A Starting Guide to Mapping Snow Depth from Drones using Structure from Motion

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Introduction

Drones, also known as unpiloted aerial vehicles (UAVs) or remotely piloted aircraft (RPAS), are gaining popularity for mapping applications because of the ease and flexibility of data collection. Although drones can carry a range of different sensor types, creating surface elevation models using a modern photogrammetry workflow known as Structure from Motion (SfM) is seeing widespread adoption. This is due in part to the perceived accessibility (quadcopter style drones with integrated high-quality cameras are readily available and affordable), and the simplicity, at minimum requiring no more than a series of overlapping images. Additionally, built-in safety features and flight planning software make data collection reliable and straightforward. In snow science/hydrology drone imagery+SfM is being used to map snow depths by differencing surface elevation between two flights, one with snow (‘snow on’) and one without (‘snow off’).

Collecting imagery from a drone can be as simple as a press of a button, but creating quality surface elevation and snow depth maps requires planning ahead and access to a high accuracy GNSS system for georeferencing. Here, the basic data collection and processing steps are summarized, including suggestions based on lessons learned over multiple seasons of mapping snow depth. These were written with common multi-rotor drones (helicopter style) in mind, however they are also generally applicable for fixed wing (airplane style) drones. Before starting a mapping project, it is the drone pilot's responsibility to be familiar with their drone and local rules and regulations.

Data Collection

Commercial (off the shelf) drone packages typically come with an internal GNSS receiver, gimbal mounted camera, and controller. These interact seamlessly with software applications designed to communicate with and control the drone and camera. The steps below assume this type of system, and adjustments may be needed if the system is custom built or if modifications have been made (for example, replacing the original camera).

Flight Planning

To make data collection simple and consistent, use flight planning software that automates flight and image capture, to pre-plan the flight area and flight pattern. The double overlap, also known as a checkerboard, flight pattern is suggested for SfM to maximize view angles and overlap between images (Figure 1). Use the same flight plan(s) to fly both snow free and snow on for consistency.

The flight pattern and flight altitude will determine the ground sampling distance, in simple terms the resolution, of the surface model and how much area you can cover in one flight. This is the trade-off when flight planning; you can cover more area at coarser resolution (fly higher, faster, and/or with less overlap) or a smaller area at higher resolution (fly lower, slower, and with more overlap). It is helpful to know the region of interest and desired resolution before flight planning to guide the flight set up parameters. If more than one flight is needed to cover the area of interest consecutive flight plans should overlap with each other to avoid gaps.

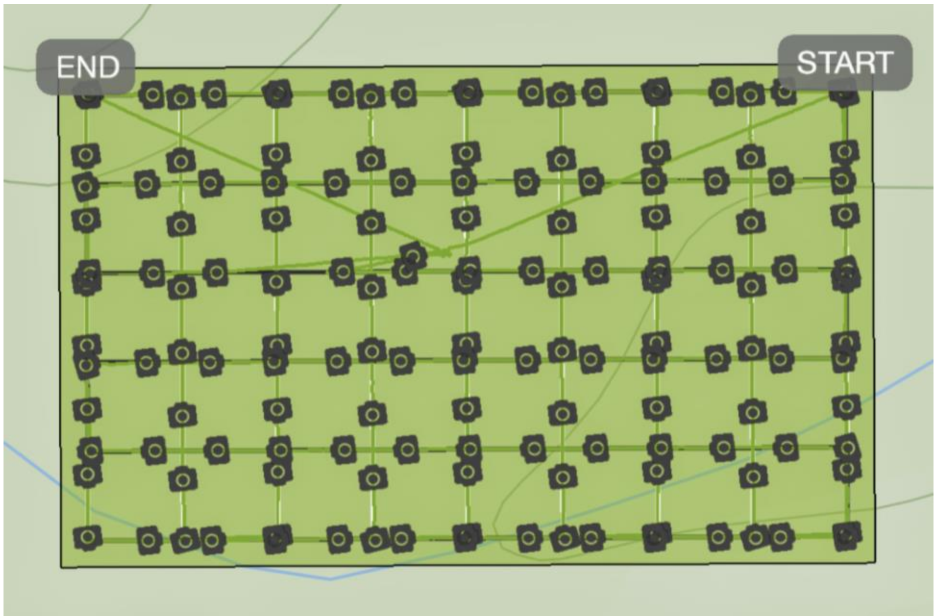

Figure 1. An example of a double overlap flight plan created in Pix4Dcapture. The grid lines show the flight pattern, and overlay a base map with contour lines. Image capture locations, pre-planned by the software to achieve the desired ground sampling distance are indicated by the camera symbol, which 'points' in the direction of flight.

There are many options for flight planning software, some of which are free, others that offer free trials (e.g. Pix4DCapture, MapPilot, DroneHarmony and several others). It is worthwhile to test options and assess functionality, for example, terrain following in complex topography or being able to specify waypoint locations. Because every flight planning software is slightly different it is worthwhile to spend time becoming familiar with the adjustable parameters, and how to map the area of interest at the desired resolution, and practice flying, before going out to map your area of interest. If you find yourself in the field without a flight plan, you can set the camera to take a picture at a defined time interval (for example, every 3 seconds) and fly a double overlap pattern manually. This should be a backup plan, though, because the flight coverage and image overlap/resolution will be inconsistent between flight lines and between consecutive flights.

Ground Control Points for Georeferencing

Although location information is typically associated with each image from the internal GNSS, it is low accuracy, particularly the elevation. Accurate geolocation is achieved through the use of location reference targets, known as ground control points (GCPs). The GCP's are distributed across the flight area, and the location of the GCP center point is measured with a high accuracy survey grade GNSS receiver (Figure 2). During processing the GNSS locations are associated with the GCP targets to georeference the model, which means to scale and project the surface model into an earth based coordinate system horizontally (x,y) and vertically (z). Although the number of GCP's needed may vary by flight area and application, a good rule of thumb is to place 10 GCP's across the flight area.

The GCP's should be visible in the imagery, high contrast and large relative to the ground sampling distance, have a clear center point, and stay in place during flight. It can be useful to label each GCP with a number to associate the correct location with the correct GCP during processing. There is no one size fits all for GCP's, and usually they can be made (or purchased) to fit the project. For flights over snow, providing an even distribution of GCP's while minimizing surface disturbance can be a challenge. Plan placement location and travel routes ahead of time to keep disturbance patterns consistent between multiple flights.

The quality of the snow depth map relies on accurate georeferencing of both the snow free and snow on surface models. The vertical accuracy, or elevation (z), is clearly important when calculating elevation difference, but maps also require accurate horizontal locations (x,y) to align with each other. Standard GNSS, including recreational receivers, have meter scale uncertainty in the x,y, and z, which is not suitable for differential mapping. The most common shortcoming of this is that your consecutive flights may be significantly offset one from the other both horizontally and vertically, which hinders accurate snow height estimation.

For this reason, it is important to use a high accuracy differential GNSS system to record GCP locations when mapping snow depth using SfM. These systems use a static reference location to correct and refine measurement locations to cm accuracy, which is done either in real time (RTK) or during post processing (PPK). Although not standard, some drones can be modified, or come equipped, with a high accuracy GNSS receiver, making the geotag for each camera location more precise. In this case, fewer or no GCP's may be needed for georeferencing.

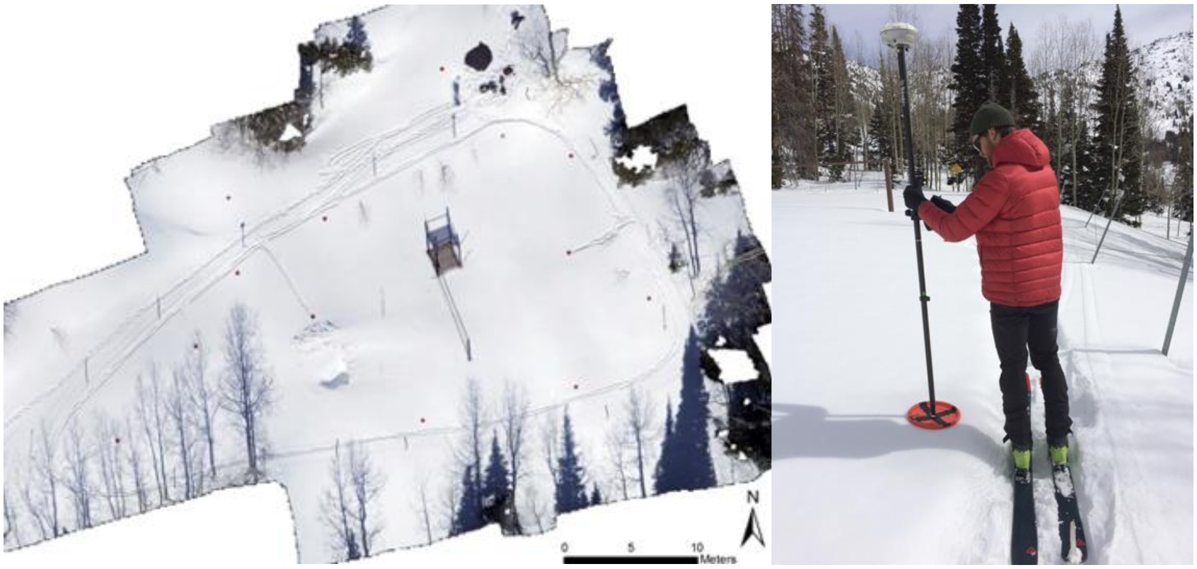

Figure 2. Placement of GCP's across the flight area for snow on flight (left), and measuring the GCP locations using a high accuracy GNSS receiver (right). The GCP's shown here were custom made from orange bucket lids, which are light enough to stay on top of snow but heavy enough not to blow away with wind, and black duct tape, for high contrast.

Data Collection for Accuracy Assessment

Accuracy assessment should be a standard part of mapping protocol, but especially when mapping in a new area, with a new drone/camera, or new flight parameters. There are two primary types of data collected in the field to assess the accuracy and quality of surface elevations and snow depth maps. 1) Control points (CPs), recorded locations not used in georeferencing, are used to assess the accuracy of vertical georeferencing by comparing measured to reconstructed elevation. The CPs can be placed, like GCPs, specifically for the flight, or can be permanent stable features in the flight area (a roof, instrumentation platform, or rock outcropping, for example). 2) For snow depths, probes are used to measure snow depths at discrete locations in the flight area. Each probing location is recorded and compared to the snow depth at that location in the snow depth map. The locations of GCP's and CP's can be measured immediately following placement, or after the flight, whereas snow depths should be measured after the flight because typically this process introduces unwanted disturbance at the snow surface.

Flight and Imagery Collection

The best time to fly for SfM imagery collection is typically in the middle of a clear sky day, when there is consistent direct illumination, and no to minimal shadowing. Direct sunlight can be especially helpful for creating surface models over clean snow that has limited visible contrast/details at the surface. Plan ahead so you have enough time to access your site and lay out GCP's. Once GCP's are placed, it is time to fly! Initiate the flight plan in the flight planning software and keep the drone in line of sight during the flight. Review images and adjust camera settings if there is image saturation, which is common when there is bright snow and direct sunlight. Store images on internal storage and/or SD card as image quality can be degraded when saving to phones or tablets.

If the flight area contains trees or dense vegetation their elevations will be poorly reconstructed by SfM due to the complexity of the structure. To minimize the vegetation impact during snow free flights, fly in the spring before green up or in the fall after leaves have dropped. For vegetation that cannot be avoided any erroneous elevations can be masked from the digital elevation model. Also note that low lying vegetation can be compressed by snow, effectively lowering the surface elevation mapped in a snow free flight, which would Introduce uncertainty into mapped snow depths.

Data Processing

The steps outlined here apply broadly to all SfM software, both open source and proprietary (for example, Agisoft Metashape, Pix4Dmapper, WebODM). Like flight planning software, there are multiple options available and some may fit your needs better than others. For example, if you are mapping frequently you may want to check functionality for batch processing/automation. Once selected, refer to documentation on how to implement each step, and to understand any adjustable parameters and how those may impact the quality or resolution of your surface model.

1. *Align Photos (build Sparse Cloud)*

This step detects distinct features in images (key points), and matches them to the same features in other images (tie points), or to say it another way, it looks for geometrical similarities shared between images. Because of the motion of flight and overlap of images, features are imaged multiple times from different angles, and this information can be used to estimate each point's position relative to other points. This creates a 3d point cloud of features that were matched between images, referred to as the sparse cloud (Figure 3a), this is the 'skeleton' of the surface model. This step also estimates the camera's position when each image was taken, which can supplement the geotag information if available, but also means that geotags are not required for SfM to successfully reconstruct the surface.

2. *Georeference*

After aligning photos, import GCP locations (x,y, z in lat/long, UTM, or reference system of choice) and associate them with corresponding GCPs. This will translate your surface model from a computer-based coordinate system to an earth-based coordinate system, allowing for further visualization and spatial analysis in GIS software after export. Note that if you have a drone with an inertial measurements unit (IMU) you may also import the pitch, roll, and yaw of the drone to better define the camera's orientation (*optional*).

3. *Build Dense Cloud*

This step calculates depth across the 3d sparse cloud using the camera positions. The algorithms fill in the geometry and scene details to create a more complete, or filled in, version of the point cloud. Appropriately, this is called the dense cloud (Figure 3b). If there is high overlap and matching of features between images the dense cloud can be so dense that individual points are not discernable, and it will resemble a continuous 3D reconstruction of the flight area.

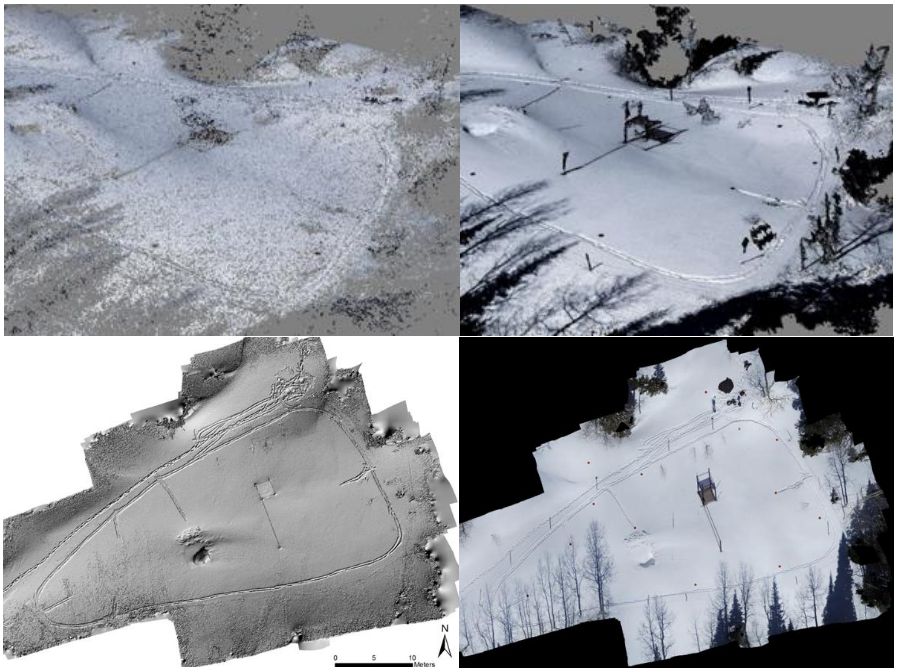

Figure 3. Sparse cloud, dense cloud, digital surface model hillshade, and orthomosaic of Atwater Study Plot (Alta, UT) on March 7th, 2017.

4. *Build digital surface elevation model*

At this step the points can be used to create a continuous digital surface elevation model (DSM) by interpolating, or triangulating, the surface elevations (Figure 3c). The output can be a gridded raster dataset, the resolution of which should be determined considering the density of points, or a triangulated irregular network (TIN) mesh. A DSM is a type of digital elevation model (DEM) that includes all features of the scene, as opposed to a digital terrain model (DTM) that includes only bare ground topography.

5. *Build Orthomosaic*

An orthomosaic creates a continuous image of the scene by mosaicking together images based on the camera and depth calculations (Figure 3d). Because it uses the digital surface model from the previous step to remove apparent distortion in the images from the camera view angle and terrain, known as orthorectification, this step comes last in the SfM software processing pipeline. Even if the primary goal of SfM is the elevation model, it is useful to output the orthomosaic to visualize the conditions at the time of flight.

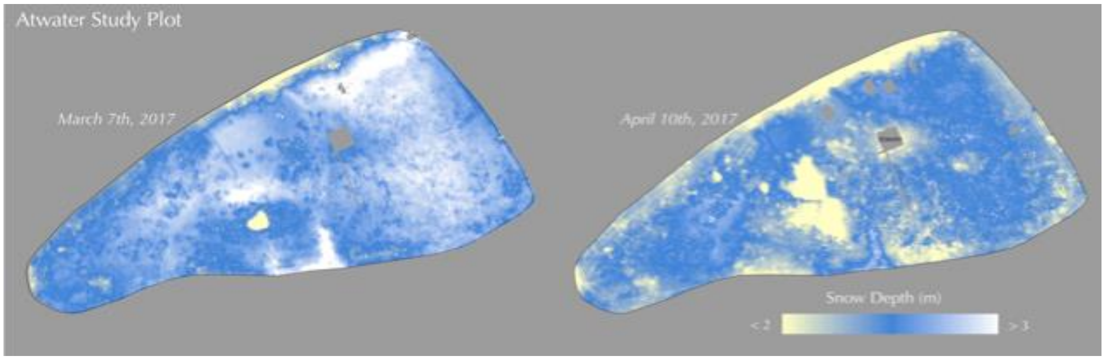

Figure 4. Maps of snow depth at 5 cm resolution across Atwater Study Plot clipped to study plot boundaries for two consecutive snow-on flights. The March 7th map (left) corresponds to the surface model shown in Figure 3.

6. *Calculate Snow Depth*

Export the snow free and snow on DSMs (geotiff is an easy format to work with across platforms) and open them in a GIS software (ArcMap/Pro, QGIS, GDAL, etc.). If the DSMs are at two different resolutions, you can align them by resampling one to match the other, typically the higher resolution is resampled to the coarser resolution. Then use raster tools (such as raster calculator, or minus utility) to subtract snow free from snow on. The resulting raster is the difference in surface elevation between the two DSMs, which is the snow depth (Figure 4). Features that were reconstructed poorly, such as vegetation or built structures, should be masked out of maps (like the instrumentation tower in Figure 4). The GIS software can also be used to assess the georeferencing using the control point locations, and snow depth, by creating spatial datasets out of the locations.

The use of SfM to map snow depth is gaining popularity and evolving and the number of studies using it is expanding. A non- exhaustive list of further reading is provided as hyperlinks here for interested readers to explore further.

- Accuracy of snow depth estimation in mountain and prairie environments by an unmanned aerial vehicle

- Quantifying Uncertainties in Snow Depth Mapping From Structure From Motion Photogrammetry in an Alpine Area

- Repeat mapping of snow depth across an alpine catchment with RPAS photogrammetry

- Intercomparison of UAV platforms for mapping snow depth distribution in complex alpine terrain

- Monitoring snow depth change across a range of landscapes with ephemeral snowpacks using structure from motion applied to lightweight unmanned aerial vehicle videos