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Using an Unmanned Aerial Vehicle (UAV) to capture micro-topography of Antarctic moss beds

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ABSTRACT

Mosses, the dominant flora of East Antarctica, show evidence of drying in recent decades, likely due to the regional effects of climate change. Given the relatively small area that such moss beds occupy, new tools are needed to map and monitor these fragile ecosystems in sufficient detail. In this study, we collected low altitude aerial photography with a small multi-rotor Unmanned Aerial Vehicle (UAV). Structure from Motion (SfM) computer vision techniques were applied to derive ultra-high resolution 3D models from multi-view aerial photography. A 2 cm digital surface model (DSM) and 1 cm orthophoto mosaic were derived from the 3D model and aerial photographs, respectively. The geometric accuracy of the orthophoto and DSM was 4 cm. A weighted contributing upstream area was derived with the *D-infinity* algorithm, based on the DSM and a snow cover map derived from the orthophoto. The contributing upstream area was used as a proxy for water availability from snowmelt, one of the key environmental drivers of moss health. A Monte Carlo simulation with 300 realisations was implemented to model the impact of error in the DSM on runoff direction. Significant correlations were found between these simulated water availability values and field measurements of moss health and water content. In the future ultra-high spatial resolution DSMs acquired with a UAV could thus be used to determine the impact of changing snow cover on the health and spatial distribution of polar vegetation non-destructively.

1. Introduction

Polar regions are experiencing rapid and severe climatic shifts, with major changes in temperature, wind speed and ultraviolet-B (UV-B) radiation already observed in Antarctica (Adams et al., 2009; Convey et al., 2009). The climate of Antarctica has experienced major changes due to both ozone depletion and as a result of increases in greenhouse gases (Thompson and Solomon, 2002; Perlwitz et al., 2008; Son et al., 2010). The rate of climate change in the high latitudes renders Antarctica one of the most significant baseline environments for the study of climate change impacts on biota. Rapid changes in vegetation have been documented in maritime Antarctica and the sub-Antarctic islands, where temperature changes are particularly pronounced (Convey et al., 2009). However, changes in temperature have been less severe across East Antarctica and this, coupled with the slow growth rates of Antarctic vegetation, suggests that change in continental Antarctica would be difficult to detect (Anisimov et al., 2001; Robinson et al., 2003). Contrary to earlier Intergovernmental Panel on Climate Change (IPCC) predictions, there is some evidence that climate change is already impacting the vegetation around Australia's East Antarctic stations (Robinson et al., 2012; Clarke et al., 2012), whilst other recent studies also show that the climate in East Antarctica may be changing more rapidly than anticipated (Chen et al., 2009; Turner et al., 2009, 2013).

Water availability, temperature, and UV-B have been identified as three key drivers for vegetation health in Antarctica (Newsham and Robinson, 2009; Wasley et al., 2006a,b; Clarke et al., 2012). Despite this, there have been few long-term studies of the response of Antarctic vegetation to climate change, especially on the continent (Robinson et al., 2003; Brabyn et al., 2006; Selkirk and Skotnicki, 2007; Convey et al., 2009). Most focus on the Antarctic Peninsula, where dramatic shifts in recorded temperature (of up to 5 °C) have resulted in the subsequent expansion of local plant communities (Turner et al., 2009), and a small number of studies have documented climate-induced change in terrestrial communities in Continental Antarctica (Brabyn et al., 2006; Selkirk and Skotnicki, 2007; Robinson et al., 2012; Clarke et al., 2012).

Some of the best-developed and most extensive vegetation communities on the continent are found in the Windmill Islands region

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of East Antarctica (Lewis Smith, 1988), with distribution of vegetation strongly influenced by microclimatic conditions, particularly water availability. Relatively small variations in water availability over small areas (e.g. <1 ha) can result in a change in community composition from moss- to lichen-dominated (Selkirk and Seppelt, 1987; Lewis Smith, 1990; Wasley et al., 2006a,b, 2012). The moss- and lichen-dominated communities are best developed where melt streams or lakes provide summer melt water and there is a rich supply of nutrients from guano in ancient penguin rookeries (Melick et al., 1994; Emslie and Woehler, 2005; Wasley et al., 2012). Evidence of long-term drying, exhibited by the prevalence of lichen-encrusted moribund moss beds, suggest a contraction of moss communities to the wettest areas with reliable water supply due to continuing isostatic uplift (Wasley et al., 2012).

Recent studies have shown that growth rates of mosses in the Windmill Islands region have slowed since the 1980s, which is consistent with accelerated drying associated with increased wind speeds around the continent as a result of ozone depletion (Clarke et al., 2012). Accelerator mass spectrometry (AMS) carbon dating of these mosses confirms that growth rates are very slow (mm per year) but strongly linked to water availability (Clarke et al., 2012). Mosses, which are the dominant plants around the coast of Antarctica, grow terminally with the youngest growing cells at the tip and the initial cells preserved at the base of shoots. In a manner similar to tree rings, this growth form sequesters carbon in a chronological sequence, meaning these old growth mosses also preserve a biochemical record (δ^{13}C) along their shoots that could provide quantitative information of water availability at the time that part of the shoot was growing (Clarke et al., 2012; Royles et al., 2012). Studies in the region have also shown a decrease in live moss and a concomitant increase in moribund moss with associated changes in turf colouration from green through red to black (Robinson et al., 2012), likely a stress response reflecting the transition between live and moribund moss as a result of drying. In addition, it is expected that further regional drying will cause a contraction in the extent of healthy moss beds (Wasley et al., 2012).

Since vegetation is largely isolated to the coastal fringe, and instrument records only extend back 50 years with limited spatial resolution, new methods of determining the location, spatial extent, and dynamics of moss beds are urgently required to resolve the extent to which Antarctic coastal climate is changing. The scale, and scattered spatial distribution, of the moss beds (tens of m^2) makes even very high spatial resolution satellite imagery (pixel size of 0.5 m) unsuitable for mapping their extent in sufficient detail. Due to logistical and weather constraints full-scale aerial photography is impractical in Antarctica and is also not detailed enough. One of the key requirements for mapping the distribution of Antarctic moss beds is the acquisition of ultra-high spatial resolution imagery, e.g. 10 cm pixel size or better, in order to capture the fine-scale spatial variability of moss health. In addition, a digital elevation model (DEM) at high resolution is required, to capture the micro-topography of small channels, rocks and boulders that affect water flow from snowmelt.

Recent developments in the use of Unmanned Aerial Vehicles (UAVs), also known as Unmanned Aircraft Systems (UAS), for remote sensing applications provide exciting new opportunities for ultra-high resolution environmental mapping and monitoring (Rango et al., 2006; Zarco-Tejada, 2008; Zhou et al., 2009; Hardin and Jensen, 2011; Watts et al., 2012). The recent special issues on UAVs for remote sensing applications (*IEEE TGRS:* March 2009; *GIScience and Remote sensing:* March 2011; *Geocarto International:* March 2011; *Remote Sensing:* June 2012) in addition to dedicated conferences, such as *UAV-g*, indicate an increasing popularity of UAVs for remote sensing and photogrammetry applications. The primary advantage of UAV-based remote sensing is the ability to bridge the scale gap between field-based observations and full-scale airborne or satellite observations. In addition, UAVs enable users to collect imagery with multiple sensors on-demand, at an unprecedented level of detail and in a cost-effective way. From a scientific perspective, UAVs allow optimisation of the sampling technique, in terms of spatial resolution and sensor type, to the objects of interest for a specific application (D'Oleire-Oltmanns et al., 2012).

In recent years, Structure from Motion (SfM) computer vision techniques have been successfully employed on multi-view UAV imagery for the generation of high resolution digital surface models (DSM) and orthophotos. The SfM technique can be applied to large collections of overlapping photographs to obtain sparse point clouds for a wide range of objects, such as buildings and sculptures. The power of this technique was demonstrated by Snavely et al. (2007) who developed the Bundler software and used it to construct 3D models of well-known world sites, such as Notre Dame, based on hundreds of overlapping photographs available from community websites. The SfM technique is based on identifying matching features in images taken from different viewpoints. Image features are identified by the scale invariant feature transform (SIFT) algorithm (Lowe, 2004), which is robust in terms of its feature descriptors for image features at different viewing angles.

More recently, several studies have successfully demonstrated the use of SfM for generation of very high resolution 3D point clouds and surface models from UAV imagery. For example, a photogrammetric technique was used to derive a DSM and orthophoto for a landslide in southern France at a spatial resolution of 4 cm (Niethammer et al., 2012), and photogrammetric and SfM approaches have been used to generate sub-decimetre resolution DSMs from overlapping aerial photography acquired by a fixed-wing UAV for the purpose of soil erosion monitoring (D'Oleire-Oltmanns et al., 2012). SfM techniques have been used to generate accurate orthophoto mosaics from a multi-rotor UAV at 1 cm resolution with 10 cm absolute geometric accuracy (Turner et al., 2012), and the accuracy of the SfM derived point clouds was quantified for a coastal erosion study, which concluded that absolute accuracies between 25 and 40 mm can be reached with a multi-rotor UAV flying at 40 m above ground level (AGL) (Harwin and Lucieer, 2012). Eisenbeiss and Sauerbier (2011) reviewed a range of UAVs and 3D processing workflows for photogrammetric applications and Verhoeven (2011) described a software workflow based on Agisoft Photoscan for 3D reconstruction from aerial photographs in the context of an archaeological application. Finally, Rosnell and Honkavaara (2012) compared an online processing approach, Microsoft PhotoSynth, to a more rigorous photogrammetric approach using SOCET SET. These recent studies all indicate that accurate 3D point clouds and surface models can be derived from multi-view UAV imagery at ultra-high spatial resolutions of several centimetres (depending on flying height). With the recent introduction of commercial software packages, such as Agisoft Photoscan[1] and Pix4UAV[2] (Vallet et al., 2012), and the increase in computing power (on both CPU and GPU) the SfM approach will become more readily available for UAV users.

The objective of this study is to use aerial photography acquired by a multi-rotor UAV to generate ultra-high resolution DSMs of Antarctic moss beds. The study builds onto work carried out by Turner et al. (2012) by applying an improved SfM technique for DSM generation and developing a Monte Carlo simulation framework for snowmelt modelling. The workflow of DSM creation is described, and the accuracy of the DSM and orthophoto mosaic are assessed. Finally, a terrain modelling technique based on the DSM is used to derive a proxy for water availability. The overall aim is to

[1] http://www.agisoft.ru.
[2] http://pix4d.com.