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Photogrammetric retrieval and analysis of small scale sea ice topography during summer melt

Dmitry V. Divine[a, b, *], Christina A. Pedersen[a], Tor Ivan Karlsen[a], Harald Faste Aas[a], Mats A. Granskog[a], Stephen R. Hudson[a], Sebastian Gerland[a]

[a] *Norwegian Polar Institute, Fram Centre, N-9296 Tromsø, Norway*
[b] *Department of Mathematics and Statistics, Faculty of Science and Technology, The Arctic University of Norway, N-9037 Tromsø, Norway*

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ABSTRACT

The paper presents a setup for photogrammetric retrievals of small scale sea ice surface topography using low-altitude aerial imagery. The setup features two digital cameras, a combined GPS receiver/inertial navigation system (INS) unit, and a laser range finder. The components are fit in a single aerodynamic enclosure mounted outside a helicopter cabin. Results from its first deployment during the field campaign on Arctic sea ice north of Svalbard during summer 2012 are shown. Comparison of photogrammetrically derived digital elevation models (DEMs) with in situ measurements of sea ice topography made on melting first year sea ice demonstrated the ability of the method to accurately recover the topography of sea ice including melt ponds with depths down to at least 0.3m. The inter-comparison of the photogrammetrically derived DEM and in situ measured elevations yielded estimates of a root mean square error (RMS) of about 0.04m and bias of 0.03m, both for sea ice freeboard and melt pond depths. The bimodality of the probability density function of measured melt pond depths was also accurately reproduced in the reconstructed DEM. Discrepancies between the measured and DEM distributions were within the range of the inferred uncertainty of the photogrammetric and in situ techniques, with some of the bias likely associated with sea ice melt during the time elapsed between in situ and aerial measurements.

1. Introduction

Knowledge of the small scale properties of sea ice surfaces is important for a better understanding of the causal factors behind the ongoing changes in sea ice cover on the pan-Arctic scale (e.g. Vihma et al. (2014)). The spatial and seasonal variability of sea ice topography at the 10^0–10^3 m scale contributes to a range of physical processes affecting the sea ice evolution throughout its seasonal cycle. Momentum exchange with the atmosphere and hence the sea ice drift and deformation, snow accumulation/redistribution patterns and surface albedo all depend on sea ice roughness. Surface topography is also considered to be one of the controlling factors for the spatial distribution of melt ponds during summer melt, with implications for summer energy balance of sea ice (Eicken et al., 2004, Landy et al., 2014, Petrich et al., 2012).

The use of laser altimetry and laser scanning techniques (LiDAR) both in aerial (e.g. Hvidegaard and Forsberg (2002); Giles and Hvidegaard (2006); Connor et al. (2009); Farrell et al. (2012); Connor et al. (2013); Dotson and Arvesen (2014); Beckers et al. (2015)) and in situ (e.g. Haapala et al. (2013), Landy et al. (2014, 2015), Petrich et al. (2012), Polashenski et al. (2012)) applications proved to be an efficient tool for retrieval of high resolution surface elevation data on spatial scales from centimeters up to hundreds of square kilometers. Laser based measurements can provide substantial spatial coverage and are computationally inexpensive but their inability to penetrate water due to the reflection of the laser beam off of the water surface is an important limitation of most laser systems during summer melt.

During summer, water runoff from melting snow and upper ice layers tends to form puddles in depressions in the sea ice surface (e.g. Fetterer and Untersteiner (1998)). These melt ponds spread rapidly and, on level first year ice, can cover up to 75% of the surface during the initial stage of surface melt (Grenfell and Perovich, 2004, Hanesiak et al., 2001, Polashenski et al., 2012). As the formation of melt ponds exerts a predominant control on albedo and solar energy partitioning on melting Arctic sea ice (e.g. Ehn et al. (2011); Eicken et al. (2004)), and due to the overall importance of albedo feedbacks in the Arctic, melt ponds and their morphological characteristics are of considerable interest in climate modeling (Holland et al., 2012, Hunke et al., 2013, Pedersen et al., 2009).

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* Corresponding author.
E-mail address: dmitry.divine@npolar.no (D. Divine).

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Visible light penetrates water and can be reflected from the bottom of melt ponds, thus photogrammetric retrievals of sea ice surface topography can address the aforementioned knowledge gaps by providing information on the spatial and temporal variability of melt pond distribution and morphology. Photogrammetry defines tools to feed a sequence of overlapping images of a scene captured from different locations into a computational scheme that recovers the 3-D coordinates of surface points from relative displacements of the scene in the image plane (e.g. Schenk (1999)). A number of challenges specific for sea ice may affect the overall performance of the method:

1. Sea ice surfaces often have relatively low contrast, with a lack of distinct objects, which can hinder solving the correspondence problem between overlapping images of the same scene.
2. The characteristic scale of sea ice surface variability in the vertical dimension is typically less than a meter (e.g. Beckers et al. (2015)), imposing special requirements on the image resolution and quality of the exterior orientation values (camera positions and attitude).
3. Sea ice drift and lack of track crossings can potentially create additional bias in the photogrammetrically reconstructed digital elevation model (DEM), such as spurious gradients along and/or across the flight track, suggesting that drift corrections should whenever possible be introduced into the coordinates of image projection centers.
4. Sea level variations associated both with a tidal motion and atmospheric pressure variability increase uncertainty in the global navigation satellite system (GNSS)-retrieved vertical coordinate.
5. Vibration and temperature changes during flight may affect the stability of the pre-measured interior orientation values (i.e. camera calibration parameters).

Photogrammetric methods have been successfully applied to study land and sea ice at a range of spatial scales and resolutions (e.g. Hagen et al., 2014, Hall and Rothrock, 1987, Kääb et al., 2014, Ryan et al., 2015). NASA has been running Operation IceBridge missions in the Arctic and Antarctic since 2010 using a purpose-fitted aircraft with a photogrammetric digital mapping system onboard (Dotson and Arvesen, 2014). However, to our knowledge, the melt ponds were not in the focus of these studies.

We present the "ICE stereocamera system" developed at the Norwegian Polar Institute over the period 2012–2015. The goal was to develop a relatively cheap yet robust solution for aerial imagery with image and navigation data quality high enough to enable photogrammetric retrievals of sea ice surface topography. The setup was meant to be employed during NPI field campaigns to provide complementary data on sea ice classes/thickness/topography during low-altitude (30–40 m) ice thickness survey flights with the Eurocopter AS-350. Section 2.1 presents the hardware setup and system operation procedures; the image and navigation data processing workflow is described in Section 2.2. More technical details about the setup and the workflow are found in Supplementary materials. Section 3 shows examples of the digital elevation models of sea ice surfaces with topography derived with the ICE stereocamera system. These are compared with corresponding in situ measurements of sea ice surface topography made on a regular grid during a field campaign in summer 2012 in the central Arctic north of Svalbard.

2. ICE stereocamera setup

2.1. Hardware setup and operation

Fig. 1. Aerodynamic enclosure of ICE stereocamera system mounted on AS-350 helicopter using a single pole utility mount.

Fig. 1 shows the setup mounted to the front of an AS-350 helicopter. Technical details of the setup including its block diagram, a list of system components, and setup configuration and operation are presented in Supplementary materials.

The main components of the ICE stereocamera system are two downward looking digital SLR cameras, a combined GPS receiver and inertial navigation system (INS), and a laser range finder which are all fitted in an aerodynamic enclosure. The two downward looking cameras are positioned with the horizontal image axes oriented along the flight direction to ensure the highest possible overlap between successive images for a broad range of flight velocities. The cameras' optical axes are parallel and aligned with the Z axis of the GPS/INS unit; the camera lenses' focal lengths are fixed to infinity.

A PXI chassis mounted inside the helicopter cabin controls the unit and logs the navigation data. The image shooting rate is set in the system firmware to one frame per second per camera, yielding two captured images per second. The setup is designed to be used in parallel with an electromagnetic device for measuring the ice and snow thickness, EM-bird (Haas et al., 2009), which NPI typically flies with the helicopter at an altitude of 35–40 m and at a speed of 30–40 m s^{-1}. The combined frame shooting rate and flight parameters ensure a 50–70% overlap between successive images. The size of the cameras' compact flash cards limits the continuous operation time of the setup to 70 min, corresponding to 4200 images per camera.

We note that the system components are mostly available on the consumer market and the setup has capacity for potential future adjustments and modifications to the system with respect to specific future research needs.

2.2. Navigation logs and image processing

Fig. S2 shows the ICE stereocamera image and data processing workflow, involving three major steps described in detail in 2.2.3.

2.2.1. Navigation data post-processing

The declared single point positioning accuracy of the GPS-INS unit is approximately 1.5 m and is sufficient for convergence of the photogrammetric solution. In order to increase the accuracy of the positioning data of the system, the raw navigation data are post-processed using the Precise Point Positioning (PPP) technique. We use a commercial package, TerraPos2 by TerraTec AS, which is capable of integrating the raw GNSS navigation files with the output from the INS. PPP yields a smooth solution for the system coordinates and attitude at a requested rate and/or at specific time points, which can be the logged timings of the frame shooting events.