

## **Detection of surface elevation changes using an unmanned aerial vehicle on the debris-free Storbreen glacier in Norway**

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Recent studies have shown that the application of unmanned aerial vehicles (UAVs) has great potential to investigate the dynamic behavior of glaciers. The studies have successfully deployed UAVs over generally contrast-rich surfaces of debris-covered glaciers and highly crevassed bare ice glaciers. In this study, the potential of UAVs in glaciology is further exploited, as we use a fixed-wing UAV over the largely snow-covered Storbreen glacier in Norway in September 2015. The acquired UAV-imagery was processed into accurate digital elevation models and image mosaics using a Structure from Motion workflow. Georeferencing of the data was obtained by ingesting ground control points into the workflow that were accurately measured with a differential global navigation satellite system (DGNSS). Geodetic accuracy was determined by comparison with DGNSS surface profiles and stake positions that were measured on the same day. The processed data were compared with a LIDAR survey and airborne imagery acquisition from September and October 2009 to examine mass loss patterns and glacier retreat. Results show that the UAV is capable of producing high-quality elevation models and image mosaics for the low-contrast snow-covered Storbreen at unprecedented detail. The accuracy of the output product is lower when compared to contrast-rich debris-covered glaciers, but still considerably more accurate than spaceborne data products. Comparison with LIDAR data shows a spatially heterogeneous downwasting pattern of about  $0.75 \text{ m a}^{-1}$  over 2009–2015 for the upper part of Storbreen. The lower part exhibits considerably more downwasting in the range of  $0.9\text{--}2.1 \text{ m a}^{-1}$ . We conclude that UAVs can be valuable for surveys of snow-covered glaciers to provide sufficient accurate elevation models and image mosaics, and we recommend the use of UAVs for the routine monitoring of benchmark glaciers such as Storbreen.