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Developing 5 m resolution canopy height and digital terrain models from WorldView and ArcticDEM data

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ABSTRACT

Digital terrain models (DTMs) and vegetation canopy height models (CHMs) are used in a wide range of earth and environmental sciences. An increasing number of CHM products are available from active, passive, and photogrammetric remotely sensed data; however, high-resolution (≤ 5 m), wall-to-wall CHMs for the arctic and northern boreal domains that are suitable for detailed spatial analysis are lacking. Recently, a 5-m spatial resolution pan-arctic digital surface model – the ArcticDEM – was created using automated stereopair analysis of high-resolution satellite data. The ArcticDEM is unprecedented in extent and spatial resolution, yet the product generally follows the uppermost surface elevation (i.e., representing a digital surface model, DSM) without regard to whether the surface is comprised of vegetation or bare-earth terrain. To address this limitation, we developed and tested an approach to map vegetation canopy height at a 5-m spatial resolution (hereafter called the local ArcticCHM), and then subtracted these estimated canopy heights from the ArcticDEM in order to create a 5-m resolution DTM (local ArcticDTM). We selected three pilot study areas (total 58 km^2) across a north-south gradient in Alaska, representing a range of vegetation types and topographic conditions. We estimated and mapped canopy height using randomForest and imputation modeling approaches, with the ArcticDEM and high spatial resolution multispectral satellite data (WorldView-2) used as predictors. Airborne laser scanning (ALS) data was used for model calibration and independent validation. Canopy height was reliably predicted across the three study areas, with the best models ranging from root mean square errors (RMSE) 2.2 to 2.6 m and R^2 ranging from 0.59 to 0.76 relative to ALS-based CHM reference data. Similarly, the RMSE between the new local ArcticDTM product and ALS-based DTM reference data was 45–68% less than similar comparisons with the ArcticDEM. Our results offer a means to extend these local ArcticDTM and CHM products to establish high-resolution products elsewhere in Alaska of high value for a wide range of earth and environmental sciences research investigations.

1. Introduction

Geospatial data of the Earth's topography and canopy height are critical for many geoscience applications, including hydrology, carbon cycling science, vegetation modeling, and geology. Past efforts to capture digital elevation models (DEM) for the earth's surface, such as the ASTER Global Digital Elevation Model (GDEM; Tachikawa et al., 2011), Shuttle Radar Topography Mission (SRTM) DEM (Rabus et al., 2003), and USGS National Elevation Dataset (NED; Gesch et al., 2002) data products, have been used extensively across many scientific disciplines. However, these moderate-to-coarse spatial resolution DEMs often characterize the surface of the earth, which includes surface vegetation, producing a digital surface model (DSM) as opposed to depicting the underlying terrain or bare ground surface–commonly referred to as a digital terrain model (DTM). DEMs that follow the uppermost surface elevation without regard for whether the surface is comprised of vegetation or bare terrain will lead to erroneous elevations (and subsequent derivatives), as there will be notable elevation increases where vegetation (especially forests) are present (Fig. 1; Hofton et al., 2006; Kenyi et al., 2009). This is problematic for studies that are interested in vegetation modeling (Franklin, 1995; Iverson et al., 1997), soil properties (McKenzie and Ryan, 1999), and hydrological applications

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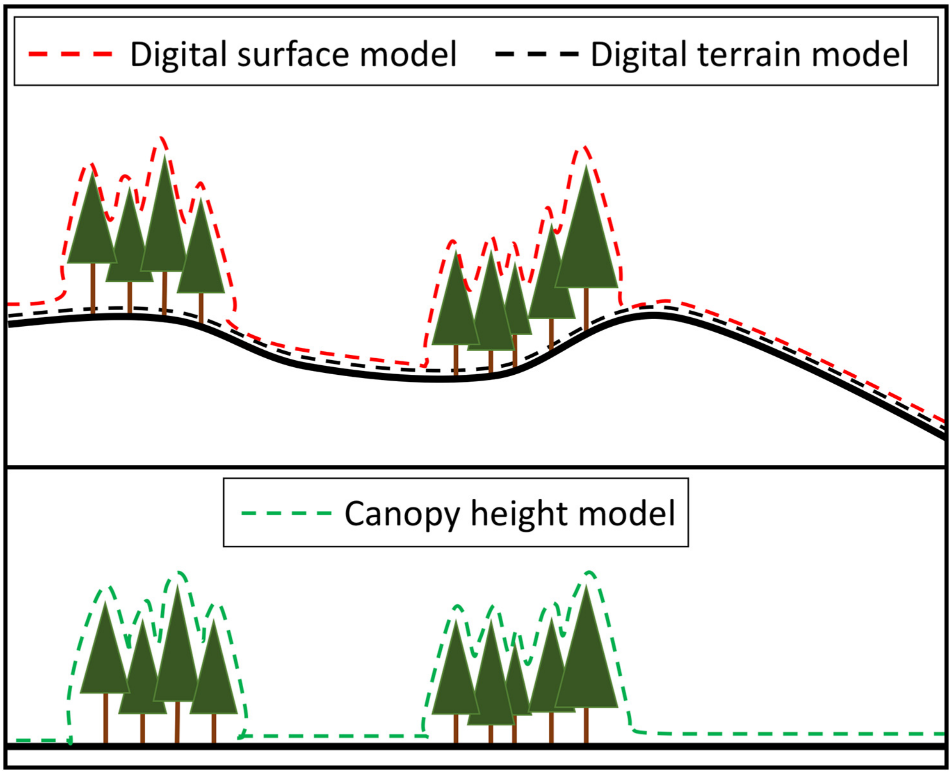

Fig. 1. Illustration of digital elevation models (DEM), that include a digital surface model (DSM) which follows the top of the vegetation canopy and a digital terrain model (DTM) which follows the underlying terrain (top panel), and a canopy height model (CHM; (bottom panel).

(Schumann et al., 2008). Hydrological applications are especially impacted as a DEM that follows the top of vegetation canopies can lead to incorrectly modeled hydrologic flow paths, floodplain elevations, or vegetation types in riparian areas. Canopy height models (CHM), generated at a fine-spatial resolution (≤5 m) can be used to create high-resolution DTMs that have vegetation heights removed from the surface characterizations (i.e., elevations found in the DEMs), leading to tremendous potential for improving many ecological and geological applications as a result of the more realistic representation of the earth's surface (Fig. 1).

With the recent advancement of automated stereogrammetry using high-resolution satellite imagery – such as WorldView-1, -2, -3, QuickBird, GeoEye, and IKONOS – development of high resolution DEMs at the 1 to 5 m spatial resolution has become feasible (e.g., Montesano et al., 2017; Neigh et al., 2014; Neigh et al., 2016; Zhang and Gruen, 2006). Stereo-photogrammetry is a well-known method for extracting three-dimensional information from two or more aerial photographs (Baltsavias, 1999). Following the availability of such data, these methods have been developed for high-resolution satellite imagery (Zhang and Gruen, 2006); and even more recently this process has been automated for high-resolution stereo-pair image processing across broad extents (Noh and Howat, 2015).

A public-private partnership – known as the ArcticDEM project – has mass-processed stereo-pair high-resolution satellite imagery for the Arctic and boreal areas north of 60°N and has created a DSM over much of the pan-Arctic at a high spatial resolution (i.e., 5 m grid cell size) (Polar Geospatial Center, 2017). Although the ArcticDEM is unprecedented in extent and provides unique detail of the topography, it generally follows the highest local surface, regardless of whether that surface represents the top of the vegetation canopy or exposed terrain, similar to the SRTM and other large area DEM datasets (Hofton et al., 2006; Montesano et al., 2017). As a result of this uncertainty concerning the nature of the surface heights captured in ArcticDEM, the utility of the product for earth science applications is reduced. Development of a high-resolution canopy height model (CHM) would allow for refinement of the ArcticDEM data product into two derivative products that (1) follow the top of the canopy (CHM) and (2) follow the underlying terrain (DTM).

Vegetation height is an important ecosystem variable that is particularly difficult to estimate using remotely sensed multispectral data. The Normalized Difference Vegetation Index (NDVI) and other passive multispectral indices lose sensitivity at higher vegetation cover (Huete et al., 1997). There is a well-known asymptotic relationship between satellite spectral response and forest structure. Typically, passive optical remotely sensed data becomes saturated at canopy cover > 60% and spectral response changes little with increases in structural attributes (see Duncanson et al., 2010 and references therein); therefore pixel locations containing medium to high biomass are challenging to characterize. Synthetic aperture radar (SAR) data including the P- and/or X-band – that (partially) penetrates vegetation surfaces – can produce DSMs and DTMs at larger spatial extents at high spatial resolution (5–15 m). For instance, the airborne Alaska Mapping Initiative IFSAR mission collected radar data across northwestern and southcentral Alaska (Glennie, 2017), while the TanDEM-X satellite formation collects global elevation data (Krieger et al., 2007) from which canopy height products can be produced (Kugler et al., 2014). In addition to radar remote sensing, lidar remote sensing – which relies on lasers that can penetrate through small openings in the canopy (Lefsky et al., 2002) – allows to distinguish between both the canopy and ground and can subsequently be used to improve the characterization of vegetation height and biomass across different forest types and developmental stages.

The space-based lidar system called the Geoscience Laser Altimeter System (GLAS) – on board of the Ice, Cloud, and land Elevation Satellite (ICESat) – acquired elevation and canopy height information periodically from space from 2003 to 2009 (Abshire et al., 2005). This sensor provided the scientific community with global data coverage at a relatively coarse spatial resolution (i.e., a single 60 m beam separated