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Surface heights over a traverse route from S16 to Dome Fuji, East Antarctica as measured by kinematic GNSS surveys in 2012–2013 and 2018–2019

Shun TSUTAKI [1]*, Kotaro FUKUI [2], Hideaki MOTOYAMA[1,3], Akihisa HATTORI[3], Jun'ichi OKUNO[1,3], Shuji FUJITA[1,3] and Kenji KAWAMURA[1,3,4]

[1] National Institute of Polar Research, Research Organization of Information and Systems, 10-3, Midori-cho, Tachikawa, Tokyo 190-8518.
[2]Tateyama Caldera Sabo Museum, 68 Ashikuraji-bunazaka, Tateyama, Toyama 930-1405.
[3] Department of Polar Science, School of Multidisciplinary Sciences, SOKENDAI (The Graduate University for Advanced Studies), 10-3, Midori-cho, Tachikawa, Tokyo 190-8518.
[4] Japan Agency for Marine Science and Technology (JAMSTEC), 2-15, Natsushima-cho, Yokosuka, Kanagawa 237-0061.
*Corresponding author. Shun Tsutaki (tsutaki.shun@nipr.ac.jp)
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Abstract: Kinematic global navigation satellite system (GNSS) measurements provide in-situ data that are crucial for detecting subtle changes in the surface height of glaciers and ice sheets. Owing to their accuracy, which is typically less than half a meter, surface heights derived from kinematic GNSS surveys are both valuable and essential for evaluating changes in geometry of glaciers and for assessing satellite altimetry. Here, we present a surface height dataset derived from kinematic GNSS measurements covering a horizontal distance of approximately 1,200 km along an inland traverse route in East Antarctica from a coastal point near Syowa Station and Dome Fuji. More than 1,750,000 GNSS survey data points were processed and saved in CSV format. Based on our error analysis, the accuracy of the height data is less than 0.4 m in the vertical direction. This dataset can be used to investigate surface height changes by comparing it with other datasets obtained in the past, as well as those from future remote sensing and in-situ observations.

1. Background & Summary

We prepared a surface height dataset for the traverse route to Dome Fuji in East Antarctica using kinematic GNSS measurements collected in the austral summers of 2012–2013 and 2018–

2019. The data covers an approximately 1,200 km length of the route with a recording time interval of 1 sec.

Previous surface height surveys using multiple satellite-based laser/radar altimetry platforms have revealed considerable mass loss of the Antarctic ice sheet in recent years[1]. These changes in Antarctic ice thickness have been inhomogeneous in space and time. For example, significant mass loss has been observed in the fast-flowing marine-terminating outlet glaciers of West Antarctica, while ice sheet mass has increased in Dronning Maud Land (DML) in coastal East Antarctica[2]. Satellite altimetry is a powerful method for covering relatively large and remote areas. These techniques enable us to evaluate surface height changes in massive polar ice sheets. However, the accuracy of the obtained measurements depends on the footprint size of the laser/radar signals and the spatial coverage of satellite tracks. Note that uncertainty also arises regarding snow and firn densities when estimating ice sheet mass change from satellite altimeter data. Accurate coordinates derived from ground-based surface height data are essential for assessing potential biases in the vertical direction of satellite altimetry data[3].

GNSS is a navigation system that determines the position of a receiver by receiving radio signals from multiple satellites (such as GPS, GLONASS etc.). The Kinematic Precise Point Positioning (Kinematic PPP) method determines the position of a receiver with high accuracy by post-processing using satellite ephemeris and clock. In the Antarctic ice sheet, kinematic GNSS measurements provide surface height data with a high accuracy of less than half a meter under the normal conditions[4]. Although their spatial and temporal coverage is limited, kinematic GNSS measurements were utilized along traverse routes from the coast to inland areas in the Antarctic ice sheet to validate height datasets compiled using radar and laser satellite altimetry data[3,5,6]. Measurements on the East Antarctic ice sheet have been conducted around ice core drilling sites at Dome Argus and over the subglacial Lake Vostok to evaluate local surface topography and the temporal changes therein[7,8]. However, few studies have been published on kinematic GNSS measurements of the surface topography of the Japanese Antarctic Research Expedition (JARE) traverse routes from the coast to Dome Fuji in the DML region.

Observations of the surface topography and height of the ice sheet in the vicinity of the JARE traverse route have been made on several occasions, beginning with surveys conducted in the late 1950s from the coast to the Mizuho Plateau[9], followed by surveys from Syowa Station to the South Pole in 1968–1969[10]. Glaciological observations including a surface topographic survey were conducted in the Dome Fuji region in 1984–1985[11]. These preliminary surveys were conducted by barometric altimetry, astronomical surveys and operating a Doppler satellite positioning. Initial surveys of surface height by GPS were performed at ten glaciological observation stations along the traverse route from base S16 to Dome Fuji in 1992[12]. From 2003 to 2004, continuous GPS measurements were conducted around Dome Fuji using a sampling interval of 30 sec to measure continuous ice surface topography[13]. A precise kinematic GNSS survey in combination with an ice radar survey covering the entire route from the coast to Dome Fuji is required to investigate the ice thickness and bedrock topography with higher accuracy[14]. However, a kinematic GNSS measurements dataset with a high-frequency sampling interval (i.e., 1 sec) for the continuous surface height has not yet been performed.

The precise observations of the surface topography by in-situ GNSS are essential for constraining the dynamics of glaciers and the surface mass balance. To investigate present surface topography with a high accuracy, kinematic GNSS measurements were carried out along the traverse route from S16 near the coast to the southern area of Dome Fuji by ground-based ice radar surveys in the austral summers of 2012–2013 and 2018–2019. This study measured surface height data along the same route using kinematic GNSS surveys. GNSS coordinates obtained at a sampling interval of 1 sec were post-processed in kinematic PPP mode. An accuracy of <0.4 m in the vertical direction was estimated from the standard deviations of the solutions. For the convenience of the user, the surface height data are available as a CSV file in WGS 84 and Polar Stereographic Antarctica coordinate systems. By comparing our height data with those measured in the past (and in the future), it is possible to measure surface height changes with a high degree of accuracy (i.e., <0.5 m). Furthermore, data obtained along the traverse route from the coast to the inland plateau is made available as evaluation data for past and future satellite altimetry data analysis.

2. Study area

From November 2012 to January 2013, the 54th JARE research team conducted a traverse expedition in the DML region of East Antarctica between the inland bases S16 (30 km from Syowa Station: 69.03°S, 40.05°E, 589 m: ellipsoid height) and S80 (80.00°S, 40.50°E, 3,627 m) (Figs.1a and 1b). In addition to kinematic GNSS measurements, a variety of glaciological observations were conducted along the ~1,200 km route of the expedition, including net snow accumulation measured by the stake method[15] and ice thickness measurements around Dome Fuji using a ground-based ice radar system.

The 60th JARE research team conducted a traverse expedition between S16 and New Dome Fuji (NDF) from November 2018 to January 2019. One of the primary purposes of the expedition was to conduct a detailed ground-based ice radar survey to the south of Dome Fuji as a part of a collaborative research project between the National Institute of Polar Research, the Norwegian Polar Institute, the University of Alabama and the University of Kansas[16]. Kinematic GNSS measurements were carried out together with ice radar surveys along an approximately 1,050 km section of the traverse route from S16 to the JARE60 base campsite (BC: 77.74°S, 39.11°E, 3,772 m), followed by a distance of 2,700 km in a 1,000 km^2 area around the BC. In the latter area, the final spacing between the survey lines ranged from 0.25 to 0.5 km.

3. Methods

3.1. Kinematic GNSS measurements

During the 54th JARE traverse expedition, surface heights were measured from 23 November to 29 December 2012 between S16 and S80. A kinematic GNSS survey was carried out from 4 to 23 January 2013 from S80 to S16 (Table 1). For the 60th JARE expedition, surface height measurements were conducted from 15 November to 10 December 2013 from S16 to the BC, from 18 to 29 December 2018 around NDF, and from 2 to 19 January 2019 along the route from the BC to S16 (Table 1). We used dual-frequency carrier-phase GNSS receivers and antennae (GEM-1 and GEM-2, ENABLER Ltd., Tokyo, Japan) to measure three-dimensional coordinates of the ice sheet surface. The GEM-1 system receives signals from the GPS and GLONASS satellite systems, and the GEM-2 system receives signals from the GPS, GLONASS and Galileo systems. The GNSS antenna was mounted to the roof of a snow-tracked vehicle (SM100S, Ohara Co., Nagaoka, Japan) (Figs. 1c and 1d). We measured the height of each roof-mounted GNSS antenna twice, once before and once after the survey. Specifically, we measured the distance between the antenna base plane ($h_{GNSSAnt}$) and the bottom of the indentation of the tracks of the vehicle into the snow ($h_{TrackDepth}$) (Fig. 1c). Accordingly, the average antenna heights ($h_{AntHeight}$) were 4.06 and 3.40 m for the 54th and the 60th expeditions, respectively (Figs. 1c and 1d). The GNSS receiver was situated inside the snow vehicle. We used a shock absorber under the receiver to prevent receiver failure due to vibration of the snow vehicle. Electrical power was supplied from the snow vehicle on the 54th expedition (DC 12V) and a lithium-ion mobile battery on the 60th expedition (DC 10.8 V, 5.8 Ah; 700-BTL033BK, Sanwa Supply Co., Ltd., Okayama, Japan). For all surveys, GNSS data were recorded at a sampling interval of 1 sec, which generated data points with a nonuniform footprint spacing of ~3 m at a vehicle speed of 10 km h^{-1}. The total number of data points obtained from the surveys was 1,263,967 and 488,292 for the 54th and 60th expeditions, respectively.

3.2. Data processing

Post-processing of the GNSS data was performed using the following steps: converting raw data to receiver independent exchange format (RINEX), processing coordinates in a kinematic mode, and checking data quality. In this section, we describe the details of this procedure.

GNSS data were converted to RINEX format using the data format conversion software package, JPS2RIN[17]. We used RTKLIB[18] for post-processing of the GNSS data. RTKLIB is an open-source program package for standard and precise positioning algorithms with GNSS, allowing us for processing GNSS data with static and kinematic modes. We processed the ionosphere-free linear combinations with L1 and L2 dual-frequency measurements with a 10° elevation mask and estimated the zenith tropospheric delays. We then processed GNSS data in kinematic PPP mode using 1-sec intervals to obtain three-dimensional coordinates. Coordinates were represented in the

WGS 84 coordinate system (EPSG:4326). Float solutions were excluded from the analysis using a threshold of twice the calculated standard deviation in the vertical direction (2 × SD-V), which was 0.36 m for the 54th expedition and 0.32 m for the 60th expedition. As a result, 99% of the data points could be used in the subsequent analysis. The distance between the GNSS antenna and the snow surface ($h_{AntHeight}$) was subtracted from the height data. Horizontal coordinates were represented both WGS 84 (EPSG:4326) and the Polar Stereographic Antarctica projection (EPSG:3031, WGS 84 reference system) for the convenience of the user. Surface heights were represented ellipsoidal heights. GNSS data were categorized according to the surveyed area and periods: S16 to S80 and S80 to S16 on the 54th expedition, and S16 to the BC, around the BC, and BC to S16 on the 60th expedition. Height data were saved as a CSV file.

4. Data Records

Surface height data are archived at the National Institute of Polar Research (for access details, see Data Citation). The spatial coverage of the data products is shown for each area on the 54th expedition (Fig. 2) and the 60th expedition (Fig. 3), respectively. The processed surface height data are stored in CSV file format. The structure of the data filenames is JARE*number*_*point start*_*point end*.csv, where *number* indicates the JARE expedition number (e.g., "54" or "60"), and *point start* and *point end* indicate the name of start and end points (or area) of the surveyed lines (e.g., "S16", "S80", "BC" or "NDF").

The Data file contains the following headers in lines 1–16: date of data file generation, affiliation, name and contact address of investigators, project name, data file name, data type, data status, observation period, horizontal coordinate system, height system, delimiter, fields, units of data. The coordinates in columns 3–7 of the CSV files are given in longitude (decimal degrees), latitude (decimal degrees), polar stereographic easting (meters), polar stereographic northing (meters) and height (meters). Columns 8–13 contain the calculated standard deviations of processed data (meters); north (SD-N), east (SD-E), vertical (SD-V), north-east (SD-NE), east-vertical (SD-EV) and vertical-north (SD-VN). Note that the standard deviations were estimated with assuming a priori error model and error parameters by the positioning options in the RTKLIB software. The absolute value of SD-NE, SD-EV or SD-VN means square root of the absolute value of north-east, east-vertical or vertical-north components of the estimated covariance matrix. The sign of SD-NE, SD-EV or SD-VN represents the sign of the covariance.

5. Technical Validation

In this section, we discuss the accuracy of the kinematic GNSS measurements. To assess the accuracy of our measurements, the precision of the kinematic measurements needs to be considered. The precision of the coordinates obtained from the kinematic GNSS surveys can be inferred by the standard deviations of the solutions calculated in the kinematic PPP post-processing step. The standard deviations of the estimated position for the 54th and the 60th expeditions were 0.02 m and 0.18 m in the horizontal direction (quadratic sum of SD-N, SD-E and SD-NE) and 0.03 m and 0.16 m in the vertical direction (SD-V), respectively. Note that the standard deviations of the 60th expedition is one order larger than those of the 54th. Presumably, the power supply of the mobile battery is sometimes less than the required power consumption of the GNSS receiver, and thus the observation and recording become intermittent. As described in section 3.2 on data processing, we used 2 × SD-V (the standard deviations of the height) to exclude the float solutions from the datasets. Uncertainty in the vertical position of the vehicle-mounted GNSS antenna during the measurements was <0.1 m, which is within an acceptable range of the accuracy in the vertical direction. This uncertainty is due to the distance between the actual snow surface and $h_{TrackDepth}$, which can vary depending on the snow surface hardness, driving speed, etc., and vertical vibration caused by the movement of the vehicle. Accordingly, the accuracy of our kinematic GNSS measurements in the vertical direction (σ_z) ranged from 0.02 m to 0.35 m for the 54th expedition and from 0.03 m to 0.33 m for the 60th expedition, as shown in those spatial distributions in Figures 2b, 2d, 3b, 3d, 3f, and 4.

6. Figures

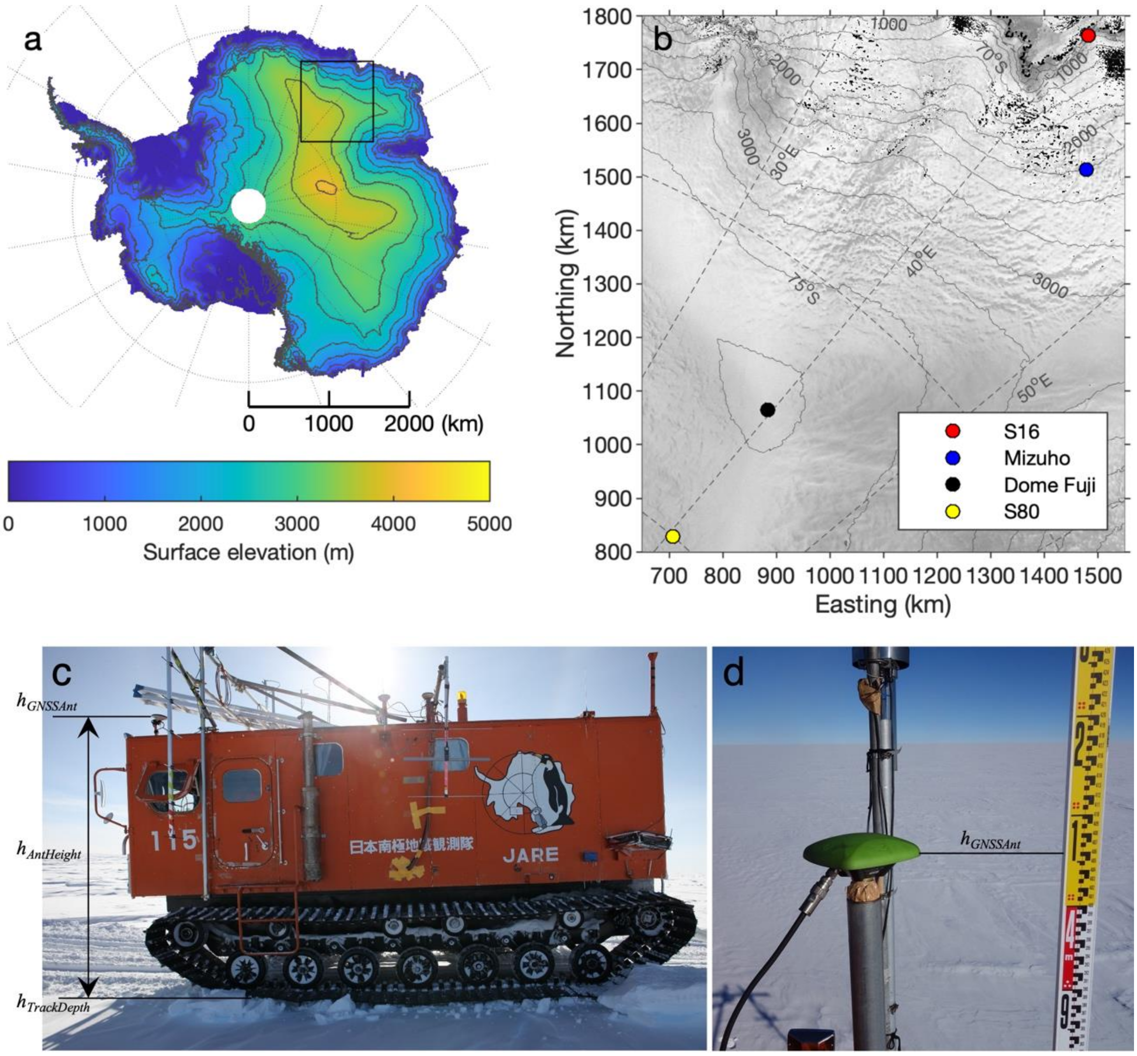

Figure 1. (a) Antarctic ice sheet surface height measured by the CryoSat-2 satellite altimeter[19]. The contours indicate surface height at intervals of 500 m. The inset shows the area of the studied region in Antarctica. (b) RADARSAT-1 image acquired in 1997 (©CSA, 1997) showing the traverse route between Syowa Station and Dome Fuji in Dronning Maud Land, East Antarctica, using the polar stereographic projection coordinate system. The contours indicate surface height at intervals of 250 m. (c) The GNSS antenna configuration on a snow-tracked vehicle (SM100S, Ohara Co.) used in 2018–2019. $H_{AntHeight}$ is the distance between the antenna base plane ($h_{GNSSAnt}$) and the depth of the sledge runners at the snow surface ($h_{TrackDepth}$). (d) The GNSS antenna set at the roof of the snow vehicle with a ruler showing $h_{GNSSAnt}$.

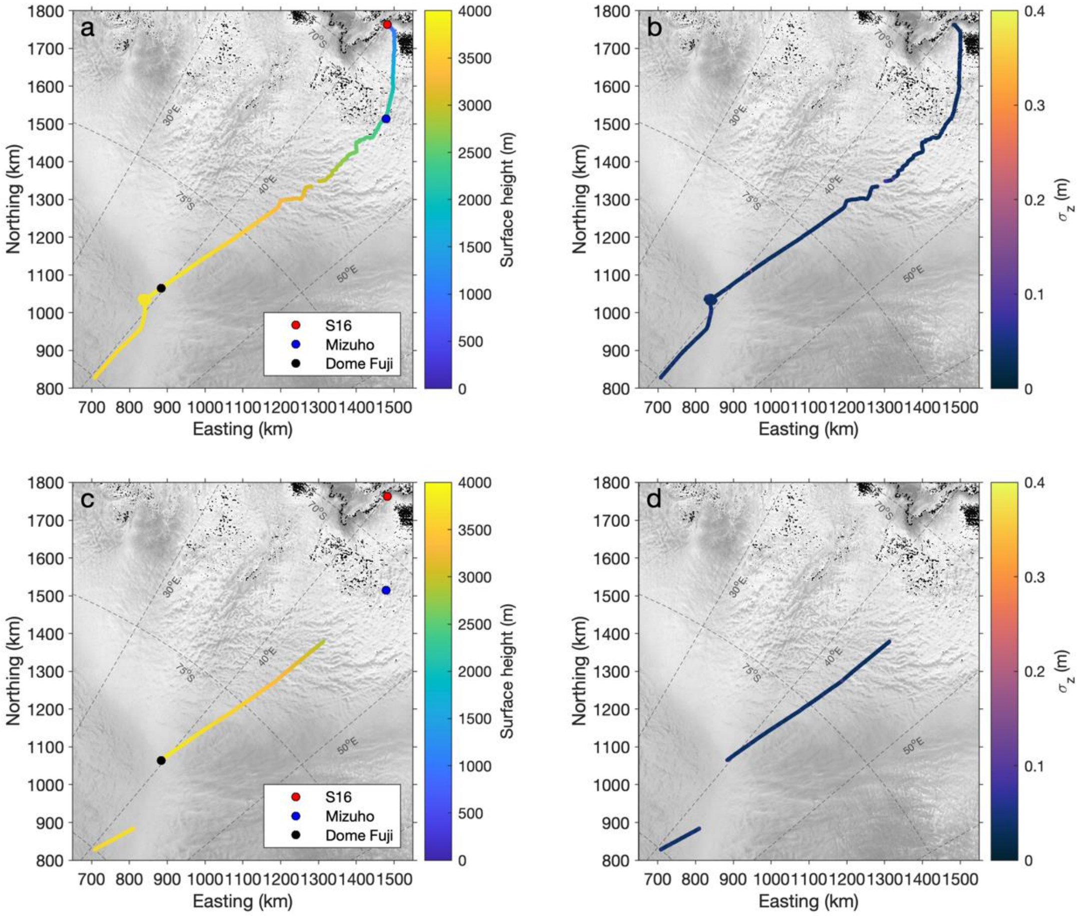

Figure 2. Surface height along the survey routes measured from (a) S16 to S80 and from (c) S80 to S16 during the 54th expedition. The accuracy of the kinematic GNSS measurements in the vertical direction (σ_z) along the survey routes from (b) S16 to S80 and from (d) S80 to S16 during the 54th expedition. The background is a RADARSAT-1 image taken in 1997 (©CSA, 1997).

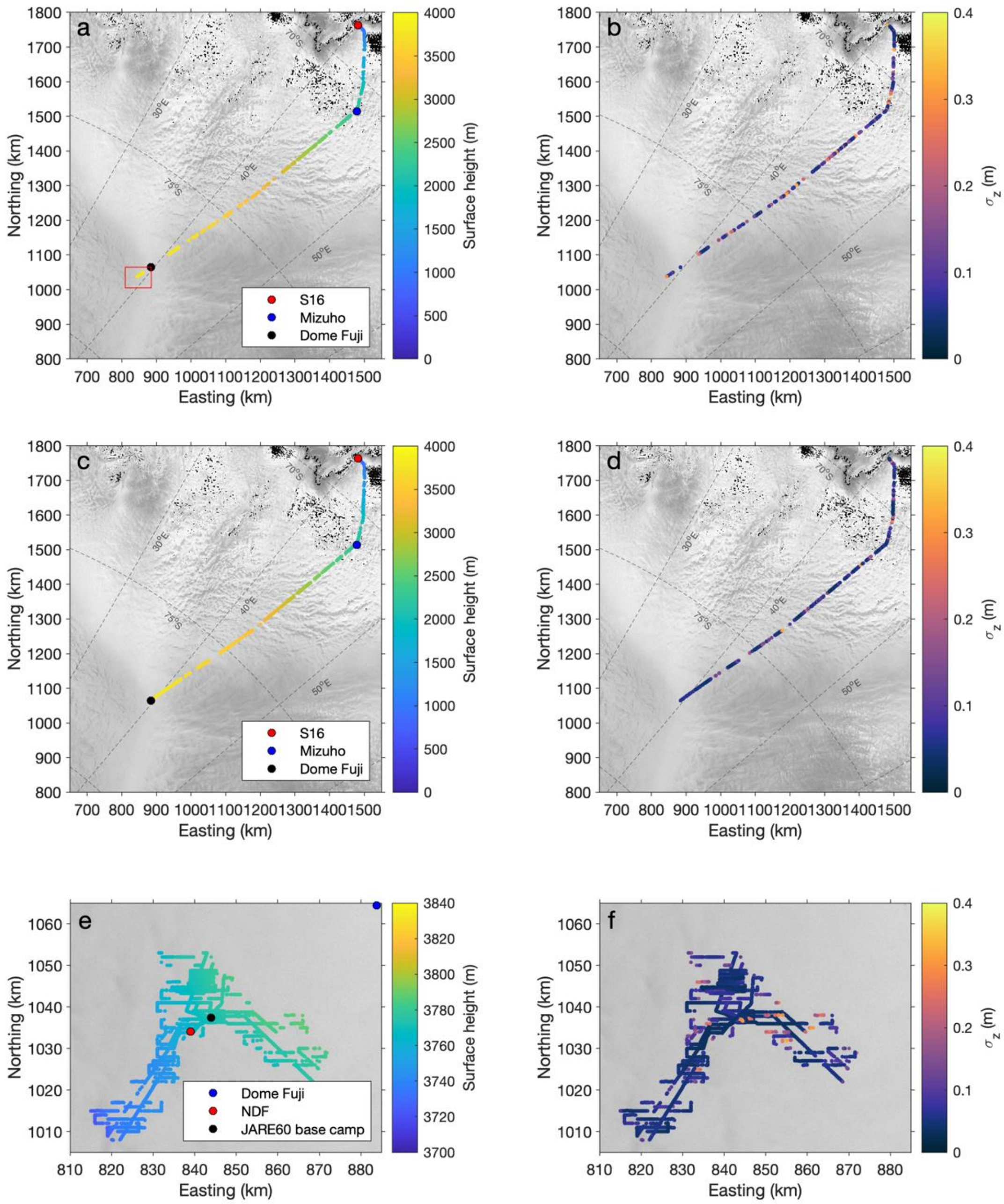

Figure 3. Surface height along the survey routes measured from (a) S16 to the basecamp (BC), (c) areas around the BC and NDF, and from (e) BC to S16 during the 60th expedition. The accuracy of the kinematic GNSS measurements in the vertical direction (σ_z) along with the survey routes from (b) S16 to the BC, (d) areas around the BC and NDF, and from (f) the BC to S16 during the 60th expedition. The background is a RADARSAT-1 image taken in 1997 (©CSA, 1997).

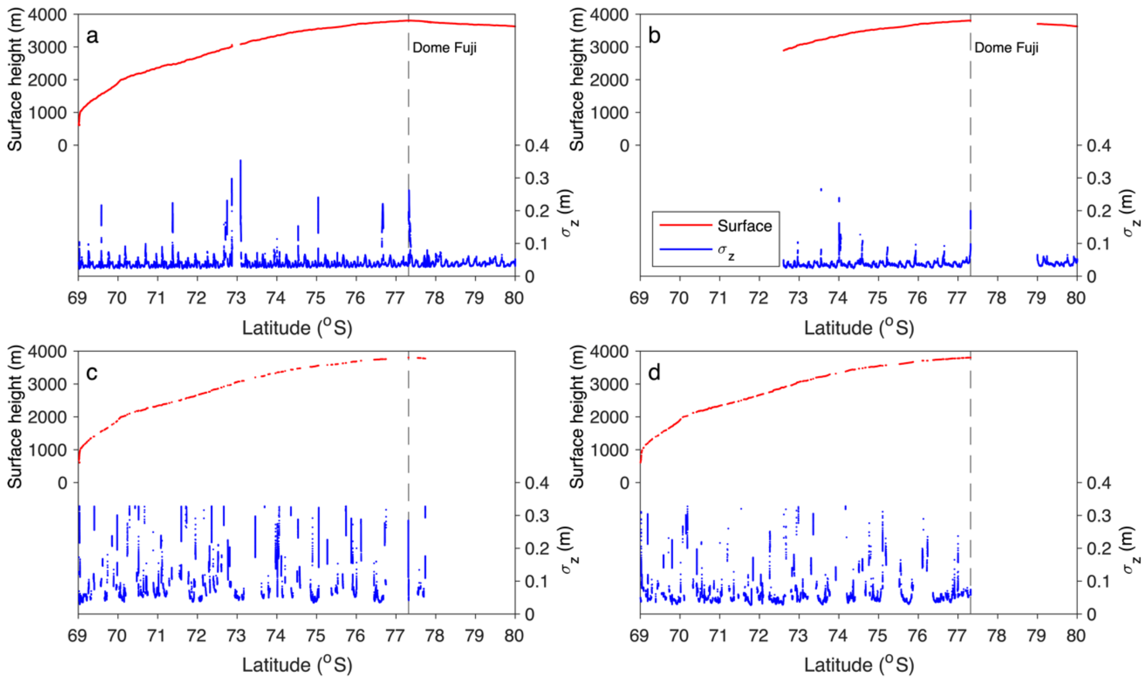

Figure 4. Surface height (red line) and the accuracy of GNSS measurements in the vertical direction (σ_z, blue line) along the surveyed route from (a) S16 to S80 during the 54th expedition, from (b) S80 to S16 during the 54th expedition, from (c) S16 to the BC during the 60th expedition, and from (d) the BC to S16 during the 60th expedition. Dashed lines indicate the location of Dome Fuji.

7. Tables

Table 1. The durations of the GNSS surveys and the number of data points. The data files are provided in CSV file format.

GNSS data filename	Date start YYYY/MM/DD	Date end YYYY/MM/DD	Number of data points
JARE54_S16_S80.csv	2012/11/23	2012/12/29	933895
JARE54_S80_S16.csv	2013/01/04	2013/01/23	329117
JARE60_S16_BC.csv	2018/11/15	2018/12/10	122722
JARE60_BC_NDF.csv	2018/12/18	2018/12/29	163546
JARE60_BC_S16.csv	2019/01/02	2019/01/19	200215

Author contributions

S. Tsutaki, K. Fukui, H. Motoyama, S. Fujita and K. Kawamura planned and conducted the field campaigns and designed the study. A. Hattori and J. Okuno performed post-processing of GNSS data. S. Tsutaki prepared the GNSS datasets and wrote the manuscript with input from all co-authors.

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Data Citations

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