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Fusion of multi-sensor surface elevation data for improved characterization of rapidly changing outlet glaciers in Greenland

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ABSTRACT

During the last two decades surface elevation data haven been gathered over the Greenland Ice Sheet (GrIS) from a variety of sensor, ranging from laser altimetry to stereoscopic DEMs derived from imaging sensors. The spatio-temporal resolution, the accuracy and the spatial coverage among the data differ widely. For example, ICESat, a spaceborne laser profiler, has a high temporal resolution but sparse spatial coverage which places the nearest ground track to the calving front of the Kangerlussuaq Glacier in East Greenland, our study site, 30 km up stream. On the other hand, stereoscopic DEMs provide almost continuous spatial coverage, but at a lower accuracy. This is a typical scenario for many rapidly changing outlet glaciers in Greenland where a fusion of the disparate data sets is highly desirable to construct detailed spatio-temporal histories of elevation change. We present in this paper how our recently developed SERAC method (Surface Elevation Reconstruction And Change detection) is well suited to cope with this fusion problem. More specifically, we describe a novel approach to adjust stereoscopic DEMs to the laser altimetry point cloud, based on height corrections determined from the time-series of elevation changes calculated by SERAC. These corrections are then used in a height adjustment of the DEMs.

1. Introduction

Comprehensive monitoring of the cryosphere has revealed increasing mass loss of the Greenland and West Antarctic ice sheets during the last two decades (Rignot, Velicogna, Van Den Broeke, Monaghan, & Lenaerts, 2011; Shepherd, Ivins, Geruo, Barletta, et al., 2012). The Antarctic and Greenland ice sheets contain enough water to raise the global sea level over 70 m (Alley, Clark, Huybrechts, & Joughin, 2005). Even a small imbalance between the snowfall and the discharge of ice and melt water into the oceans can be a major contributor to global sea-level rise and thus affect coastal populations. Consequently, a detailed knowledge and understanding of outlet glacier and ice sheet behaviors is not only an interesting research issue but is of great societal importance.

Observations of recent, dramatic changes challenged the traditional view of slowly evolving ice sheets. For example, velocities and thinning rates of outlet glaciers have increased significantly (Moon, Joughin, Smith, & Howat, 2012; Thomas, Frederick, Krabill, Manizade, & Martin, 2009; Wingham, Wallis, & Shepherd, 2009), iceberg calving occurs more frequently, and millennia-old floating ice shelves are disintegrating (Domack et al., 2005). The ability to predict rates of global climatic change, melting ice, and rising seas through the next century relies on an accurate understanding and modeling of the great ice sheets, which requires a precise reconstruction of their topography and evolution with time. During the last two decades surface elevation data have been acquired from a variety of different sensors, including satellite laser altimetry observations from ICESat (Ice Cloud and land Elevation Satellite, (Schutz, Zwally, Shuman, Hancock, & Dimarzio, 2005; Zwally et al., 2002)), airborne laser altimeter data from ATM (Airborne Topographic Mapping system, (Krabill et al., 2002)) and LVIS (Land, Vegetation, and Ice Sensor a.k.a. the Laser Vegetation Imaging Sensor (Blair, R, & Hofton, 1999)). Additionally, stereoscopic Digital Elevation Models (DEMs) derived from satellite imaging systems, such as Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER, Abrams (2000)), Satellite Pour l'Observation de la Terre (SPOT, Bouillon et al. (2006)), and high resolution earth imaging satellites (e.g., IKONOS, QuickBird, WorldView-1 and 2, GeoEye-1, Pleiades, Toutin (2004)), have also become available. Generally, these DEMs have a vertical accuracy of meters, that is at least one order of magnitude lower compared to the sub-meter accuracy of laser altimetry points. However, their spatial coverage is nearly continuous while repeat altimetry is confined to narrow profiles or a swath width of a few hundred meters. Thus it makes sense to fuse these disparate data sets, ideally in a system that would consider the different accuracies and point densities, and would also deliver consistent results, including error estimates.

Repeat altimetry and DEMs derived from stereo imagery have long been used to monitor the cryosphere, but mostly for mapping multi-year average elevation changes (e.g., Howat, Smith, Joughin, & Scambos, 2008; Pritchard, Arthern, Vaughan, & Edwards, 2009; Thomas et al., 2009; Zwally et al., 2011) rather than reconstructing detailed temporal histories. As surface elevation observations are often collected with

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varying spatial resolutions at slightly different locations, the derivation of accurate elevation histories has remained a challenging task. We have recently developed SERAC (Surface Elevation Reconstruction And Change detection) for calculating surface elevation and surface elevation change (Schenk & Csatho, 2012). SERAC determines elevation changes of small surfaces, called surface patches, in contrast to other methods that are attempting to obtain changes from a small set of individual observations located in close proximity (Pritchard et al., 2009; Zwally et al., 2011). Originally developed for ICESat laser altimetry data, we have expanded SERAC to include other surface elevation data, for example ATM and LVIS. In this paper we present results from combining stereoscopic DEMs with laser altimetry data. We also report about a new way to correct stereoscopic DEMs so that they fit the time-series of elevation changes much closer, based on their theoretical precision.

2. Objectives and rationale

We pursue two objectives in this study. First, we extend the calculation of elevation change histories in time and space by including observations other than laser altimetry, such as DEMs derived from high resolution satellite imaging sensors and aerial photogrammetry. The second objective is to develop a new method to correct the DEMs such that they best fit to the time-series of laser altimetry point clouds depicting a changing glacier surface.

Repeat laser altimetry missions compromise spatial for temporal resolution. For example, ICESat provided repeat elevation measurements along pre-determined ground tracks on average three times per year (Schenk & Csatho, 2012, Table 1). The spatial separation of these ground tracks is small toward the poleward boundaries of data acquisition (±86°) but increases rapidly toward the equator. The spatial and temporal coverage of airborne altimetry are even more limited. NASA's Program for Regional Climate Assessment (PARCA, 1993–2009) and Operation IceBridge (OIB, 2009–2013) missions have been collecting data annually in Greenland and more recently in Antarctica. To facilitate change detection, a significant portion of the flights are dedicated to repeating previous missions (Abdalati et al., 2002; Koenig, Martin, Studinger, & Sonntag, 2011), leaving a sampling pattern that is often times not dense enough. For example, on the Kangerlusssuaq Glacier in East Greenland, our study area, the nearest ICESat ground track is about 30 km from the calving front and most repeat ATM flight lines follow the central flowline, leaving large areas uncovered (Fig. 1). This is typical for many other outlet glaciers, for example in SE Greenland, where dramatic recent velocity fluctuations indicate large mass balance variations (Moon et al., 2012). On the other hand, stereoscopic DEMs provide almost continuous spatial coverage (Howat et al., 2008). Thus, it makes eminent sense to fuse (combine) DEMs and laser altimetry to broaden the spatial coverage of surface elevation and change rates.

Stereoscopic DEMs are at least one order of magnitude less precise than laser altimetry. Often times they are affected by systematic errors, arising from a multitude of sources, such as satellite jitter, problems with unstable interior and exterior camera orientation, partial cloud coverage or the presence of ground fog, and too low image definition that causes problems in matching stereoscopic images. In summary, numerous sources affect the quality of stereoscopic DEMs, making the accuracy much worse than the precision. Hence, it is crucial to find a way to correct the DEMs before they enter the joint adjustment with laser altimetry data to calculate time-series of elevation changes.

Table 1
Data used in this research. The first three entries are laser altimetry systems (also called LIDAR) from NASA and the remaining five entries deliver DEMs. The column *period* refers to the time period of the data used in this study.

Source	Platform	Period	Repeat	Data type
ICESat	Satellite	2003–2009	Yes	LIDAR
ATM	Airplane	1993–2012	Yes	LIDAR
LVIS	Airplane	2010–2012	Yes	LIDAR
SPOT	Satellite	2007–2008	Yes	DEM
ASTER	Satellite	2001–2012	Yes	DEM
Aerial	Airplane	1981	No	DEM
DISP	Satellite	1966	No	DEM
TopoMap	Map	1933	No	DEM

3. Study area and data sources

The Kangerlussuaq Glacier in east Greenland, one of Greenland's three largest glaciers, serves as our study area (Fig. 1). It drains approximately 3% of the GrIS with a balance discharge of about 23 km^3 a^{-1} and has been thinning since repeat ATM surveys started in 1993 (Thomas et al., 2009). In 2004–2005, it underwent a dramatic retreat, acceleration and thinning, indicating a significant change in ice dynamics (Howat, Joughin, & Scambos, 2007). Mass loss rate peaked at 40 Gt a^{-1} in April 2005, followed by a gradual decrease to 10 Gt a^{-1} by 2008 (Howat et al., 2011). Owing to its fast velocity and recent large mass loss, the Kangerlussauq Glacier has become one of the most intensely studied outlet glaciers. Numerous research papers have been published describing its velocity, thickness and calving front evolution as well as resulting mass balance changes (Csatho, Bolzan, Van Der Veen, Schenk, & Lee, 1999; Howat et al., 2007, 2008, 2011; Thomas et al., 2000, 2009). These observations, together with similar histories of Jakobshavn Isbræ and Helheim Glacier, formed the basis of several recent numerical modeling studies, estimating GrIS contribution to sea-level rise by 2100 (Nick et al., 2013; Price, Payne, Howat, & Smith, 2011). However, the elevation change reconstruction of the Kangerlussuaq Glacierhas remained incomplete, due to the sparse spatial coverage of repeat laser altimetry measurements.

We have selected several data sources and combined them to demonstrate the fusion capability of SERAC and our unique method to adjust stereoscopic DEMs to laser altimetry point clouds. Laser altimetry data acquired by ICESat spaceborne and ATM/LVIS airborne systems, stereoscopic DEMs from Declassified Intelligence Satellite Photographs, aerial photographs, ASTER and SPOT satellite imagery, and a DEM derived from an old topographic map are used in the computation of time-series of surface elevation changes since the 1930s.

Stereoscopic DEMs are obtained from two stereo images that are acquired at slightly different times by two stereo sensors. A traditional way to express the geometry of stereo images is the base/height (B/H) ratio. The base is the distance between the two images and height refers to the flying height. The B/H ratio relates to the intersecting angle of the projection rays of two corresponding image points. It gives a good indication of the precision of the intersection, that is, of DEM points. A B/H ratio of 0.5 to 0.6 is considered good, ratios <0.5 hold inferior vertical precision (Wolf & Dewitt, 2000, pp. 409–410).

The position of corresponding points in stereo images is found automatically by matching (Schenk, 1999, chap. 10–11). There is a suite of problems associated with matching, particularly with gray level matching where the gray level function of a small image patch is compared with candidate image patches in the other image. This matching technique works well if the image function (e.g. distinct distribution of gray levels in the image patches) is high, the approximate location of the corresponding point is good to a few pixels, and the geometric distortion of the image patches, due to image projection, is small. Image patches with no or low contrast lead to unreliable, erroneous or no matches at all. This is often the case with images over surfaces covered with snow or ice, or images with (partial) cloud coverage. Therefore, stereoscopic DEMs are usually only available along coastal regions of ice sheets and their precision rapidly decreases when moving further up on the ice sheet.

The very different characteristics of stereoscopic DEMs, compared to laser altimetry, is actually welcome news to fusion: within the coastal regions, especially on outlet glaciers, we usually have yearly elevation changes that are comparable or greater than the (low) precision of stereoscopic DEMs. Also, elevation changes can vary abruptly over relatively small areas. To capture these changes requires a far denser