A COMPARISON OF ICE FREEBOARD MEASUREMENT BY ICESAT AND ENVISAT ALTIMETERS

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ABSTRACT

Remote sensing plays an essential role in the continuous monitoring of sea ice in polar regions. This study fills the gap in literature by conducting a cross-mission analysis between ICESat and EnviSat from 2005 to 2009. The methodology consists of two parts: 1) Compare ocean surface elevation measurement. 2) Deriving freeboard from ICESat and EnviSat independently. Results show that: 1) There is a strong correlation between ICESat and EnviSat measured surface elevation. 2) Despite the penetration ability of Ku band radar altimeter, EnviSat measured elevation is consistently above ICESat. 3) According to the estimated freeboard, Southern Beaufort Sea is dominated by first year ice.

Index Terms— Sea ice; free board; altimeter; Arctic

1. INTRODUCTION

As global warming becomes one of the most pressing issues, the monitor of sea ice has attracted increasing attention. Sea ice thickness (SIT) is a critical, yet least investigated parameter in understanding the physical process of the polar ocean [1]. SIT is commonly derived from freeboard by assuming hydrostatic equilibrium [6-8]. Remote sensing is a powerful tool for monitoring polar regions that are hostile for in situ observations. There are various satellites aimed at cryosphere monitoring, such as ERS-1, ERS-2, EnviSat, ICESat, CryoSat, etc. The laser altimeter onboard ICESat and radar altimeter onboard EnviSat both measure surface elevation and ocean topography. However, few studies have done the cross-mission analysis between ICESat and EnviSat derived elevation. [3] performed a crossover analysis between ERS-2, EnviSat and ICESat to assess the precision and accuracy of altimeter data over continental ice sheets (Greenland and Antarctica). Results show that these three datasets differ significantly over sloped surface (up to 26 m). [1] and [2] compared radar altimetry with airborne laser data. Similar to [3], [2] also reported a positive correlation between elevation differences and surface slope. However, [1] found that there is good agreement between RA-2 derived and airborne laser measured sea ice elevations, especially over leads where the overall mean difference is about 1cm. Currently, there is a lack of research on the difference between RA-2 and ICESat measured elevation over sea ice.

This study has three objectives: First, compare the surface elevation measurements from ICESat and EnviSat. Second, discuss the possibility of using coincident radar and LiDAR measurement to derive snow depth. Third, derive freeboard from ICESat and EnviSat independently and compare the results.

2. STUDY AREA AND DATASETS

The study area is located in the Southern Beaufort Sea Gyre, north of Alaska. In order to understand the mechanism of fresh water accumulation and other physical process in the Beaufort Gyre, four moorings are deployed underwater (shown as stars in Fig.1) by the Beaufort Gyre exploration project providing ice draft, ice motion, salinity, etc. According to [4], first year (FY) ice is becoming the dominant ice type and multi-year (MY) ice is becoming rare. The declining of ice extent has threatened the survival of polar bears [11]. Our study helps to understand the seasonal variation of sea ice thickness.

Table 1 Datasets information

Dataset	Operational period	Resolution	Operate by
ICESat	2003-2009	60m footprint	NASA
EnviSat RA-2	2002-2012	18km footprint	ESA
EnviSat ASAR	2002-2012	150m	ESA
Aqua AMSR-E	2002-2011	Vary with band	NASA

Three datasets are used in this study (Table 1): ICESat level-2 GLAH13 product, EnviSat Radar Altimeter-2

Geophysical Data Record, and EnviSat ASAR wide swath images.

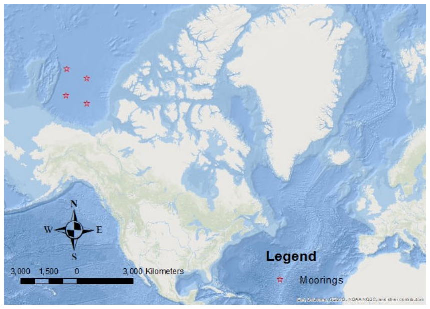

Fig.1. Study Area

3. METHOD

Sea ice is treated as a two- layer model with a snow layer on top of the sea ice pack. This model was adopted from [5]. ICESat freeboard (F_I) is defined as the vertical distance between the air/snow interface to sea surface, whereas the EnviSat freeboard (F_E) is defined as the vertical distance between the snow/ice interface to sea surface. This is because of the Ku band of radar altimeter is known to have certain abilities to penetrate dry snow and reflect at snow-ice interface [6, 7].

3.1. Surface elevation measurements from ICESat and EnviSat

Surface elevation was extracted from existing records from 2005 to 2009. The ICESat GLAH13 product provides sea ice and open ocean elevation that has been corrected for geodetic and atmospheric affects. Surface elevation is acquired after saturation correction has been applied.

In order to take advantage of the overlapping footprint, the elevation information is extracted by averaging overlapping footprint at 0.3 km interval using the Broadview Radar Altimetry Toolbox (BRAT). The Geophysical Data Record (GDR) is corrected prior to analysis. Based on the descriptions in [10], the applied corrections are as follows: "Geophysical Corrections = Inverse Barometer + Sea State Bias + Ionospheric Correction + Ocean Tide + Polar Tide + Earth Tide + Wet Tropospheric Correction + Dry Tropospheric Correction", of which the dry Tropospheric correction is the largest correction that is approximately 2.3m and has to be added to the range measurement.

3.2. Freeboard Retrieval

There are three approaches to derive freeboard from ICESat [5]: 1) identify tiepoints from ICESat profile and coincident SAR image. 2) identify records whose reflectivity is lower than the background snow, and the elevation exceeds an expected deviation below that of the local mean surface elevation. 3) identify tiepoints solely based on the elevation exceeds certain deviation of local mean surface elevation. Essentially, the derivation of freeboard is the attempt to discriminate lead from sea ice. Similar to [8], we adopt the third approach by using an estimation of leads percentage to define tie-points.

ICESat measured elevation reference to current geoid model (h) is presented in Fig.2. As can be seen, the relative elevation variation can reach 1m, which obviously cannot be used as freeboard measurement. To remove such error, a 20-km running mean for h is calculated (h_m) (Fig.2), which will be used as a new reference plane to calculate SSH. The elevation profile referenced to this new plane is denoted h_r, which is derived by h-h_m.

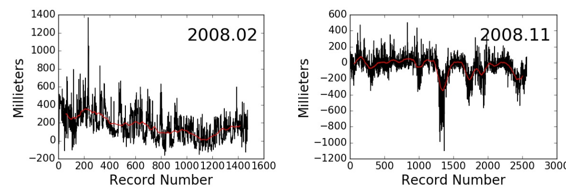

Fig.2 ICESat elevation referenced to geoid (h, black) and 20 km running mean (h_m, red). November and February 2008.

h_m is then treated as the new reference plane. According to [9], leads cover 6% to 9% of the surface areas in winter in Arctic peripheral seas. Thus, we assume that ICESat can detect lead in at least 6% in a 50km segment of profile. That is, the ocean level at any footprint is determined by averaging the lowest 6% of the h_r value within +/-25 km of that point, which is about continuous +/-150 points. Then, freeboard at a given footprint is derived by h_r-h_s (Fig. 3).

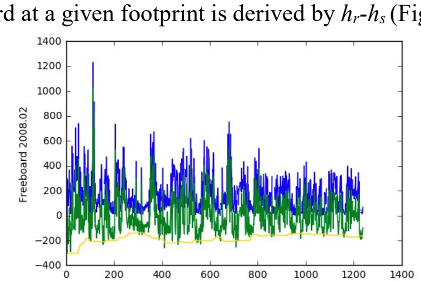

Fig.3 hr (green): elevation reference to the running-mean plane, hs (yellow): estimated sea surface height, F (blue): estimated freeboard). February 2008.

To validate the SSH estimation, near-coincidence ASAR images are used to compare with ICESat profiles. Fig.4 displays a 100 km ICESat profile over 1-day earlier ASAR image. Result shows reasonable agreement. There are a few places with ICESat elevation drop but no leads are shown on the SAR image. One possible explanation is that the ICESat track was 1 day later than the SAR image. It is possible that the lead formed within this period, thus not detected by

ASAR. Overall, the comparison clearly shows the identification of lead from ICESat profile is doable.

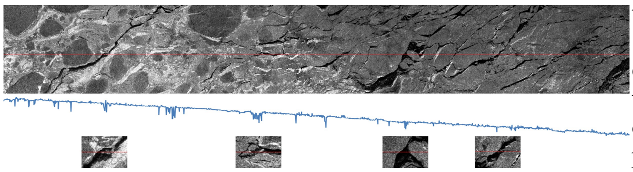

Fig.4 Validation of open ocean surface estimation with SAR image

4. RESULTS

In respect to our objectives, the results are presented in the following three sections.

4.1. Comparison of surface elevation measurements

The comparison of surface elevation measured by ICESat and EnviSat is presented in Fig.5. The scatterplot is created by comparing the elevation of each ICESat record with its nearest Radar altimeter sample. It can be seen that there is a strong correlation between these two sets of measurements. However, the ICESat measured elevation is almost consistently below EnviSat measured elevation by 1.5m.

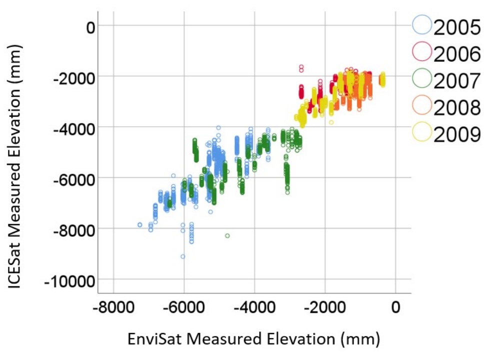

Fig.5 Comparison of surface elevation reference to WGS84 Ellipsoid

4.2. Using a combination of radar and LiDAR altimeters to derive snow depth over sea ice

The original assumption of radar altimeter scatters at snow/ice interface is no longer valid after the surface elevation measurement comparison. Thus, the attempt to estimate snow depth does not succeed. Nevertheless, if the mechanism of radar altimeter scattering can be better understood, it is still possible to derive snow depth from coincident radar and LiDAR altimeters. Ku band Radar altimeter's ability to penetrate dry snow has been well acknowledged [12, 13]. However, it was also observed as being highly affected by snow characteristics such as wetness, density and temperature [13, 14]. In order to further investigate the impact of snow characteristic, the relationship between surface temperature and difference in ICESat and RA2 measured elevation is analyzed.

Surface temperature is derived using AMSR-E brightness temperature measurement based on the formula presented in [15]. This method utilizes the difference in grey body emissivity in different wavelengths to estimate surface temperature. A correlation analysis is performed to determine if temperature has an effect on Ku band radar penetrability. Result shows that the Pearson correlation is 0.056 with a p-value of 0.066. Even though the correlation is significant at 0.1 level, it is difficult to determine the impact of temperature with such a low correlation.

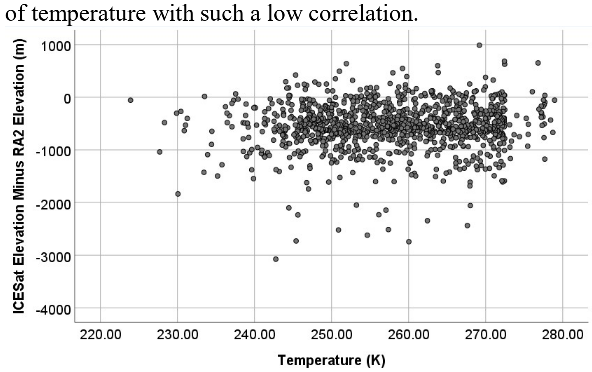

Fig.6 Comparison of surface elevation reference to WGS84 Ellipsoid

4.3. Comparison between ICESat and EnviSat derived freeboard

F_I measurements of each month are shown in Fig.7. There are two distinct types of histogram representing different ice type distribution. The results match well with the findings in [8]. Most of the figures display asymmetric, left-skewed distribution, which indicates this area is dominated by first year ice with freeboard less than 0.4m. Few figures display symmetric distribution (June 2005, May 2006, June 2006, April 2009), which indicates a mixture of first year ice and multiyear ice. The last histogram (October 2009) displays two separate peaks, which indicates the ice are in transition, with the first peak represents young ice or open water, and the second peak represents thicker, multiyear ice.

F_E is derived by subtracting mean surface height from the elevation measurement. Due to ocean dynamic and sea ice motion, the mean sea surface height is not an efficient representation of real time SSH. The majority freeboard estimation varies from -0.5m to 2.5m, with a peak at 1.5m. Based on common knowledge and F_I measurement, this is not a realistic representation of freeboard.

5. CONCLUDING REMARKS

The study filled the gap in cross-mission analysis by comparing the ocean surface elevation measured by ICESat and EnviSat in the Beaufort Sea Gyre, and analyzed the current difficulties in data integration. Results show that the measurements from two satellite match well. However, in order to acquire more accurate freeboard estimation, the source of echo for radar altimeter measurement needs to be determined.

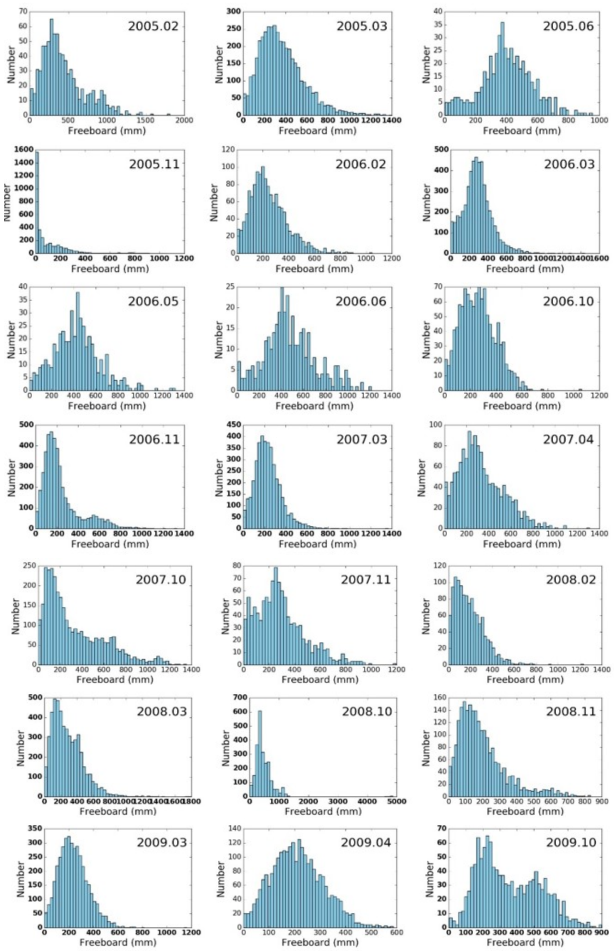

Fig.7 F_I distribution by month

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