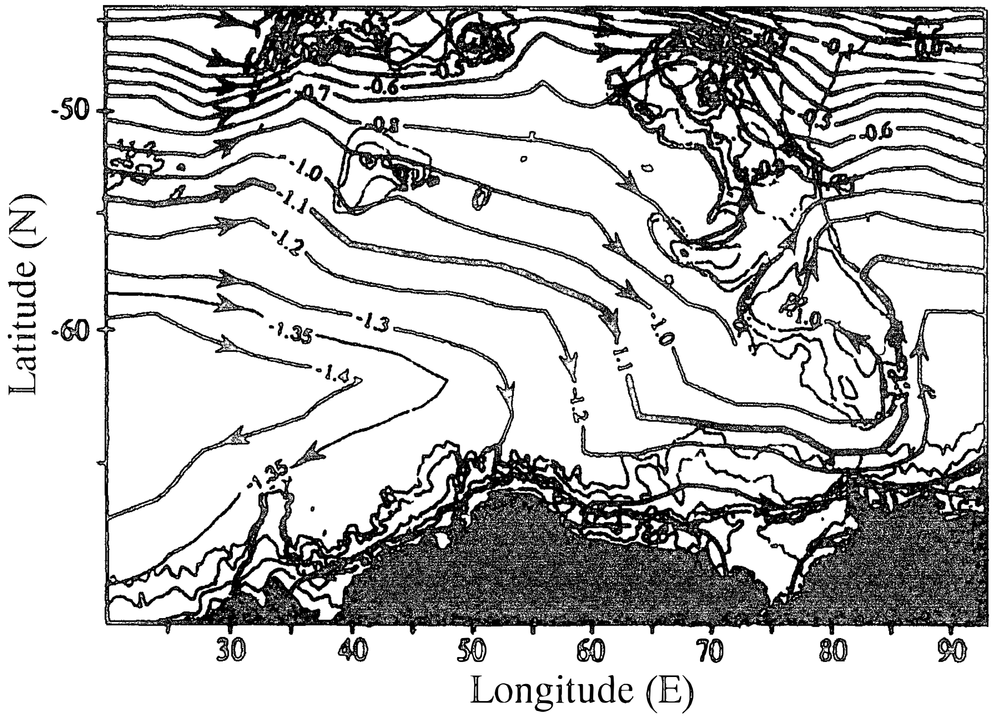

Fig. 6. SSDT derived from the FRAM after Park and Gambéroni (1995).

difference reaches 0.5 m. The large difference may suggest the existence of a strong current along the coast.

5. Conclusion

We carried out GPS measurements on sea ice at five sites in Lutzow-Holm Bay. The obtained ellipsoidal heights on the WGS84 Ellipsoid were averaged after applying corrections for oceanic tidal variations and the atmospheric pressure effect to estimate the hourly height of the ice surface. On site, the distance between the sea surface and the ice surface was also measured and the sea surface height was computed from the ice surface height and the distance. By subtracting geoidal height obtained from the EGM96 model from the SSH, we finally obtained the SSDT at each site.

The SSDTs range from -0.8 to -1.4 m and show good agreement with those from a numerical model FRAM in magnitude.

In this study, we derived accurate SSHs on sea ice at five sites, but the method employed here will require too much effort to observe at many sites over a wider area. One of the alternative and promising candidates to measure SSH is airborne laser altimetry. It will ensure effective measurement of surface height of sea ice over a wide area, and enable us to determine the ice surface within a few centimeters accuracy. If sea ice thickness or depth to the seawater surface from the sea ice surface can be estimated rapidly, we may determine SSH topography over a wide sea ice region.

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