Precision and Accuracy of Satellite Radar and Laser Altimeter Data Over the Continental Ice Sheets

Anita C. Brenner, John P. DiMarzio, and H. Jay Zwally

***Abstract*—The unprecedented accuracy of elevations retrieved from the Ice Cloud and Land Elevation Satellite (ICESat) laser altimeter is investigated and used to characterize the range errors in the Environmental Satellite (Envisat) and European Remote Sensing 2 Satellite (ERS-2) radar altimeters over the continental ice sheets. Cross-mission crossover analysis between time-coincident ERS-2-, Envisat-, and ICESat-retrieved elevations and comparisons to an ICESat-derived digital elevation map are used to quantify the radar elevation error budget as a function of surface slope and to investigate the effectiveness of a method to account for the radar altimeter slope-induced error. The precision and accuracy of the elevations retrieved from the ICESat Geoscience Laser Altimeter System and the European Space Agency radar altimeters on ERS-2 and Envisat are calculated over the Greenland and Antarctic ice sheets using a crossover analysis. As a result of this work, the laser precision is found to vary as a function of surface slope from 14 to 59 cm, and the radar precision varies from 59 cm to 3.7 m for ERS-2 and from 28 cm to 2.06 m for Envisat. Envisat elevation retrievals when compared with ICESat results over regions with less than 0.1° surface slopes show a mean difference of 9 ± 5 cm for Greenland and -40 ± 98 cm over Antarctica. ERS-2 elevation retrievals over these same low surface slope regions differ from ICESat results by -56 ± 72 cm over Greenland and 1.12 ± 1.16 m over Antarctica. At higher surface slopes of 0.7° to 0.8°, the Envisat/ICESat differences increase to -2.27 ± 23 m over Greenland and to 0.05 ± 26 m over Antarctica.**

***Index Terms*—Altimetry, ice, laser measurements, radar altimetry, remote sensing.**

I. Introduction

SATELLITE altimetry over the continental ice sheets has proven to be a valuable tool in studying decadal ice sheet mass balance changes by yielding measurements of elevation changes over the past 26 years over Greenland and Antarctica [1]–[3]. Since 1991, we have had continuous coverage of all of Greenland and Antarctica to 81.5° south by the European Space Agency (ESA) radar altimeters on the European Remote Sensing Satellites (i.e., ERS-1 and ERS-2), and Environmental Satellite (ENVISAT). In 2003, the Ice Cloud and Land Elevation Satellite (ICESat) was launched by the National Aeronautics and Space Administration (NASA) carrying the Geoscience Laser Altimeter System (GLAS) instrument [4]. GLAS has three lasers, each of which was projected to last a period of 1–1.5 years and give a precision of under 20 cm over the continental ice sheets. Problems with the first two lasers occurred, which have forced changes to the mission operations plan. Instead of operating continuously, the remaining lasers have been powered on and off at three- to six-month intervals to maximize the use of the ICESat mission for elevation change studies. The existing ICESat data set, with its unprecedented accuracy and precision, is now a valuable tool for quantifying the accuracy and improving the interpretation of the radar altimetry measurements.

TABLE I
SUMMARY OF THE DATA USED IN THIS PAPER

Mission	Time span in 2003	Mode	Waveform bin resolution (cm)	Source
ERS-2	2/21-3/31	ice mode	174	UK-PAF
ICESat/Laser 1	3/5-3/21	NA	15	Release 18
ENVISAT	10/1-11/31	fine mode	46	ESA SGDR
ICESat/Laser 2a	9/25-11/18	NA	15	Release 21

Most previous validations of radar altimetry have used airborne laser data [5] and *in situ* measurements, both of which have limited geographic coverage. Recently, GLAS data have been used to access the accuracy of Antarctic digital elevation maps (DEMs) produced mostly from radar altimetry [6]. In this paper, we compare the very precise ICESat data, which cover large portions of Greenland and Antarctica with time-coincident ERS-2 and Envisat data giving a maximum limit to the residual errors remaining in the radar-retrieved elevations. The differences in the radar- and laser-retrieved elevations include errors in the radar retrievals due to inaccurate modeling of surface penetration, the slope-induced error caused by the large radar footprint, and limitations in the ability of the processing algorithm to retrieve a precise geolocated elevation. The major errors in the laser retrieval are due to inaccurate modeling of the saturation and forward scattering affects on the return and the inaccuracies in the retrieved laser pointing angle. The slope-induced error in the laser retrievals is not a concern because of the narrow divergence of the laser beam. The radar altimeters cannot maintain track over regions of large surface slope; however, they measure through all atmospheric conditions. The laser altimeter can measure over all ice sheet surfaces, but it cannot measure through thick clouds.

This paper uses a crossover analysis with intramission passes to calculate the relative accuracy or precision of height

Manuscript received June 6, 2006; revised August 14, 2006. This work was supported in part by the National Aeronautics and Space Administration Cryosphere Program and in part by the Ice Cloud and Land Elevation Satellite Project Scientist.

A. C. Brenner is with Science Systems and Applications, Inc., Lanham, MD 20706 USA (e-mail: Anita_Brenner@ssaihq.com).

J. P. DiMarzio is with Stinger Ghaffarian Technologies, Inc., Greenbelt, MD 20770 USA (e-mail: john.p.dimarzio@gsfc.nasa.gov).

H. J. Zwally is with the National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, MD 20771 USA (e-mail: H.J.Zwally@nasa.gov).

Digital Object Identifier 10.1109/TGRS.2006.887172

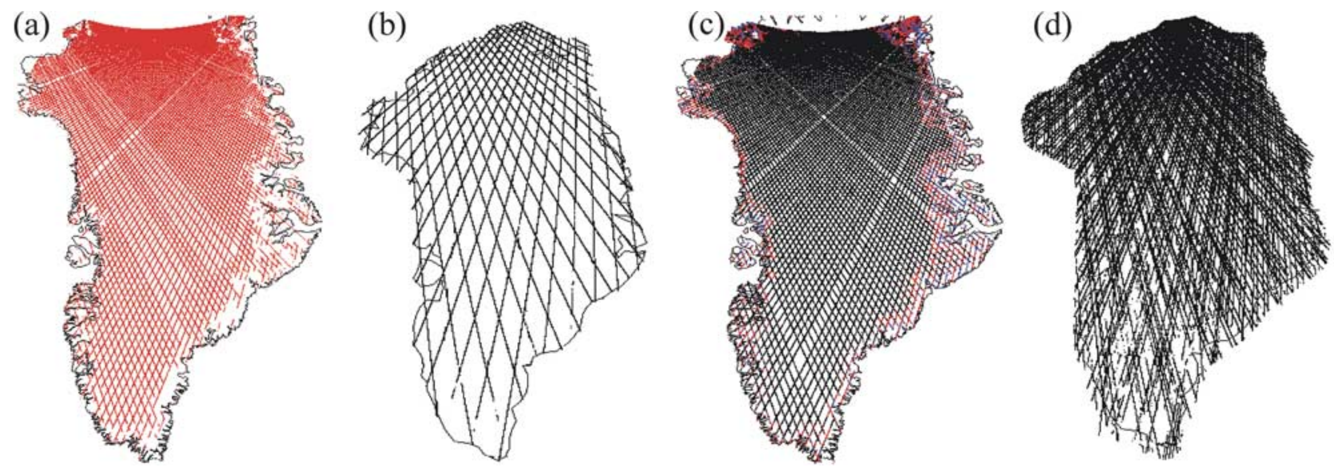

Fig. 1. Data used for the Greenland portion of the study. Black is ICESat or Envisat fine mode. Red is ERS-2 ice mode or Envisat medium-resolution mode, and blue is Envisat coarse mode. (a) ERS-2. (b) ICESat Laser 1. (c) Envisat. (d) ICESat Laser 2a.

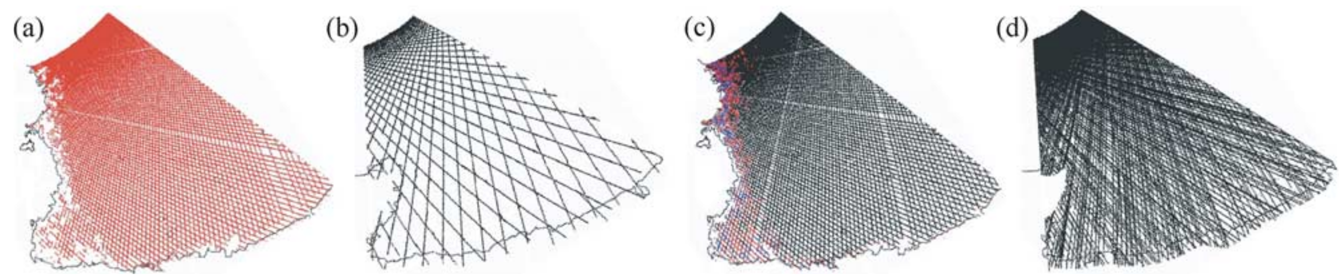

Fig. 2. Segment of the data used for the Antarctica portion of the study. Black is ICESat or Envisat fine mode. Red is ERS-2 ice mode or Envisat medium-resolution mode, and blue is Envisat coarse mode. (a) ERS-2. (b) ICESat Laser 1. (c) Envisat. (d) ICESat Laser 2a.

elevations retrieved from ERS-2, Envisat, ICESat Laser 1, and ICESat Laser 2a measurements. This procedure also yields an accuracy calculation from crossovers over the nonsloping regions. The accuracy of the radar altimeter relative to the laser is calculated from intermission crossovers using time-coincident radar- and laser-retrieved elevations. A quantitative measurement of the difference between ERS-2- and Envisat-retrieved elevations over the continental ice sheets as a function of surface slope, as processed with the NASA Goddard Space Flight Center (GSFC) algorithms, is achieved by direct comparison between ERS-2 and Envisat and by comparing them individually to the ICESat-retrieved elevations. In addition, a quantitative evaluation of the effectiveness of the radar altimeter slope-induced error correction is carried out using the radar–laser intermission crossovers and by comparing the radar-retrieved elevations to an ICESat-derived DEM. In this paper, we investigate the precision and accuracy of the laser- and radar-retrieved elevations using the GSFC retrackers and radar slope correction procedures. Other approaches have been used by other investigators and will produce different results.

II. Data Description

ICESat Laser 1 operated from February 20 to March 29, 2003, for which time-coincident ERS-2 ice sheet data were also obtained. The Envisat data over the ice sheets for this time period have not yet been distributed to the authors. ICESat Laser 2 operated from September 25 to November 19, 2003, and will be referred to as Laser 2a. ESA has distributed the time-coincident Envisat data for the Laser 2a time period; however, the ERS-2 altimeter was no longer operating over the ice sheets. A summary of the data used in this paper is given in Table I.

V. Summary

ICESat-derived elevations are significantly more accurate and of higher precision than those derived from the radar altimeters. Therefore, ICESat can be used to determine the general magnitude of the residual error in the ERS-2- and Envisat-derived elevations. The ICESat data used for this paper were of a preliminary nature and still include errors due to imprecise pointing knowledge, saturation, and atmospheric forward scattering. Corrections for saturation and atmospheric forward scattering are being worked on by the ICESat science team, as is improvement in the pointing knowledge. This paper shows the precision of ICESat-retrieved elevations over the ice sheets to vary from 14 to 50 cm as a function of surface slope.

The radar altimeter-derived elevation accuracy is driven by the slope-induced error. The results show that Envisat data have improved precision and accuracy over ERS-2 data as expected by the finer resolution range bins used. In regions of very low slope, the Envisat data agree to within 9 cm $\pm$ 0.5 m with the ICESat results over Greenland. The GSFC range correction for the slope-induced error corrects for a good portion of the error at slopes less than 0.9°. However, the correction is not accurate enough to combine the laser and radar measurements in elevation change studies. The laser–radar results show, as expected, that the threshold retracker gives less accurate absolute elevations than the GSFC V4 retracker but has better internal consistency as evidenced by the lower noise levels.