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The use of sun elevation angle for stereogrammetric boreal forest height in open canopies

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ABSTRACT

Stereogrammetry applied to globally available high resolution spaceborne imagery (HRSI; <5 m spatial resolution) yields fine-scaled digital surface models (DSMs) of elevation. These DSMs may represent elevations that range from the ground to the vegetation canopy surface, are produced from stereoscopic image pairs (stereopairs) that have a variety of acquisition characteristics, and have been coupled with lidar data of forest structure and ground surface elevation to examine forest height. This work explores surface elevations from HRSI DSMs derived from two types of acquisitions in open canopy forests. We (1) apply an automated mass-production stereogrammetry workflow to along-track HRSI stereopairs, (2) identify multiple spatially coincident DSMs whose stereopairs were acquired under different solar geometry, (3) vertically co-register these DSMs using coincident spaceborne lidar footprints (from ICESat-GLAS) as reference, and (4) examine differences in surface elevations between the reference lidar and the co-registered HRSI DSMs associated with two general types of acquisitions (DSM types) from different sun elevation angles. We find that these DSM types, distinguished by sun elevation angle at the time of stereopair acquisition, are associated with different surface elevations estimated from automated stereogrammetry in open canopy forests. For DSM values with corresponding reference ground surface elevation from spaceborne lidar footprints in open canopy northern Siberian *Larix* forests with slopes < 10°, our results show that HRSI DSMs acquired with sun elevation angles > 35° and < 25° (during snow-free conditions) produced characteristic and consistently distinct distributions of elevation differences from reference lidar. The former include DSMs of near-ground surfaces with root mean square errors < 0.68 m relative to lidar. The latter, particularly those with angles < 10°, show distributions with larger differences from lidar that are associated with open canopy forests whose vegetation surface elevations are captured. Terrain aspect did not have a strong effect on the distribution of vegetation surfaces. Using the two DSM types together, the distribution of DSM-differenced heights in forests ($\mu = 6.0$ m, $\sigma = 1.4$ m) was consistent with the distribution of plot-level mean tree heights ($\mu = 6.5$ m, $\sigma = 1.2$ m). We conclude that the variation in sun elevation angle at time of stereopair acquisition can create illumination conditions conducive for capturing elevations of surfaces either near the ground or associated with vegetation canopy. Knowledge of HRSI acquisition solar geometry and snow cover can be used to understand and combine stereogrammetric surface elevation estimates to co-register and difference overlapping DSMs, providing a means to map forest height at fine scales, resolving the vertical structure of groups of trees from spaceborne platforms in open canopy forests.

1. Introduction

1.1. High resolution spaceborne imagery for forest structure patterns

High resolution spaceborne imagery (HRSI) is the orbital, Earth observation component of the broader class of very-high resolution (VHR) imagery, which includes airborne data. Currently, HRSI includes primarily multispectral sensors (e.g., SPOT-6 & -7, KOMPSAT-3 & -3A, WorldView-1, -2, -3, & -4) from both the commercial and government sectors. These data can be used to complement forest inventories with detailed characterization of forests across broad extents (Wulder et al., 2004). Access to commercial HRSI (<5 m spatial resolution) data (at no direct cost) has been a catalyst for continuing to develop methods for quantifying forest attributes and ecosystem properties (Neigh et al., 2013a). Previous work with optical imagery has highlighted the value of image texture, seasonal brightness differences among image

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features, and object-based analysis for understanding the spatial patterns of forest structure at multiple scales (Berner et al., 2012; Chopping, 2011; Coburn and Roberts, 2004; Kayitakire et al., 2006; Lamonaca et al., 2008; Mallinis et al., 2008; Manninen et al., 2009; Ozdemir and Karnieli, 2011; Wolter et al., 2009).

1.2. HRSI stereogrammetric estimates of forest canopy surfaces

One use of HRSI is the application of stereogrammetry to estimate surface elevations. Recently, work with this HRSI application has involved detailed surface elevation mapping, characterizing canopy surface elevations, and quantifying height and biomass density in a variety of forests (Baltsavias et al., 2008; Lagomasino et al., 2015; Montesano et al., 2014; Neigh et al., 2016, 2014; Persson et al., 2013; Poon et al., 2007; Shean et al., 2016; Vega and St-Onge, 2008). The pointing capabilities of HRSI platforms (e.g., QuickBird, IKONOS, GeoEye-1, WorldView-1, -2, -3, & -4) provide along-track (i.e. near simultaneous) stereoscopic image pairs (stereopairs), where two image acquisitions are captured of the same location from different angles within the same orbit. Stereogrammetry applied to these acquisitions produces fine-scaled (~1 m) estimates of the elevation of surface features with pre-registration vertical accuracies of <4.5 m (Aguilar et al., 2014; DigitalGlobe, 2014; Dolloff and Settergren, 2010; Hobi and Ginzler, 2012). Often, HRSI-derived estimates of vertical forest structure are made by linking the canopy surface elevations captured in the stereogrammetrically-derived digital surface model of elevations (DSM) with coincident estimates of the ground surface elevation from another data source. In remote forested regions, coincident estimates of ground surface elevation beneath the forest canopy are often unavailable or spatially limited. In the open canopy forests along the boreal (taiga) - tundra ecotone (TTE) this results in forest height uncertainties too broad for capturing the vertical component of TTE form and preventing a clear depiction of the differences in the important spatial patterns of structure (Montesano et al., 2016). However, in these open canopy forests, there may be an opportunity to exploit the visible ground surface between gaps in tree cover to capture near-coincident ground and canopy surfaces, and thus three-dimensional forest structure, with HRSI. Stereogrammetric forest height estimation is based on this concept of capturing both ground and canopy surfaces from stereogrammetry and examining their differences to explore three-dimensional forest structure.

1.3. HRSI acquisition characteristics

A central feature of HRSI data is the variation in image acquisition characteristics. These characteristics explain the position and orientation of both the imaging platform and the sun relative to the surface targets in the field of view. This sun-sensor-target (SST) geometry describes the average relative position of these components in space at the time of image acquisition. For each image, these include the average off nadir viewing and elevation angles, and the average elevation and azimuth angles of the sun, and surface feature topography. This geometry is influenced in part by the target's diurnal and seasonal sunlight regime, which is a function of the earth's orientation relative to the sun, the target's latitude and topographic position, and the sensor's orientation relative to the sun and the target. As this geometry changes, so does image radiometry both from one image to the next, but also within a given image (Aguilar et al., 2013; Epiphanio and Huete, 1995; Honkavaara et al., 2009; Kimes, 1983; Korpela et al., 2011; Ranson et al., 1985; Wang et al., 2004; Widlowski et al., 2001).

Due to the off-nadir pointing capabilities of HRSI sensors, SST geometry over the same location can vary widely. This wide variation can affect image radiometry through differences in how features are viewed and illuminated, and thus the appearance of vegetation structure between images (Asner & Warner, 2003; Kane et al., 2008; Wulder et al., 2008). This is particularly apparent in summer acquisitions at high latitudes, where the position of the sun throughout the diurnal cycle affects image texture in open canopy forests. In these forests, both forest structure and ground are visible to the sensor. However, the sun's orientation relative to forest structural components (crowns and stems) can be different from that relative to the ground. These changes in orientation not only affect how shadows are cast, but also alter the illumination of surface features such that the difference in brightness (the contrast) between 2 features in one acquisition will not necessarily be maintained in a second acquisition with different SST geometry. These differences can affect the ability to distinguish and measure surface features, such as trees.

In addition to the SST geometry of a single acquisition, stereopairs can be described by additional geometry that explains the orientation of each viewing position with the target. The angles that describe this orientation are the convergence angle, the bisector elevation angle, and the asymmetry angle. The convergence angle, related to the base-to-height ratio (the distance between sensors relative to the height above the target surface), is formed between two observation rays along a plane with the target (the epipolar plane). The bisector angle explains the degree of obliqueness of the epipolar plane relative to the ground plane. The asymmetry angle is the angle formed between the line perpendicular to, and the line that is the bisector of, the line within the epipolar plane that is parallel to the ground plane (Jeong and Kim, 2014, 2016). All three angles affect the horizontal and vertical accuracies of a three-dimensional model. Often, the convergence angle is used to provide a general understanding of the quality of the stereopair geometry for estimating feature heights (Aguilar et al., 2013). The reader is referred to Jeong and Kim, 2016 for a detailed description of stereopair geometry and their influence on positioning errors.

The variation in image acquisition characteristics is a feature of HRSI stereogrammetry that provides both an opportunity and a challenge for estimating surface elevations in a variety of land covers. Given the high spatial resolution (<1 m) of surface elevation estimates, there is potential for capturing detailed vertical structure in open canopy forests. The challenge lies in identifying the conditions under which features contrast sufficiently with the image background, and understanding both the source of this variation in contrast and the resulting variation in surface elevation measurements.

1.4. Spatial detail in open canopy biome boundary forests

The structure of biome boundary (ecotone) vegetation at the northern limits of the open canopy circumpolar TTE is predicted to change, with important expressions of change controlled by local factors (Bonan et al., 1995; Bonan et al., 1992; Holtmeier and Broll, 2005; Soja et al., 2007). Recent work demonstrates the local scale variability of forest structural change (e.g., height, density and cover) which may be linked to the local spatial pattern of current horizontal and vertical structure of trees (ecotone form) (Harsch and Bader, 2011). At these local scales the effects of topography, wind, disturbance, soil and permafrost characteristics along with long and short term site history (glaciation, fossil treelines, seed availability, soil development, and disturbance) on forest structure patterns are evident, and their relative importance may modify how structure varies across sites (Bunn et al., 2011; Case and Duncan, 2014; Dalen and Hofgaard, 2005; Frost et al., 2014; Hofgaard and Wilmann, 2002; Kirdyanov et al., 2013; Lloyd et al., 2011). These current forest structure patterns, captured in fine spatial detail with HRSI, may explain the dynamics of structural change across the open canopy biome boundary forests of the TTE (Danby and Hik, 2007; Harper et al., 2011; Harsch et al., 2009; Hofgaard et al., 2012; Holtmeier, 2009). Thus, the spatial variability in forest structure patterns, the relevance of these patterns to dynamics and the measurement scales needed to capture these patterns across global domains may warrant remote sensing methodologies