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Comparison of Envisat radar and airborne laser altimeter measurements over Arctic sea ice

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ABSTRACT

Sea ice thickness is a crucial, but very undersampled cryospheric parameter of fundamental importance for climate modeling. Advances in satellite altimetry have enabled the measurement of sea ice freeboard using satellite microwave altimeters. Unfortunately, validation of these new techniques has suffered from a lack of ground truth measurements. Therefore, an airborne campaign was carried out in March 2006 using laser altimetry and photo imagery to validate sea ice elevation measurements derived from the Envisat/RA-2 microwave altimeter.

We present a comparative analysis of Envisat/RA-2 sea ice elevation processing with collocated airborne measurements collected north of the Canadian Archipelago. Consistent overall relationships between block-averaged airborne laser and Envisat elevations are found, over both leads and floes, along the full 1300 km aircraft track. The fine resolution of the airborne laser altimeter data is exploited to evaluate elevation variability within the RA-2 ground footprint. Our analysis shows good agreement between RA-2 derived sea ice elevations and those measured by airborne laser altimetry, particularly over refrozen leads where the overall mean difference is about 1 cm. Notwithstanding this small 1 cm mean difference, we identify a larger elevation uncertainty (of order 10 cm) associated with the uncertain location of dominant radar targets within the particular RA-2 footprint. Sources of measurement uncertainty or ambiguity are identified, and include snow accumulation, tracking noise, and the limited coverage of airborne measurements.

1. Introduction

The areal extent of Arctic sea ice, and its generally negative trend of about 10% depletion per decade since 1979, have been well monitored by passive microwave satellites (e.g., Comiso, 2002). However, accurate knowledge of sea ice thickness and its spatial and temporal variability have been more difficult to acquire. Submarine and other in-situ observations of ice thickness (Rothrock et al., 1999), while they indicate a thinning, are sparse and infrequent. But recently techniques have been demonstrated using satellite altimetry, both radar (Laxon et al., 2003) and laser (Zwally et al., 2008), to monitor thickness. Thickness and extent of sea ice are important components of the ocean-atmosphere system in the Arctic, particularly in the ice-albedo feedback. Good estimates of ice thickness are critical for input into, and constraining of, global climate or coupled atmosphere-ocean models (e.g., McLaren et al., 2006) and for quantifying total sea ice mass and monitoring the global spatial and seasonal variations of this mass.

Sea ice thickness may be estimated using measurements of sea ice freeboard (i.e., ice elevation above local sea level) along with a characterization of the vertical density structure of sea ice. Both radar and laser altimeters have been used successfully to measure sea ice freeboard from satellites (Laxon et al., 2003; Kwok et al., 2004; Zwally et al., 2008). Laxon (1994), Laxon et al. (2003), have developed sea ice processing schemes whereby satellite microwave radar altimeter returns are retracked and optimized for sea ice, yielding estimates of sea ice freeboard and ice type characterization. This processing has been applied successfully to ERS-1 & 2 radar altimeters and the similar Envisat dual frequency RA-2 Radar Altimeter. Although these radar altimeters provide excellent coverage of all Arctic seas south of 81.5°N, the validation of such sea ice elevation measurements is hampered by the lack of surface truth data. To redress this lack of data, the Arctic Aircraft Altimeter (AAA) 2006 Campaign was carried out on March 27, 2006 to gather measurements of sea ice surface characteristics from multiple airborne instruments simultaneously with overpasses of the Envisat and ICESat satellites. This study focuses on Envisat radar measurements of sea ice elevations and does not attempt any examination of laser altimetry from ICESat. The Laser Radar Altimetry (LaRA) airborne field campaign of 2002 attempted to establish some validation of Envisat and ERS-2 altimetry over sea ice, but was limited

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to just a few useable ERS-2 and no Envisat data due to Envisat technical problems (Giles et al., 2007).A field campaign described by Leuschen et al. (2008) compared airborne laser and radar altimeter measurements, but no satellite altimetry, over Antarctic sea ice.

We present an analysis of airborne laser altimeter and photo imagery data collected during the AAA 2006 Campaign to explore the usefulness of these data in validating the sea ice elevations derived from RA-2 return waveforms and an associated processing scheme (Laxon et al., 2003; Laxon, 1994). A statistical comparison of RA-2 and spatially averaged ATM elevations is carried out to examine the general trends along the full Envisat leg of the AAA flight track (Fig. 1). More detailed examination is made of both the RA-2 sea ice elevations and ice type designations using the finer scale laser measurements and photo imagery. We find that Envisat radar satellite altimetry, with appropriate waveform processing, yields estimates of sea ice elevation that compare well with airborne laser altimetry measurements. The effects of uncertain snow depth are significant in laser-radar comparisons as laser altimeters will measure elevations of snow accumulated on sea ice while radar altimeters (operating in the Ku-band) will penetrate snow cover to measure elevations at the snow/ice interface (Beaven et al., 1995; Giles et al., 2007; Leuschen et al., 2008). Effects of snow penetration by the Envisat radar are carefully assessed in our study. In addition, we show how heterogeneities in the ice field, such as leads slightly offset from the satellite nadir, can in some instances corrupt Envisat elevation estimates and require careful interpretation.

2. Airborne data

Fig. 1 shows the March 27, 2006 flight path followed by a NASA P-3 aircraft during the AAA Campaign. Meteorological conditions observed during the flight, and confirmed by daily gridded NCEP data, were generally dry and cloud-free. The cloud-free conditions were verified by onboard photo imagery. The aircraft underflew the Envisat satellite, following the orbital ground track of Cycle 46, revolution 201. The AAA validation flight began at Point A (74.87° N, 143.42° W) at 19:28 UTC heading northeast. At ~80.5°N, the flight diverted north-west to underfly the ICESat satellite, then reversed its track to return to, and continue northeast along the Envisat track finishing at Point B (81.45° N, 92.26° W) near Nansen Sound at 23:50 UTC. The resulting flight path included over 1300 km of Envisat altimeter ground track and 300 km of ICESat/GLAS ground track. Validation of ICESat data is the subject of a separate investigation. The Envisat satellite was over Point B in Fig. 1 at 21:44 UTC and traversed to Point A at 21:47 UTC. The longest temporal separation between Envisat measurements and aircraft measurements was about 2 h 20 min at point B and the shortest separation of about 13 min occurred near 80.5°N. The ATM data swath was found to be offset southeast from the exact Envisat nadir ground track by about 200–500 m. The Envisat altimeter footprints are sufficiently large (nominally 2 to 10 km in diameter) that they still encompass the flight path.

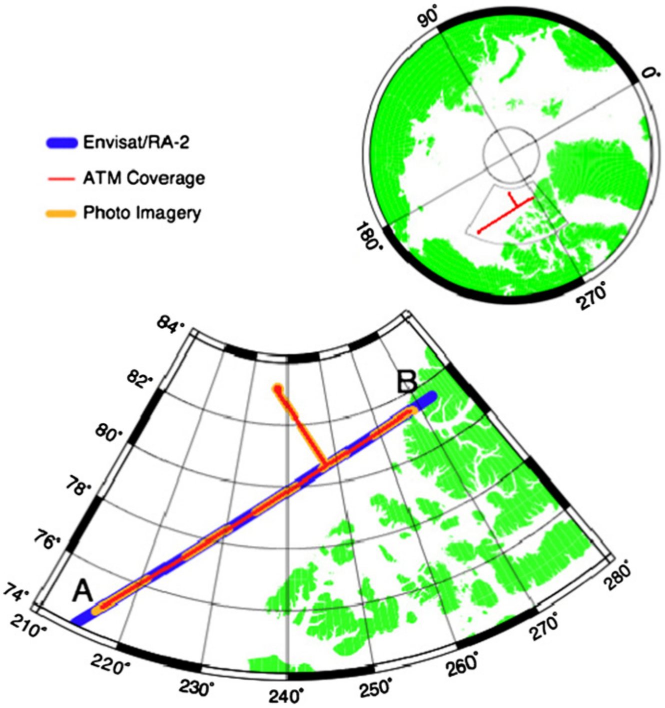

Fig. 1. Flight path followed by NASA P-3 aircraft during the Arctic Aircraft Campaign on March 27, 2006. Blue line is the under-flown Envisat track, red line indicates coverage of the ATM laser altimeter, and the yellow lines show the semi-continuous photo imagery coverage along the flight. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The aircraft was equipped with several instruments to monitor sea ice along the flight path. These included a laser altimeter, a microwave radar altimeter, a snow radar, and two bottom mounted digital cameras. Data collected from the Delay-Doppler Phase Monopulse (D2P) microwave radar altimeter (Leuschen & Raney, 2005) and the snow radar was unavailable for this study. Future analysis will include comparisons with measurements from the airborne microwave altimeter. This study focuses on measurements derived from the laser altimeter and the imagery provided by the cameras. The laser altimeter is NASA's Airborne Topographic Mapper (ATM). The ATM is a conical-scanning laser ranging system operated at a wavelength of 532 nm with a pulse repetition frequency of 5 kHz and a scan rate of 10 Hz with an off-nadir scan angle of 22° (Krabill et al., 2002). Aircraft location was determined with global positioning system (GPS) techniques, and aircraft heading, pitch, and roll were measured by inertial navigation systems. Typical flight parameters constrained the ATM observation geometry to an across-track scan swath of 400 m, the laser illuminating a 1 meter diameter footprint sampled approximately every 5 m along- and across-track near the center of the scan swath, the sampling becoming significantly finer (sub-meter) near the edges of the swath. The beam of the ATM generally backscatters sufficiently from a snow or ice surface to measure the time delay of a return signal and determine a total propagation distance. The rare presence of liquid water along the AAA flight path resulted in some measurement dropouts, probably due to the ATM beam being forward scattered by the extremely smooth surface. The travel time data were combined with GPS navigation measurements and aircraft orientation parameters to derive surface elevation measurements relative to the WGS84 reference ellipsoid, with a typical accuracy better than 10 cm (Krabill et al., 2002). Two Kodak DC4800 digital cameras were used to gather photographic imagery of the sea ice and snow surface along the flight path. Nominal surface coverage of a single image was 640 m (along-track)×420 m (across-track). Two cameras were necessary to assure image frame overlap along the flight path due to the refresh delay of the Kodak DC4800. Memory constraints on the cameras required the periodic downloading of images, resulting in the coverage gaps evident in Fig. 1.

3. Satellite altimeter data

Envisat is a European Space Agency (ESA) satellite which carries 10 earth observing instruments including the Radar Altimeter-2 (RA-2)—a pulse-limited nadir-looking, two-frequency (13.575 GHz in the Ku-Band is the primary frequency, 3.2 GHz in S-band is the secondary frequency) radar similar in function to its predecessors, ERS-1 and ERS-2, which also used Ku-band (13.8 GHz) altimeters. The Envisat RA-2 transmits 1800 pulses/s and averages 100 return pulses to generate 18 Hz waveforms. Such 18 Hz RA-2 waveform data collected during the AAA 2006 campaign were retracked and processed using