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ICESat's performance and the application in Dome A area in Antarctica

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Abstract This paper summarized the on-orbit measurement performance of GLAS, and analyzed the precision of its data products. By comparing the high-accuracy ICESat measurements with the GPS ground surveys during 21st CHINARE inner ice sheets expedition, it is analyzed and validated that the suggested Dome A area and the measured peak point of Antarctica inner ice sheets defined during 21st CHINARE are both correct.

Key words GLAS, on-orbit performance, GPS, Dome A, ICESat

The Ice, Cloud and Land Elevation Satellite (ICESat) is Earth's first polar orbiting satellite carrying a laser altimeter, launched from Vandenberg Air Force Base California U.S. on January 13, 2003. The Geoscience Laser Altimeter System (GLAS) on the ICESat was designed, constructed and tested at NASA Goddard Space Flight Center (GSFC). ICESat is an integral part of NASA's Earth Observing System (EOS), and its primary purpose is to determinate the inter-annual and long-term changes in polar ice-sheet volume (and inferred mass change) with sufficient accuracy to assess their impact on global sea level change (Zwally *et al.* 2002). Although ICESat has been designed to meet the demanding requirements of cryosphere applications, the GLAS measurements have interdisciplinary applications to land topography, hydrology, vegetation canopy heights, cloud heights and atmospheric aerosol distributions. This paper summarized the on-orbit measurement performance of GLAS to date, and analyzed the accuracy of its elevation measurements, then investigated the digital elevation model (DEM) of inner ice sheets in China expedition research areas, which was generated by using the data of satellite laser altimetry.

1 Introduction

The combined GLAS and spacecraft bus are collectively known as ICESat, which uses the GPS tracking system to determine the GLAS reference position in space.

The spacecraft allows to agilely pointing to the selected target, which may offset the nominal nadir track. Such off-nadir pointing is allowed up to ±5°, that is the locations away from the ground reference track up to ±50 km. In the polar regions, to get high-accuracy measurements, ICESat always points to the reference track to compensate for natural orbit drift and enable near repeats (±100 m) of the tracks.

ICESat runs on the near-polar low Earth orbit of approximately 600 km altitude with a 94° inclination. The diameter of laser footprints is averaged only 60 m, spaced at 172 m along-track. Two reference orbits (or tracks) have been used by the mission: an 8-day exact repeat and a 91-day exact repeat (with a 33 day sub-cycle). The 8-day interval is adopted to enable frequent repeats of ground calibration sites (near McMurdo Dry Valleys in Antarctica) and the longer interval is adopted to provide denser track coverage for science applications.

2 GLAS on-orbit performance

The laser 1 was activated over Svalbard Norway at 15: 18 MST, on February 20, 2003. The GLAS 1064 nm measurements showed strong echo pulses from the surface and cloud tops, whereas the operation of 532 nm detectors was delayed. After ten days, laser 1 showed unusual and faster than expected energy decline, and it failed on the 38th day. It discovered unexpected manufacturing defects in the laser diode pump arrays used in the flight lasers (Abshire *et al.* 2005). The problem was in an inaccessible area in a commercial part and was latent in its effects, so its symptoms were not evident in the earlier prelaunch part life tests or in pre-flight laser test.

To maximize its duration, the ICESat mission was re-planned to operate the remaining two GLAS lasers for three 33-day campaigns per year. This reduced the GLAS measurement duty cycle from 100% to 27% per year. The laser operation campaigns were given in Table 1. The campaigns after Laser 2a operation period repeat the last 33 days of the 91-day repeat cycle of Laser 2a.

Table 1 Laser Operation/Science Campaign Summary

Laser Campaign	Start Date Y-M-D	End Date Y-M-D	Orbit Repeat datys	Laser Campaign	Start Date Y-M-D	End Date Y-M-D	Orbit Repeat datys
L1	2003-02-20	2003-03-29	8	L 3a	2004-10-03	2004-11-08	91/33
L 2a	2003-09-25	2003-10-04	8	L 3b	2005-02-17	2005-03-24	91/33
L 2a	2003-10-04	2003-11-18	91/33+	L 3c	2005-05-20	2005-06-23	91/33
L 2b	2004-02-19	2004-03-21	91/33	L 3d	2005-10-21	2005-11-24	91/33
L 2c	2004-05-18	2004-06-21	91/33	L 3e	2006-02-22	2006-03-27	91/33

During Laser 2a operation period, all instrumentation operated at or near expected performance, and the laser was precisely pointing to the ground reference orbit over the ice sheets. The accuracy of Laser 2a measurements is best. During other periods, some instruments didn't operate at normal state, for example, laser 1 was not pointing to the reference track over the ice sheets, therefore the spacing between repeat tracks varied from hundreds of meters to 1 kilometer. In addition, during some campaigns, diminished laser energy in the 532 nm channel has affected the atmospheric channel measurements (Schutz *et al.* 2005). So the measurements of Laser 2a campaign were adopted by most experiments.

Although instrument issues have delayed the completion of full calibrations of the elevation products, the full set of data is being reprocessed with the goal of reaching the high accuracy exhibited by the Laser 2a Release 21 and data from other operation periods. Fricker *et al.* (2005) used GPS ground surveys to show that the absolute accuracy of L2a Release 21 over salar de Uyuni (after saturation correction) is about 2 cm. Martin *et al.* (2005) used accurate terrain models, which have been independently generated by the NASA Airborne Terrain Mapper in the Western U.S. and in the Dry Valley's of Antarctica, to show that Laser 2a Release 21 range bias is less than 2 cm and pointing error is less than 2 arcsec(1– σ).

3 Application of ICESat Data in Dome A Area

ICESat measurements include fifteen standard data products, generated by the ICESat-Science Investigator-led Processing System (I-SIPS). They are available from the National Snow and Ice Data Center (NSIDC). In the polar regions, the accuracy of the surface elevation measurements is about 15 cm. With the high-accuracy GLAS data, the precise three-dimensional model of polar ice sheets can be produced. By comparing GLAS elevation measurements with GPS ground survey text during 21st CHINARE inner ice sheets expedition, this paper analyzed and validated that the Dome A area defined by RAMP DEM and the measured peak point of Antarctica inner ice sheets by GPS are both correct.

The route survey range of 21st CHINARE inner ice sheets expedition is 69° 22′16″ S - 80° 22′ 00″ S, 76° 15′ 53″ E-77°59′ 26″ E. Doctor Zhang Shengkai, a member of the 21st CHINARE, defined the Antarctic inner ice sheets peak point in Dome A area by using ground GPS survey, on January 18, 2005. The point is located at 80°22′00″ S, 77°21′11″ E, with the altitude of 4093 m.

Human have never reached the Dome A area before, so there is no data from the field observation. Initially the CHINARE team adopted the Radarsat Antarctic Mapping Project Digital Elevation Model (RAMP DEM) with 200 m resolution to predict the location of inner ice sheets peak point. RAMP DEM data were collected from multiple data sources, including satellite/airborne radar altimeter, GPS surveys and geodetic maps, and most of them were collected during the 1980s and 1990s. Based on the RAMP DEM, the potential peak point was defined, then from the point expanding about 100 km × 100 km area known as Dome A area (figure 1). In Dome A area, the vertical accuracy of RAMP DEM is better than 7.5 m. Figure 1 shows that the peak point may be located in two possible areas: Area I and Area II. The coordinates of Area I center is 80°28′29″ S, 76°50′14″ E, and that of

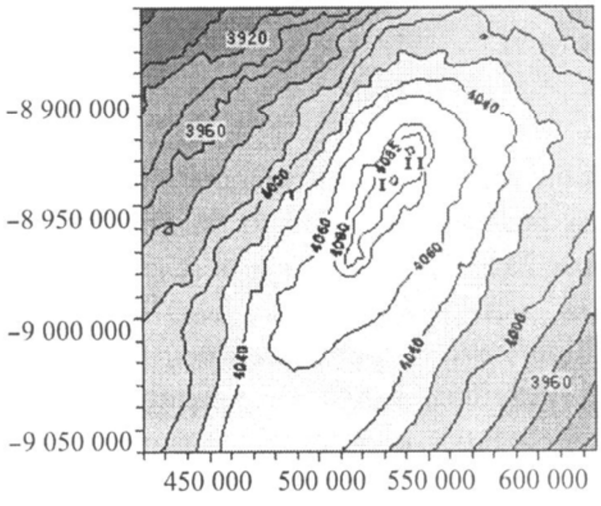

Fig. 1 Contour map of Dome A based on RAMP DEM (Central meridian: 75° E, False easting: 500 km).

Area II center is 80°21′26″ S, 77°20′53″ E, spacing at about 15 km. The field observation by GPS during 21st CHINARE validated that the Antarctic inner ice sheets peak point located in Area II, consistent with the result of RAMP DEM.

The verification data used in this paper is the polar ice sheet altimetry product——GLA12 data, part of the ICESat's fifteen data products. The used data is from Laser 2a operation period of version 24. The coverage range is 68°-86°S, 75°-79°E, including the ground survey area of 21st CHINARE inner ice sheets expedition.

ICESat used the same ellipsoid as TOPEX/Poseidon and Jason-1 used. To compare the ICESat data with the field observation, it needs to transform the ICESat measurements into WGS-84 coordinate system used by GPS. The differences in geodetic latitude and longitude between ellipsoids will produce a horizontal displacement of only a few centimeters, which is well below the GLAS accuracy in horizontal geolocation, so the displacement can be ignored. Accounting for different ellipsoids with adequate accuracy, the elevation adjustment is a straightforward function of latitude. It is possible to approximate the change in elevation between ellipsoids for particular latitude using an empirical formula as follows

$$\Delta h = h_2 - h_1 = -((a_2 - a_1)^* \cos^2 B + (b_2 - b_1)^* \sin^2 B) \qquad (1)$$

Where Δh is the difference in elevation between ellipsoids. B is geodetic latitude. h_1 and h_2 is elevations for ellipsoids 1 and 2, respectively. a_1 and a_2 is equatorial radii of ellipsoids 1 and 2, respectively. b_1 and b_2 is polar radii of ellipsoids 1 and 2, respectively.

To draw the ice sheets topography, it is needed to grid the ICESat discrete data. The GLAS elevation measurements are quite dense in interested area (Figure 2), and the topog-

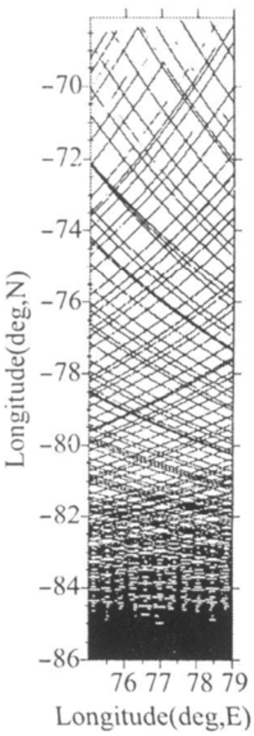

Fig. 2 ICESat data from Zhongshan Station to Dome A area

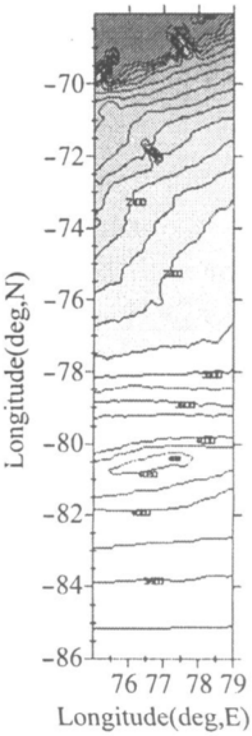

Fig. 3 Zhongshan Station to Dome A area's contour by ICESat data

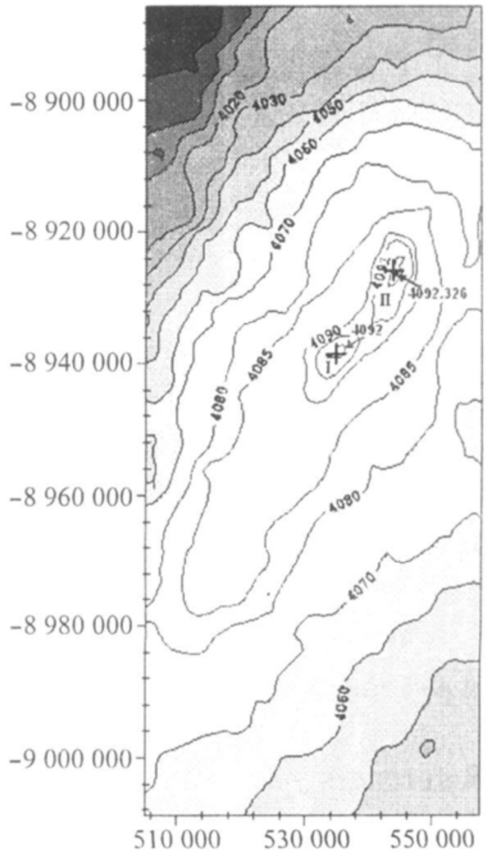

Fig. 4 Dome A area's contour by ICESat data

raphy is relatively flat along the expedition line. So Kriging method was used to grid the ICESat data by Surfer software. The ice sheets DEM from Zhongshan Station to Dome A is given in figure 3.

Gauss Project was done with the Dome A area selected from the DEM of Zhongshan Station to Dome A area as shown in figure 3, with 75° E central meridian and 500km false easting. Its isoline map is shown in figure 4. There are four isolines whose elevation values are greater than 4090 m, 4090 m, 4091 m, 4092 m and 4092.326 m respectively. According to the distribution of GLAS elevation measurements, the area where elevation value is greater than 4091 m can be divided into two small regions. The two regions and their centers are respectively in consistent with the Dome A peak point possible Area I and Area II defined by RAMP DEM. So it can conclude that the Area I and Area II defined by RAMP DEM are reasonable.

In figure 4, the area, where elevation value is greater than 4092.326 m, is contained in the possible Area II defined in RAMP DEM, and its center coordinates is 80°21′36″ S, 77°20′24″E. The maximum elevation value from ICESat data is 4092.408 m, located at 80° 21′ 46″ S, 77° 20′ 13″ E, which is about 500 m away from the field survey Dome A peak point. So it is proved that the Antarctica inner ice sheets peak point indeed lays in this area and the Dome A peak point determined by GPS ground survey during 21st CHINARE is accurate.

4 Conclusions

This paper analyzed the ICESat's on-orbit performance and its elevation measurements. ICESat data can be used to generate the Antarctic ice sheets DEM, satisfying the requirements of polar research. Among all CLAS campaigns, Laser 2a measurements are the best, with high density and high accuracy, which can be used to analyze the polar glacier movement and the ice sheets environment change.

In this experiment, the ICESat data were first adopted to validate the position of Antarctic inner ice sheets peak point determined during 21st CHINARE. The DEM of Dome A area derived from ICESat data is consistent with the RAMP DEM, and the Dome A peak point measured by GPS ground survey is located in the highest area of the ICESat DEM, quite near the max measurement of GLAS. So it validates that the interested Dome A area defined in RAMP DEM and the Dome A peak point measured by GPS during 21st CHINARE are both correct.

Moreover, the data from GPS ground survey also validate the accuracy and reliability of the space measurements.

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