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Implications of changing scattering properties on Greenland ice sheet volume change from Cryosat-2 altimetry

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ABSTRACT

Long-term observations of surface elevation change of the Greenland ice sheet (GrIS) is of utmost importance when assessing the state of the ice sheet. Satellite radar altimetry offers a long time series of data over the GrIS, starting with ERS-1 in 1991. ESA's Cryosat-2 mission, launched in 2010, provides an invaluable radar altimetry dataset for monitoring the current changes of the ice sheets due to its dense spatial and temporal coverage of these areas. Here, we investigate the effects of including different parameters which describe the shape of the return radar waveform (waveform parameters) in the elevation change algorithm, to correct for temporal changes in the ratio between surface- and volume-scatter in Cryosat-2 observations. We present elevation and volume changes for the Greenland ice sheet in the period from 2010 until 2014. The waveform parameters considered here are the backscatter coefficient, and the leading edge width, which are both available in the ESA Cryosat-2 Level-2i data product. Investigations into relocation of radar reflection points are also included.

Inter-comparison of the Cryosat-2 derived elevation changes with those derived from Operation IceBridge laser data suggests waveform parameters to be applicable for correcting for changes in volume scattering. The best results in the Synthetic Aperture Radar Interferometric mode area of the GrIS are found when applying only the backscatter correction, whereas the best result in the Low Resolution Mode area is obtained by only applying a leading edge width correction. Using this approach to correct for the scattering properties, a volume loss of $-292\pm38\ \mathrm{km}^3\ \mathrm{yr}^{-1}$ is found for the GrIS for the time span November 2010 until November 2014. The inclusion of waveform parameter corrections and improved relocation for the GrIS, helps to reconcile the satellite-derived elevation changes with those observed by Operation IceBridge. However, the bias of temporal changes in the scattering horizons of Cryosat-2 is not entirely removed and suggests that future improvements could be made by including climate data and/or additional waveform parameters to make additional corrections in the Cryosat-2 radar altimetry.

1. Introduction

The Greenland ice sheet (GrIS) is in a state of change (Barletta et al., 2013; Helm et al., 2014; Kjeldsen et al., 2015; Sasgen et al., 2012; Shepherd et al., 2012), which is manifested by a thinning of outlet glaciers, which control the majority of the dynamic change of the GrIS (Csatho et al., 2014; Khan et al., 2014; Simonsen et al., 2015). With the observed warming of the high Arctic (Dahl-Jensen et al., 2009), much attention has been devoted to quantifying the changes of the GrIS, and multiple satellite missions have observed the elevation changes over the ice sheet (Helm et al., 2014; Johannessen et al., 2005; McMillan et al., 2014; Pritchard et al., 2009; Shepherd et al., 2012).

The European Space Agency (ESA) has a long tradition of operating satellite radar altimeters starting with the European Remote Sensing (ERS) satellites, ERS-1 and ERS-2, operating from 1991 to 2000 and 1995 to 2011, respectively, followed by the Environmental Satellite (Envisat) operating from 2002 to 2012 (Laur and Liebig, 2014). Following Envisat, the ESA Cryosat-2 radar altimetry mission was launched in April 2010, and is still operating. In the near future, data will also be available from ESA's Sentinel-3 Synthetic Aperture Radar (SAR) altimeter (Malenovský et al., 2012). In addition to the ESA radar missions, the National Aeronautics and Space Administrations (NASA) satellite mission Ice, Cloud, and land Elevation Satellite (ICESat) carried a laser altimeter (Abshire et al., 2005), providing detailed information of elevation change in the period 2003–2009.

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Furthermore, the Indian/French SARAL satellite (Satellite with the ARgos (Advanced Research and global observation satellite) and ALtimeter), was launched in February 2013 (Rémy et al., 2015).

The ESA radar altimeters operate at Ku-band frequency (13.6 GHz) and the signal may therefore penetrate into snow, while the SARAL radar altimeter (referred to as AltiKa) operates at Ka-band (37 GHz) which is less affected by surface penetration into snow (Rémy et al., 2015). The theoretical dry-snow penetration depth for Ku-band is around 10 m and less than 1 m for Ka-band (Rémy et al., 2015). The algorithm used to analyze the radar return waveforms (retracking algorithm) limits this penetration depth to less than 2 m for the ESA Level-2 Cryosat-2 retracking, as shown during the 2012 melt event (Nilsson et al., 2015). Infrared lasers, such as ICESat, has negligible surface penetration and individual measurements are reflected by the snow/air interface. Lasers operating in different wavelengths may experience limited surface penetration though. The Airborne Topographic Mapper (ATM) operated by the NASA Operation IceBridge uses green lasers, which also suffer from surface penetration, the magnitude of which depends on numerous factors, e.g., grain size and incidence angle. However, due to the nature of the green laser, the penetration depth of it is expected to be orders of magnitudes less than for the Ku-band radar on Cryosat-2.

The issue of surface penetration has been acknowledged since the first radar altimetry missions and several approaches have been used to separate actual surface elevation changes from those induces by changes in scattering properties. A widely used approach is to account for the changing surface conditions by including corrections for the correlation between elevation changes and changes in specific radar waveform parameters, such as the backscatter coefficient, leading edge width and trailing edge slope (Flament and Rémy, 2012). Another approach is to develop and apply a retracker algorithm, if possible, that tracks the actual snow surface. Helm et al. (2014) adapted this latter approach by applying a threshold first-maximum retracker algorithm (TFMRA) to Cryosat-2 data, and found a mean volume loss of 375 ± 24 km^3 yr^{-1} for the GrIS for the period January 2011 until January 2014. Recently, and again applying specialized retracking, Nilsson et al. (2016) found a volume loss of 289 ± 16 km^3 yr^{-1} from January 2011 to January 2015.

Here, we have dedicated our investigations to the retracking available from ESAs Cryosat-2 Baseline B Level-2 from the in-depth product (BL2i) (ACS, 2012; Bouzinac, 2012). As the retracked elevation in the ESA Cryosat-2 BL2i product likely to be affected by surface penetration, we utilize waveform parameters to correct for the temporal changes in the complex subsurface structure of the firn as manifested in the ratio between surface- and volume-scatter in Cryosat-2 observations, following the approach of Flament and Rémy (2012). The two waveform parameters, backscatter coefficient (Bs), and the leading edge width (LeW) (see Fig. 1) are the only waveform parameters available in the ESA Cryosat-2 BL2i, hence the only parameters included in our investigations of deriving elevation changes of the GrIS.

During the operational period of Cryosat-2, the GrIS has seen large diversity in its climatology, with extremes in accumulation, surface melt, ice sheet run-off and refreezing in the firn (Machguth et al., 2016). In the summer of 2012, an unprecedented melt event was observed across the GrIS, during which as much as 98.6% of the entire surface of the GrIS surface experienced melt for a few days in July (Nghiem et al., 2012). Nilsson et al. (2015) showed the 2012 melt event to be evident in the ESA Cryosat-2 L2 data as an apparent elevation increase of a magnitude of more than 0.5 m at surface elevations above 2000 m. This observation is in contrast to the actual surface lowering detected by in-situ observation concurrent with the melt event (Forsberg et al., 2013; Nghiem et al., 2012). The elevation change detected by CryoSat-2 was attributed to the formation of ice lenses (strong radar reflectors) a few centimeters below the surface, and was correlated with a sudden change in scattering properties and waveform parameters. A persistence change was observed in the leading edge width (LeW), with a decrease from about 6 m to about 3 m. The LeW slowly recovered with about 1 m within 1.5 years of observations (Nilsson et al., 2015).

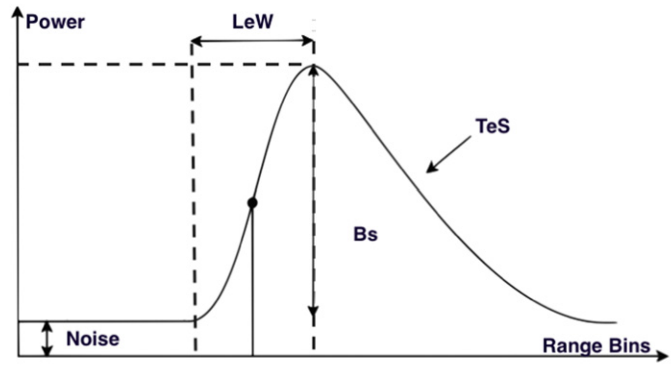

Fig. 1. Schematic drawing of a radar waveform. Idealized waveform described by the leading edge width (LeW), trailing edge slope (TeS) and backscatter (Bs) parameters as indicated.
Source: The figure is adapted from Nilsson et al. (2015).

The elevation change observed from radar altimeters over the interior ice sheets is not necessarily the same as the change observed by LiDAR, (Nilsson et al., 2015; Sørensen et al., 2015), as climate variability induces changes in the surface penetration of the radar. We assume the LiDAR to track the physical surface of the ice sheet and thereby over time to record surface elevation change (SEC), whereas the radar elevation change (REC) may contain an imprint of subsurface changes. We do want to emphasize that the difference between SEC and REC depends on the retracker algorithm used (Nilsson et al., 2015), the area considered (Sørensen et al., 2015), and the specifications of the radar system.

With the loss of ICESat in 2009 and continuation of the long record of radar altimetry observations, a growing demand for understanding the physics of radar measurements in relation to REC/SEC has presented itself. Among others, Khvorostovsky (2012) and Flament and Rémy (2012) have suggested that by applying waveform corrections, the retracker dependency of the derived elevation change may be limited because the retracked surface is then moved to the physical surface, thereby allowing for the SEC to be derived from the radar data. The ESA release of Cryosat-2 retracking data parameters is utilized to estimate the GrIS REC, and investigate the effect of the inclusion of these waveform parameters. The final product should provide a REC consistent with the SEC derived from LiDAR observations and represent the SEC as closely as possible or with well defined biases. Here, we derive Cryosat-2 REC using eight parameterizations, and compare the results to LiDAR SEC results to identify a preferred REC algorithm (and hence volume change) derived from ESA Cryosat-2 BL2i data.

2. Data

2.1. ESA's Cryosat-2 Baseline B

ESA's CryoSat-2 was launched into a non-sun synchronous orbit on April 8th 2010, at an altitude of 717 km and orbit inclination of 92°. The full repeat cycle is 369 days with a sub-cycle of 30 days. The main satellite payload is the SAR/Interferometric Radar ALtimeter (SIRAL), supported by Doppler Orbit and Radio Positioning Integration by Satellite (DORIS), and Laser Retro-Reflector (LRR) ranging for orbit determination (ESTEC, 2007). Over the GrIS, Cryosat-2 operates in two modes. In the interior parts of the ice sheets, it operates in the Low Resolution Mode (LRM), which is equivalent to the conventional beam-limited mode applied by previous Ku-band radar altimeters.