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Satellite derived photogrammetric bathymetry

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ABSTRACT

Satellite Derived Bathymetry (SDB) is being adopted as a cheaper and more spatially extensive method for bathymetric mapping than traditional acoustic surveys, with research being conducted by the Canadian Hydrographic Service under a Government Related Initiatives Program (GRIP) of the Canadian Space Agency. Established SDB methods involve either an empirical approach, where a regression between known depths and various colour indexes is developed; or a physics-based Radiative Transfer Model (RTM) approach, where light interactions through the water column are simulated. Both methods have achieved vertical accuracies of around 1 m. However, the empirical approach is limited to areas with existing *in-situ* depth data, and has limited applicability in heterogeneous benthic environments, while the physics-based approach requires precise atmospheric correction. This paper proposes a through-water photogrammetric approach which avoids these limitations, in heterogeneous seafloor environments, by using feature extraction and image geometry rather than spectral radiance to estimate bathymetry. The method is demonstrated in Coral Harbour, Nunavut, Canada using a WorldView-2 stereo pair. A standard photogrammetric extraction was performed on the stereo pair, including a blunder removal and noise reduction. Apparent depths were then calculated by referencing under-water points to the extracted elevation of the water-line. Actual in-image depths were calculated from apparent depths by applying a correction factor to account for the effects of refraction at the air-water boundary. A tidal reduction brought depths to local chart datum, allowing for validation with Canadian Hydrographic Service survey data showing a mean error of 0.031 m and an RMSE of 1.178 m. The method has a similar accuracy to the two established SDB methods, allowing for its use for bathymetric mapping in circumstances where the established methods are not applicable due to their inherent limitations.

1. Introduction

Bathymetric data of nearshore environments is critical in fields such as maritime transport, coastal zone management, fisheries, environmental protection and management, marine science, maritime boundary delimitation, defence, tourism, and recreation (IHO, 2005). Traditional bathymetric mapping is conducted using ship-borne acoustic surveys, which often achieve centimetre-level accuracy, but are time-consuming, expensive, and not typically conducted in nearshore areas shallower than 4 m (Witmer et al., 2016). Satellite Derived Bathymetry (SDB) is being widely adopted as a relatively cheap and spatially extensive technique to support traditional surveys by filling gaps, monitoring changes in areas with highly dynamic seafloor features, and charting inadequately surveyed areas (Jegat et al., 2016). Under a Government Related Initiatives Program (GRIP) of the Canadian Space Agency (CSA), the Canadian Hydrographic Service (CHS) is investigating SDB as a method for chart updating. The current SDB methods in use can broadly be classified into two categories: a physics-based approach, which simulates light interacting with the water surface, water column and seafloor; and empirical models, which develop regressions between *in-situ* calibration data and spectral radiance.

The physics-based approach uses Radiative Transfer Models (RTM) to forward-model a range of possible remote sensing reflectances as a function of water quality, water depth, and bottom reflectance. This forward model is then inverted to estimate depth by identifying the modeled remote sensing reflectance which most closely resembles that observed in each pixel (Lee et al., 1999; Hedley et al., 2009). Accuracies of up to 0.91 m Root Mean Square Error (RMSE), down to a depth of about 13 m, have been demonstrated under ideal conditions using airborne hyperspectral imagery (Dekker et al., 2011), though satellite-based applications have been less encouraging (Knudby et al., 2016a; Hedley et al., 2016). The challenge of atmospheric correction over water (Nazeer et al., 2014), necessary to calculate the precise estimates of sea-surface reflectance needed for the modelling (Vahtmäe and

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Kutser, 2007) remains a limiting factor, especially in Arctic regions with low sun elevations (Knudby et al., 2016b).

The empirical approach relies on *in-situ* bathymetric data to calculate a regression between a natural logarithmic band ratio, typically log (Blue)/log(Green), and the corresponding depth (Stumpf et al., 2003). In principle, this method is designed to work in heterogeneous benthic environments consisting of both light substrates (sand/rock) and dark substrates (vegetation), assuming no change in water quality across a scene. In practice however, performance in such environments is unsatisfactory (Su et al., 2014), requiring the omission of results over dark substrates, or the application of complicated, locally adapted models for each substrate (Vinayaraj et al., 2016). This method has been widely adopted by hydrographic offices for the purpose of navigational charting, with accuracies similar to those found using a physics-based approach (Mavraeidopoulos et al., 2017).

This paper proposes a third option for SDB, which applies the photogrammetric technique in conjunction with a correction accounting for refraction at the air-water boundary. Because photogrammetry is a geometric operation which does not rely on accurate spectral information, no spectral atmospheric correction is necessary, making it useful in areas where physics-based approaches perform poorly due to difficult atmospheric conditions such as low light, strong adjacency effect, high aerosol density, and variations in atmospheric state within a scene. It is also well suited for heterogeneous environments where the empirical approach is unreliable, and for areas lacking in-situ data where the empirical approach cannot be implemented. Such techniques have been used for close-range fluvial bathymetry using handheld (Bird et al., 2010) and Unmanned Aerial Vehicle (Dietrich, 2017) platforms, as well as ocean bathymetry using airborne platforms (Murase et al., 2008) and satellite imagery (Cao et al., 2016). This paper provides detailed documentation of the workflow involved in satellite derived photogrammetric bathymetry, and demonstrates that errors are comparable to colour-based methods.

Satellite photogrammetry relies on the known location and orientation of imaging sensors to triangulate point features in stereo imagery (Schenk, 2005). A Rational Function Model (RFM) uses 80 Rational Polynomial Coefficients (RPCs) to convert between image-space (line and sample) and object-space (XYZ coordinates) in a block adjustment allowing for feature triangulation (Cheng, 2011). The RPCs are defined based on ephemeris, the satellite's position in 3-dimensional space at the time of exposure, measured by GPS as in-track/cross-track positions/altitude; and attitude, the orientation of the sensor, measured by gyros and a star tracker as pitch/roll/yaw (Grodecki and Dial, 2003) (Fig. 1).

Positional bias may be introduced into a photogrammetrically extracted Digital Elevation Model (DEM) due to small errors in ephemeris and attitude measurements. These are, for the most part, translational, and spatially consistent throughout a scene (Fraser et al., 2006). Using only RPCs for image positioning, DigitalGlobe reports an accuracy of CE90 = 3.5 m (horizontal), and LE90 = 3.6 m (vertical) for WorldView-2 (DigitalGlobe, 2016a). Correcting this bias involves constraining the RFM in a bundle block adjustment, using image tie points or external data such as Ground Control Points (GCPs). Tie points are created on land surface features which are identifiable in both images of a stereo pair, and help constrain the model by refining the relative position of the two images (Rupnik et al., 2016).

This paper presents a proof of concept for the derivation of nearshore bathymetry from a photogrammetric extraction of stereo imagery. WorldView-2 imagery has been selected due to its extremely high resolution and excellent positional accuracy, allowing for DEM extraction without the use of GCPs to attain a horizontal accuracy of 3–4 m. The principle can be easily extended to other high resolution, stereo-capable sensors, and can be implemented using any professional-level photogrammetry software suite.

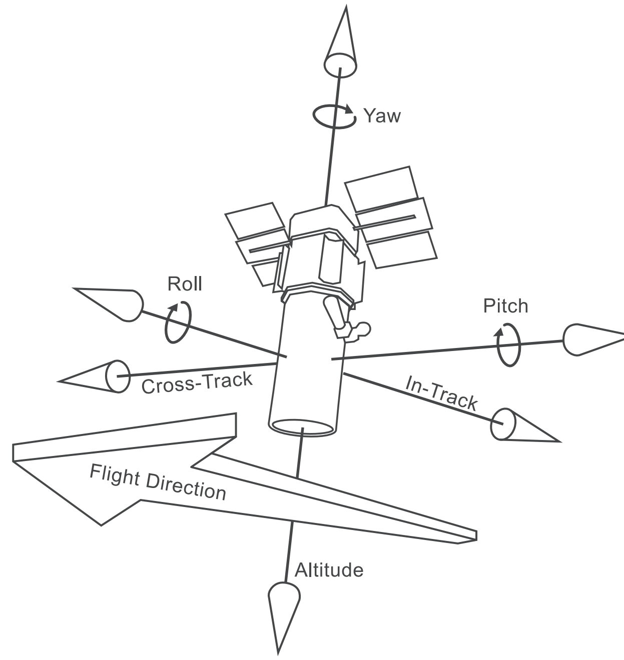

Fig. 1. The six axes of movement, overlain over WorldView-2.

2. Study area and data

The Canadian Arctic provides an ideal location to develop the photogrammetric bathymetry approach, owing to its exceptionally clear water and a suitable benthic environment. Image matching algorithms used in photogrammetry software identify points or edges which are common to both images (Potuckova, 2004), so it is necessary for the sea floor to contain relatively small, contrasting objects to provide adequate features for matching. Coral Harbour, in Nunavut, Canada (Fig. 2), was selected as an ideal study area due to its large expanse of optically shallow water containing such features.

Considerations for imagery selection included the time of year, as the area is only clear of sea ice in late summer; lack of waves or ripples, which would affect stereo feature matching and refraction correction; and water clarity for a maximized optical extinction depth, as occasionally the area is inundated with suspended sediment. A summary of the selected stereo pair is shown in Table 1.

Multispectral imagery in *Stereo Ortho-Ready 2A* format, with a spatial resolution of 2 m, was used in all processing steps. Though terrestrial photogrammetric work benefits from the improved spatial resolution of the panchromatic band or a pansharpened dataset, the unique requirements of through-water photogrammetry make this approach problematic. The spectral response of the panchromatic band in WorldView-2 data skews heavily towards the red and near-infrared (NIR) wavelengths (Fig. 3), severely limiting its water-penetrating ability. Pansharpening the multispectral data has a similar detrimental effect.

Validation data was provided by the Canadian Hydrographic Service as point depth measurements, with a vertical datum represented as *Chart Datum*, defined as the mean lower low water at large tide for Coral Harbour (DFO, 2016).

3. Methods

The method consisted of four main processing steps: photogrammetric extraction, error and noise removal, refraction correction, and datum reduction.