**An improved approach of total freeboard retrieval with IceBridge Airborne
Topographic Mapper (ATM) elevation and Digital Mapping System (DMS) images**

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Abstract

The existence and detection of leads are critical to obtain a local Sea Surface Height (SSH) reference for computing total freeboard and sea ice thickness from NASA's IceBridge Airborne Topographic Mapper (ATM) elevations. However, the shaded areas of the Digital Mapping System (DMS) images and the biased ATM elevations impact the correct determination of leads and SSH. This study develops an automated approach to overcome the above challenges and to correctly determine SSHs by combining DMS images, ATM L1B's apparent reflectivity and statistical discrimination. Dynamic pixel intensity thresholds are established to classify leads under different solar illuminations. This automated approach is then validated by manual selection in detecting SSHs. The high agreement of SSHs from this automated approach with those from manual selection indicates the reliability and usefulness of this approach. Within a 45-km section of one ATM L1B file, SSH demonstrates a linear gradient, which is applied to derive SSHs where there are no leads. The resulted SSHs are then used to compute total freeboard and ice thickness. This automated approach is also tried to retrieve SSH and then compute the total freeboard on one entire IceBridge sea ice flight each in Arctic and Antarctica.

Keywords: Leads; Sea surface height; Total freeboard; Sea ice thickness; IceBridge

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1. Introduction

Obtaining an instantaneous Sea Surface Height (SSH) reference is critical for retrieval of total freeboard and sea ice thickness with airborne or spaceborne altimeter (Onana et al., 2013; Yi et al., 2015). Total freeboard is the difference of altimetry height between snow (sea ice) surface and nearby open water or thin sea ice (Xie et al., 2011; Wang et al., 2013; Kwok and Maksym, 2014). Sea ice is often loaded with snow and covers the ocean with leads in the Arctic Ocean and in the circumpolar Southern Ocean, particularly in polar winter and spring. Leads are defined as cracks or openings in the sea ice cover that expose open water or thin sea ice. Altimetry instruments normally survey the surface height of snow/sea ice at centimeters precision relative to the World Geodetic System reference ellipsoid (WGS 84). Since the actual ocean surface is subjected to tidal, ocean current and atmospheric pressure variations, the ocean surface topography predicted by current numerical models are not capable to provide the required accuracy (centimeters) and spatiotemporal resolution (meters or tens meters) needed for satellite and airborne laser altimetry (Kwok et al., 2012). Therefore, in order to determine the total freeboard and sea ice thickness using laser or radar altimetry data like NASA's Ice, Cloud and land Elevation Satellite (ICESat), an instantaneous local SSH reference using the same elevation data must be obtained first (Kwok et al., 2006; Kurtz et al., 2009; Laxon et al., 2013; Xie et al., 2013).

Several approaches have been developed to compute the SSH reference using altimetry data. The principle in common is to find the laser altimetry elevations over leads, areas of open water or very thin ice, as the SSH reference (Zwally et al., 2008; Kwok et al., 2012).

Thus, identification of leads is crucial for a precise estimation of SSH reference and a prerequisite to compute the total freeboard and sea ice thickness (Xie et al., 2013).

The first type of approaches is to directly classify a certain percentage of the lowest-elevation samples along a range of a flight track as the sea surface tie points. The average height of those tie points is taken as an SSH reference. This is because the surface height of open water or thin sea ice is theoretically lower than that of the nearby sea ice/snow-covered surface (Zwally et al., 2008; Farrell et al., 2009; Yi et al., 2011; Xie et al., 2011, 2013; Kurtz and Markus, 2012; Price et al., 2013). Zwally et al. (2008) assume that at least 2% of ICESat laser shots fall on leads within a 50-km section of a profile in the Weddell Sea, Antarctica, and the SSH reference at a given footprint was then empirically given by the average of the lowest 2% of the ICESat elevations within 25km each side of that point along the flight track. This method has been widely applied to process the ICESat data for retrieval of total freeboard and sea ice thickness since no high resolution photography images were collected simultaneously or no other data could be used to identify leads for the ICESat altimetry data (Zwally et al., 2008; Yi et al., 2011; Xie et al., 2011, 2013; Kurtz and Markus, 2012; Price et al., 2013). Meanwhile, an optimal percentage threshold (e.g., 2%) actually depends on leads' size and spatial distribution, and the size of the laser shots also introduces a potential source of error (Zwally et al., 2008; Wang et al., 2013).

The second type of approaches utilizes the altimetry data to identify leads by the waveform characteristics (Kurtz et al., 2014; Yi et al., 2015) or by the apparent reflectivity of the transmitted laser pulses (Kwok et al., 2012; Kwok and Maksym, 2014). The apparent

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reflectivity (R) is defined as the ratio of the reflected laser signal strength to the transmitted signal strength. Both quantities are provided in the data released for each laser shot. Leads of thin sea ice or open waters cause weak backscatter in the laser signal as compared to normal sea ice cover, i.e., low apparent reflectivity. Thus, the reflectivity values can be used to identify the sea surface tie points of SSH within leads (Kwok et al., 2012; Kwok and Maksym, 2014). Although R values within leads are low, our spatial and statistical analysis show that there are similar low R values in some areas of the snow/sea ice surface, too. Therefore, it is challenging to determine an optimal threshold of apparent reflectivity for distinguishing leads from sea ice due to the complexity of surface conditions. In addition, the waveform characteristic data are not released to the public, thus constraining the widespread application of this method to retrieve the SSH with the laser altimetry data (Yi et al., 2015).

The third type of approaches uses optical images that were taken simultaneously with the laser altimetry data to visually identify leads, and the average height of the laser shots within leads is taken as the SSH reference (Wang et al., 2013; Onana et al., 2013; Kurtz et al., 2013). In the Operation IceBridge (OIB) airborne campaigns, high resolution natural color imagery were collected by the Digital Mapping System (DMS) and georeferenced to match the altimetry data retrieved from the Airborne Topographic Mapper (ATM) system. Wang et al. (2013) used the DMS images to identify leads in the Bellingshausen Sea, Antarctica, then selected the ATM L1B data within leads for computing the SSH reference. Onana et al. (2013) developed a sea-ice lead detection algorithm using minimal signal (SILDAMS) from DMS images to extract leads and to classify sea ice types within leads. The average height of ATM

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samples within leads was used as the SSH reference.

However, there are several issues in applying DMS images to determine leads and SSHs. Due to extensive cloud cover, low solar elevation angles and the presence of high ice ridges or icebergs along OIB Arctic and Antarctic flights, the shaded sea ice areas on DMS images are mistakenly classified as leads by SILDAM and other similar algorithms (Onana et al., 2013). When the ATM shots over those shaded sea ice areas are taken as the sea surface tie points to compute SSH, they normally overestimate the SSH and then underestimate the total freeboard and sea ice thickness. Moreover, DMS images are acquired under different solar illuminations from early morning to late afternoon, and the reflected pixel intensities of sea ice vary with solar illuminations. Thus, a series of dynamic pixel intensity thresholds are needed to automatically classify leads from sea ice under different solar illuminations. Alternatively, the SILDAMS algorithm involves with several signal transformation and statistical frequency analysis, which requires additional huge computing capacity and still can not distinguish the shaded areas from leads (Onana et al., 2013; Kurtz et al., 2013). In addition, the weak reflected signal strength within leads causes some low-bias of laser elevation estimates (Kwok et al., 2012; Kurtz et al., 2013), and the azimuth-dependent bias of the ATM L1B data could not be completely corrected (Yi et al., 2015). Those biased elevation data might be included in the leads-extracted samples and should be excluded from the sea surface tie points for computing SSH through statistical screening.

Fortunately, the apparent reflectivity of IceBridge ATM data is little affected by the sun shade. The reflectivity of laser shots within shades of sea ice is much higher than that within

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leads (Kwok et al., 2012; Kwok and Maksym, 2014), thus reflectivity values can be applied to exclude those laser shots extracted by shaded sea ice areas, which are misclassified as leads from DMS images. Therefore, the main objective of this study is to develop an automated approach to detect leads and to correctly extract the sea surface tie points within leads by combining DMS images and the apparent reflectivity of ATM L1B data. In addition, statistical analysis is applied to screen out other outliers caused primarily by the elevation bias and to identify the representative tie points for computing SSH, total freeboard and sea ice thickness from ATM data.

2. Study Area and Data

2.1 Study Area

The purpose of NASA's IceBridge airborne campaigns is to bridge the gap in polar observations between ICESat in orbit from 2003 to 2009 and ICESat-2, planned for launching in 2017. The OIB campaigns had surveyed the Arctic in March-May and Antarctica in October-November annually since 2009 by airborne instruments, primarily including ATM, DMS, and snow radar for sea ice and ice sheets. Each year from 2009 to 2012, there were three particular sea ice flights in the Southern Ocean, one in the Bellingshausen Sea and two (one in 2011) in the Weddell Sea. The sea ice flight tracks in the Bellingshausen Sea were similar over the four years, and their offshore tracks were almost identical as shown in Fig. 1. The four sections on the sea ice flight on October 23, 2011 and on October 13, 2012 are used to validate our automated approach in this study.

Figure 1. The IceBridge sea ice flight in Antarctica on October 23, 2011 and four selected study sections of A, B, C and D, which are the areas covered by ATM L1B files of 2011023_150557 (HHMMSS), 2011023_151852, 2011023_153148 and 2011023_160407. The length of each section is about 45 km, and the flight distance from A to D is about 500 km. The red triangle symbols are the SIMBA *in situ* study sites in 2007.

The basic information of the OIB sea ice campaigns in Bellingshausen Sea, Antarctica from 2009-2014 are summarized in Table 1. OIB did not survey this area in 2013. Aircraft survey normally operated from local 8:30am to 4:00pm with Sun Elevation Angles (SEA) larger than 23 degree, which guarantees the necessary solar illumination for the DMS digital camera. One exception was on October 13, 2012, when the survey began late at 10:08 and finished at 4:21pm with SEA of 17 degree, and a few part (2.8%) of the DMS images were acquired after 3:40pm with SEA < 20° and pixel modal intensity of sea ice <80 (DN values).

Table 1. Facts on IceBridge campaigns in the Bellingshausen Sea, Antarctica from 2009-2014.

SEA: Sun Elevation Angle.

Date	Start Time	SEA (°)	End Time	SEA (°)	Image Count	Time as SEA=20°	Image count SEA<20°	Image Ratio SEA<20°
2009/10/21	8:35	23	15:56	24	16860	16:24	0	0
2010/10/30	9:21	27	13:44	30	11117	16:50	0	0
2011/10/23	8:40	24	15:31	25	24347	16:25	0	0
2012/10/13	10:08	27	16:21	17	13610	15:40	375	2.8%
2014/11/13	8:36	30	15:14	31	27437	17:30	0	0

2.2 Airborne Topographic Mapper (ATM)

ATM is an airborne Light Detection And Ranging (LIDAR) system that provides swath measurements of surface elevation by using laser beam at a wavelength of 532 nm with a pulse repetition frequency of 5 kHz and an off-nadir scan angle of ~15 degrees (T2 scanner) or 23 degrees (T3 scanner). The ATM altimetry data are acquired using the T3 scanner in the Antarctic campaigns and have a cross-track width of ~400 m, a footprint size of ~1 m and an along track interval of 5m (Krabill et al., 2009; Kwok et al., 2012; Wang et al., 2013). The

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L1B data are the ATM Level-1B Qfit Elevation and Return Strength data that provide spot elevation measurements over sea ice (snow) and ice sheet surfaces. The elevation data are given in geographic latitude and longitude referencing to and above the WGS84 ellipsoid (Krabill et al., 2009; Farrell et al., 2011). Martin et al. (2012) estimated that ATML1B data have horizontal accuracy of 74 cm, vertical accuracy and precision of 6.6 cm and 3 cm, respectively.

The ATM L1B Qfit elevation, transmitted and return signal strength data obtained from National Snow and Ice Data Center (NSIDC) are used in this study. The L1B elevation data are the instantaneous surface height along the flight track with geoid, tides, and inverse barometer removed (Kurtz et al., 2013), and should not be a function of its scanner azimuth. However, the scanner azimuth-related elevation bias in the 2009 L1B data of Antarctic sea ice flights found in Yi et al. (2015) are confirmed in our analysis (Fig. 2a). Such systematic bias in the L1B elevation data had been corrected and greatly reduced in the following Antarctic sea ice campaigns in 2010, 2011 and 2012, although it may still exist in some individual L1B files (Fig. 2b, c, d). In this study, all L1B data are examined for such bias, and all biases are corrected with the empirical equation obtained in Fig. 2a, before the SSH, total freeboard and sea ice thickness are calculated. Although those corrected data do not generate significant difference in statistics for total freeboard and ice thickness calculation for a determined SSH due to the large quantity of L1B laser shots (Yi et al., 2015), they may bias the SSH if those biased elevation data are extracted as leads for the sea surface tie points for computing SSH since the number of tie points is quite limited.

Figure 2. Mean relative elevations of ATM L1B varying with scanner azimuth on October 21, 2009, October 30, 2010, October 23, 2011, and October 13, 2012. Each black line is an average of one L1B file track (~30 km in 2009 and 2010, 45 km in 2011 and 2012, over one million laser shots). Each point on a black line is the average of elevations over 10 degree of scanner azimuth. The relative elevation is against the average height of all ATM L1B data on each black line. The red line is the mean of all black lines; green dashed lines are the boundaries of the mean with (plus and minus) one standard deviation; the cyan lines (b, c, d) are those with relatively large elevation bias.

1.3 Digital Mapping System (DMS)

The Digital Mapping System (DMS) is an airborne digital camera that acquires high resolution (0.1m at altitude of 500m) natural color and panchromatic imagery from low and

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medium altitude (Dominguez, 2010). Its principal purpose in this effort is to identify leads for determining SSH reference by the ATM elevations within leads. The georeference accuracy of DMS images is greatly improved in the new version released in early 2012 and has an uncertainty of less than one meter (Onana et al., 2013; Wang et al., 2013). This improvement makes it possible to extract the L1B data points within leads as the sea surface tie points for computing an instantaneous SSH reference.

3. Methods and Data Analysis

3.1 Manual Selections of SSH

This study selects four sections (A, B, C and D) at the same locations along the offshore flight tracks in the Bellingshausen Sea in 2011 and 2012 (Fig.1). These four sections are applied to validate our approach for determining the SSH reference and computing total freeboard and sea ice thickness. Table 2 summarizes the section lengths, selected DMS images, number of DMS images with leads and the conditional mean areal ratio of leads on DMS images with leads. Each section (~45 km long and 300 m wide) is the area covered by one ATM L1B file with over one million individual laser shots. DMS images (roughly 600m long and 400m wide) are systematically selected at a spatial interval of around one kilometer so that one SSH can be obtained manually from ATM L1B data as ground truth once leads are identified.

Table 2. Selected four sections of ATM L1B files and number of DMS images on October 23, 2011 and October 13, 2012 in the Bellingshausen Sea, Antarctica.

Items	Sections	10/23/2011	10/13/2012
Length (km)*	A	47	42
	B	46	47
	C	43	43
	D	42	42
Selected DMS images	A	49	45
	B	49	46
	C	45	46
	D	44	44
DMS images with leads	A	22	18
	B	17	17
	C	21	8
	D	8	11
Ratio of lead areas over DMS images with leads	A	33.8%	6.5%
	B	24.7%	19.5%
	C	6.7%	11.0%
	D	0.6%	6.8%
	Mean	16.5%	10.9%

Note: * Length is the roughly distance calculated using the mean aircraft speed (120m/s) and the time between the first and the last laser shot of the ATM L1B file on each section.

Leads normally have lower elevations and weaker reflectance than snow/sea ice surface (Fig. 3), and can be easily detected from DMS images (Onana et al., 2013). The selected DMS images are first used to identify leads visually, within which the ATM L1B tie points are manually selected. The average height of the L1B tie points within leads on a DMS image is then taken as a local SSH reference and also used to validate the SSH computed from other automated approaches. As shown in Fig.3a, the surface elevations within leads are lower than

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those on the snow-covered sea ice surface, while the elevations within leads have a large range of variations up to 20 cm due to the complex lead surface conditions. One difficulty in manual selection is to determine the suitable tie points within leads, which are used to compute the SSH reference. Wang et al. (2013) manually selected the low tie points to compute an SSH by discarding some of the lowest points, which tend to underestimate the SSH if they are chosen as the sea surface tie points. This is because ATM's green wavelength laser energy can penetrate into open water, thus resulting in an attenuated (too low) SSH (Farrell et al., 2011), and the weak backscatter laser signal strength over leads may also result in a lower surface elevation (Kwok et al., 2012; Kurtz et al., 2013).

The SSH references in this study are also obtained by manual selection and are used to validate those derived from the automated approach. Table 3 presents an example of the tie points selected within leads on each DMS images along section A on October 23, 2011. On each DMS image with leads, at least 3 (maximum 10) tie points of L1B data within leads are selected. Abnormally low data points, which are 0.22m on average lower than the mean height of those selected tie points, are discarded. Those selected tie points within leads have similar height with a mean standard deviation of 2 cm (ranging from 1 to 5 cm), and their mean height is treated as the SSH reference. These individual SSHs are used to validate those derived from the automated approaches. The SSHs where there was no lead are interpolated from the empirical equations derived from those with leads (Wang et al., 2013).

Figure 3. The spatial distributions (a) and histograms (b) of L1B elevations (m) and the pixels' intensities in the red band (c) over the entire DMS image of 20091021_16182544. The two intensity peaks (~35 and ~170) in (c) are respectively from leads and snow/ice. The red rectangular part is illustrated for lead classification in Fig. 7.

Table 3. Height statistics of manual selection of tie points and discarded points within leads on each DMS image on October 23, 2011 on section A, where 49 DMS images were selected and 23 of them were identified with leads. The lowest two points are illustrated as discarded points.

DMS Image order ID	Number of Tie points	Mean SSH (m)	Standard Deviation (m)	Discarded point 1 (m)	Discarded point 2 (m)	Mean H _{DP} (m)	H _{DP} - SSH (m)
2	6	-9.07	0.01	n/a	n/a		
4	6	-9.05	0.01	n/a	n/a		
16	10	-9.14	0.03	-9.24	-9.21	-9.23	-0.09
17	4	-9.19	0.05	-9.33	-9.34	-9.33	-0.14
18	9	-9.18	0.01	-9.29	-9.28	-9.29	-0.10
19	10	-9.22	0.03	-9.50	-9.42	-9.46	-0.24
20	3	-9.25	0.04	-9.33	-9.36	-9.34	-0.09
21	10	-9.22	0.03	-9.32	-9.35	-9.33	-0.11
22	3	-9.32	0.01	-9.40	n/a	-9.40	-0.09
26	10	-9.30	0.02	-9.46	-9.49	-9.48	-0.18
33	10	-9.38	0.03	-9.54	-9.52	-9.53	-0.15
34	4	-9.46	0.02	-9.60	-9.62	-9.61	-0.15
36	8	-9.75	0.04	-10.13	-10.10	-10.11	-0.36
38	10	-9.57	0.02	-9.74	-9.71	-9.72	-0.16
39	3	-9.63	0.01	-10.00	-9.95	-9.98	-0.34
40	9	-9.64	0.02	-9.75	-9.94	-9.85	-0.21
43	10	-9.64	0.01	-9.74	-9.73	-9.73	-0.10
44	9	-9.62	0.04	-9.82	-9.92	-9.87	-0.25
45	10	-9.67	0.01	-9.83	-9.93	-9.88	-0.20
46	4	-9.61	0.02	-9.92	-10.19	-10.05	-0.44
47	10	-9.73	0.01	-9.90	-9.87	-9.88	-0.15
48	4	-9.75	0.03	-10.86	-9.96	-10.41	-0.66
49	9	-9.67	0.03	-10.19	-10.00	-10.09	-0.42
		Mean	0.02			Mean	-0.22

3.2 Automated Extraction of SSH from DMS and ATM

1) Dynamic pixel intensity thresholds

Leads are optically dark features with low pixel intensities in the high resolution natural color DMS photographic image (Fig.3a). The reflected pixel intensities (DN values) of leads and snow/thick sea ice surface demonstrate two distinguishable modes around 30 and 170 in the red band at local time of 10:18am, respectively (Fig.3c). The pixel intensities of green and blue bands have similar distribution modes as well (not shown). The images in Fig.4 illustrate the detailed variations of the pixel intensity profile in the red band on pure snow-covered thick sea ice (a & c) and on mixed snow-covered sea ice and leads (b & d). Thus, leads can be easily identified by the different pixel intensities of leads and snow/sea ice from DMS images. Considering the complex situations of leads (including open water, thin sea ice, gray sea ice), an optimal pixel intensity threshold used to distinguish leads from snow/sea ice are the mean of their modal intensities, e.g., 100, the mean of 30 and 170 at this case (Fig. 3c and Fig. 4d). Gray ice is young ice of 10-15 cm thick without snow cover, and some of the gray ice are classified as leads if their pixel intensities are lower than the intensity thresholds. The resulting uncertainty of SSH depends on the ratio of extracted ATM tie points within gray ice to those within other lead areas.

Figure 4. DMS image over pure snow/sea ice surface (a) and mixed snow/ice and leads (b) and their corresponding pixel intensity profiles (c) and (d). The blue lines on images (a) and (b) are the tracks of the pixels intensity profiles on plots (c) and (d), and the red triangles on (a) and (b) are the locations of the red lines on (c) and (d).

The pixel intensities of snow/sea ice are determined by the solar illumination and vary with the Sun Elevation Angles (SEA). OIB DMS images are mostly acquired from local 8:30am to 4:00pm in the OIB Antarctic sea ice campaigns (Table 1). Accordingly, the modal intensities of leads and snow/sea ice vary with SEA and were mostly around 160 on October 23, 2011 and 110 on October 13, 2012, when it had lower SEAs and thus smaller pixel

intensity than the former (Fig. 5). The observed optimal DN Thresholds (DNT) varied around 90 and 60 respectively from 10:00am to 2:00 pm on both dates, and then decreased with SEA. Two series of DNTs are simulated according to the ratio of solar illumination ($\sin(\text{SEA})$) at different local time and image locations based on the observed DNTs at the largest SEA near 12:40pm of that day. The simulated DNTs were similar to the observed ones from 9:30am to 2:00pm on both dates and are applied in the automated approach to classify leads in this study (Fig. 5). Due to different weather condition and sun illumination intensities (SEA), the DNTs must be determined according to the image intensity at the largest SEA of that day.

Figure 5. Variations of pixel modal intensity (DN) for snow/sea ice, DN thresholds (red band, right-hand vertical axis) and sun elevation angle ($\sin(\text{SEA})$, left-hand vertical axis) with local time. The simulated DN Thresholds (DNT) are proportional to the $\sin(\text{SEA})$ based on the observed DNT at the largest $\sin(\text{SEA})$ at noon. SEA varies with time and location.

2) Leads classification

The automated approach consists of four models and is developed on the platform of ArcGIS using model builder and Python scripts (Fig. 6). The first model involves ATM L1B data pre-processing, converting the L1B binary files into text files and then shape files.

Figure 6. Flowcharts of the automated approach, consisting of (1) ATM L1B data pre-process, (2) Leads detection, (3) SSH computation, (4) Total freeboard and sea ice thickness computation.

Figure 7. Description of (a) the original DMS image, (b) the initial classification of leads (dark: off-image or image frame; blue: leads; light gray: snow/sea ice), (c) the post-classification of leads, and (d) the selected ATM L1B laser shots within leads. On plots (b), (c), and (d), the blue color represents the classified leads, and light gray color stands for snow-covered thick sea ice. This image is the upper left rectangular part labeled in Fig. 3a.

The second model, leads detection, is the kernel of this approach. The original DMS (0.1 m pixel size) images (Fig. 7a) are classified into three categories (Fig. 7b), off-image (0-2, dark area), leads (3-DNT, blue area) and snow/sea ice (DNT-255, light gray area). The

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dynamic pixel intensity thresholds of 3-DNT within the red band can classify all open water and thin sea ice without snow cover under different sun illumination conditions from 7:00am to 5:00pm, but also include some shaded pixels primarily due to dark images, cloud, ridges and icebergs on the snow-covered sea ice (Fig. 7b). Those areas of less than 100 pixels (corresponding to a window of $1\text{ m} \times 1\text{ m}$) are clumped to the neighboring sea ice areas, thus removing most small shaded areas due to ridges and icebergs (Fig. 7c). The post-classified raster is converted to a polygon feature, which is used to extract the L1B point data within leads in the third model.

3) SSH computation

The third model is applied to compute the SSH reference by extracting the L1B tie points and screening out the outliers. Those leads will be used to extract the ATM L1B data if they are larger than 10 m^2 and less than 95% of the DMS image. In order to ensure the extracted tie points are fully within leads, only lead polygons with area $> 10\text{ m}^2$ (roughly $3\text{ m} \times 3\text{ m}$) are used to extract the L1B tie points. This considers the integrated impacts of shaded areas, the footprint size (1m) of ATM laser shots, and the geolocation uncertainties ($\sim 1\text{m}$) of ATM laser shots and DMS images (Krabill et al., 2009; Kwok et al., 2012; Martin et al., 2012). Actually, the lead area threshold of 1 m^2 normally extracts more L1B data points than those of 4 and 10 m^2 on Section C and D on October 23, 2011 (not shown). After applying the filters of laser shots' reflectivity threshold (< 0.25 or larger) and the height range of $\text{mean} \pm \text{one standard deviation}$ (height), the tie points and mean SSH for different lead thresholds are almost identical. This indicates that most of those excess points for the 1 m^2 threshold are caused by

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the small shaded areas on sea ice. One of the primary purposes applying a minimum polygon area threshold (10 m^2) is to screen out those small shaded areas of sea ice, which were 1.8% in areas on those images without any leads, e.g., on section D on October 13, 2012.

Even so, some large shaded areas of sea ice under thick cloud or beside high ridges/icebergs are classified as leads, which are further used to extract L1B shots as the sea surface tie points; for example, the false lead in the red circle on Fig.7c is on thick sea ice and is caused by the shade of a ice ridge on Fig.7a; the corresponding extracted L1B elevation is 1 m higher than that within a neighboring true lead (Fig. 7d). Meanwhile, the apparent reflectivity (R) of L1B data is little affected by the shade or cloud and is much higher than those within leads, e.g., the R values within leads and shade were 0.15 and 0.38, respectively (Fig. 7d). The R threshold of 0.25 (or a larger value) is used to sieve out those points extracted by sea ice shade instead of leads (Kwok et al., 2012; Kwok and Maksym, 2014). Most laser points extracted by shaded areas of sea ice have higher elevations and R values and are removed by using the R threshold (Fig. 8). Accordingly their mean elevation (SSH) decreases from -9.90 ± 0.47 to -10.08 ± 0.25 after applying the R threshold. Moreover, two data points with abnormally higher elevations still exist after applying the R threshold. Those points have much higher elevation than the mode and can not be taken as the SSH tie points. The final step is to further remove the evident outlier points beyond the height range of mean $\pm$ one standard deviation (Fig. 8b, -10.08 ± 0.25). The remaining tie points are used to compute the SSH (-10.13 ± 0.08), which is lower and less variability than that without removing the outliers.

Figure 8. The elevation histogram from (a) all tie points extracted from the DMS image-classified leads and (b) those tie points of plot (a) with $R < 0.25$ over the DMS image in Fig. 3a. The two vertical dashed green lines on plot (b) are the elevation range between the mean minus (-10.34) and plus (-9.83) one standard deviation. Those tie points whose elevations fall within this range are used to compute the new average (-10.13) as the SSH reference.

In addition, there were more dark or vignetting DMS images in the Arctic OIB campaigns (e.g., in 2011) than in the Antarctic campaigns. This is probably because most Arctic OIB campaigns surveyed the Arctic Ocean with higher latitudes (70-85 degrees) in March and April, when the solar illumination angles are low, resulting in more shaded areas and more dark and vignetting DMS images. Those dark and vignetting DMS images have similar pixel intensity ranges (e.g., 3-30) of leads and are classified as leads by the dynamic pixel intensity thresholds of 3-DNT. Those false leads are screened out for retrieving SSH in our approach by filtering a leads area ratio of 95% (or a larger value) since the entire dark and vignetting DMS images are classified as leads and real leads only occurs on part of a DMS

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image. In other words, if the classified leads' area ratio is larger than 95% of the DMS image, those leads will not be used to extract L1B data. Without excluding those false leads, it will generate large uncertainty in retrieving SSH from those abnormal images especially in the OIB Arctic campaigns. Alternatively, those dark and vignetting DMS images can be excluded in the image pre-processing as well.

3.3 Computation of Total Freeboard and Sea Ice Thickness

The last model is used to compute the total freeboard and sea ice thickness using the SSH reference obtained in the third model (Fig. 6). For those DMS images without lead, the SSH is interpolated linearly from neighboring SSH with leads. Each SSH is used as an SSH reference within a ± 0.5 km section centered at a DMS image. The total freeboard is then obtained in Equation (1).

$$F = H_s - H_r \quad (1)$$

$$F = F_i + D_s \quad (2)$$

where F is the total freeboard, consisting of snow depth (D_s) and ice freeboard (F_i) (Xie et al., 2011); H_r is an instantaneous SSH reference, and H_s is an ATM measured snow (or ice if no snow) surface height. Both H_r and H_s are surface heights relative to the WGS84 ellipsoid given by ATM L1B data or the corrected surface height if azimuth-related bias being identified (Fig. 2).

Sea ice thickness is estimated using the buoyancy equation (3) in the Bellingshausen Sea during winter/spring transition assuming that snow, ice and sea water are in isostatic

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equilibrium using the bulk densities of snow, sea ice and sea water (Zwally et al., 2008; Weissling et al., 2011; Wang et al., 2013). This equation is the same as and derived from that in Zwally et al. (2008) by replacing the F with F_i and D_s in Equation (2).

$$T_i = \frac{\rho_w F_i + \rho_s D_s}{\rho_w - \rho_i} \quad (3)$$

where F_i is close to zero for Antarctic sea ice, and $D_s \approx F$; ρ_s , ρ_i , and ρ_w are the bulk densities of snow (360 kg/m^3), ice (915 kg/m^3) and sea water (1029 kg/m^3).

Snow depth (D_s) is one of the most critical variables in applying equation (3) to compute ice thickness after obtaining the total freeboard F . Deriving sea ice thickness in the Southern Ocean of Antarctica is not comparable with that in the Arctic Ocean since there is a thick snow cover on the top of sea ice in Antarctica. According to the SIMBA *in situ* study near Section D in 2007 (Fig. 1), the absolute values of ice freeboard (F_i) during early and middle spring (e.g., October and November, maximum accumulation of snow and sea ice) were in a range of a few centimeters ($0 \pm 5 \text{ cm}$) from sea level in most cases, and the mean snow depth was actually close to the mean total freeboard, i.e., $D_s \approx F$ (Xie et al., 2011; Weissling et al., 2011). Thus, sea ice thickness is computed by the total freeboard F ($F = D_s \mid F_i = 0$) using Equation (3) without directly measuring snow depth (D_s).

Alternatively, sea ice thickness could also be computed through an empirical relationship derived from *in situ* ice thickness and total freeboard (Xie et al., 2011; Weissling et al., 2011; Xie et al., 2013; Ozsoy-Cicek et al., 2013). Statistically, the ice thickness computed by the buoyancy equation (assuming zero ice freeboard) and by the empirical relationship are

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similar in the Bellingshausen Sea in October and November (Wang et al., 2013). Thus, relative sea ice thickness in this study is computed using the buoyancy equation (3).

4. Results and Discussions

4.1 Leads and SSH Reference

The spatial variations of SSH on October 23, 2011 are illustrated in Fig. 9. The SSH values are derived from manual selection and from our automated approach of DMS-classified lead extraction. SSHs by both methods are in agreement by $r \geq 0.98$ and a mean difference of 0.01 m to 0.07m. When there were more large leads on sections A, B and C on October 23, 2011, the number of SSH references obtained from DMS automated classification are similar to those from manual selection. In contrast, the automated approach had fewer SSH references than those by manual selection on section D, where there were fewer large leads than those on sections A, B, C. Actually, all leads were detected in the original classification by the pixel intensity threshold from those five images where no SSH were obtained by the automated approach on section D. Some of those skipped leads were clumped to neighboring sea ice during post-classification in three images due to their narrow leads ($<1\text{m}$), while those skipped leads in another two images were used to extract L1B shots successfully. However, those shots within re-frozen thin ice surface had large R values and were not used to compute SSH.

Figure 9. Sea Surface Heights (SSH) by manual selection and DMS-classified lead extractions on sections of A, B, C and D on October 23, 2011. The bold dash line is the trend line of SSH by manual selection. MD is the Mean Difference of SSH by DMS-classified lead extraction and by manual selection over DMS images with leads.

Leads area thresholds of 1 m^2 and 4 m^2 are also tested, but no significant difference is found. It is challenging to determine an optimal leads area threshold because of the variability of leads shape. The 10 m^2 threshold (roughly $3\text{m} \times 3 \text{ m}$) is applied in this study, considering the integrated impacts of small shaded areas, the footprint size (1m) of ATM laser shots, and the geolocation uncertainties ($< 1\text{m}$) of ATM laser shots and DMS images (Krabill et al., 2009; Kwok et al., 2012; Martin et al., 2012). Compared to the manual selection, the reduced number of SSHs by this automated approach is an acceptable sacrifice for higher accuracy of

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automatic classification under situations with quite narrow leads (roughly < 1 m wide).

The existence of leads is critical to obtain a local SSH reference. Table 2 summarizes lead distributions obtained by our automated approach using DMS image classifications in 2011 and 2012. The leads distribution has a large spatial heterogeneity due to different locations and the sea ice movement. The mean areal percentage varied from 0.6% on section D to 33.8% on section A with a mean value of 16.5% in 2011, and from 6.5% on section A to 19.5% on section B with a mean of 10.9% in 2012. Within a section 45 km long (Fig. 9), SSH demonstrates a linear gradient, which is applied to derive other SSH where no leads are present. All SSHs are then utilized to compute total freeboard and sea ice thickness on the four sections in 2011 and 2012.

The ATM L1B observed SSH can be split into two parts. One is the local SSH gradient, and the other is the difference between the ellipsoid height and the geoid height. The geoidal undulations have not been removed from the ATM L1B elevation data at a local scale of 45 km in this study, while such geoidal undulations are removed before ice thickness analysis using ICESat elevation data at the regional scale in Kwok et al. (2012). Therefore, there are large differences of the absolute SSHs (or L1B ellipsoid heights) on different sections, e.g., ~ -9.5 m on section A and -18.5 m on Section D in 2011, ~ 500 km distance between section A and section D (Fig.1 & 9). These large variations in SSHs are relative to the ellipsoid heights, and are unimportant in this study since these large variations will be canceled out in calculating the total freeboard by subtracting the local-based SSH reference from the same set of data (Zwally et al., 2008; Wang et al., 2013).

4.2 Total Freeboard and Sea Ice Thickness

The histograms of both total freeboard and ice thickness are uni-modal, tailing off toward the larger values (Fig. 10 & 11). The modes of total freeboard (ice thickness) on October 23, 2011 were 0.10 m (0.40 m), 0.30 m (1.00 m), 0.40 m (1.20 m) and 0.40 m (1.40 m) on section A, B, C, and D (Table 4), and their mean values were 0.24 m (0.77 m), 0.42 m (1.31 m), 0.47 m (1.49 m) and 0.48 m (1.52 m), respectively. The values of total freeboard and ice thickness are negatively correlated with the areal ratio of leads, i.e., the larger the areal percentage of leads on sections A and B than those on Sections C and D (Table 1) in 2011, the smaller the values of total freeboard and ice thickness were (Table 4). The total freeboard and ice thickness on October 13, 2012 were larger than those on October 23, 2011, especially on sections A and D (Tables 4 & 5).

Table 4. Statistics of total freeboard and sea ice thickness (unit: m) based on the ATM L1B data using Equations (1)-(3) on October 23, 2011.

	Section A		Section B		Section C		Section D	
	Total Freeboard	Ice Thickness	Total Freeboard	Ice Thickness	Total Freeboard	Ice Thickness	Total Freeboard	Ice Thickness
Mean	0.24	0.77	0.42	1.31	0.47	1.49	0.48	1.52
Mode	0.10	0.40	0.30	1.00	0.40	1.20	0.40	1.40
Median	0.18	0.57	0.36	1.14	0.42	1.32	0.43	1.37
Standard deviation	0.22	0.69	0.26	0.80	0.24	0.76	0.29	0.91

Table 5. Statistics of total freeboard and sea ice thickness (unit: m) based on the ATM L1B data using Equations (1)-(3) on October 13, 2012.

	Section A		Section B		Section C		Section D	
	Total	Ice	Total	Ice	Total	Ice	Total	Ice
	Freeboard	Thickness	Freeboard	Thickness	Freeboard	Thickness	Freeboard	Thickness
Mean	0.47	1.49	0.46	1.46	0.43	1.37	0.62	1.94
Mode	0.30	1.00	0.30	1.00	0.40	1.00	0.60	1.60
Median	0.38	1.18	0.39	1.22	0.37	1.17	0.57	1.81
Standard deviation	0.34	1.04	0.32	1.06	0.24	0.75	0.34	1.05

Figure 10. Frequency distribution of total freeboard on four sections of A, B, C and D from ATM L1B data on October 23, 2011 in Bellingshausen Sea. The L1B data samples for each section are around one million.

Figure 11. Frequency distribution of sea ice thickness on four sections of A, B, C and D from ATM L1B data on October 23, 2011 in Bellingshausen Sea.

Among the four sections on October 23, 2011, section A had the largest leads ratio and the lowest total freeboard and ice thickness (Tables 2 & 4, Fig. 10 & 11). The first three columns of the total freeboard histogram (71%) comprises values between 0.1 m and 0.4 m (Fig. 10), and the first three columns of the ice thickness histogram (52%) range from 0.2 m to 0.8 m (Fig. 11). In addition, on sections B and D, there were 0.4% and 0.6% of total freeboard above 2 m (Fig. 10b & 10d), which are considered to be icebergs; therefore total freeboards were given a maximum cutoff value of 2 m (Wang et al., 2013). Accordingly, the

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511 histogram of ice thickness on sections B and D also had a long tail for thick sea ice, and 0.5%
512 and 0.7% of ice thickness was greater than 6 m (Fig.11b & 11d), which are assigned a
513 maximum cutoff value of 6 m (corresponding to a total freeboard of 2m) according to the ice
514 profile observed in the 2007 SIMBA cruise (Weissling et al., 2011).

515 The values of total freeboard (0.40 ± 0.25 m) on the four sections in 2011 in this study are
516 similar to those (0.48 ± 0.21 m) on segment 1 in Kwok and Maksym (2014), which studied the
517 same OIB sea ice flight in the Bellingshausen Sea on October 23, 2011. The total freeboards
518 show near linear relationship with snow depths (P.21, Fig.12e, Kwok and Maksym, 2014).

519 Without accurate measurements of snow depth, the total freeboard is a reasonable
520 approximation of snow depth to compute the sea ice thickness by assuming a zero sea ice
521 freeboard in the southern ocean winter and spring (Xie et al., 2011; Weissling et al., 2011;
522 Kurtz and Markus, 2012; Ozsoy-Cicek et al., 2013). This assumption of zero ice freeboard is
523 regional and seasonal specific predicated on the large volume of snow present on sea ice in
524 the Bellingshausen Sea, causing the snow/ice interface nearly at local sea level.

525 The above total freeboard and ice thickness are based on the original ATM L1B data,
526 which have a small footprint and a huge volume of data. It is difficult to make a spatial
527 distribution map of total freeboard and ice thickness for a large area using L1B data. For
528 instance, there are over 1 million data points on a 45km long and 0.3 km wide profile of one
529 L1B file, while there were only about 6000 ATM L2 data points on the same profile. ATM L2
530 data are the smoothed values of ATM L1B data over an along-track profile of ~60 m and a
531 fixed cross-track profile of 80 m (Krabill et al., 2009), but is challenging to be used for

resolving leads and SSHs (Wang et al., 2013). Using the same SSHs identified by ATM L1B data, the mean and median values of total freeboard and ice thickness calculated using the L2 data are similar with those from the L1B data (Wang et al., 2013). Fig. 12 presents the spatial distributions of total freeboard and ice thickness profile using ATM L2 data and the SSH reference identified from ATM L1B data on section C in 2011. Each zero total freeboard value represents where leads were located and SSH were determined. Similar with Fig. 10c & 11c, 69% (59%) of total freeboard (ice thickness) fall within a range from 0.3 m to 0.8 m (1.0 m to 1.8 m).

Figure 12. Total freeboard and ice thickness profile from ATM L2 data (total 6133 samples) on sections C in the Bellingshausen Sea using SSHs derived by automated DMS classification and ATM L1B data on October 23, 2011. Ice thickness is computed using total freeboard by Equations (3). The bold lines are running means of 100 L2 data points, which approximately equals to the total L2 samples over one DMS image area.

Besides the validation studies on the four selected sections on both dates, the automated approach is applied to process the DMS images and ATM L1B data for retrieving SSH and computing total freeboards on the entire sea ice flights in Antarctica on October 23, 2011 and on October 13, 2012. There are larger total freeboard near the coast and smaller values in the offshore areas (Fig. 13). In addition, this approach is also tried on one flight along offshore of western Greenland (Fig. 14). This shows that our approach is capable to process the normal DMS images and L1B data for classifying leads and retrieving SSH in OIB's both Antarctic and Arctic campaigns although it is developed based on the physical features of sea ice in the Southern Ocean of Antarctica. There was a large proportion of abnormal dark and vignetting DMS images in the OIB Arctic campaigns, e.g., in 2011. Those abnormal DMS images were falsely classified as leads and were screened out for extracting ATM L1B data by a lead area ratio of 95% in our processing. More investigations are needed to handle the abnormal dark and vignetting DMS images and ATM data in the Arctic OIB campaigns due to its special geographic location and sea ice characteristics.

Figure 13. The spatial distribution of mean total freeboard derived from DMS images and L1B data in the Bellingshausen Sea of Antarctic on October 23, 2011 (a) and on October 13, 2012 (b).

a. 2011 OIB flights

b. Total Freeboard on 2011/4/28

Figure 14. The Operational IceBridge (OIB) Arctic sea ice flights in 2011 (a) and the distribution of mean total freeboard (b) derived from DMS images and ATM L1B data along the offshore flight of western Greenland on April 28, 2011.

5. Summary and Remarks

NASA's IceBridge mission has operated for eight years since 2009 and yielded unprecedented three-dimensional observations of Arctic and Antarctic ice sheets and sea ice. These measurements are critical for various topics, such as algorithm development, assessment of satellite retrieval, parameterization and evaluation of oceanic and climatic

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models, and incorporation into climate data record for analysis of interannual variability and long-term trends in sea ice and ice sheet properties. However, we are still facing several challenges on how to make full use of those vast observations, especially in estimating sea ice thickness from ATM elevations.

In order to mitigate the impact of shaded areas of DMS images and the biased ATM elevation data on determination of SSH, this study develops an automated approach to determine leads and SSH by combining DMS images, ATM L1B's apparent reflectivity and statistical discrimination. We demonstrate the applications of our approach in computing total freeboard and sea ice thickness using DMS images and ATM data on the selected four sections along the sea ice flight track in the Bellingshausen Sea in 2011 and 2012. The high agreement of SSHs from our automated classification with those from manual selections indicates the reliability and usefulness of our approach.

Within a 45-km section of one ATM L1B file, SSH demonstrates a linear gradient, which is applied to derive other SSH where there was no lead; then all SSHs are applied to compute total freeboard and ice thickness. There were higher total freeboard and thicker ice thickness on October 13, 2012 than those on October 23, 2011, especially on sections A and D. In the two flight profiles examined, the area ratio of leads (i.e. sea ice concentration) is negatively related to total freeboard and ice thickness; the larger the area ratio of leads on section A in 2011, the smaller the values of total freeboard and ice thickness were.

This automated approach is also tried on one OIB's entire flight each in Antarctic and Arctic and can be utilized to process the vast amount of the normal DMS images and ATM

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data acquired since 2009 to retrieve the instantaneous SSH, which may then be utilized to compute total freeboard and sea ice thickness. More investigations are needed to handle the abnormal dark and vignetting DMS images and ATM data in the OIB Arctic campaigns.

Acknowledgements

This study was supported by the Natural Science Foundation of China (#41371404), the Water Resource Science and Technology Innovation Program of Guangdong Province (#2016-19), Fundamental Research Funds from Sun Yat-sen University (#15lgzd06), and the Open Foundation of the State Key Laboratory of Desert and Oasis Ecology (#G2014-02-06), Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences. Co-authors S.F. Ackley and H. Xie acknowledge support by the National Science Foundation (#1341717) and the ONR Grants (#N00014-13-1-0435) to the University of Texas at San Antonio, USA. Undergraduates Ruowei Liu contributed great efforts on identifying leads from DMS images and manually selecting the ATM L1B tie points within leads. We thank all researchers and staff from the IceBridge program and the NSIDC for retrieving, processing and distributing the ATM data and DMS images. The comments and suggestions from three reviewers and two editors greatly improve this manuscript and are highly appreciated by all authors.

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