# UAS Photogrammetry of Homogenous Snow Cover

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*Abstract: Photogrammetry of the snow cover is expected to be difficult, because of its homogenous, low-contrast surface, hindering the automated detection of matching points to generate digital surface models. On the other hand there is rising request for high spatial resolution snow depth and snow surface type mapping as well as snow avalanche event documentation. Unmanned aerial systems (UAS) enable flexible, efficient and economic data acquisition, even within inaccessible alpine terrain. The efficient and economic generation of high-quality digital surface models (DSM) of snow covered surfaces would be a major step forward for many applications in snow hydrology and hydropower generation, avalanche research and warning, for winter tourism as well as for alpine ecology investigations.*
*We investigate the performance of UAS-based structure-from-motion (SfM) photogrammetry on very homogenous snow surfaces at the test site Tschuggen at 2,000 m a.s.l. close to Davos, Switzerland under diffuse illumination conditions, caused by a completely overcast sky, a situation that could be described as "worst case" for photogrammetry. We investigate the benefit of near infrared information (λ > 830 nm), compared to imagery acquired within the visible part of the electromagnetic spectrum (λ = 400 – 700 nm) and a combination of these two. We evaluate the accuracy of the different digital surface models (DSMs) qualitatively and quantitatively by applying differential Global Navigation Satellite System measurements with an expected accuracy better than 10 cm in x, y and z directions. The results of this study enable an assessment of the potential and the limitations of SfM photogrammetry for applications on snow-covered terrain.*

## 1 Introduction

Snow type, snow depth and their spatiotemporal distribution in alpine regions are key parameters for many applications ranging from hydropower, drinking water supply, hydrological modeling, snow avalanche and flooding hazard mitigation, winter tourism, road and railway maintenance to ecological applications such as alpine or arctic habitat monitoring. In combination with snow density models, snow depth measurements can be calculated to snow water equivalent values (JONAS et al. 2009), describing the amount of water that is stored in the snowpack. Even though the spatial variability of alpine snow cover is known to be very high (SCHWEIZER et al. 2008; LOPEZ-MORENO & NOGUES-BRAVO 2006), ranging from nearly zero to several meters within short distances of a few meters.
Currently, snow depth is operationally measured using automated weather stations (AWS) or observers in the field (EGLI 2008) for various applications such as the Swiss avalanche warning or flood forecasting. The main issue of these measurements is that they are all acquired at point

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locations and are not spatially continuous. This is a key issue for most applications, which are based on snow depth information as input, because the snow cover is spatially variable in particular within alpine terrain (SCHWEIZER et al. 2008).
To overcome this limitation, airborne (ALS) and terrestrial laser scanning (TLS) was successfully applied to map snow depth mapping over small catchments (e.g. DEEMS et al. 2013; GRÜNEWALD et al. 2010; MOTT et al. 2010; PROKOP 2008). With this method, high spatial resolution of better than 1 m and vertical accuracies better than 0.1 m can be achieved. However, data acquisition is time-consuming and often costly (BÜHLER et al. 2015a). UAS-based laser scanning has also been introduced is not yet fully operationally implemented. First devices exist but are very costly in particular considering the high risk of UAS-operation under alpine conditions, i.e. high winds and gusts, low temperature, lack of landing spots et cetera.
Photogrammetry can offer an economic and flexible alternative to laser scanning. First attempts to map snow depth photogrammetrically, using scanned aerial imagery, were already made 50 years ago (SMITH et al. 1967) and the topic was investigated in detail by CLINE (1993, 1994). However, their results suffer from image saturation and insufficient reference data leading them to the conclusion that photogrammetry has much potential but is not yet accurate enough for large-scale snow depth mapping. LEDWITH & LUNDEN (2010) used scanned aerial imagery to derive digital elevation models over glaciated and snow-covered areas in Norway. They report a mean accuracy of 2.8 m in comparison to differential Global Navigation Satellite System (dGNSS) transects, which is clearly too low for meaningful snow depth mapping in alpine regions.
With the current improvement in sensor technology and photogrammetric data processing, in particular the structure from motion (SfM) approach (KOENDERINK & VAN DOORN 1991; POLLEFEYS et al. 2004; WESTBOY et al. 2012; Crandall et al. 2013), digital photogrammetry developed to an efficient and highly accurate tool for surveying applications. First investigations on snow prove its applicability for snow depth mapping with sensors on manned aircrafts (LEE et al. 2008; BÜHLER et al. 2015a; NOLAN et al. 2015) to cover large areas and UAS (VANDER JAGT et al. 2015; BÜHLER et al. 2016; DE MICHELE et al. 2016; HARDER et al. 2016) to cover smaller areas with high spatial resolution. The reported accuracies range from approximately 0.30 m to 0.05 m root mean square error (RMSE). These recent results underline the potential of the proposed technology for spatially continuous snow depth mapping with high vertical accuracies that have the potential to complement or even substitute the currently applied point HS measurements. However, the legal regulations to fly UAS vary substantially for different countries or even states and counties. The regulations have to be checked carefully before data acquisitions with UAS can be planned. The regulations for Switzerland are listed under https://www.bazl.admin.ch/bazl/en/home/good-to-know%20/drones-and-aircraft-models.html and are comparably user friendly.
In this study we test SfM photogrammetry in a “worst case” scenario with very homogenous new snow cover and diffuse illumination caused by a closed cloud cover.

## 2 Test site, data acquisition and experimental setup

### 2.1 Test site Tschuggen, Davos GR, Switzerland

The test site Tschuggen is located at the bottom of the Flüela valley at an elevation of 1,940 m a.s.l., close to the timberline. This spot is well accessible even during the winter season, because the Flüela pass road is regularly cleared until this point. The high-alpine valley bottom features both quite flat alpine meadows and hilly alpine terrain. The main land cover is a mixture of bushes (mainly alpine rose, juniper and erica) containing steep rocky outcrops and sparse larch and pine trees. Only moderate HS variability can be expected at this site in an average winter season because it is usually not exposed to high winds. The mean slope angle of the test site is 19° ranging from 0 to 83° (BÜHLER et al. 2016).

On 8 January 2016 we had particular conditions: this particular date was immediately after a 0.10 m of fresh snow fall and the sky was completely overcast, leading to diffuse illumination (Fig. 1). We expect the combination of these two conditions to be "worst case" for photogrammetry on snow, as it leads to minimal contrast. We could visually not make out any contrast in most snow-covered areas. Therefore we expect to be able to investigate the limits of photogrammetry on snow with this dataset.

Fig. 1: The Falcon 8 flying at Tschuggen on January 8 2016. The sky is overcast and the new snow cover shows nearly no contrast.

### 2.2 UAS Falcon 8

As described in (BÜHLER et al. 2016), the Ascending Technologies (AscTec) Falcon 8 octocopter (Fig. 1) is equipped with a customized Sony NEX-7 camera. The Falcon 8 has been in serial production since 2009 and can be customized with different sensor systems. The system weighs 2.3 kg (incl. camera) and can be transported to remote locations fully assembled in a special backpack, a prerequisite for most alpine applications. Onboard navigation sensors (Global Navigation Satellite System GNSS, Inertial Measurement Unit IMU, barometer and compass) and an adaptive control unit permit high positional accuracy and stable flight characteristics even in challenging conditions found in alpine environment with limited accessibility, low temperatures, high wind speeds and complex terrain.

The applied Sony NEX-7 system camera features a 24 MP APS-C CMOS sensor and is equipped with a small and lightweight Sony NEX 20mm F/2.8 optical lens (81 g). By removing the built-in near infrared filter, the camera sensor is also sensitive within the near infrared part of the spectrum. This allows us to mount the lens with different filters: visible colors (RGB, $\lambda$ = 550 – 770 nm), undefined NIR (without filter, combined visual and NIR information) and near infrared only (NIR830, $\lambda$ > 830 nm). The near-infrared sensitivity is expected to have advantages on snow-covered surfaces (BÜHLER et al. 2015b). The camera is connected to the Falcon 8 by a gimbal with active stabilization and vibration damping and is powered by the UAS battery. The viewfinder of the camera is transmitted to the ground control station as video signal and the basic camera functions such as the exposure time can be controlled from the ground.

## 2.3 Experimental setup

We acquired imagery in RGB, near infrared undefined (NIR) and near infrared ($\lambda$ > 830 nm, NIR830) wavelengths immediately after each other (total of 104 images per data acquisition). Blurred pictures were eliminated manually. The illumination conditions were nearly constant. An image overlap of 70 % along-track and across-track was chosen, which is based on our experience, a good compromise between the amount of time required for data acquisition and quality of the resulting DSM. The flight elevation above ground was approximately 100 m, the air temperature was -6°C and the mean wind speed was 25 km/h, with wind gusts of up to 35 km/h from southeastern direction (measured at the automated weather station Flüela, 4 km from Tschuggen).

For the absolute orientation, 10 reference points (RPs), distributed over the entire test site, were used to georeference the RGB and NIR imagery. The RPs, blue crosses sprayed on the snow, were measured with a Trimble GeoXH differential GNSS with an expected accuracy of better than 0.10 m. As the RPs are not visible within the NIR830 imagery, because the spray seems to absorb the same amount of radiation as the surrounding snow, so we had to rectify the NIR830 imagery using RPs visually identified within the RGB orthophoto. We applied 11 checkpoints (CPs), which were not used for the rectification process (Fig. 2).

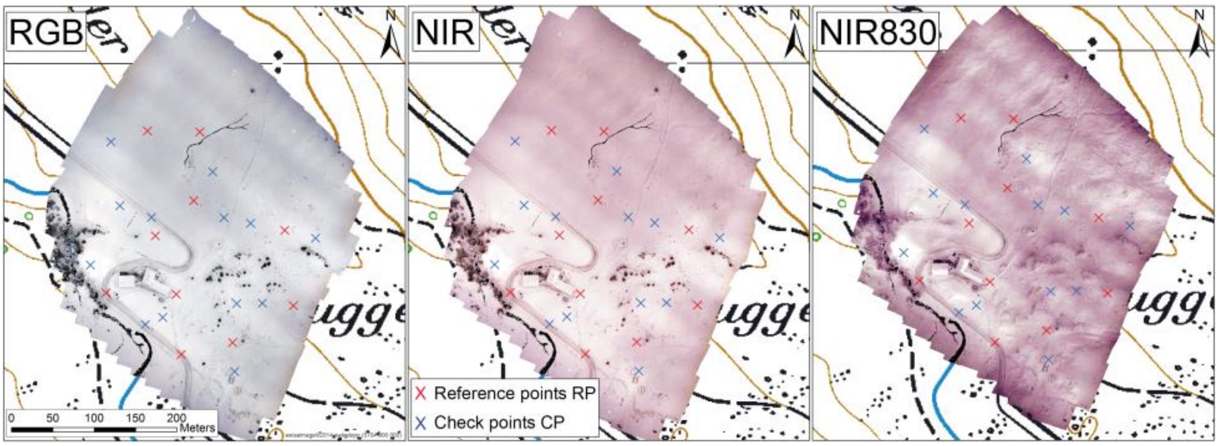


Fig. 2: RGB, NIR and NIR830 orthophotos of the test site Tschuggen with the applied reference (RP) and check points (CP).

The imagery was processed using AgiSoft PhotoScan Pro v. 1.2.4. The imagery was aligned automatically and we used the default moderate filter to generate the point cloud. The DSMs were exported with a spatial resolution of 0.10 m using the PhotoScan interpolation algorithm. We classified the point clouds using the classification tool implemented in PhotoScan Pro into ground points and noise/unclassified. As we want to compare the different input imagery we keep all processing parameters constant.

## 3 Results and discussion

### 3.1.1 Orthorectification

The achieved average accuracy of the orthorectification process (calculated by the Photoscan Pro software) is 0.17 m (x = 0.08 m, y = 0.08 m, z = 0.13 m) for the RGB imagery and 0.16 m (x = 0.09 m, y = 0.07 m, z = 0.11 m) for the NIR imagery. In the NIR830 imagery, the sprayed points are completely invisible due to similar reflection characteristics as the surrounding snow, we only realized this fact during this study. Therefore we have to reference the NIR830 imagery applying reference points taken from the RGB orthophoto, close to the original RPs. The achieved accuracy based on the RGB reference points are 0.16 m (x = 0.08 m, y = 0.11 m, z = 0.07 m). These orientation accuracies are all in the same range, however we observe a small shift between the NIR830 and the other two datasets.

### 3.1.2 Qualitative DSM evaluation

We already generated DSMs on March 11 2015 under clear sky conditions and on a snow cover that did not get covered by new snow recently. Under such conditions only very few outlier and no holes occur within the DSM (Fig. 3). The achieved RMSE values of the UAS snow depth map compared to manual avalanche probe measurements is better than 0.10 m on short grass and rocks (Bühler et al. 2016). These results lead to the conclusion, that high-quality surface models can be generated on snow, if the illumination conditions are good (clear sky, high contrast) and the snow cover is not extremely homogenous.

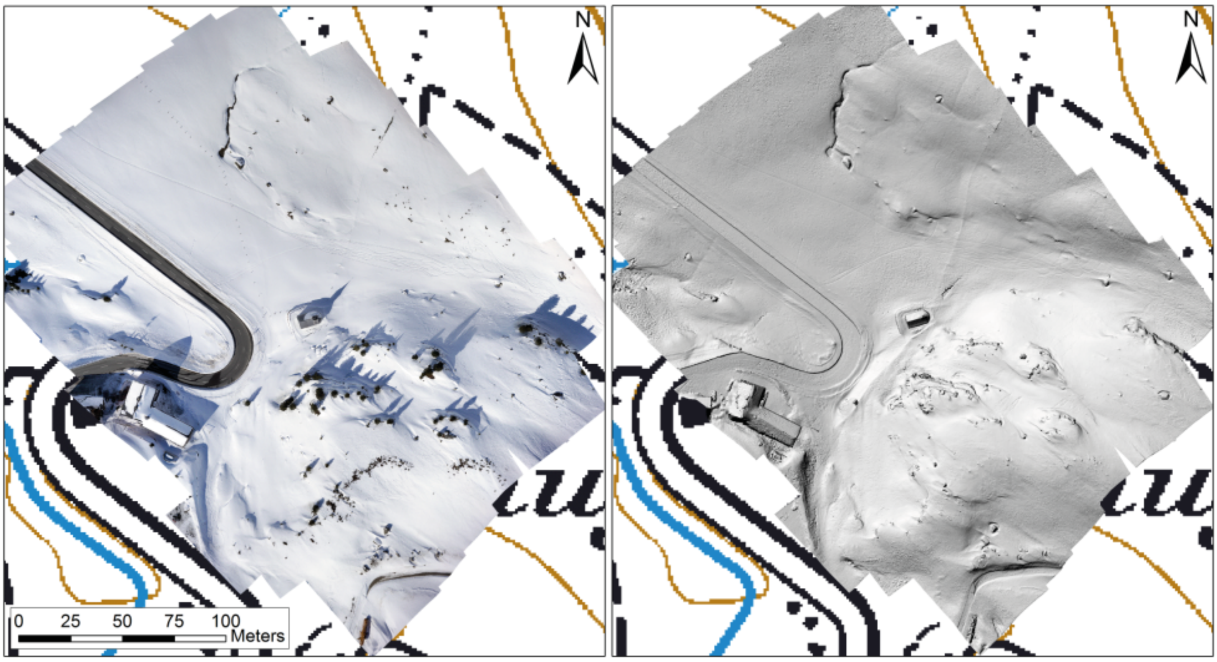


Fig. 3: Reference data acquisition on March 11 2015 under clear sky conditions several days after the last snowfall. Nearly no noise can be identified in the hillshade of the DSM (right) except at the very edge where the image overlap gets insufficient.

In contrast to the data from March 11 2015, the DSM generated from the data acquired on January 8 2016 show obvious errors within the homogenous parts of the snow cover. Large interpolated areas, outliers up to several meters and noisy sections occur. The RGB and NIR data result in similar amounts of corrupted surfaces. But the NIR830 data result in considerably less corrupted area and therefore in a better DSM result, even though it is also not completely free of noisy errors (Fig. 4).

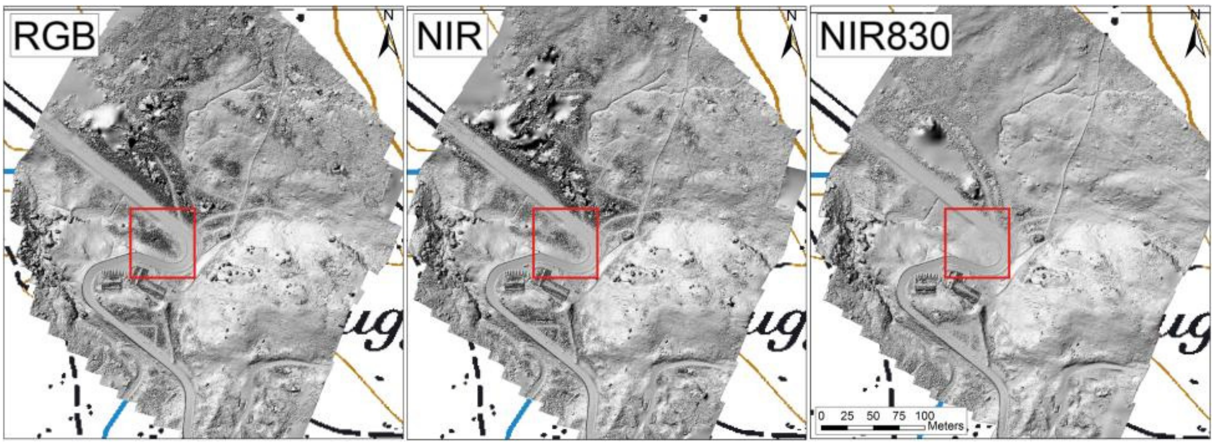


Fig. 4: Hillshades of the DSMs generated from the data acquired under "worst case" conditions. The homogenous snow cover results in very noisy surfaces with amplitudes of up to several meters or even holes, which have to be interpolated. This is most obvious within the northwest part of the test site above the road. The hilly section in the southeast part of the test site shows a quite smooth surface in all bands.

The effect of the different wavelength gets better visible by zooming into a very homogenous snow cover spot at the U-turn curve of the road. To visualize the effects we draw a line profile across this snow spot (Fig. 5). The profile and the hillshade views reveal that the quality of the DSM improves considerably from RGB over NIR to NIR830. This result is surprising on the first sight as the visual impression is best for RGB and worst for NIR830 imagery. However if the imagery is enhanced, the NIR830 shows more contrast and details within the homogenous snow cover as it is already demonstrated by BÜHLER et al. 2015b.

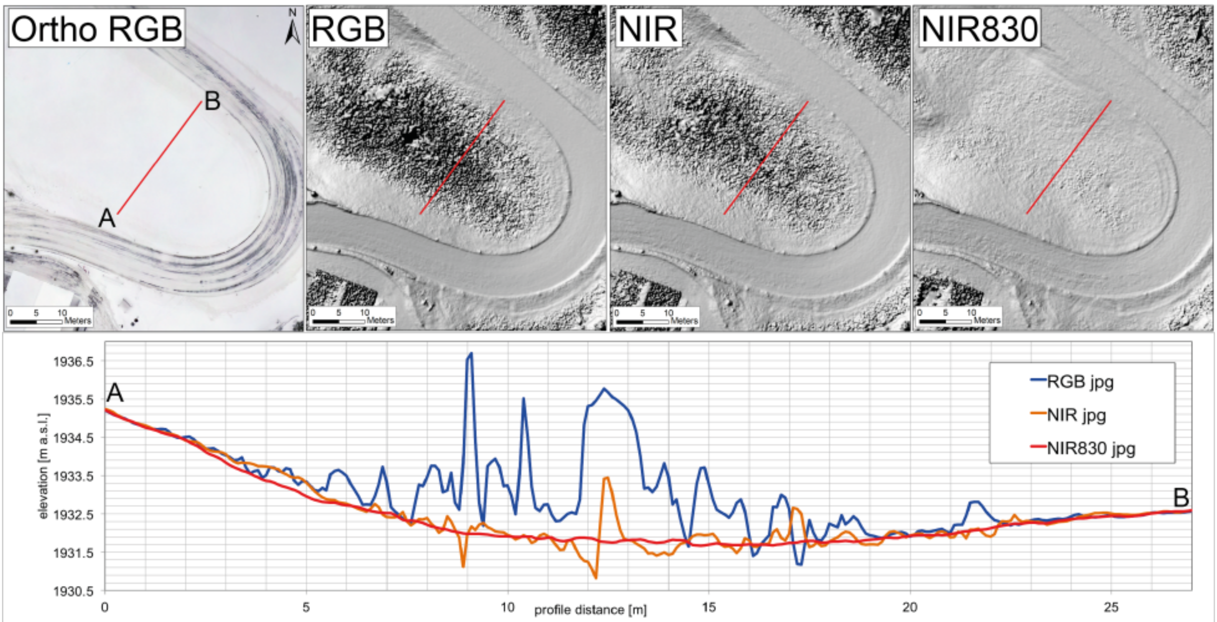


Fig. 5: Profiles across a homogenous snow spot for the different unfiltered DSMs.

The qualitative 3D analysis of the point clouds around the chapel in the middle of the test site reveals that large outliers of several meters occur within the homogenous snow covered parts. We classify the point clouds into ground points, noise and other points (Fig. 6). By only using the ground points for DSM generation, the large outliers are eliminated. However there are still noisy errors with amplitude in the range of 0.5 m within the ground points. Furthermore not all corrupted points are correctly classified, in particular where the point density is low, leading to large areas with wrong elevation values, interpolated within low quality points (Fig. 7).

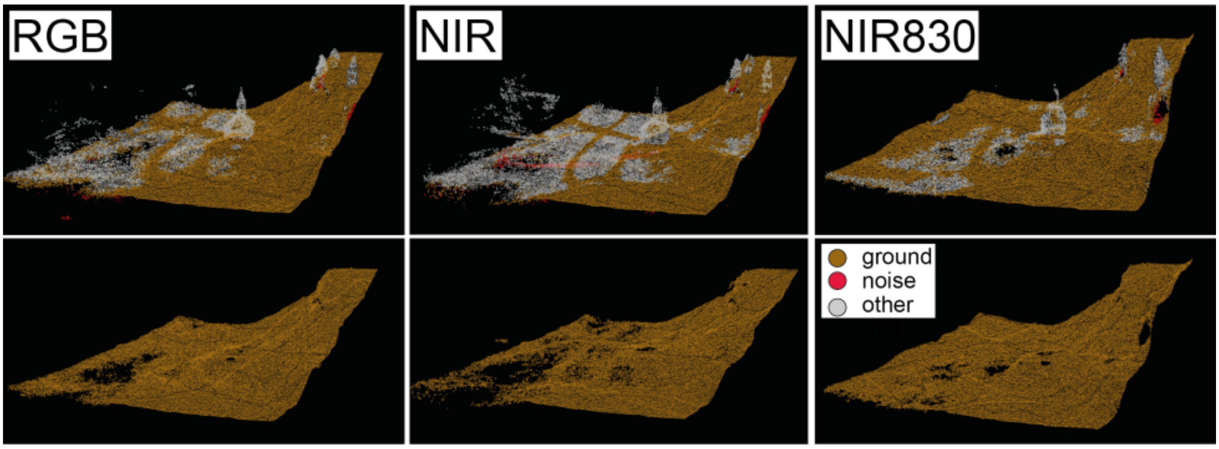


Fig. 6: Point clouds of the different data sets around the chapel in the middle of the test site. The lower tab shows only the points classified as ground.

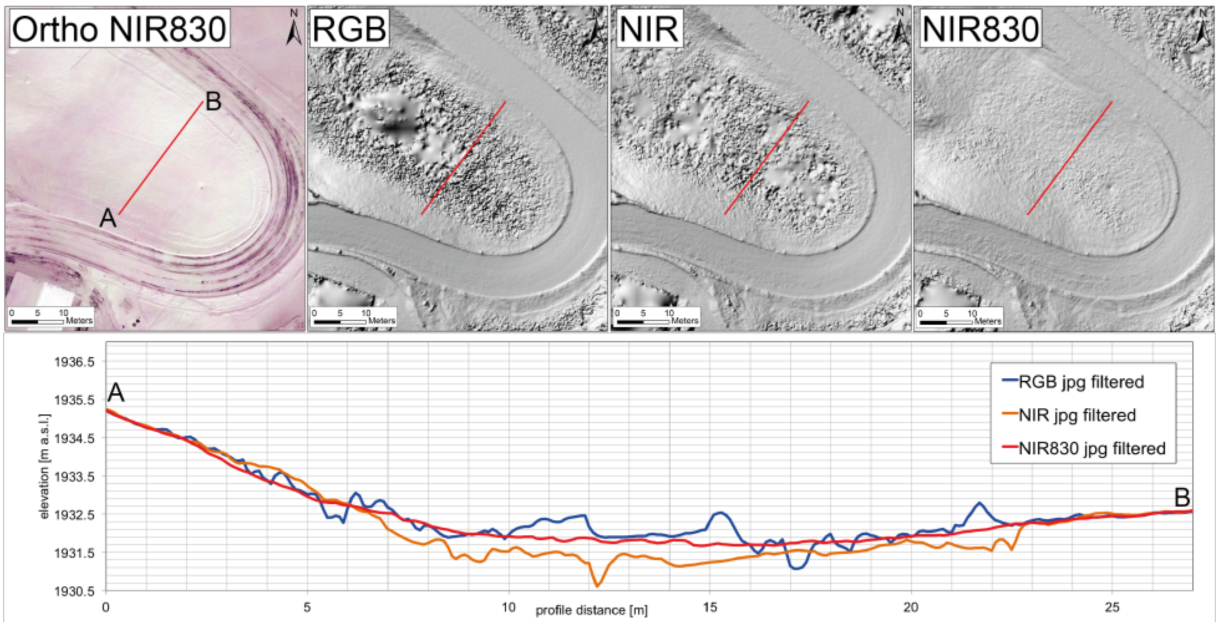


Fig. 7: Profiles across a homogenous snow spot for the different filtered DSMs.

Even though the large outliers are eliminated, big differences in DSM quality still remain within the different bands. The quality of the NIR830 data is again considerably better than the NIR and RGB DSMs. These results clearly indicate the additional value of near infrared bands for surface model generation in particular within homogenous snow spots.

### 3.1.3 DSM precision at the check point (CP) locations

We analyze the elevation values at the 11 CP locations comparing them to the GNSS elevation (accuracy < 10 cm) to quantitatively compare the different DSMs. Here the picture is different from the qualitative assessment: the RMSE of the NIR830 DSM is approximately 30% higher than for RGB and NIR (Tab 1.) However, the number of points gets higher as more details on the snow cover are detectable in the near-infrared band. Additionally more points are produced in RGB and in NIR that are classified as noise or other points than ground. These noise points as well as unclassified outliners lead to the very noisy surfaces of the unfiltered DSMs (Fig. 5, Fig. 6).

We suppose that the higher RMSE of the NIR830 DSM is caused by the different orthorectification. As the sprayed crosses are invisible within the NIR830 imagery we had to apply different reference points, which lead to a slight shift and probably cause the larger deviation from the GNSS elevation at the checkpoint locations. As we had to deploy the RPs and CPs before the flight, our ski tracks disturbed the homogenous snow cover and generated contrast. PhotoScan Pro uses this contrast to successfully match points without outliers. Therefore the RMSE values are very low at the checkpoint locations. This result indicates that the results of RGB and NIR are good if there is enough contrast present. However it limits the quantitative quality assessment to areas with high contrast, which was not the main aim of this study.

Tab. 1: Summarized errors of the 11 different DSMs compared to the GNSS elevation at the check point locations and description of the different point clouds and their classification.

| | **Mean error (bias)** | **Standard deviation error** | **RMSE** | **N° of point total [mio]** | **ground points [%]** | **noise [%]** | **unclassified [%]** |
|---|---|---|---|---|---|---|---|
| **RGB jpg** | -0.02 m | 0.12 | 0.18 m | 68.96 | 92.24 | 0.56 | 7.20 |
| **NIR jpg** | -0.03 m | 0.11 | 0.16 m | 71.37 | 83.40 | 0.45 | 16.15 |
| **NIR830 jpg** | -0.09 m | 0.19 | 0.27 m | 76.80 | 93.83 | 0.19 | 5.98 |

# 4 Conclusions

Recent investigations by BÜHLER et al. (2015), NOLAN et al. (2015), VANDER JAGT et al. (2015), BÜHLER et al. (2016), DE MICHELE et al. (2016) and HARDER et al. (2016) showed that the longstanding assumption, photogrammetry is not able to generate high quality digital surface models on snow covered terrain, is incorrect under favorable illumination conditions and over weathered snow surfaces. Photogrammetry can successfully be applied to map snow depth with high spatial resolution even within high alpine terrain.

To investigate the limitations of photogrammetry on snow we explore a “worst case” scenario: homogenous new snow cover and diffuse illumination caused by a completely overcast sky. Under these conditions, the human eye is not able to detect contrast over large parts of the snow cover. The resulting DSMs, calculated based on the RGB and the NIR imagery are, as expected, corrupted by noisy errors with amplitudes up to 10 m and large holes where no points can be matched by the commercial software Agisoft PhotoScan Pro. But if we apply near infrared bands (NIR), the results get better and if we apply near infrared input (NIR830) only, the resulting DSMs are significantly better (Fig. 5). Errors still occur over the most homogenous snow patches but large parts can be mapped surprisingly well. This result supports the assumption by BÜHLER et al. (2015b) that near infrared bands bring significant additional value for point matching over snow covered areas.

The results of this study indicate that digital photogrammetry is able to generate high quality digital surface models and orthophotos even under suboptimal illumination conditions and over very homogenous new snow cover if near infrared bands are applied. The extremely homogenous parts of the snow cover cannot be mapped satisfactorily but large part of the test site can. This opens the door for various applications where spatial continuous snow cover and snow depth information is requested.

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