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Combined airborne laser and radar altimeter measurements over the Fram Strait in May 2002

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Abstract

Knowledge of sea ice thickness is critical for the prediction of future climate, and for assessing the significance of changes in thickness. Sea ice thickness can be calculated from radar or laser satellite altimetry measurements of freeboard. However, a lack of knowledge of snow depth introduces significant uncertainties into these calculations.

This paper compares the first coincident airborne laser and radar altimetry data over sea ice, collected during the Laser Radar Altimetry (LaRA) field campaign. LaRA was a flight of opportunity that provided valuable data to explore techniques to validate satellite measurements of ice freeboard, and the possibility of combining laser and radar measurements over snow covered sea ice to calculate the snow depth. Two new methods were created to analyse these data sets: a new radar retracker and a radar power simulator, which models radar returns from the laser data.

We present the first quantitative analysis of data from the LaRA laser and radar altimeters, and demonstrate the potential of combining laser and radar altimetry to estimate snow depth. LaRA elevation estimates compare well with elevations from the radar altimeter onboard ERS-2 at the sub-meter level and the study provides lessons for future validation of satellite altimetry data over sea ice. Laser elevations are consistently higher than the radar elevations over snow covered sea ice. As LaRA was a flight of opportunity, no coincident in-situ measurements were available. Nevertheless, the difference between the reflecting surface of the laser and radar is consistent with snow depth from climatology and the analysis techniques developed in this paper will be useful for future radar and laser altimetry comparisons.
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Keywords: Radar altimetry; Laser altimetry; Sea ice thickness; Snow depth

1. Introduction

Knowledge of Arctic sea ice thickness is critical to our estimates of sea ice reduction and consequently increased fresh water input into the Greenland, Iceland and Norwegian Seas, a factor that may ultimately affect the thermohaline circulation (Aagaard & Carmack, 1989). Sea ice also inhibits the transfer of heat, moisture and momentum between the atmosphere and the ocean (Ledley, 1993) and has a high albedo compared to the ocean (Curry et al., 1995), so is an important component in climate models. Therefore, systematic, basin-wide estimates of sea ice thickness are required for both model improvement (Rothrock et al., 2003) and trend detection (McLaren et al., 1990). While analyses of passive microwave satellite data have provided a record of sea ice extent for approximately the past 30 years (Comiso, 2006), in-situ ice thickness measurements are spatially and temporally limited (Bitz et al., 2001). One of the two main objectives of the forthcoming European Space Agency satellite radar altimetry mission, CryoSat-2, is to provide an estimate of the trend in spatially averaged sea ice thickness (Wingham et al., 2001).

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Table 1
Typical values of parameters in Eqs. (3) and (4), the error in the calculation of sea ice thickness for radar and laser altimetry respectively, for May

Parameter	Typical value	Reference	Error estimate	Reference
Ice freeboard [1] (f_i)	0.3 m	Haas (2002)	0.03 m	Giles and Hvidegaard (2006)
Snow freeboard (f_s)	0.6 m	From f_i and h_s	0.02 m	Kwok et al. (2004)
Snow depth (h_s)	0.3 m	Warren et al. (1999)	0.11 m	Warren et al. (1999), RMS on h_s for May
Water density (ρ_w)	1023.8 kg m^{-3}	Wadhams et al. (1992)	0.5 kg m^{-3}	Wadhams et al. (1992)
Ice density (ρ_i)	915.1 kg m^{-3}	Wadhams et al. (1992)	5 kg m^{-3}	Wadhams et al. (1992)
Snow density (ρ_s)	319.5 kg m^{-3}	Warren et al. (1999)	3 kg m^{-3}	Warren et al. (1999)

[1] Assumes that at least 50 individual freeboard estimates are summed in-order to estimate the mean ice freeboard.

Measurements of sea ice freeboard from satellites (carrying either radar or laser altimeters) have been used to calculate sea ice thickness on a basin wide scale (Laxon et al., 2003) and on a local scale (Kwok et al., 2004). Sea ice thickness is calculated by measuring the elevation of the ice above the water (ice freeboard) if using a radar altimeter, or ice plus snow (snow freeboard) if using a laser altimeter, and assuming hydrostatic equilibrium. The equations to calculate sea ice thickness from freeboard measurements by radar and laser altimeters respectively are

$$h_i = \frac{f_i \rho_w}{(\rho_w - \rho_i)} + \frac{h_s \rho_s}{(\rho_w - \rho_i)} \quad (1)$$

$$h_i = \frac{f_s \rho_w}{(\rho_w - \rho_i)} + \frac{h_s(\rho_s - \rho_w)}{(\rho_w - \rho_i)} \quad (2)$$

where f_i is the radar measured ice freeboard and f_s is the laser measured snow freeboard, h_i, ρ_i and h_s, ρ_s are the thicknesses and densities of the ice and snow respectively and ρ_w is the density of the water.

However, there are uncertainties associated with both these techniques. If we are to use these data sets with confidence we must understand the errors associated with calculating ice thickness, and reduce these errors to a level useful for trend detection and model validation.

The main error sources are:

For radar altimetry;

1) Uncertainty in the location of the radar scattering surface in the snow/ice system. Laxon et al. (2003) assume that the radar reflects from the snow/ice interface. This assumption is based on laboratory measurements by Beaven et al. (1995). However, there are no direct observations to confirm this assumption.

5. Conclusions

We have analysed the first coincident airborne laser and radar altimetry data over sea ice, which, in addition, was also gathered beneath a satellite radar altimeter. The experiment was originally designed to validate spaceborne measurements of sea ice freeboard and to compare coincident laser and radar altimetry data elevations over snow covered sea ice. The results provide lessons for future validation of satellite altimetry data over sea ice and, for the first time, explore in a quantitative manner, the potential for combing laser and radar altimetry to estimate snow depth, the largest uncertainty in calculating sea ice thickness from altimeter measurements of ice/snow freeboard.

We used a newly developed retracker to retrieve ice and water elevations from the radar echo. Although this method allowed comparisons of the airborne and satellite elevation estimates at the sub-meter level, the uncertainties are too large to provide validation of the satellite ice thickness measurements to the desired accuracy. Complex topography can, in some places, confuse the simple retracker and result in significant biases over rough ice surfaces. Our analysis also points to the need to ensure that airborne data is coincident in time and space with the satellite ground track to as high a degree as possible. Ideally the design of the survey area of the field campaign should also cover the extent of the satellite footprint or the area over which the satellite measurements are averaged. For radar altimeters, such as those onboard ERS-2 and Envisat, the survey area would need to be a few kilometers wide. By surveying the surface in this way one has the opportunity to sample the surface as the spaceborne instrument would have.

When comparing the laser and radar data on the aircraft we accounted for complex topography by designing a new algorithm (the D2P power simulator) to simulate the radar returns using the laser derived elevation data. The simulator accounts for varying surface topography as well as variations in the pitch and roll of the aircraft, which can also affect the shape of the radar's return echo. The results from the D2P power simulator demonstrated that the laser-measured surface was consistently higher than the radar-measured surface over snow covered sea ice, consistent with the hypothesis that the radar penetrates to the snow/ice interface. The difference in the elevation of the surface measured by the laser and radar altimeters (Δh) is typically 0.3 m (including the correction for the likely bias due to a drift in the calibration) and is consistent with observed snow depth. Moreover the distribution of Δh compares well to the snow depth distribution from Sturm et al. (2002). The results from this study show that elevation estimates from simple retracking algorithms for airborne radar data may degrade in accuracy over complex topography, due to changes in the return echo shape. Taking this into consideration, the application of the techniques we have described to data from more recent field campaigns, where some in-situ snow depth data have been gathered (e.g. Cavalieri & Markus, 2006), may help shed more light on the questions of radar penetration, and the potential to calculate snow depth from radar and laser altimetry.