Measurement of snow cover depth using 100 × 100 meters sampling plot and Structure from Motion method in Adventdalen, Svalbard

Radim Stuchlík[1*], Jan Russnák[1], Tomáš Plojhar[2], Zdeněk Stachoň[1]

[1]*Department of Geography, Faculty of Science, Masaryk University, Kotlářská 2, 611 37 Brno, Czech Republic*
[2]*Department of Physical Geography and Geoecology, Faculty of Science, Charles University, Albertov 6, 128 00 Prague, Czech Republic*

Abstract

We tried to verify the concept of Structure from Motion method for measuring the volume of snow cover in a grid of 100 × 100 m located in Adventdalen, Central Svalbard. As referencing method we utilized 121 depth measurements in one hectare area. Using avalanche probe a snow depth was measured in mentioned 121 nodes of the grid. We detected maximum snow depth of 2.05 m but snowless parts as well. From gathered depths' data we geostatistically (ordinary kriging) interpolated snow surface model which we used to determine reference volume of snow at research plot (5 569 m^3). As a result, we were able to calculate important metrics and analyze topography and spatial distribution of snow cover at the plot. For taking photos for Structure from Motion method, bare pole in hands with a camera mounted was used. We constructed orthomosaic of research plot.

Key words: snow depth, visual images, mapping, 100 × 100 m sampling plot, Svalbard, UAS

DOI: 10.5817/CPR2016-2-14

Received December 2, 2016, *accepted* January 24, 2017.
[*]Corresponding author: Radim Stuchlík <radim.stuchlik@mail.muni.cz>
Acknowledgements: This work was supported by the project NF-CZ07-ICP-1-032-2014 „Polar ecology course –geosciences" under the auspice of the EEA grants & Norway grants and by the Ministry of Education, Youth and Sports (MEYS) large infrastructure project LM2015078 "Czech Polar Research Infrastructure". The authors would also like to thank to the Czech Arctic Research Infrastructure "Josef Svoboda Station" (as a part of the Czech Polar Research Infrastructure, CzechPolar2) and its crew for their support.
Following softwares were used: Adobe Lightroom 5.7, Fast Stone Photo Resizer 3.3, Agisoft Photoscan Professional Edition 1.2.0 (64 bit), MeshLab 1.3.4, ArcMap 10.3.1 for Desktop, ArcScene 10.3.1 for Desktop, Gimp 2.8.6, Matlab R2016a.

Introduction

Snow in the Arctic Regions has major influence on the environment (Bruland et al. 2001). As it is solid precipitation it is quite complicated to measure such precipitation correctly (Goodison 2006), *e.g.* because of the fact that already fallen snow can be transported with the wind to different places and be again measured as a new precipitation *etc.* (Strangeways 2004). To distinguish whether we deal with new or already fallen snow might be thus challenging. On the top of it, it is also difficult, or impossible, to acquire appropriate data about snow cover (depth, volume, distribution, water equivalent), especially in polar regions due to its remoteness.

Limitations explained above motivate researchers to study parameters of snow in regions as Svalbard and to develop new viable methods how to measure snow cover parameters (depth, volume, distribution, water equivalent) with better effectiveness and lower costs than current methods of direct measurement offer. In these days of big data phenomenon, even in this field of study, the demand for quickly available and reliable data is present which put another pressure on new approaches in research of snow. Using remote sensing via UAS (Unmanned Aerial System) might be one of such solution. Not only it is fast to gather data in the field this way, but also, with constantly rising speed of computer processing, it becomes viable method to provide reliable information about snow cover, almost in real time. Pilot has to be near the field of study, of course.

What interests' researchers most in regard with snow are three fundamental parameters: snow water equivalent, snow cover depth and its spatial distribution. Such pieces of information, plus derived information about a volume of thawed water, can be useful for flood risk managers, hydrologists or for researchers studying properties of snow worldwide.

In our study, we tried to measure snow depth using 100 × 100 m sampling plot approach and Structure from Motion (SfM) method (Snavely 2008). 100 × 100 m grid (described below) was used as a reference method for SfM method. 100 × 100 m sampling plot is widely used *e.g.* in CALM approach designed to observe the response of the active layer and near-surface permafrost to climate change (Brown et al. 2000, Shiklomanov et al. 2008).

To measure the snow cover surface, we used the Structure-from-Motion (SfM) technique has its origins in the computer vision community. The approach is most suited to sets of images with a high degree of overlap that capture the full three-dimensional structure of the scene viewed from a wide array of positions, or as the name suggests, images derived from a moving sensor. SfM tools can make direct use of photography to generate sparse 3-D point clouds from these photosets (Snavely 2008). The technological revolution in geomatics brought this method into geosciences as low-cost, user-friendly photogrammetric technique for obtaining high-resolution datasets at a range of scales (Westoby et al. 2012).

Because of circumstances described further, we were not able to create georeferenced snow surface model (non-georeferenced part of site 2 was created only). Nevertheless, we confirmed that usage of SfM method allows creating such model. 121 depth measurements in one hectare were used as input to the ordinary kriging to interpolate base-surface of the sampling area. Subsequently based on the density of snow measurements the snow volume was calculated for both 100 × 100 m sampling plots in the Site 1 and Site 2 as well (*see* Fig. 1).

Some authors, who did similar research, are mentioned in part Background research. Most of them used remote sensing method to acquire images of snow cover (using either UAS or manned aircraft) and then used SfM method to create snow surface model.

Expansion of utilizing Unmanned Aerial Systems (UAS) is fast currently. It is also known as UAV (Unmanned Aerial Vehicle), RPAS (Remotely Piloted Aircraft Systems) (UAVS, online). Every system or most of these systems should consist at least of a vehicle and remote control. Another accessory, as FPV (First Person View), telemetry, datalink, fail-safe systems, *etc.* are strongly recommended, because these accessories enhance navigation and safety of the flight. The UASs are used in different kind of human activities from online surveying to creating large-scale topographic maps (Stuchlík et al. 2015). The particular UASs vary in shape, size, weight, types of engines, wings, endurance, *etc*. Eisenbeiss (2009) and other studies give a basic overview of these systems (*e.g.* Stuchlík 2015, Aber et al. 2010). It is important to consider all aspects of a project when choosing particular UAS. For example, for scanning long and narrow area (*e.g.* river), different kind of UAS should be selected then for scanning square elements (*e.g.* field) (Wu et al. 2008). UASs can carry a variety of sensors. Most of them carry sensor, which can collect data from the visual spectrum (it is crucial for navigation, too). Furthermore, it can carry another sensor/s (thermographic camera, infrared camera, RADAR, LiDAR and many other sensors) (*e.g.* Stuchlík et al. 2015, Yohandri et al. 2011, Wallace et al. 2012). Some of these mentioned sensors can be used for snow cover/depth monitoring (*e.g.* Cimoli 2015). On the other hand the usage of the UAS is relatively dependent on the weather conditions which can be harsh even during the Arctic summer (*e.g.* Láska et al. 2012, Láska et al. 2013).

Background Research

At the beginning, we tried to use the UAS for the purpose of areal snow cover depth mapping. The aim was to compare existing digital elevation model (DEM) created by images acquired from the camera mounted on UAS and digital elevation model of the study area (Norwegian Polar Institute 1). Previously Nolan et al. (2015) did similar research when they compared DEM of snow cover created by images gained from manned aircraft with thousands of ground measurements in Alaska. Observed standard deviation between DEM (gained from manned aircraft) and reference ground measurements was approximately 0.1 m. De Michele et al. (2016) and Bühler et al. (2016) measured snow depth in Switzerland and in Italy, respectively. Cimoli (2015) mapped snow depth by using UAS in Svalbard and Greenland. These researchers primarily assured that the Structure from Motion (SfM) method, which was used for creating a 3D model from sequences of 2D images could join images, which have almost no texture (*e.g.* they are covered by snow).

We already had experiences with using UAS on Svalbard. The pilot research was successfully carried out in Adolfbukta area in summer 2015. Parts of Nordenskiöldbreen glacier and proglacial river were monitored. Visual camera and thermocamera were combined (Stuchlík et al. 2015). There are many other studies using UAS on Svalbard, for example, Mora et al. (2015), Rippin et al. (2015), Berman et al. (2012), Mayer et al. (2012), Reuder et al. (2009).

Study area

The study areas are located on Spitsbergen Island of the Svalbard archipelago. The site 1 is ~5 km away from the Longyearbyen (southeast direction) and is located in Adventdalen valley on 78.1813°N, 15.7371°E. This site is mostly flat. The site 2, the research plot for SfM, is ~4 km northeast of Longyearbyen and is situated on 78.2373°N, 15.8099°E. It is a whole day sun illuminated south oriented slope of the Adventdalen valley ~45 m a.s.l. We may assume that it is a part of river terrace of Adventelva river. During the measurement on April 1, 2016 there was a significant snowdrift up to 2 m. The study area of site 2 was selected to include gentle and steeper slope and also flat surface to cover most possible landforms. The day of measurement was sunny without any clouds. The temperature was about -15°C. Approximately two weeks before the acquisition a thawing period occurred. The week before the acquisition was freezing (about -25°C) and few days before the acquisition snowing period occurred.

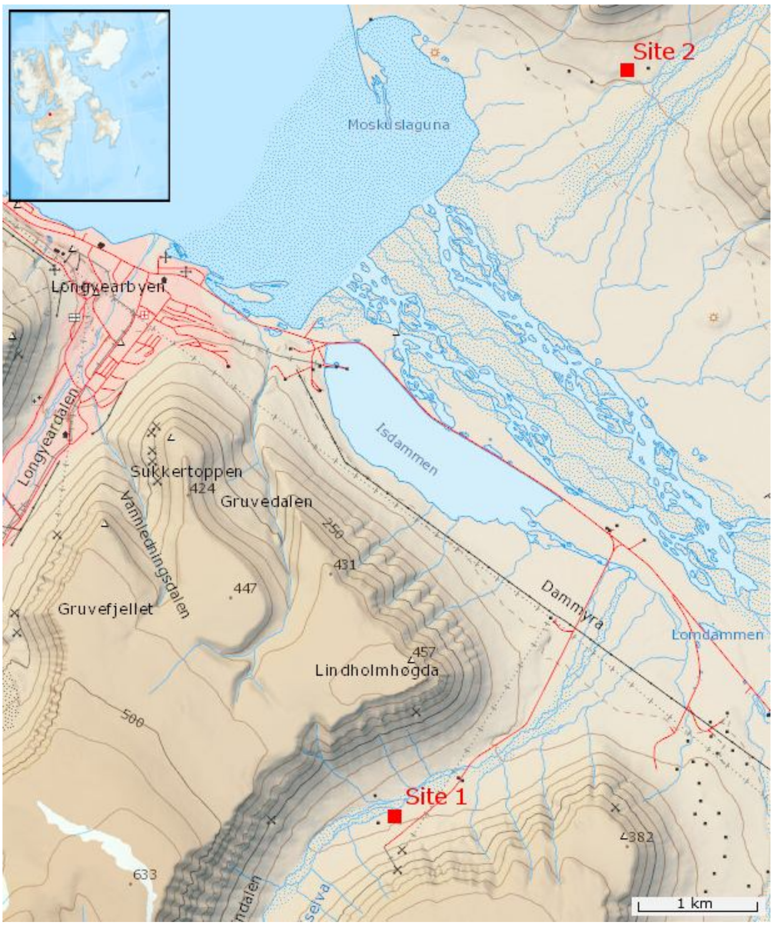

Fig. 1. Study areas (Site1 and Site 2). *Source*: Norwegian Polar Institute 1 (online).

Data

We have combined various data sources for our study including own measurements and images acquiring and available open data sources as well.

As described below we have acquired many images from our GoPro camera using UAS/avalanche probe. Using avalanche probe we made 121 point snow depth measurements in Site 1 and Site 2. We also measured the density of snow at 16 different spots in Adventdalen valley during April 2016. These values were used for snow water equivalent calculation.

For our measurements comparison we used a published snow cover depth of Svalbard Airport observation, ~9 km away from the site 2. The Norwegian Polar Institute offers the download of the official topographic basemap datasets for Norwegian polar land areas. The data is under Creative Commons CC BY 4.0 license. Available DEM is in 5-meter resolution GeoTIFF file format. We used this digital elevation model like reference base heights for our study (Norwegian Polar Institute 2, online).

Material and Methods

A six motors (hexacopter) DJI/Tarot 690 was originally planned for data acquiring. For more information about used UAS *see* Stuchlík et al. (2015). The UAS was exposed to severe frost, so the flight was shortened from the usual flight time to ~8 min. After two flights (on site 1) UAS was unable to operate probably due to a congealed central unit or remote control. Therefore additional flights could not be operated.

As mentioned before, due to severe weather and following technical problems with the UAS, we had to improvise. A combination of an avalanche probe and GoPro camera became the first-pick candidate.

GoPro HD Hero 3+ Black edition camera had the following setting: (1) focal length – 2.77 mm; (2) field of view – 100°; (3) resolution – 12 Mpix (4000 × 3000); (4) shutter speed – 1×500^{-1} seconds; (5) ISO – 100.

This improvised remote sensing method was applied, but with some consequences. GoPro camera was mounted on the top of 4-meter long avalanche probe and headed to the ground. Snow cover was scanned from a height of ~3 m to secure obtaining of enough overlapping images, hence going through study area in 2.5 m wide strips was necessary. It was also crucial to scan snow cover without leaving footsteps. One hundred meters long twine was anchored on the two opposite edges of sampling plot and secured. This approach helped us to keep the pathway as straight and parallel beside strips as possible. When we mapped one entire strip we shifted the twine to next one moving it 2.5 m aside. For reference measurements of snow cover depth, we selected the middle size area of 100 × 100 m with a fishnet of 10 × 10 m cells. 121 snow cover depth was measured in nodal points of this fishnet. The scheme and measuring points are shown in Fig. 2.

We also calculated snow water equivalent at 16 different spots scattered in surrounding valleys (Endalen and Todalen mainly). This allows us to estimate average snow water equivalent of study sites. Snow water equivalent was calculated as follows:

SWE [mm] = (*snow depth* [mm] × *snow density*) / *water density* *Eqn. 1.*

Note: *average snow depth* – 0.56 m (depth of snow measured using avalanche probe in 121 nodes of the grid), *snow density* – 331 kg × m^{-3} (measured by snow melting in 16 spots scattered in Adventdalen valley), *water density* – 999.84 kg × m^{-3} (routinely used constant for water density).

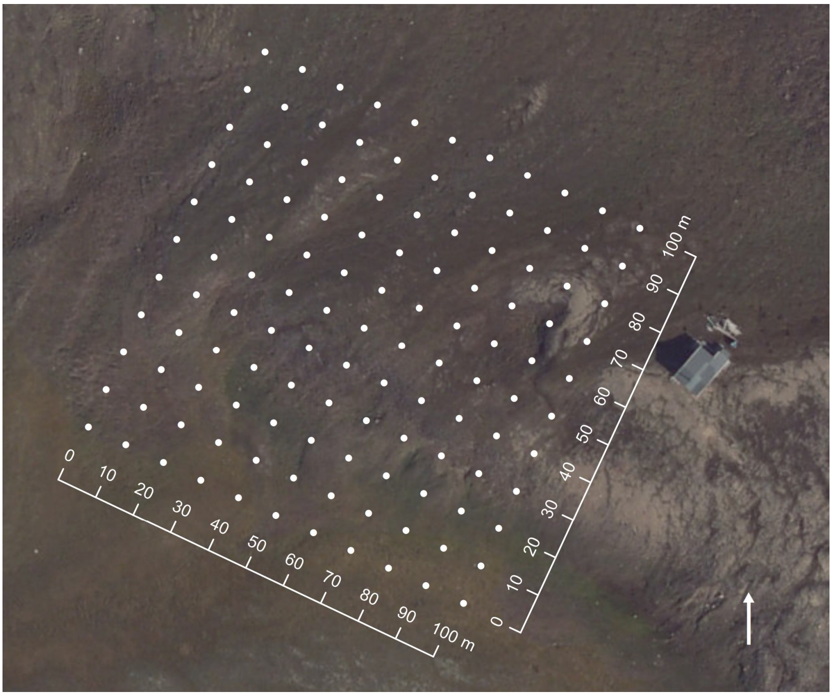

Fig. 2. Measuring points in the study area (orthophoto from Norwegian Polar Institute 1, online).

Image processing

The main complication connected with the usage of avalanche probe with GoPro for scanning snow cover was the acquisition of a big amount of data. 16 000 images (72 GB) were acquired from the site 2. Their processing was very time-consuming and a very high-performance hardware demanding. Useless, unnecessary and duplicate images were removed, suitable images were corrected (described below). Nevertheless we had to analyse 12 000 images (21 GB).

After removing useless images the first correction for GoPro camera images was the "fish-eye" distortion removal (*see* Fig. 3) using Adobe Lightroom 5.7. Next step was cropping of 40% of every image due to distortion of the edges. Using Fast Stone Photo Resizer 3.3 was images size reduced to 2400 × 1800 pixels, *see* Fig. 4. Then all edited images were uploaded to Agisoft Photoscan Professional Edition 1.2.0 (64 bit). As mentioned before Structure from Motion (SfM) method was used. The main advantage of this method is a capability to process images which do not have parallel view axis.

We experienced two fundamental problems when trying to process images taken from GoPro camera mounted on the bare pole. First, as mentioned before, anomalously huge amount of data was received due to much slower movement through the research plot, which drastically limited processing of data. Second, despite straight pathway, GoPro camera did not scan accurately only particular strip, because snow pole transferred vibration of walking. So snow pole with GoPro camera swung. A mix of these two problems caused the impossibility to create a high-quality result.

Fig. 3. "Fish-eye" correction.

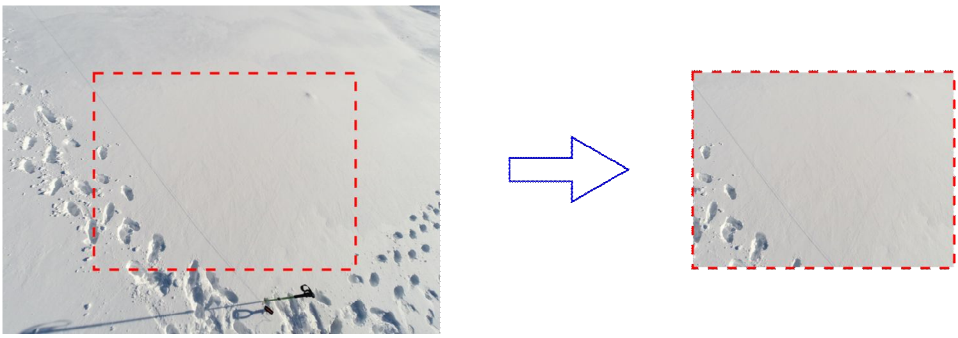

Fig. 4. Distorted image sides cropping.

Results

We calculated that median of snow depth above the lackluster overhang which runs from northwest to southeast approximately in the middle of research plot was 0.08 m and snow is distributed nearly uniformly, while below the overhang it was 1.03 m and distribution of snow is more scattered. If lower half of plot is divided into two equal quarters, we got medians of the lowest quarter of 1.39 m and the second lowest quarter of 0.72 m. Maximum snow depth was calculated in the most concave parts of research plot. The volume of the snow mass at the study site 2 was

5 569 m^3 (calculated as an integral of difference between given DEM topo and geostatisticaly interpolated DEM) and the average snow cover depth was calculated as 0.56 m.

The snow surface model, which was created using the 100 × 100 m sampling plot measurements, is displayed in Fig. 5. The snow cover distribution is visualized in Fig. 6. The red line in Fig. 5 symbolizes the profile graph for the snow thickness visualization in Fig. 7.

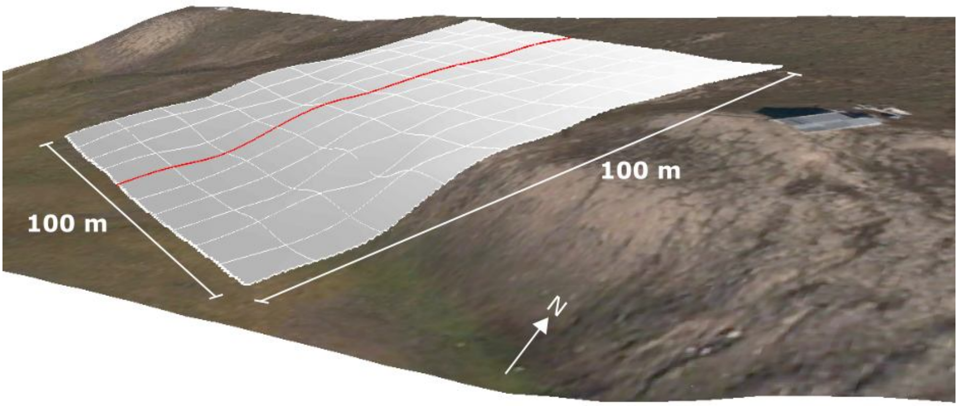

Fig. 5. Snow surface model of the Site 2. Created by 121 sampling measurements above local topography including profile line shown in Fig. 7. *Topography source*: Norwegian Polar Institute 2 (online).

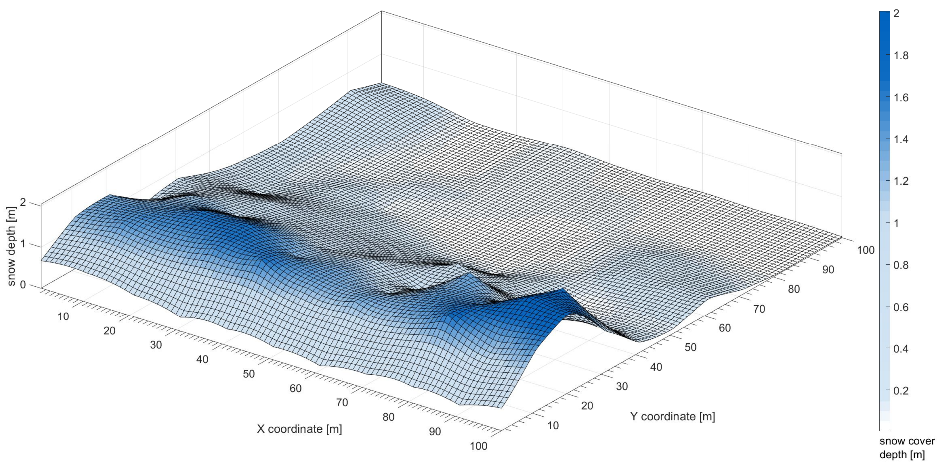

Fig. 6. Snow cover distribution on the Site 2.

As explained earlier, the research plot was intentionally selected as a slope. It can be seen in Fig. 6 that snow is not distributed uniformly at the plot. Parts with higher altitude, which are mostly convex or flat (*see* Fig. 5), and hence are more exposed to the wind effect, show much less snow than lower parts (snow was most probably blown away). Lover parts are, in opposite, more concave and more or less hidden from wind effects behind the overhang. Inflection point of slope can also be found near said overhang. The slope shape is visible in Fig. 5 and in the profile graph in Fig. 7 even better. The 3D topography and snow cover depth is displayed in Fig. 8 and snow depth hypsometry curve constructed from measured depths is shown in Fig. 9.

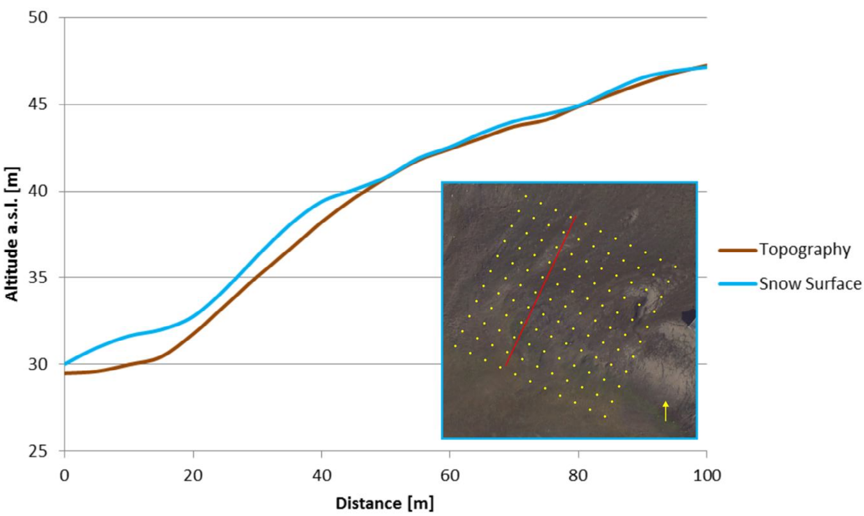

Fig. 7. The site 2 snow surface and topography profile graph of selected line (shown in Fig. 5). *Topography source*: Norwegian Polar Institute 2 (online).

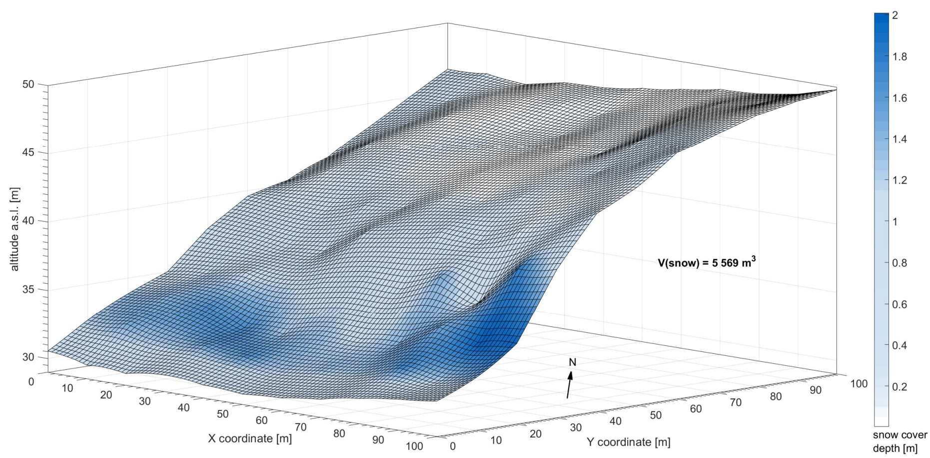

Fig. 8. The site 2 3D topography and snow cover depth.

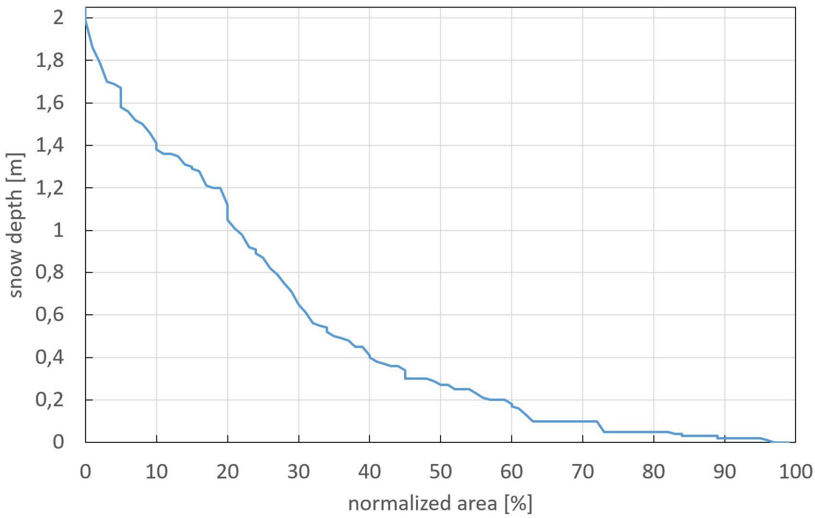

Fig. 9. Snow cover hypsometry curve constructed from measured depths on the Site 2.

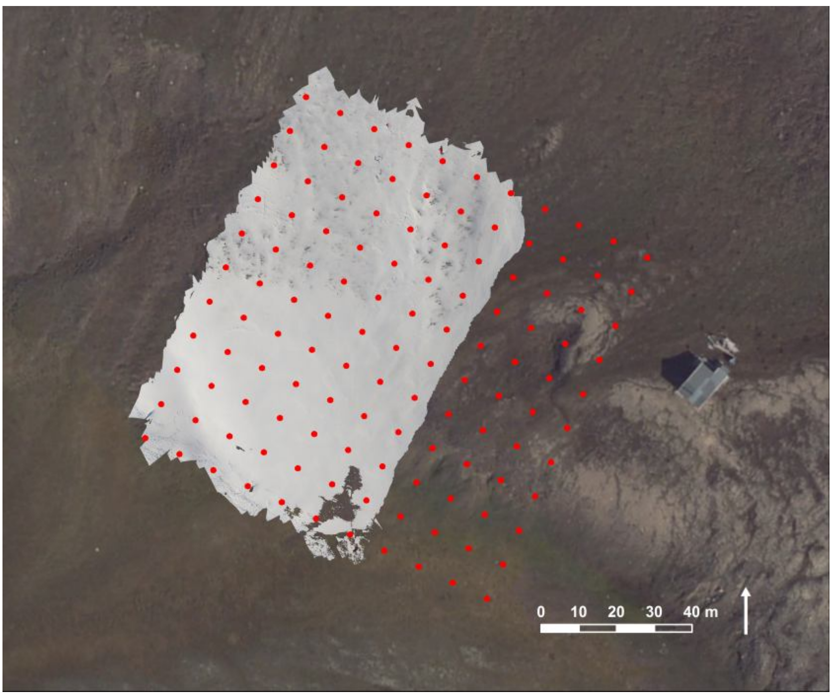

Fig. 10. Processed orthomosaic from the site 2 (white), 100 × 100 m sampling plot (red points) overlying orthophoto from Norwegian Polar Institute 1 (online).

Apart from our main research plot for SfM method, we made similar measurements at the site 1 in Endalen Valley (*see* Fig. 1). This site is mostly flat which is apparent from its less dissected relative relief. There are no evident structural patterns at the site 1 and snow cover depth and its distribution reflects it, average snow cover depth was calculated as 0.17 m. Standard deviation error of elevations of terrain at the site 1 is 0.9078 at mean altitude of 65.71 m a.s.l. (1.38%), while on the site 2 it is 6.5204 at mean altitude of 40.27 m a.s.l. (16.19%). We calculated a volume of snow at the site 1 as 1 683 m^3. The average value of snow density in surroundings of study area was measured as 331 kg × m^{-3} (16 spots scattered in Adventdalen valley). This gives extrapolated average snow water equivalent of 185 mm for the site 2 and of 56 mm for the site 1.

We were able to create orthomosaic composed from images, obtained from snow pole with GoPro, only for small part of the site 2 (*see* Fig. 10). Unfortunately, this part does not contain GCPs (Ground Control Points), so it is impossible to accurately georeference acquired orthomosaic and compare with snow cover layer created by using 100 × 100 m sampling plot. Partly georeferenced orthomosaic is shown in Fig. 10.

Discussion and Conclusions

Despite all problems, we gained solid results. Distribution of snow depth on the site 2 was found out with high precision of centimeters. Apart from our core subject of a research, we realized that there could be a correlation between underlying surface morphology and its snow cover depth distribution. Two tests were made to evaluate this presumption. First was a study of the site 1 located in Endalen valley (7 km off the site 2, *see* Fig. 1) where we made 100 × 100 m sampling plot as well with a result of average snow cover depth of 0.17 m (more or less flat area with small change in altitude of less than 5 m). Second was published snow cover depth of the Svalbard Airport observation site (flat area) which is 9 km away from the site 2. On April 1, 2016, it was measured 0.09 m of snow depth there. Both values seem to be in a good consensus with snow depths' we measured at morphologically similar parts of the site 2 (flat and almost flat parts). We think that such additional analysis of fundamental morphometry parameters in study area might be used together with several directly measured data (by SfM method) at meticulously selected sites for statistical estimation of snow cover depth in nearby locations which would, if validated, drastically lower the costs of a research.

Higher parts of the site 2 show much less snow than lower parts. It is, most probably, because of combination of convexness and exposition to wind effects. A decrease of snow cover in higher parts can be caused by rocks, too. Because many of the rocks were exposed to sunlight, so they could warm surroundings and consequently causing the snow thaw. Overall snow volume at site 2 was 5 569 m^3 and average snow depth was ~0.56 m. The vast majority of snow was allocated in the lower part. The site was studied in detail and distribution of snow in each type of terrain in the site is now well known; so we think it could be reference area for counting snow depth in other similar places.

We wanted to verify a concept of measurements of the snow cover volume from a sequence of images, gained from the Unmanned Aerial System in hostile conditions of Polar winter. A combination of data from the UAS measurements with data obtained from 100 × 100 m sampling plot and possibly terrain model could provide information about snow height and snow volume. Further, we wanted to test the UAS in harsh weather conditions. We would like to maintain the UAS flight in the summer and scan terrain without the snow cover to create the DEM and compare it with the existing 5 m DEM from Norwegian Polar Institute which was used as reference base heights in the study.

We came out from studies done *e.g.* in Alaska, Greenland and Svalbard, too. There are no mentions of technical problems with the UAS due to the severe frost. We have found out operational UAS limitations. The first problem could be connected with “frozen” batteries. This eventuality was rejected because batteries were stored in warm conditions until its connection and warming itself. Once the battery is under voltage, it could not be a problem for a battery to keep warm enough. Batteries in remote control were in a good condition too, because RC was not switched off. We think that central unit, which is responsible for transferring signal from the receiver to rotors, frozen.

Usage of the UAS in mentioned conditions has disadvantages. Main limitations are the weather conditions. It seems to be a temperature about ca. -12°C. Unfortunately, this is average temperature for the winter period in the study area, therefore there are only a few days with temperature above the mentioned limit. During our stay, there were more extreme weather conditions. Our method should not have other disadvantages regarding usage of the UAS. The narrow strip of snow cover was created, using SfM method, from images obtained from the UAS. We have proven that a possibility to join many images of snow cover based on texture really exists.

The main advantage of our method is a utilization of 100 × 100 m sampling plot as exact reference layer. This layer could be compared with processed images gained *e.g.* from the UAS. We would like to investigate three “types” of terrain: plane, slope, and notch. Always 1 ha would be scanned from the UAS and then measured by utilizing 100 × 100 m sampling plot. After comparison these layers, we will be able to say what root mean square error is for each of these three types of terrain. This procedure would be applied several times at different places to find out standard deviations for each types of terrain. After that such evaluation here is a possibility to scan larger areas without utilization of 100 × 100 m sampling plot. The last question is how to compute snow water equivalent without a direct snowpack measurement. It would be possible using radar. Radio wave can go through snowpack and reveal its internal structure. If internal structure is known, we will be able to estimate a density of snow pack and compute snow water equivalent. After these steps, a total amount of water in the snowpack could be estimated.

Laser scanner should be used instead of an optical camera (or parallel), but it entails other specifics. Both radar and laser scanner are a so-called active method. It means that these sensors have to emit a beaming, which is partly reflected back from objects to sensors. According to the intensity and other parameters of backward beaming it is possible to recognize some characteristics of the object from which reflected beaming comes from. We are also planning real-time and online transfer of data from the UAS to the ground station, too. The UAS can carry a portable computer which could partly process data on board and transfer it to the ground station. The question is what kind of transfer could be the best. It has to be fast and must not interfere with remote control and FPV. LTE (Long Term Evolution – high-speed internet technology for mobile devices) should be a good choice. With this proceeding, data could be processed immediately during flight. So it allows acceleration of entire processing.

References

ABER, J. S., MARZOLFF, I. and RIES, J. B. (2010): Small-Format Aerial Photography: Principles, Techniques and Geoscience Applications. 266 p.

BERMAN, E. S. F., FLADELAND, M., LIEM, J., KOLYER, R. and GUPTA, M. (2012): Greenhouse gas analyzer for measurements of carbon dioxide, methane, and water vapor aboard an unmanned aerial vehicle. *Sensors and Actuators, B: Chemical*, 169: 128-135.

BROWN, J., HINKEL, K. M. and NELSON, F. E. (2000): The circumpolar active layer monitoring (CALM) program: Research designs and initial results. *Polar Geography*, 24: 165-258.

BRULAND, O., SAND, K. and KILLINGVEIT, Å. (2001): Snow distribution at a High-Arctic site at Svalbard. *Hydrology Research*, 32: 1-12.

BÜHLER, Y., ADAMS, M. S., BÖSCH, R. and STOFFEL, A. (2016): Mapping snow depth in alpine terrain with unmanned aerial systems (UAS): potential and limitations. *The Cryosphere*, 10: 1075-1088.

CIMOLI, E. (2015): Determining Snow Depth Distribution from Unmanned Aerial Vehicles and Digital Photogrammetry. Master Thesis, Technical University of Denmark, Denmark. 71 p.

DE MICHELE, C., AVANZI, F., PASSONI, D., BARZAGHI, R., PINTO, L., DOSSO, P., GHEZZI, A., GIANATTI, R. and DELLA VEDOVA, G. (2016): Using a fixed-wing UAS to map snow depth distribution: an evaluation at peak accumulation. *The Cryosphere*, 10: 511-522.

EISENBEISS, H. (2009): UAV Photogrammetry. Dissertation thesis, ETH Zurich, Switzerland. 201 p.

GOODISON, B. (2006): Challenges in Snow Measurement: Solid Precipitation and Snow Cover. ECMWF Seminar on Polar Meteorology. 6 p.

LÁSKA, K., CHLÁDOVÁ, Z., AMBROŽOVÁ, K. and HUSÁK, J. (2013): Cloudiness and weather variation in central Svalbard in July 2013 as related to atmospheric circulation. *Czech Polar Reports*, 3: 184-195.

LÁSKA, K., WITOSZOVÁ, D. and PROŠEK, P. (2012): Weather patterns of the coastal zone of Petuniabukta (Central Spitsbergen) in the period 2008–2010. *Polish Polar Research*, 33: 297-318.

MAYER, S., JONASSEN, M. O., SANDVIK, A. and REUDER, J. (2012): Profiling the Arctic Stable Boundary Layer in Advent Valley, Svalbard: Measurements and Simulations. *Boundary-Layer Meteorology*, 143: 507-526.

MORA, C., VIEIRA, G., PINA, P., LOUSADA, M. and CHRISTIANSEN, H. H. (2015): Land cover classification using high-resolution aerial photography in Adventdalen, Svalbard. *Geografiska Annaler, Series A: Physical Geography*, 97: 473-488.

NOLAN, M., LARSEN, C. and STURM, M. (2015): Mapping snow depth from manned aircraft on landscape scales at centimeter resolution using structure-from-motion photogrammetry. *The Cryosphere*, 9: 1445-1463.

REUDER, J., BRISSET, P., JONASSEN, M., MÜLLER, M. and MAYER, S. (2009): The Small Unmanned Meteorological Observer SUMO: A new tool for atmospheric boundary layer research. *Meteorologische Zeitschrift*, 18: 141-147.

RIPPIN, D. M., POMFRET, A. and KING, N. (2015): High resolution mapping of supra-glacial drainage pathways reveals link between micro-channel drainage density, surface roughness and surface reflectance. *Earth Surface Processes and Landforms*, 40: 1279-1290.

SHIKLOMANOV, N.I., NELSON, F.E., STRELETSKIY, D.A., HINKEL, K.M. and BROWN, J. (2008): The Circumpolar Active Layer Monitoring (CALM) Program: Data Collection, Management, and Dissemination Strategies. Proceedings of the 9th International Conference on Permafrost, Institute of Northern Engineering, University of Alaska, Fairbanks, 1: 1647-1652.

SNAVELY, K. (2008): Scene Reconstruction and Visualization from Internet Photo Collections. University of Washington, USA, 189 p.

STRANGEWAYS, I. (2004): Improving precipitation measurement. *International Journal of Climatology*, 24: 1443-1460.

STUCHLÍK, R. (2015): UAV data and its utilization in crisis management. Masaryk university, Brno, 92 p.

STUCHLÍK, R., STACHOŇ, Z., LÁSKA, K. and KUBÍČEK, P. (2015): Unmanned Aerial Vehicle – Efficient mapping tool available for recent research in polar regions. *Czech Polar Reports*, 5: 210-221.

WALLACE, L., LUCIEER, A., WATSON, CH. and TURNER, D. (2012): Development of a UAV-LiDAR System with Application to Forest Inventory. *Remote sensing*, 4: 1519-1543.

WESTOBY, M.J, BRASINGTON, J., GLASSER, N. F., HAMBREY, M. J. and REYNOLDS, J. M. (2012): 'Structure-from-Motion' photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology*, 179: 300-314.

WU, Y., ZHANG, Q. and LIU, S. (2008): A contrast among experiments in free low-altitude unmanned aerial vehicles photography: security, quality & efficiency. ISPRS XXXVII Congress, 1223 - 1228 p.

YOHANDRI, V., WISSAN, I., FIRMANSYAH, P., AKBAR, P. R., SUMANTYO, J. T. and KUZE, H. (2011): Development of circularly polarized array antenna for synthetic aperture radar sensor installed on UAV. *Progress In Electromagnetics Research C*, 19: 119-133.

Web sources

INTERNATIONAL PERMAFROST ASSOCIATION [online]: Manual for monitoring and reporting permafrost measurements, http://ipa.arcticportal.org/images/stories/tsp_manual.pdf.

NORWEGIAN POLAR INSTITUTE 1 [online]: TopoSvalbard, http://toposvalbard.npolar.no/.

NORWEGIAN POLAR INSTITUTE 2 [online]: Terrengmodell Svalbard (S0 Terrengmodell) [Data set], https://doi.org/10.21334/npolar.2014.dce53a47

SVALBARD AIRPORT OBSERVATION SITE [online]: https://www.yr.no/place/Norway/Svalbard/Svalbard_Airport_observation_site/almanak.html?dato=2016-04-01.

UAVS [online]: Unmanned Aerial Vehicle Systems Association, https://www.uavs.org/uas.