Would you Dare to Map Snow with a Drone?

Kyriaki MOUZAKIDOU and Bertrand MERMINOD, Switzerland

Key words: cartography, deformation measurement, engineering survey, GNSS/GPS, photogrammetry, positioning, remote sensing, risk management, snow, UAV

SUMMARY

While photogrammetry has been well investigated and documented for years, its applicability on unfavourable surfaces such as snow is still ambiguous. The spatiotemporal variability of the snowpack plays a critical role in local climate systems. Not only water management and ecology investigations, but also hazard prevention and risk evaluation generate a higher demand for information about snow surfaces. As critical areas are not accessible at certain periods, remote sensing technologies are strongly recommended. In this paper, we highlight the significance of using Unmanned Aerial Vehicles (UAVs) for high-resolution snow mapping. We also concentrate on the challenges occurring when using the principles of photogrammetry on snow covered areas. Snow depth and its spatial distribution are important for a wide range of applications. Their regular and accurate determination is necessary especially for detecting notable short-term changes. Over time, various practices have been developed to monitor snow depth, each one presenting a set of advantages and limitations. UAVs have become particularly useful. Their use has shown considerable advantages compared with manned aircrafts, LiDAR (Light Detection And Ranging) and manual snow surveys. By using photogrammetric techniques to process the imagery, Digital Surface Models (DSMs) of snow can be produced with one-decimetre horizontal and vertical accuracies. Nevertheless, snow constitutes a challenging surface. The accessibility of the area, the material transfer and the weather conditions constitute the first obstacles for the mapping mission. At the same time, the homogeneity of the snow surface and the extreme contrast between full-reflectance and shadow zones have an impact on the imagery. State-of-the-art airborne photogrammetry methods boost new investigations in the snow science community. Near-InfraRed imagery (NIR) has shown some potential to identify tie points. Furthermore, different procedures have been applied to classify and to extract the snow extent. In parallel, it is suggested to store images in raw formats in order to preserve the resolution. The proper calibration of the camera is also highly recommended. All the aforementioned challenges require the development of specific expertise. The flight planning - including the choice of the camera - must account for the light conditions. Finally, the lack of obvious patterns in the images may call for non-default settings during the data processing. There is a demand for flexible snow mapping operated locally at short notice, and this contribution provides an insight into what can be expected when using UAVs under these conditions.

Would you Dare to Map Snow with a Drone?

Kyriaki MOUZAKIDOU and Bertrand MERMINOD, Switzerland

1. INTRODUCTION

Changes in snowpack can have dramatic consequences for the environment, the infrastructures and the population. Seasonal snow helps regulate the temperature of the earth's surface. Once it melts, the water fills rivers and reservoirs (NSIDC, 2020). However, snow has always involved risk, since it is a complex and constantly changing material (SLF, 2020).

Thus, scientists become increasingly interested in snow attributes and have developed ways to continuously measure snow surfaces. An increasing need for more accurate snow observations and models at different temporal and spatial resolutions arises.

1.1 Snow-surface mapping

Specific snow attributes like extent, albedo, grain size, depth, density, Snow Water Equivalent (SWE), temperature and contaminants, allow tracking rapid surface changes. They are used as model inputs to assess snow quality. However, up-to-date high-resolution geoinformation is required to provide reliable monitoring.

Snow-surface energy-balance models need the above spatially distributed parameters. With additional information about snowpack layers, they can be used to calculate snow transformation processes (metamorphism) (Dozier et al., 2004). Such models require an estimate of snow albedo, which varies both spatially and temporally (Winther, 1993). Organic and inorganic impurities, which affect the albedo, may be responsible for accelerating snowmelt phenomena (Komuro et al., 2015), and thus need to be separately inspected.

Applications that profit from snow investigations constitute, amongst others, water management processes. Information on snow density, especially when combined with snow depth, is important for hydrological predictions. These two characteristics are jointly used to refine SWE measurements (Elder et al., 1998). For a given basin, SWE allows to estimate the volume of water that may be mobilized during snowmelt episodes. It enables basin managers to forecast snowmelt peak flows and to assess the risk of snowmelt triggered floods. Although SWE can be estimated using several remote sensing techniques (Kunzi et al., 1982; Takala et al., 2011), its direct calculation allows assessing these estimations.

Assessing the trade-off between added costs is an analytical procedure in the construction domain, e.g. when building a polar station. By mapping the snow-surface, planners can quantify the volume of snow drifted against, and cleared from structures (Hawley et al., 2019).

Understanding the effects of changing snowscapes on their wildlife communities is critical (Maier, 2019). Both in polar and alpine environments, some habitats and their associated ecosystems are expanding, while others are undergoing rapid contraction (Boelman et al., 2019). For these reasons, ecological inspections can substantially benefit from snow data at multiple spatial resolutions and temporal scales.

For natural hazard management, frequent and detailed snow information has a significant impact. Mitigation measures can be developed and assessed, such as snow barriers (Ducrey, 2020). At the same time, critical avalanche slopes can be monitored in order to protect communities and vital infrastructure. Especially in alpine regions, which are densely populated, avalanches constitute a primary concern. Assessing avalanche risks requires deep knowledge of the terrain, the snow properties and weather conditions. Risk-prevention strategies can be considerably assisted by modern tools and precise techniques.

1.2 Remote-sensing techniques

In order to define the abovementioned snow attributes, different techniques have been developed through years. The simplest and oldest one is manual probing. Technological advances have come to the traditional manual probing through self-logging (Figure 1). GPS-linked snow probes have extended measurement capabilities. However, this technique introduces severe limitations including repeatability and can be hazardous in avalanche areas.

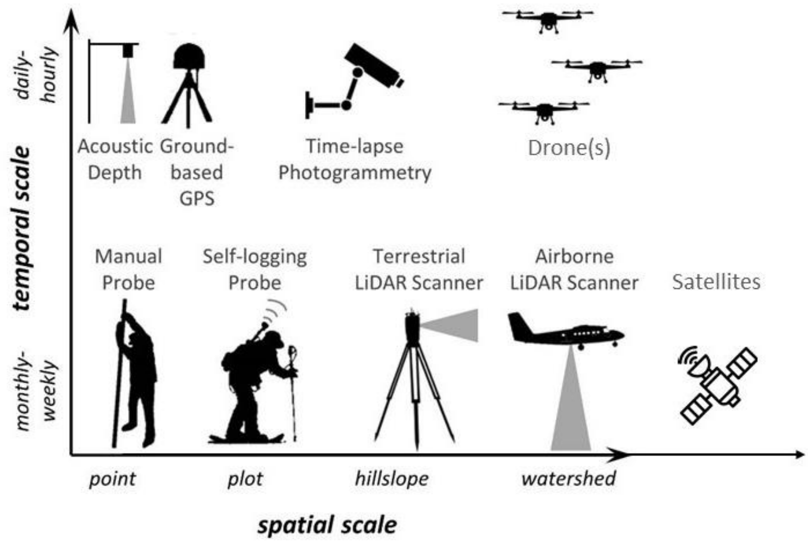

Figure 1: Technologies for snow monitoring at different scales. Adapted from Small et al. (2020).

Hydrometeorological observational networks are able to provide routine measurements. Nonetheless, this information is pointwise and subject to local snowpack characteristics and vegetation (Dozier et al., 2004). Besides, observational sites are usually sparsely and non-evenly distributed (Miziński et al., 2017). When combined with field observations, weather station measurements can be densified. Even in this case though, they are still unable to capture small-scale spatial variabilities.

As a consequence, remote sensing technologies are strongly favoured. They can regularly and safely provide maps of snow properties at a range of resolutions.

Time-lapse cameras are extensively used for monitoring the dynamics of seasonal snow. By placing stakes within the camera field of view, the snow depth can be measured.

This technique is used to estimate snow cover extent, as well as snow albedo by analysing the radiometric resolution of the images. Nevertheless, earth-fixed cameras are prone to small deformations, e.g. temperature dilatation, frost heave, or thaw settlement (Filhol et al., 2019), and they do not offer enough flexibility.

Terrestrial (TLS) and Airborne Laser Scanning (ALS) became the preferred methods for spatially continuous snow-cover maps. Due to the multiple laser returns, it is more convenient to obtain the bare ground, which is later needed to reconstruct the snow depth. In snow-free Digital Surface Models (DSMs) provided by cameras, the vegetation factor is interfering and the resulted DSM can be higher than the actual ground surface. This has an adverse effect on the estimated snow-depth, because low-vegetation is pressed down towards the ground under the weight of overlying snow (Hawley et al., 2019). Thus, Light Detection And Ranging (LiDAR) became the most established method for acquiring snow spatial data, since they penetrate the vegetation coverage. LiDAR sensors can operate reliably day and night and even in hazardous environments. Although providing the highest resolution, their main disadvantage is the high expense of using such sensors and their restricted repeatability.

Turning toward the space, there are also numerous snow attribute products which are based on satellite observations (Hall et al., 2002). Although they provide the highest spatial coverage, the resolutions achieved are not sufficient to observe short-term changes. High-resolution satellite imagery (30cm - 5m) can be obtained on request, but at an expensive cost. Data collection is directly dependent on the trajectory of the satellites and raises data availability issues. In addition, snow absorbs contaminants from the atmosphere. Through satellite imagery, it is difficult to discriminate between their absorption in the atmosphere or in the snow (Dozier et al., 2004).

Radar technology has been deeply investigated in the field of snow surveying. In the microwave part of the electromagnetic spectrum, radar waves can penetrate snow to a depth of 10 m (Shi, 2008). Synthetic Aperture Radars (SAR) provides high-resolution snow property measurements over broad areas in all weather and time conditions. However, the backscattering signal is directly linked to the incidence angle, and sets limitations in steep-mountainous areas. In such cases, the variation in backscatter is not related with the surface cover type, but with the relief instead. Hence, the effect of topography constitutes a major problem when using radar to monitor snow, particularly in mountainous regions.

1.3 Unmanned Aerial Vehicles (UAVs)

Remote-sensing techniques applied on UAVs have a great potential to close the scale gap, and to complement other remote sensing data, such as satellite imagery. Apart from the cloud-coverage penetration, the spatial resolution of satellite data complicates the identification of snow patches. They are not suitable for evaluating discontinuous snow cover in small basins (Niedzielski et al., 2018). The spatial heterogeneity of snow surfaces poses a so-called mixed pixel problem. The sensor may measure radiance reflected not only from snow, but from rock, soil, and vegetation as well. In order to capture snow characteristics, snow-covered areas must, therefore, be mapped at subpixel resolution.

Advances in digital photogrammetry have made it possible to produce accurate snow-depth maps through airborne sensors. Manned Aerial Vehicles (MAVs) have the advantage of covering large areas and can reach centimetre accuracy (Vallet et al., 2000; Nolan et al., 2015). Vallet et al. (2004) developed a system which integrates several sensors rigidly integrated together: a digital camera, a tactical grade Inertial Measurement Unit (IMU), a Global Positioning System (GPS) antenna and an airborne LiDAR. This portable mapping system embedded on a helicopter, offers autonomous 3D surface mapping of snow-surfaces with decimetre accuracy. In spite of the fast deployment and the non-dependency on Ground Control Points (GCPs), there are great expenses related to the acquisition, the maintenance and the operation of such platforms. Moreover, in mountainous landscapes MAVs have restricted flexibility. The scale of the imagery is not uniform since the steep relief results in different ground sampling distance and hence, different spatial resolution in one image.

Monitoring alpine or polar environments is logistically challenging. An extra degree of flexibility and ease of deployment is required when surveying highly-variable surfaces like snow (Cimoli et al., 2017). Drones have become particularly useful towards this direction, since they overcome the limitations of the other techniques. In particular, they provide spatial continuous measurements and they offer high precision, flexibility and repeatability. Furthermore, they offer are low-cost surveys compared to airplane missions and reduced risk for surveyors. They are also quick to implement in emergency situations (Vallet et al., 2000). Despite it is required for UAVs to be operated within the visual line of sight, they still allow the remote mapping of inaccessible areas (Bühler et al., 2017).

UAVs allow generating DSMs and orthomosaics in mountainous areas with centimetre to decimetre resolution (Cimoli et al., 2017; Maier, 2019). Commonly available unmanned aerial systems and affordable off-the-shelf sensor payloads can capture the high spatial and temporal variability of the snowpack.

1.4 Paper objectives

In this paper we concentrate on the determination of snow depth and its spatial distribution using high-resolution imagery, in order to detect short-term changes. We particularly focus on the challenges for UAV-based photogrammetry on snow-covered surfaces. The alpine snow cover has a high spatial variability in horizontal and vertical directions. This is attributed mainly to the various alpine terrain properties as well as the influence of wind and solar radiation. Thus, when passing from theory to practice, not only do we need to account for specific parameters for proper flight-planning, but also to develop a specific expertise.

2. SNOW MAPPING CHALLENGES

2.1 Accessibility

The first most obvious challenge is the accessibility of the area-of-interest. Depending on the location, skis (and skiers) are necessary to carry the equipment. In spite of the flexibility UAVs offer, approaching high-risk zones, e.g. avalanche release and deposit zones, is considered reckless. At the same time, the UAV federal guideline for operating within the line-of-sight restricts their use in mountainous regions, where there are natural obstacles.

In studies that concern snow depth accuracy, and not absolute elevation accuracy, uncertainties of the model can be evaluated using snow probes. Measurements in sample positions can assess the accuracy of the model prediction. In this case though, multiple measurements are needed to account for the presence of small ground irregularities under the snow cover (Cimoli et al., 2017), while such a workflow is impossible in high-risk slopes.

Reference points measured on the ground can quantify the uncertainties of the final DSM. However, placing them on the snow surface is a risky mission. Sometimes trained skiers install the reference points and survey them, i.e. acquisition of 3D-coordinates, since the receiver must be held on the snow surface. Moreover, arranging the GCPs in a meaningful spatial distribution is time-consuming and often hazardous.

2.2 Weather conditions

Even if the weather forecast is accurate, adverse conditions such as instant strong wind and bad visibility may force interrupting the flight mission. The atmospheric conditions in high-alpine terrain often exceed the operational limits given in the technical specifications of UAVs. In the majority of the cases, the lower operating temperature is set to 0° C. Nonetheless, in temperatures close to this limit, the battery suffers performance issues and thus the flight duration drops dramatically. Moreover, under high wind velocity, specific systems are not able to maintain aerial control. Some less-resistant platforms also have altitude restrictions, e.g. flight duration and stability decrease distinctly above 3500 m.

In alpine or polar campaigns, these abovementioned operational limits are often exceeded. Hence, not only do they expose the mapping platform to danger, but they also have an impact on the imagery.

2.3 Image contrast

A characteristic of snow-covered areas is the high light-contrast between full-reflectance and shadow areas. The snow albedo is close to 1 in the visible part of the electromagnetic spectrum. This high and constant reflectance is related not only to the solar zenith angle, but also to the snow grain-size, impurities on the snowpack and the thickness of it. These characteristics influence snow spectral albedo and consequently the reflectivity of snow surfaces, especially when covered with fresh snow. Furthermore, in mountainous areas or under overcast sky, shadows are projected on the snow surface, triggering major changes in illumination.

Compensating bright and dark areas constitutes the main snow mapping challenge. In order to avoid information loss, the user is called to adjust the camera settings, like the ISO, the aperture, or the shutter speed. In digital photography, these three settings control the brightness, the contrast and exposure of an image, in a way depicted in Figure 2.

The sensor sensitivity is quantified by the ISO number. The higher it is, the more sensitive to light the sensor is. For outdoor shooting and especially for high-reflective snow surfaces, a low ISO-number, e.g. 100-200, is highly suggested. Aperture controls the quantity of light that reaches the image sensor and defines the camera depth of field. In snowy mountain regions, a narrow lens opening, e.g. f/8 or more, is recommended. The shutter speed is measured in fractions of a second and it should be adjusted according to the velocity of the drone. In mapping applications, it is reasonable to use fast shutter speeds to capture the topography, since a slow one can lead to blurry imagery.

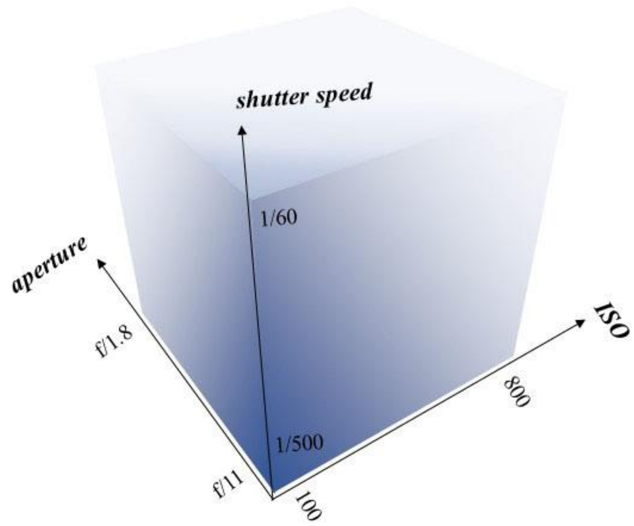

Figure 2: Value range of the three main camera settings and the way they affect the brightness of an image. The closer to the axis origin, the darker the image texture.

Should these settings be combined incorrectly, they create an overexposed image. Overexposure occurs when the sensor of the camera does not record any details in the brightest parts of an image. On the contrary, underexposure occurs when the sensor of the camera records no details in the darkest parts of an image. However, in the latter case the camera is able to display information about the lost details.

Most digital cameras have these main attributes automatically set, hence limiting the mapping capabilities. The wide contrast range of the snow imagery, not only may it call for non-default settings, but it also determines the time of the flight. The proper time of the day reduces deep shadows within the study area.

2.4 Snow-surface homogeneity

Another important obstacle that needs to be tackled is the homogeneity of the snow surface. The way it affects mapping is spotted on the photogrammetric processing. In 3D reconstruction processes, key-points are detected in all images and their intrinsic matches are used to reconstruct the entire scene. This matching stage is crucial. Key-points retrieval primarily relies on the presence of identifiable features, represented by a set of pixels among the pictures. Homogeneous surfaces, such as snow, deteriorate the feature detection, and thus complexify the reconstruction process (Westoby et al., 2012). Ski traces on the snowpack would constitute ideal tie-points. Nevertheless, they are scarce in remote mountainous areas and especially in avalanche-prone slopes.

The absence of key-points to link the images results in weak 3D models. As a result, the obtained DSMs can be biased up to 10m (Bühler et al., 2017), while large gaps occur where no point matching is achieved.

2.5 Software packages

Even if the image texture is satisfactory for photogrammetric processing, there still remains the challenge of their software treatment. Despite the fact that the work pipeline of each package is based on the well-known photogrammetry concepts, their implementation seems to differ. Recent studies reveal these differences (Sona et al., 2014), related not only with the number of tie-points detected, but with deviations in the final products, as well.

As a commercial product, the algorithms used in each software are not publicly documented. The underlying processes can be more or less seen as a black box. As a consequence, it is necessary to test the capabilities of different systems, in order to carefully assess the accuracies of the final products and be aware in the choice of the system suitable for the survey purpose.

3. CASE STUDIES: TECHNIQUES

Snow scientists have put into practice the opportunities that UAVs offer, in order to address some of the aforementioned challenges. The techniques that have been used can be separated into two categories; those concerning the improvement of the image texture and those regarding the georeferencing of the imagery.

3.1 Image texture

Feature identification is prone to be negatively influenced by motion blur, sensor noise, as well as low-texture images, as mentioned in paragraph 2.4. Matching and reconstruction algorithms are heavily dependent on the complexity of the image texture. The sharpness of natural scene determines the quality of the point cloud data. Hence, the way features are depicted on images is of vital importance.

3.1.1 <u>Raw images</u>

In order to improve complex image representations and boost processing algorithms, acquiring images in compressed formats, e.g. jpg, was widely preferred. However, due to quantization and rounding to integers during the compression process, there is a significant loss of information. Compressed images (8bits) result in a consequent decrease in the number of returned key-points, and in an ultimately reduced point density. This loss of topographic complexity is not desirable when interpreting homogeneous snow-surface models.

Raw image formats, on the contrary, contain a wider dynamic range. The stored image data contain values with nearly no loss. Using high radiometric resolution cameras (12-16bits), more colour information is stored per image, thus more-detailed texture of the mapping area is obtained. In addition, treatments such as white balance, camera settings or exposure are not applied beforehand on the image. This attribute allows for manual post-processing. Recent studies have revealed the significance of raw image formats. Although their storage size is almost two and a half times larger than their compressed version, more key-points were matched and higher accuracies were achieved in snow-surface mapping (Schiess, 2019).

3.1.2 Post-treatment processes

For the overexposed parts of snow-surface high radiometric resolution was proven inadequate to disclose enough information (Schiess, 2019). Since most feature detection algorithms distinguish between objects through comparing the brightness levels of certain neighbourhoods with adjacent ones, it is desirable to improve the local contrast in raw images. Hence, it is essential to enhance details of the snow texture on the image, yet preserving the global intensity value-distribution. In such cases, image processing methods, such as histogram equalization, are employed to adjust image contrast.

The flattening property of histogram equalization affects not only the image contrast, but the brightness, as well. The classical adaptive histogram equalization method or improved versions of it, e.g. CLAHE - Contrast Limited Adaptive Histogram Equalization (Maier, 2019), are effective non-linear contrast enhancement algorithms, applied in many digital image processing systems. However, the resulting images may be subject to noise, and thus low-pass filters need to be applied for its removal.

3.1.3 Near-InfraRed (NIR) imagery

Under favourable illumination conditions and on snow covered areas with sufficient sharp ground features, data from the visual part of the electromagnetic spectrum provide notable results for matching. In any other situation though, the resulted imagery is unrealistic or difficult to interpret. In this framework, recent studies discussed below have shown the potential of NIR sensors to substantially enhance image matching and improve the photogrammetric products of snow surfaces.

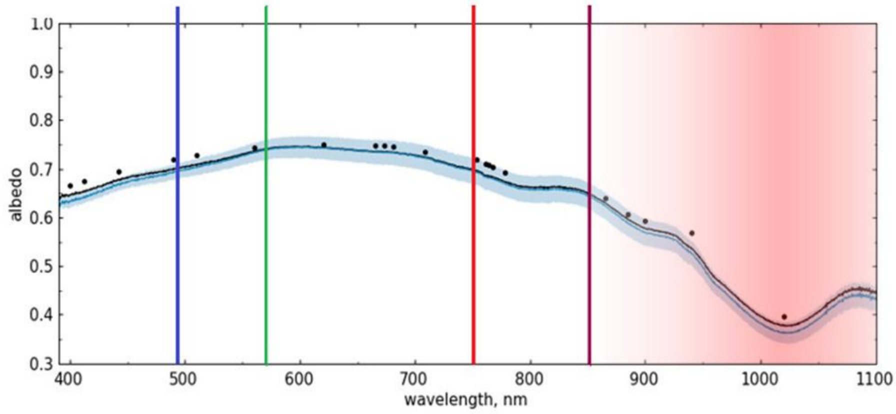

Figure 3: Snow albedo in different parts of the electromagnetic spectrum. In the NIR part, snow absorbs big quantity of the incoming radiation, hence albedo diminishes. Adapted from Kokhanovsky et al. (2019).

In the NIR part of the spectrum, the portion of light reflected back to the sensor is highly dependent on the composition of the snowpack surface. In fact, within the NIR range (λ = 0.75–1μm), snow absorbs up to 75% of the incoming solar radiation. Hence, snow albedo diminishes within these wavelengths. The quantity of radiation absorbed, which corresponds to albedo reduction, depends on the snow grain size (Warren, 1982). This attribute has already been applied to map and distinguish different snow-surface types (Bühler et al., 2015).

Snow researchers have exploited low snow reflectance in the NIR part of the spectrum, to reconstruct snow-heights. UAV-based photogrammetry has been applied in different 'worst-case' scenarios to eventually highlight the additional value of NIR imagery (Bühler et al., 2017). Not only is the image saturation lower due to the reduced reflectance, but there are also more discrete features due to various snow grain sizes.

The application of Principal Component Analysis (PCA) on multispectral data confirmed the potentials of red-edge and NIR bands for snow-mapping applications (Maier, 2019). In order to reduce the amount of data yet retaining the majority of stored information, PCA transforms the data into a new feature space. A main finding of this transformation is the significant amount of information that the red components, i.e. red, red-edge and NIR band, contain.

3.2 Georeferencing

The usage of GCPs in UAV-based photogrammetry applications for snow-mapping, offers robustness, increases the accuracy, and quantifies the uncertainties on the final DSM. Their distribution plays a critical role on georeferencing the imagery and, thus, their placement needs to be carefully examined. Cledat et al. (2020) propose a method for defining the minimal and most-efficient GCP-signalization in complex terrain in the scope of ameliorating global precision. As mentioned in paragraph 2.1, due to restricted accessibility of the snowy mapping site, the placement of reference points is cost and time intense, and often hazardous. Hence, the need to circumvent the use of any GCP is imperative.

3.2.1 Fixed-point matching

According to Vander Jagt et al. (2015), providing that snow-depth can be accurately retrieved without GCP information, areas could be directly mapped without the need to expose field personnel to dangerous weather conditions. It is worth mentioning that snow-depth distribution is retrieved by subtracting the snow-free DSM of the mapping site from the snow-covered one. Hence, if a fixed point is co-visible in both the snow-free and the snow-covered datasets, the two surface models can be aligned without surveying the points in the field. However, there is a constraint regarding the placement of such GCPs. Spots need to be found that remain clearly visible even after a heavy snowfall.

Based on the fixed-point approach, Miziński et al. (2017) performed automated georeferencing by using land cover elements, mainly trees. They employed the Iterative Closest Point (ICP) algorithm to perform point cloud matching and they recorded a mean absolute error of the snow-depth estimation at around 38cm. One limitation of this technique is that the trees, alike to GCPs, also need to be well spatially distributed in the study area.

3.2.2 Aerial control

The need for reference points is significantly reduced with the implementation of assisted aerial triangulation, or else called integrated sensor orientation, while they are eliminated on direct georeferencing, or else called direct sensor orientation. It is known that precise determination of the position and attitude of the drone stabilizes the imagery and provides an improvement to the final mapping accuracy. GNSS and IMU sensors, generally fused together to obtain conventional navigation solutions for aerial vehicles, have been used for snow-mapping applications. Applying direct georeferencing techniques, snow depth has been estimated with a Root Mean Squared Error (RMSE) of 18.4cm (Vander Jagt et al., 2015), whereas implementing assisted aerial triangulation, a RMSE of 8.5cm was achieved (Harder et al., 2016).

The established processing pipeline suggests obtaining the GNSS/IMU solution in a separate step and then importing the data into the bundle-adjustment as weighted observations. Cucci et al. (2017) propose an innovative approach of this typical workflow. Employing a formulation of Dynamic Networks, they included raw inertial and GNSS observations, i.e. position and velocity of the drone, directly into the bundle adjustment. This technique recorded significant accuracy improvement in demanding mapping scenarios, such as denial of GNSS signals or challenging geometry (Cucci et al., 2019), e.g. corridor mapping or limited number of tie-points.

Moreover, it is acknowledged that calibration of the camera interior orientation parameters is necessary for precise mapping (Cledat, 2020). Calibration flights should be planned at different heights and in a well-controlled calibration field. In this way, the usually correlated camera parameters become decorrelated. An in-flight calibration of these parameters is not suggested especially above snow-surfaces, because of the high uncertainties on the point-cloud (Schiess, 2019). At the same time, a calibration of the lever arm between the GNSS phase centre and the camera projection centre is highly recommended. The possibility of estimating the lever arm within-the-flight calibration is rather criticised, since it is correlated with other orientation parameters (Rehak, 2017).

4. FUTURE RESEARCH

Since georeferencing of the imagery seems to evolve along with the development of high-performance navigation sensors and advanced processing pipelines, attention should be drawn to image texture enhancement. State-of-art methods (Jian et al., 2019) need to be implemented to account for the challenging contrast and texture conditions.

Deep learning techniques can enhance image structure and boost the performance of the snow-depth reconstruction algorithms. Hence, accurate snowpack configurations obtained can be imported into simulation models to estimate snow characteristics. Proper flight planning and workflow ought to be developed considering methods mentioned in previous paragraphs, targeting to accurate snow depth mapping.

5. CONCLUSIONS

Challenges related with the sampling and modelling of the snowpack can be tackled by employing state-of-the-art technologies. Remote sensing techniques based on UAVs allow for accurate snow-surface mapping and high-resolution snow-depth reconstruction. Commonly available platforms and affordable off-the-shelf sensor payloads can capture the high spatial and temporal variability of the snowpack.

Applying the principles of photogrammetry, though, on unfavourable surfaces such as snow-covered areas is a challenging mission. The underlying problems are linked not only with the accessibility of the study area, but also with the current weather conditions. The installation of GCPs is affected by the morphology of the area, while the battery performance is highly dependent on the local temperatures. At the same time, the wide contrast range of snow imagery may call for non-default camera settings. The time of the flight should be carefully chosen, since it can reduce deep shadows within the study area. Snow-surface homogeneity constitutes the major problem since it sets restrictions on the key-point matching process. Moreover, proprietary software packages should be considered with care. Their proprietary algorithms are not designed for the specific conditions prevailing on snow.

The radiometric resolution of the imagery is a significant factor when mapping homogeneous surfaces. In addition, raw images allow for a post-treatment compared to the compressed ones. Histogram equalization algorithms improve image texture and correct the exposure, but they are subject to noise. It should not be neglected that underexposed images are advantageous, since hidden information can be retrieved. At the same time, NIR imagery has shown significant potentials for texture enhancement.

Direct georeferencing is advantageous or even necessary when few features are available on the ground and/or the determination of their position is dangerous. Finally, system calibration in a proper calibration field is worth implementing. Defining angular and spatial offsets amongst the sensors, have a direct impact on the final mapping accuracy.

REFERENCES

Boelman, N.T., Liston, G.E., Gurarie, E., Meddens, A.J.H., Mahoney, P.J., Kirchner, P.B., Bohrer, G., Brinkman, T.J., Cosgrove, C.L., Eitel, J.U.H., 2019. Integrating snow science and wildlife ecology in Arctic-boreal North America. Environmental Research Letters, 14:1, 1-17, IOP.

Bühler, Y., Meier, L., Ginzler, C., 2015. Potential of operational high spatial resolution near-infrared remote sensing instruments for snow surface type mapping. IEEE Geoscience and Remote Sensing Letters, 12:4, 821-825.

Bühler, Y., Adams, M.S., Stoffel, A., Boesch, R., 2017. Photogrammetric reconstruction of homogeneous snow surfaces in alpine terrain applying near-infrared UAS imagery. International Journal of Remote Sensing, 38:8-10, 3135-3158, Taylor & Francis.

Cimoli, E., Marcer, M., Vandecrux, B., Bøggild, C.E., Williams, G., Simonsen, S.B., 2017. Application of low-cost UASs and digital photogrammetry for high-resolution snow depth mapping in the Arctic. Remote Sensing, 9:11, 1144, MDPI.

Cledat, E., Jospin, L.V., Cucci D.A., Skaloud, J., Mapping quality prediction for RTK micro-drones operating in complex environment, ISPRS 2020 (under review)

Cledat, E., Cucci, D.A., Skaloud, J., Camera calibration models and methods for corridor mapping with UAVs, ISPRS 2020 (under review)

Cucci, D.A., Rehak, M., Skaloud, J., 2017. Bundle adjustment with raw inertial observations in UAV applications. ISPRS Journal of Photogrammetry and Remote Sensing, 130:1-12, Elsevier.

Cucci, D.A., Skaloud, J., 2019. On raw inertial measurements in dynamic networks. ISPRS Ann. Photogrammetry Remote Sensing and Spatial Information Sciences, IV-2/W5, 549-557.

Dozier, J., Painter, T.H., 2004. Multispectral and hyperspectral remote sensing of alpine snow properties. Annual Review of Earth and Planetary Sciences, 32, 465-494, Annual Reviews.

Ducrey, L., 2020. Suivi des hauteurs de neige pour la renovation ciblee de paravalanches

Elder, K., Rosenthal, W., Davis, R.E., 1998. Estimating the spatial distribution of snow water equivalence in a montane watershed. Hydrological Processes, 12:10-11, 1793-1808, John Wiley & Sons.

Filhol, S., Perret, A., Girod, L., Sutter, G., Schuler, T.V., Burkhart, J.F., 2019. Time-Lapse Photogrammetry of distributed snow depth during snowmelt. Water Resources Research, 55:9, 7916-7926, John Wiley & Sons.

Hall, D.K., Riggs, G.A., Salomonson, V.V., DiGirolamo, N.E., Bayr, K.J., 2002. MODIS snow-cover products. Remote Sensing of Environment, 83, 181-194, Elsevier.

Harder, P., Schirmer, M., Pomeroy, J., Helgason, W., 2016. Accuracy of snow depth estimation in mountain and prairie environments by an unmanned aerial vehicle. The Cryosphere, 10:6, 2559-2571, Copernicus.

Hawley, R.L., Millstein, J.D., 2019. Quantifying snow drift on Arctic structures: A case study at Summit, Greenland, using UAV-based structure-from-motion photogrammetry. Cold Regions Science and Technology, 157, 163-170, Elsevier.

Jian, W., Zhao, H., Bai, Z., Fan, X., 2019. Low-light remote sensing images enhancement algorithm based on fully convolutional neural network. In: Wang L., Wu Y., Gong J. (eds) Proceedings of the 5th CHREOC 2018, 56-65, Springer, Singapore.

Kokhanovsky, A., Lamare, M., Danne, O., et al., 2019. Retrieval of Snow Properties from the Sentinel-3 Ocean and Land Colour Instrument. Remote Sensing, 11:19, 2280, MDPI.

Komuro, Y., Suzuki, T., 2015. Relationship between the concentration of impurity and albedo in snow surface. Atmospheric and Climate Sciences, 5:4, 426-432, Scientific Research Publishing.

Kunzi, K.F., Patil, S., Rott, H., 1982. Snow-cover parameters retrieved from Nimbus-7 scanning multichannel microwave radiometer (SMMR) data. IEEE Transactions on Geoscience and Remote Sensing, GE-20:4, 452-467.

Maier, K., 2019. Direct multispectral photogrammetry for UAV-based snow depth measurements. KTH Library, KTH Royal Institute of Technology, Stockholm.

Miziński, B., Niedzielski, T., 2017. Fully-automated estimation of snow depth in near real time with the use of unmanned aerial vehicles without utilizing ground control points. Cold Regions Science and Technology, 138, 63-72, Elsevier.

Niedzielski, T., Spallek, W., Witek-Kasprzak, M., 2018. Automated snow extent mapping based on orthophoto images from unmanned aerial vehicles. Pure and Applied Geophysics, 175:9, 3285-3302, Springer.

Nolan, M., Larsen, C., Sturm, M., 2015. Mapping snow depth from manned aircraft on landscape scales at centimeter resolution using structure-from-motion photogrammetry. The Cryosphere, 9:4, 1445-1463, Copernicus.

NSIDC, National Snow and Ice Data Center, All About Snow. Accessed 16 January 2020. https://nsidc.org/cryosphere/snow.

Rehak, M., 2017. Integrated sensor orientation on micro aerial vehicles. PhD thesis, EPFL.

Schiess, S., 2019. UAV based photogrammetry for snow height determination with GNSS/INS assisted aerial control. Master Thesis, Geodetic Engineering Laboratory, EPFL.

Shi, J., 2008. Active microwave remote sensing systems and applications to snow monitoring. In: Liang S. (eds) Advances in Land Remote Sensing, 19-49, Springer.

Skaloud., J., Vallet, J., 2002. High accuracy handheld mapping system for fast helicopter deployment. International symposium on Geospatial Theory, ISPRS Comm IV. Ottawa, Canada.

SLF, Institute of snow and avalanche research, Swiss Federal Institution for Forest, Snow and Landscape Research WSL. Accessed 16 January 2020. https://www.slf.ch/en/snow.html.

Small, E., Raleigh, M., Terrestrial Hydrology Research Group, Geological Sciences, University of Colorado – Boulder. Accessed 13 January 2020. http://geode.colorado.edu/~small/snowdensity.html.

Sona, G., Pinto, L., Pagliari, D., Passoni, D., Gini, R., 2014. Experimental analysis of different software packages for orientation and digital surface modelling from UAV images. Earth Science Informatics, 7, 97-107, Springer.

Takala, M., Luojus, K., Pulliainen, J., et al., 2011. Estimating northern hemisphere snow water equivalent for climate research through assimilation of space-borne radiometer data and ground-based measurements. Remote Sensing of Environment, 115:12, 3517-3529, Elsevier.

Vallet, J., Skaloud, J., Koelbl, O., Merminod, B., 2000. Development of a helicopter-based integrated system for avalanche mapping and hazard management. International Archives of Photogrammetry and Remote Sensing, 33, 565-572, Amsterdam.

Vallet, J., Skaloud, J., 2004. Development and experiences with a fully-digital handheld mapping system operated from a helicopter. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Istanbul, Vol. XXXV, Part B, Commission 5.

Vander Jagt, B., Lucieer, A., Wallace, L., Turner, D., Durand, M., 2015. Snow depth retrieval with UAS using photogrammetric techniques. Geosciences, 5:3, 264-285, MDPI.

Westoby, M.J., Brasington, J., Glasser, N.F., Hambrey, M.J., Reynolds, J.M., 2012. 'Structure-from-Motion' photogrammetry: A low-cost, effective tool for geoscience applications. Geomorphology, 179, 300-314, Elsevier.

Winther, J.G., 1993. Short- and long-term variability of snow albedo. Hydrology Research, 24:2-3, 199-212, IWA.

BIOGRAPHICAL NOTES

Kyriaki holds an Integrated Master Diploma in Rural & Surveying Engineering from the Aristotle University of Thessaloniki (AUTh), Greece. She chose her specialization in the Department of Cadastre, Photogrammetry & Cartography, where she dived into photogrammetry and remote sensing. She elaborated her Master thesis in the Karlsruhe University of Applied Sciences (HsKA), Germany, where she performed data fusion to reconstruct the historic digital terrain model of the extended area of Maulbronn Monastery Complex. In August 2019, she was accepted as a Doctoral student in the Geodetic Engineering Laboratory (TOPO) of the Ecole Polytechnique Fédérale de Lausanne (EPFL). In parallel with her Ph.D. studies, Kyriaki is an active member of the organization team of the 33rd International Geodetic Student Meeting.

CONTACTS

Ms Kyriaki Mouzakidou
Ecole Polytechnique Fédérale de Lausanne – Laboratoire de Topométrie (EPFL – TOPO)
Station 18 – Bâtiment GC
1015, Lausanne
SWITZERLAND
Email: kyriaki.mouzakidou@epfl.ch