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Testing the ice-water discrimination and freeboard retrieval algorithms for the ICESat-2 mission☆

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ABSTRACT

The ICESat-2 mission will provide routine estimates of sea ice freeboard from profiles of surface heights acquired by its photon-counting lidar: the Advanced Topographic Laser Altimeter System (ATLAS). In this paper, we describe and test procedures devised to separate returns of ice from open water — a crucial step in the estimation of local sea levels for freeboard calculations. The two data sets used in these tests, one each from winter and summer, were acquired by a Multiple Altimeter Beam Experimental Lidar (MABEL) implemented to support pre-launch development of retrieval approaches. Our approach first identifies likely open water returns using surface photon and background count rates as proxy indicators of apparent surface reflectance. Since these measured rates are noisy estimates of expected reflectance, relative surface heights are used to refine the selection of the candidate sea surface samples. Results show that winter freeboard distributions are consistent with expected regional variability, and the nearly identical repeat-track freeboard distributions during summer show retrieval consistency. From coincident lidar coverage, variability of sea level samples identified in the MABEL and Airborne Topographic Mapper (ATM) lidar profiles are 1.6 cm and 2.6 cm, with the overall difference between the distributions at 0.00 ± 0.15 m. This demonstrates the viability of the algorithms. The parameters used in these procedures will serve as a baseline and as a guide for understanding algorithm reliability. It is expected that they will be adjusted post-launch to reflect the on-orbit performance of ATLAS.

1. Introduction

NASA's Ice, Cloud and Land Elevation Satellite-2 (ICESat-2), currently planned for launch in late 2017, will provide observations to quantify the changes in ice sheets and sea ice, and key insights into their behavior (Abdalati et al., 2010). Instead of an analog lidar used for ICESat (Zwally et al., 2002; Abshire et al., 2005; Schutz, Zwally, Shuman, Hancock, & DiMarzio, 2005), the Advanced Topographic Laser Altimeter System (ATLAS) on ICESat-2 will employ a photon-counting approach to improve measurement sensitivity with lower resource (power) demands on the satellite platform. ATLAS will provide the heights of individual geolocated photons rather than recorded waveforms. The profiling configuration is designed to have six across track beam: the multiple beams address the need for unambiguous separation of ice sheet slope from elevation changes (Zwally et al., 2011) and provide denser sampling of the sea ice cover.

One of the analyzed science products from the ICESat-2 mission is sea ice freeboard of the polar oceans, i.e., the height of the ice surface above local sea level. The freeboard product is intended to enable calculations of sea ice thickness. While freeboard estimates have been produced for the analog lidars on the ICESat mission (Kwok, Cunningham, Zwally, & Yi, 2007; Farrell, Laxon, McAdoo, Yi, & Zwally, 2009) and Operation IceBridge (OIB) (Kwok, Cunningham, Manizade, & Krabill, 2012; Kurtz et al., 2013), the lidar data from ICESat-2 is unique in that the photon height distributions from ATLAS have to be analyzed somewhat differently even though the physical basis for these calculations remain unchanged. To obtain sea ice freeboard, an important step is to identify the sea surface returns that could be used to estimate the local sea surface. For ICESat, investigators have used estimates of reflectance and surface relief statistics (Kwok et al., 2007), lowest level filtering (Yi, Zwally, & Robbins, 2011), and waveform characteristics (Farrell et al., 2009) to separate the ice and sea surface returns. The OIB procedures (Kurtz et al., 2013) are aided by coincident and contemporaneous digital camera images and radiometer data.

To support pre-launch development of freeboard retrieval approaches, Multiple Altimeter Beam Experimental Lidar (MABEL) data were collected during two dedicated airborne campaigns over the Arctic Ocean. MABEL is an airborne photon-counting (PC) lidar used as a technology demonstrator for the PC instrument (ATLAS) on the ICESat-2 mission (McGill, Markus, Scott, & Neumann, 2013). The two deployments of MABEL provided snapshots of winter (April 2012) and summer conditions (July 2014). Preliminary investigations of the first

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MABEL flight over the Arctic Ocean can be found in Kwok et al. (2014) and Farrell et al. (2015). We use these data sets to test algorithms for ice-water classification and for calculations of freeboard using the retrieved sea surface heights. The objective of this paper is to describe these algorithms and how we have assessed their usefulness using the MABEL data sets.

The paper is organized as follows. Section 2 describes the data used, especially those from the MABEL instrument. In Section 3, the phenomenology of photon returns from the sea ice cover is examined, and we describe an approach used to separate the returns of ice from open water/leads. Section 4 outlines the method used to select open water samples for determining the local sea level for freeboard calculations; derived freeboard distributions from two MABEL flights (one in winter and one in summer) are examined. In Section 5, we compare the freeboards from MABEL with those from a nearly coincident surface profile acquired by another lidar — the Airborne Topographic Mapper (ATM) lidar. Summary remarks and conclusions are provided in the last section.

2. Data description

In this section, we provide brief descriptions of the MABEL and ATM instruments, and their data sets. Data from the ATM instrument are used in the assessment of the MABEL freeboards.

2.1. MABEL instrument

The relevant instrument parameters are summarized in Table 1. For a more detailed description of the MABEL instrument and design, the reader is referred to McGill et al. (2013). The MABEL laser has a pulse width of ~2 ns. For the data used here, the lidar was operated with a pulse repetition frequency (PRF) of 5 kHz. At the nominal ground speed (~200 m/s) and altitude (~20 km) of the ER-2 platform, a pulse is transmitted approximately every 4 cm along-track. At that altitude, the laser illuminates a ground spot of ~2 m ($1/e^2$) in diameter within the 4 m telescope field of view (FOV: ~210 μrad). For a subset of the data along the ER-2 tracks, aerial images captured by an attached camera system are available. These images are useful for identifying surface types (e.g., open water, snow-covered ice, thin ice, etc.) sampled by the lidar.

A characteristic of PC systems is the detector dead time (t_d), which is the time required for the detector to recover from a photon event (the triggering of the detector) before the next photon can be detected. Thus, if the photons rates are high (i.e., number of photons from the surface), the reduced sampling efficiency introduces the possibility height biases. The photomultiplier tube (PMT) detectors on the 532 nm channels have dead times of ~2.5 ns. For MABEL, the surface return and background rates (discussed in Section 3) are much lower than 400 MHz ($1/t_d$), thus an insignificant fraction of photons events occur during the dead time, so the sampled rate is linear with the input rate and the likelihood of height biases are negligible.

Analyzed MABEL products (Release 10) contain geolocated elevations of individual photons between −1 km and 5 km relative to the World Geodetic System (WGS) 84 ellipsoid. Products are distributed as data-files each containing 60 s of surface returns from 300,000 pulses, covering ~13 km along track. Henceforth, we refer to these as MABEL file-segments.

Table 1
Comparison of relevant MABEL and ICESat-2 instrument parameters and expected performance. ATLAS has three beam pairs: each pair has a strong and a weak beam with higher and weaker laser energies. High photon rates are expected from the strong beam and vice versa.

Parameter	ICESat-2/ATLAS	MABEL
Operational altitude, R	490 km	20 km
Wavelength, λ	532 nm	532 nm
Pulse repetition frequency	10 kHz	5 kHz
Footprint ($1/e^2$)	31 mrad (15 m)	100 mrad (2 m)
Swath width	±3.00 km	±1.05 km
Signal levels — winter sea ice (pe/shot)	Expected (Strong/Weak beam)	Expected
Snow-covered ice (albedo = 0.9)	1.6/6.2	0.2
Open lead (albedo = 0.15)	0.26/1.0	0.04

2.2. MABEL sea ice campaigns

The data sets used here are from two Arctic deployments: April 2012 (spring) and July 2014 (summer). The first in April 2012 acquired sea ice data along two dedicated flightlines: one that was >3000 km in length (April-08) and the other >1000 km (April-10) (Fig. 1). These lines were selected to provide a broad sampling of ice conditions prior to the expected onset of melt over Arctic sea ice cover. The April-8 flightline acquired sea ice data over the Lincoln Sea, north of the Greenland coast, the Fram Strait and the East Greenland Sea. The second flightline (April-10) re-surveyed the track just east of the Greenland Coast. On April-10, the ER-2 was joined by the P-3 aircraft from Operation IceBridge (Koenig, Martin, Studinger, & Sonntag, 2010), which provided near-coincident ATM coverage of the MABEL surveys for assessment of performance and to support algorithm development. The second campaign in July 2014 acquired data that are representative of summer melt conditions; three flightlines were acquired but we focus on the July-29 round-trip flight to the North Pole; it was flown along the 150°W meridian (Fig. 1c).

2.3. MABEL instrument performance — ice returns

Table 1 compares the instrument performance of MABEL and ATLAS over sea ice. The reader is referred to Kwok et al. (2014) for a more detailed discussion of the differences between MABEL and ATLAS, and the use of MABEL as a development system. Based on their estimates, from examining the April 2012 data set, the observed per-shot photoelectron count is ~0.2 for snow-covered sea ice and ~0.04 for open water lead. Photoelectrons are photon events recorded by the lidar system. In this paper, we use photon counts and photoelectron counts interchangeably.

2.4. ATM lidar

The ATM instrument is a relatively well-characterized analog lidar that has been used to provide high-precision lidar mapping of sea ice and ice sheets (Krabill et al., 2002; Kwok et al., 2012). Briefly, it 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 20 Hz; the off-nadir scan angle is 15°. With nominal OIB flight parameters (i.e., operating altitude and ground speed: 500 m and 250 kts), the ATM scanning geometry provides an across-track scan swath of ~250 m. Near the center of the swath, the spacing between neighboring laser footprints, of ~1 m in diameter, is approximately 3–4 m in the along- and across-track directions. The sample density is higher (sub-meter) near the edges of the swath due to the conical scanning geometry of the system. We note here that this lidar does not provide contiguous spots on the ground. Typical elevation accuracy is better than 10 cm (Krabill et al., 2002). Retrieved elevations are provided in data files that cover tracks of ~35 km in length, each containing over a million elevation estimates.

2.5. Subsurface returns at 532 nm

The use of 532 nm technology offered higher photon return rates (i.e., more sensitive detectors) and a more stable laser. It is recognized, however, that the use of 532 nm introduces scattering within the