A high-frequency and high-resolution image time series of the Gornergletscher - Swiss Alps - derived from repeated UAV surveys

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Abstract. The rapid growth of drone technology provides an efficient means to monitor the response of alpine glaciers to climate warming. Here we report a new dataset based on images collected during ten intensive UAV surveys of the Gornergletscher glacial system (Switzerland) carried out approximately every two weeks throughout the summer 2017. The final products, available at: https://doi.org/10.5281/zenodo.1487862 (Benoit et al, 2018), consist in a series of 10 cm resolution ortho-images, Digital Elevation Models of the glacier surface, and Matching Maps that can be used to quantify ice surface displacements and velocities. Used on its own, this dataset allows mapping the glacier and monitoring surface velocities over the summer at a very high spatial resolution. Coupled with a classification or feature detection algorithm, it enables extracting structures such as surface drainage networks, debris or snow cover. The approach we present can be used in the future to gain insights into ice flow dynamics.

1 Introduction

Glacier ice flows by deformation and sliding in response to gravitational forces. As a glacier moves, internal pressure gradients and stresses create visible surface features such as glacial ogives, crevasses and medial moraines (Cuffey and Paterson, 2010). Furthermore, the surface of glaciers is also shaped by local weather conditions, which are responsible for the snow accumulation and ablation. Related processes generate distinct morphologies such as supra-glacial streams, ponds and lakes.

Glacier surface features evolve continuously, and these changes provide insights into the structure, internal dynamics and mass balance of the glacier. Important efforts have been made to monitor glacier surfaces, from early stakes measurements at the end of the 19th century (Chen and Funk, 1990) to present-day in-situ topographic surveys (Ramirez et al, 2001; Aizen et al, 2006; Dunse et al, 2012; Benoit et al, 2015) and remotely sensed data acquired from diverse platforms: ground-based devices (Gabbud et al, 2015; Piermattei at al, 2015), aircrafts (Baltsavias et al, 2001; Mertes et al, 2017) or satellites (Herman et al, 2011; Kääb et al, 2012; Dehecq et al, 2015; Berthier et al, 2016). Recently, the development of Unmanned Aerial Vehicles

(UAVs) has enabled glaciologists to carry out their own aerial surveys autonomously, rapidly, and at reasonable costs (Whitehead et al, 2013; Immerzeel et al, 2014; Bhardwaj et al, 2016; Jouvet et al, 2017; Rossini et al, 2018). This technology is particularly attractive to map alpine glaciers whose limited size allows a satisfying coverage at a centimeter to decimeter spatial resolution.

5 Here we provide a homogenized and high-resolution remote sensing dataset encompassing the ablation zone of the Gornergletscher glacial system (Valais, Switzerland, Fig 1). The raw images have been acquired by UAV flights carried out approximately every two weeks during the summer 2017 (from May 29 to October 30) and covering around 10 km^2. The dataset is made of 10 consecutive ortho-mosaics and Digital Elevation Models (DEMs) of the area of interest at a 10 cm resolution. It is therefore one of the most exhaustive surveys of the surface of a temperate glacier currently available. 10 Geometrical coherence of the dataset is ensured through the application of a comprehensive photogrammetric processing (i.e. images are ortho-rectified and properly scaled). In addition, the orthomosaics are stackable thanks to a co-registration procedure. The dataset can therefore be seen as a high resolution time-lapse of the Gornergletscher ablation zone, combining spectral (orthomosaics) and geometrical-3D (DEMs) information on the glacier surface. In addition to orthomosaics and DEMs that are snapshots of the area of interest, we also provide a product that we call Matching Maps (MMs) to achieve a temporal 15 monitoring of the glacier. In practice, a Matching Map associates to each pixel of an orthomosaic (respectively a DEM) its counterpart in the next orthomosaic recorded two weeks later. MMs can then be used to track the flow of ice over time, and in turn to quantify ice surface displacements and velocities.

Potential uses of this dataset are numerous. Single orthomosaics and DEMs can be used to map the surface of the glacier and to extract features of interest such as the surface drainage network (Yang and Smith, 2012; Rippin et al, 2015), debris or snow 20 cover (Racoviteanu and Williams, 2012). Alternatively, the complete time series of orthomosaics and DEMs can be used for detection and quantification of changes at the surface of the glacier (Barrand et al, 2009; Fugazza et al, 2018). Finally, the time-lapse coupled with the Matching Maps is an interesting tool to monitor ice surface velocity and deformation (Ryan et al, 2015; Kraaijenbrink et al, 2016), and in turn ice flow dynamics at the glacier surface. The Matching Maps provide a quantification of the ice velocity at every location on the surface of the glacier, which can be used to calibrate or to validate 25 ice flow models, especially for the Gornergletscher which was extensively used as a modeling benchmark (see for instance (Werder and Funk, 2009; Riesen et al, 2010; Sugiyama et al, 2010; Werder et al, 2013)).

2 Data acquisition

2.1 Study site

The Gornergletscher is located in the Valais Alps in southern Switzerland (Fig 1a). It is part of a glacier system involving five 30 tributaries and ranges from 2200 m to 4634 m a.s.l. (Fig 1b). The ablation area, which is the main focus of this study, is a 4km

long and relatively flat ice tongue (slope around 6%) that is deeply incised by meltwater channels and partially debris covered (Fig 1c). This ablation area is preceded by a steeper part (south-west of the Monte Rosa Hütte, Fig 1c) characterized by the presence of numerous crevasses. The entire Gornergletscher system (i.e. the terminal tongue and its five tributaries) covers an area of almost 50 km² and its mainstream is 12 km long, making it one of the largest European glaciers (Sugiyama et al, 2010).

The Gornergletscher system has been widely studied since the 1970s due to its significant size, its relatively easy access, and because a glacier-dammed lake often threatened the downstream Matter valley with glacier outburst floods (Sugiyama et al, 2010; Werder et al, 2009; Werder et al, 2013). The long history of glaciological studies in this area has shown that the mass balance of the Gornergletscher system was stable from the 1930s to the early 1980s, and significantly dropped since then (Huss

10   et al, 2012). This can be associated with the rise of its Equilibrium Line Altitude (ELA) due to a warming of the local average yearly temperature. The ELA stands nowadays around 3300m according to studies carried out at the neighboring Findelgletscher (Sold et al, 2016).

In this context, the current dataset aims at complementing the past studies about the Gornergletscher system by documenting

15   the behavior of its ablation zone during an entire summer, at a time when this glacial system is thought to be out of equilibrium with a clear trend toward glacial retreat. Specifically, this dataset focuses on the monitoring of the glacier surface at high spatial and temporal resolution.
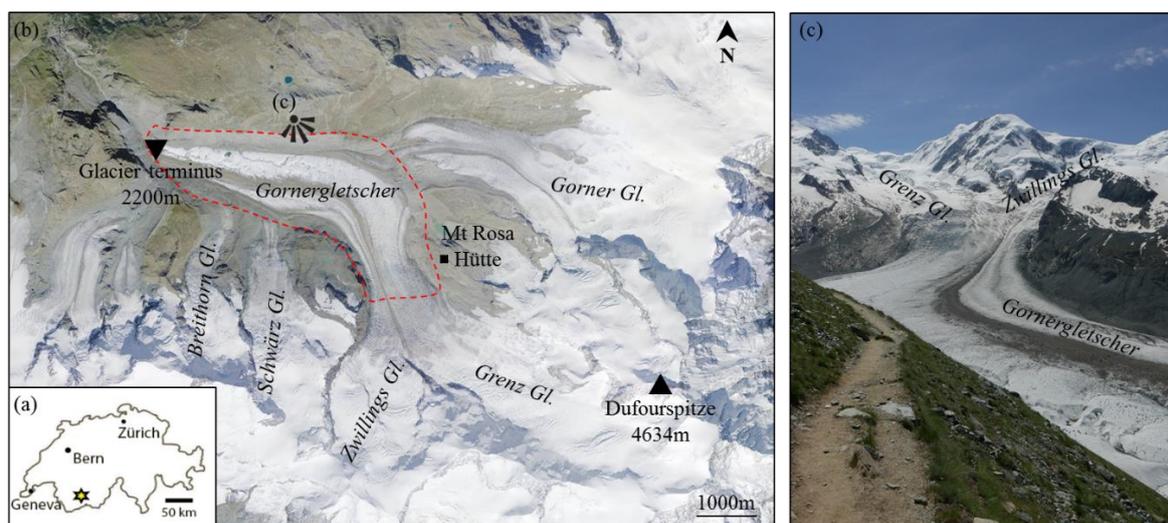
Figure 1: The Gornergletscher system. (a) Situation map; (b) overview of the Gornergletcher system, dashed red line: area of

20   **interest; (c) picture of the glacier tongue.**

2.2 UAV surveys

The primary data are RGB images acquired by repeated UAV surveys over an area of 10 km². A fully autonomous fixed-wing UAV of type eBee from SenseFly, equipped with a 20 megapixels SenseFly S.O.D.A camera, has been used for image acquisition (Vallet et al, 2011). For flight planning and UAV piloting, the eMotion3 software was used.

Raw images were acquired with a ground resolution ranging from 7.3 cm to 8.8 cm for the glaciated parts of the area of interest. In addition, for the requirements of photogrammetric processing, flight plans have been designed to allow for an overlap between images ranging from 70% to 85% in the flight direction, and from 60% to 70% in the cross-flight direction. These specifications have led to flight altitudes ranging from 300 m to 600 m above ground. The flight time was limited to about 30

10 min in field conditions. Thus, the coverage of the full area of interest required 4 to 8 separate flights per session, i.e. each day of acquisition (Table 1). Overall, 10 sessions have been conducted in 2017, from May 29 to October 30. The main features of these flights are summarized in Table 1:

Date	Acquisition Time (CET)	# of flights	# of pictures
2017/05/29	14:00 – 16:00	4	749
2017/06/09	12:30 – 15:30	8	935
2017/06/21	11:30 – 13:30	7	930
2017/06/27	11:30 – 14:00	5	1059
2017/07/13	12:30 – 14:00	4	830
2017/07/26	13:00 – 16:00	6	1125
2017/08/15	12:30 – 16:00	7	1121
2017/10/04	12:00 – 15:30	7	1107
2017/10/18	13:00 – 15:00	4	846
2017/10/30	13:00 – 15:30	6	1084

15 **Table 1: UAV flights carried out for raw glacier image acquisition.**

3 Data processing

3.1 Generation of co-registered orthomosaics and DEMs

For each session, all pictures have been processed with the photogrammetric software pix4DMapper ((Vallet et al, 2011), Fig 2) using the processing template called '3Dmaps' which is designed for nadir image acquisitions, as is the case for the current

5 dataset. Within this template, the processing options have been kept at their default values, except for the resolution option that has been set to 10 cm/pixel in order to prescribe a constant resolution across all final products. During the photogrammetric processing, the raw pictures are first oriented by bundle adjustment, and then an ortho-rectified image (orthomosaic) and a Digital Elevation Model (DEM) are generated for each day of interest. The results are referenced in the WGS84 reference frame using the UTM_zone32 projection. The accuracy of this initial geo-referencing is limited to a few meters since the

10 positioning of the UAV used in the bundle adjustment derives from code-only GPS data.

To improve the coherence of the co-referencing of the different sessions, all products are co-registered to the reference of the June 9 acquisition (Fig 2). To this end, the coordinates of several stable points of the landscape (16 to 70 among a set of 74, see Table 2 and Fig 4) are extracted from the bundle adjustment of June 9, and used as Ground Control Points (GCPs) for the

15 bundle adjustments of the other dates. These stable points are mostly salient features of the bedrock or erratic boulders on the deglaciated banks of the glacier. The co-registration leads to orthomosaics and DEMs that are stackable. Therefore, in the final products, the bedrock remains stable between consecutive dates, while the glaciated parts move and deform. Consequently, if a time-lapse is created from the co-registered products, the glacier appears to flow while the surrounding landscape remains static. Fig. 2 summarizes the acquisition and processing chain used to derive the final products of the dataset.
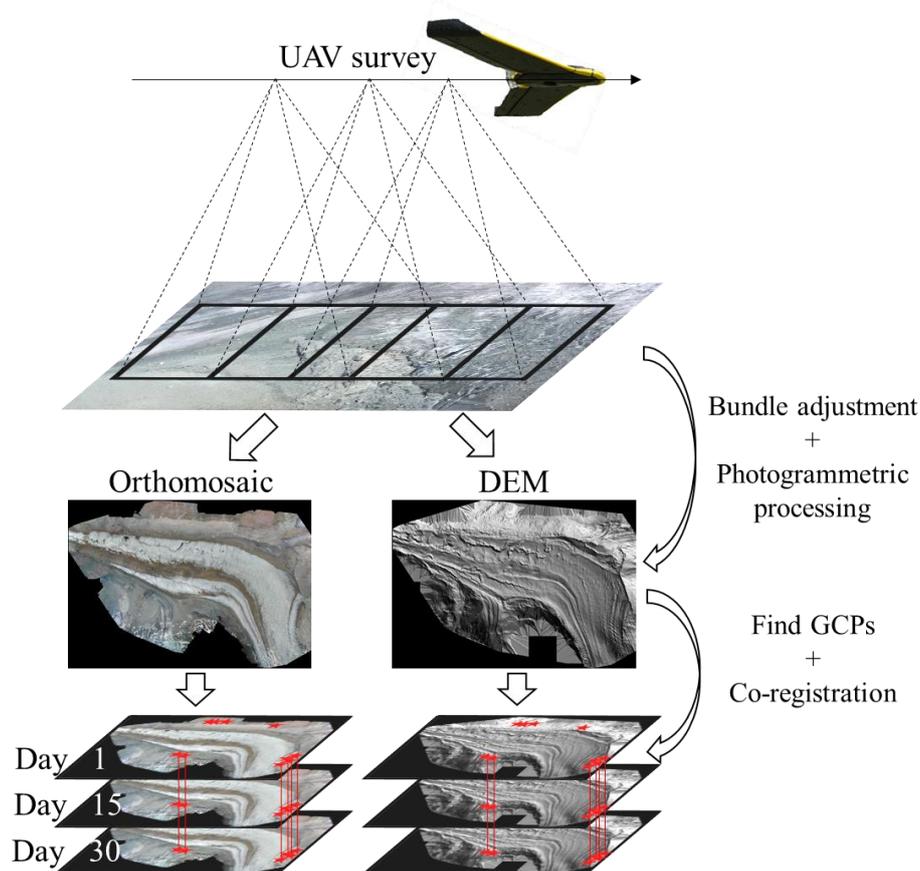
Figure 2: Acquisition and processing chain used to derive the co-registered orthomosaics and DEMs

3.2 Surface displacement tracking: generation of Matching Maps

Consecutive co-registered orthomosaics enable to quantify horizontal displacements at the surface of the glacier. In the present dataset, this information about ice surface displacements is provided by the Matching Maps (MMs, Fig 3). In practice, a MM is an image that pairs the positions of similar ice patches at times t and $t+dt$ (dt being the time span between consecutive acquisitions) (Fig 2). The footprint of the MM is the overlap of the footprints of the orthomosaics at times t and $t+dt$.

The MMs are obtained by image matching of pairs of orthomosaics. The orthomosaic at time t is taken as a reference, and a 51 x 51 pixels patch extracted from this image is searched for in the orthomosaic corresponding to the next session (day $t+dt$). To speed up the processing and avoid wrong matches with very distant patches, the homolog patch at day $t+dt$ is searched for in a neighborhood of 2000 x 2000 pixels centered on the position of the original patch at day t. The criterion used to evaluate the similarity between both patches is the mean absolute error (MAE) between pixels computed on grayscale images. The patch of the image $t+dt$ leading to the lowest MAE with the original patch at time t is then considered the counterpart of this

patch at time *t+dt*. Finally, the displacements (in pixels) between the two patches along the East-West and the North-South directions are recorded into the MM. This operation is repeated for all possible patches in the reference orthomosaic.

The raw MMs can be noisy due to the presence of outliers in the pattern matching procedure (yellow areas in the raw displacement maps in Fig 3). These outliers originate from the dissimilarity between subsequent orthomosaics, due to, for example, changing shadows or changes at the glacier surface (snowfall, snow or ice melting, etc.). To mitigate the impact of these outliers, we first locate them, then we mask the impacted areas, and finally we interpolate the remaining reliable displacements to fill the gaps generated by the mask. Unreliable areas in the raw MMs are assumed to be aggregates of pixels with spatially incoherent displacement values embedded in a matrix of displacements that vary smoothly in space (i.e. the reliable displacements). The borders of unreliable areas are detected as locations with strong spatial gradients, with a detection threshold set at 15 cm of horizontal deformation per day. A mask of reliability is then created by setting the areas with strong gradient to 0 and the remaining of the mask image to 1. The outlier areas (i.e. small aggregates of unreliable values) are then filtered out by applying the opening operator of mathematical morphology to this mask with a structuring element of size 50 x 50 pixels. This operation leads to switch the value of the mask from 1 to 0 for all aggregates of pixels smaller than 50 x 50 pixels. Hence, we obtain a mask with 1 at locations with reliable displacements and 0 where the measured displacements are considered as outliers. Finally, the values of the MM at masked locations are interpolated from the reliable measurements. The selected procedure is iterative. At each iteration, it attributes to the masked values the mean of the reliable values in a 500 pixel neighborhood in the East-West and North-South directions. The values that remain masked after 10 iterations are considered as too far from the informed areas to be filled and are set to -99 to denote no data. Fig. 3 summarizes how MMs are derived from pairs of consecutive co-registered orthomosaics and filtered to remove outliers.
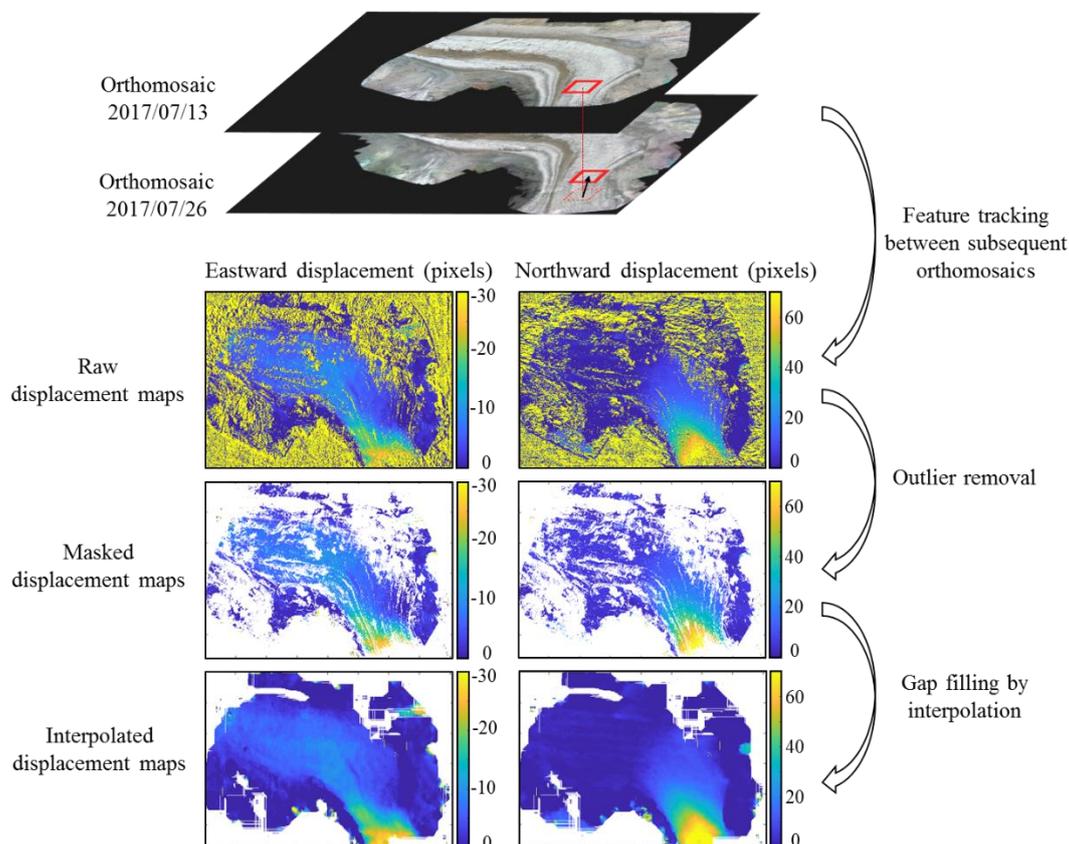
Figure 3: Processing chain used to compute a matching map between two subsequent orthomosaics. The procedure is illustrated for the 2017/07/13 – 2017/07/26 period.

4 Quality assessment

5 ### 4.1 Bundle adjustment and co-registration

A primary validation of this dataset consists in checking the relative orientation of the cameras during the bundle adjustment, as well as the co-registration of orthomosaics and DEMs. Processing reports detailing the quality of the bundle adjustment for each session are available along with the dataset (see Sect. 5.1).

10 Table 2 displays three indices summarizing the quality of both bundle adjustment steps. First, the mean reprojection error (in pixels) quantifies the mismatch in the raw images between the observed and the modelled position of tie points used during the relative orientation step. The sub-pixel level of errors (Table 2, column 2) ensures that the orientations of the camera are reliable. Next, the co-registration step is assessed by the mean Root-Mean-Square (RMS) error of GCP coordinates. This statistic measures the stability of GCP coordinates between different bundle adjustments. Under ideal conditions, the value of

the mean RMS error on GCPs should be close to the ground pixel resolution of the raw images (i.e. 7.3 cm to 8.8 cm) because an operator is able to identify points of interest with a pixel level precision. The slightly higher values obtained in the present case (9 cm to 21 cm, Table 2, column 3) are due to the difficulty of precisely identifying GCPs under changing environmental conditions (e.g. sunlight exposition or snow cover). The errors in GCP identification degrade the mean RMS error, but they

5   are expected to have a mild impact on the co-registration itself because they are not correlated and tend to compensate each other. Note that late in the season (i.e. for the last acquisition on October 30th) it became difficult to identify GCPs due to strong shadows, hence the small number of GCPs at that time.

date	Relative orientation: mean reprojection error (pix)	Co-registration: Mean RMS error (m)	Co-registration: # GCPs
2017/05/29	0.138	0.210	66
2017/06/09	0.136	Reference	Reference
2017/06/21	0.123	0.189	66
2017/06/27	0.146	0.193	68
2017/07/13	0.120	0.107	63
2017/07/26	0.117	0.206	70
2017/08/15	0.118	0.175	69
2017/10/04	0.125	0.122	38
2017/10/18	0.127	0.146	43
2017/10/30	0.125	0.092	16

Table 2: Quality assessment of the bundle adjustment procedure.

10   **4.2 Orthomosaics and DEMs**

In addition to the bundle adjustment, we also validate the final products of the photogrammetric processing (Fig 4a), i.e. the co-registered ortho-mosaics and DEMs. To this end, individual orthomosaics and DEMs have first been visually checked to track the presence of artifacts. A careful examination of all products shows that the glaciated parts (Fig 4b) as well as the neighboring ice-free areas (Fig 4c) are well reconstructed in both orthomosaics and DEMs. It is found that edges of the area

15   of interest can present artifacts due to the low number of overlapping images in these areas (see the processing reports to identify them). This leads to unreliable photogrammetric reconstructions and in particular shear lines (Fig 4d). Despite these relatively minor artifacts restricted to the edges of the surveyed area, the whole glaciated parts and their near margins are satisfyingly reconstructed in both orthomosaics and DEMs.
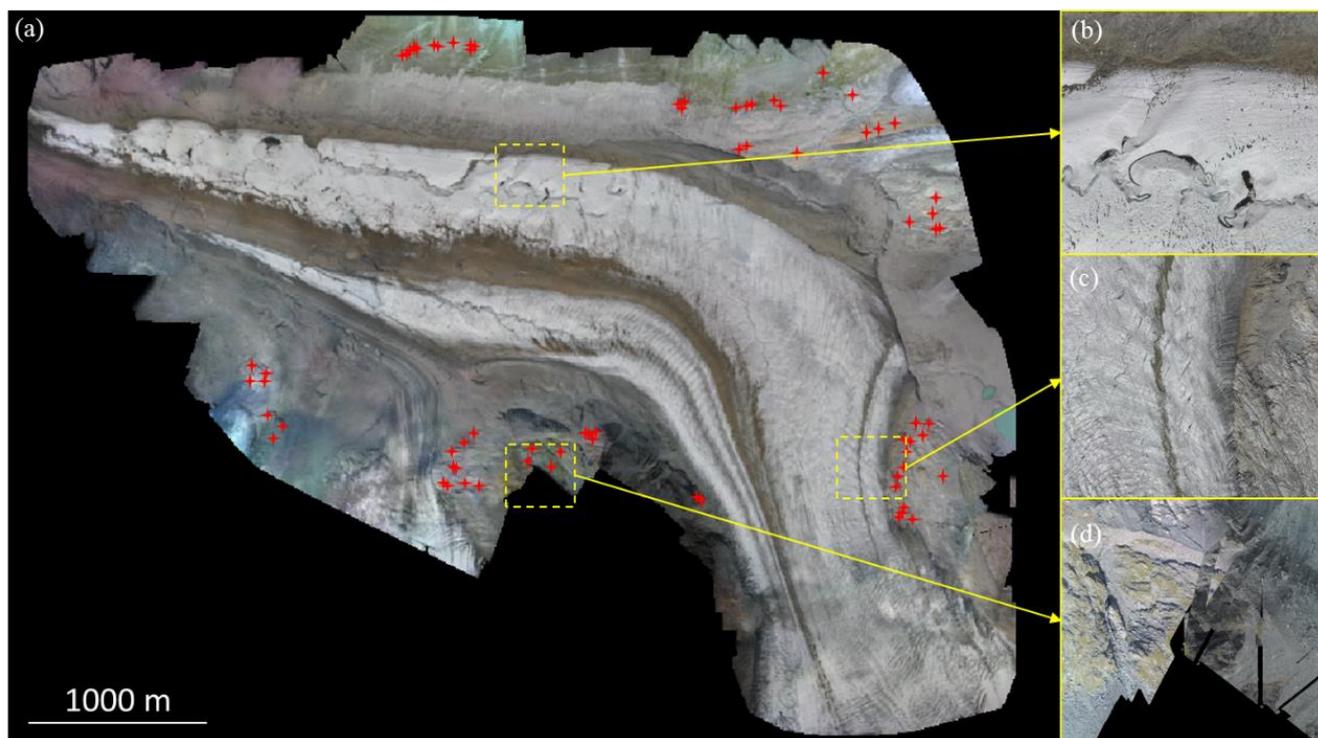
Figure 4: Quality assessment of the orthomosaics. (a) Overview of one orthomosaic (2017/08/15). Red stars: GCPs used for co-registration. (b) - (c): Examples of areas where the photogrammetric processing worked properly. (d): Example of area on the boundary of the domain where the photogrammetric processing produced artifacts (mostly shear lines).

4.3 Matching Maps

In addition to the visual inspection of individual photogrammetric products, we also assess the quality of the co-registration procedure by quantifying in the MMs the stability of several areas that are most likely static, as well as the observed spatial patterns of glacier surface velocity. To this end, we select several validation locations on the glacier and aside (Fig 5) and we compute their horizontal velocity by dividing the displacements recorded in the MMs by the time elapsed between the

10 acquisitions. Note that in Fig. 5 the velocity is averaged over 10 x 10 m^2 areas, corresponding to 10000 single measurement points, centered on the validation points in order to smooth out the local variability of the signal.
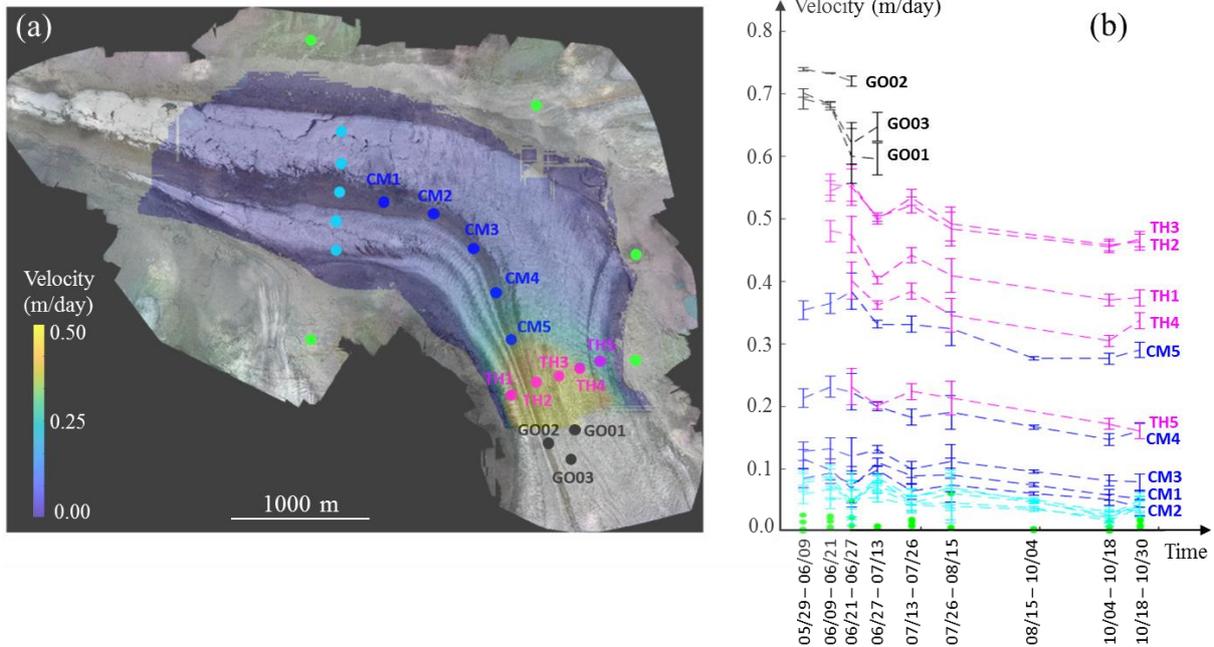
Figure 5: Quality assessment of the Matching Maps. (a) Locations of the validation points. The background colors represent the horizontal surface velocity derived from the MM related to the period 07/13 – 07/26. (b) Observed horizontal surface velocities at validation locations. Error bars show 1σ errors. The errors reported for UAV-based velocities are empirical errors and are equal to the quadratic mean of velocities recorded at ice-free locations (green dots in (b)). The errors reported for GNSS-based velocities (i.e. at locations GO01, GO02 and GO03) are theoretical errors accounting for the uncertainty introduced by the tilt of the support of GNSS receivers over time.

Fig. 5b displays the observed horizontal velocity in the domain for summer 2017. In case of perfect photogrammetric processing, co-registration, and feature tracking, the apparent velocity of the ice-free areas (in green on Fig 5) should be zero. While it is not exactly the case due to inherent processing errors and measurement noise, the mean velocity is very low (1.2 cm/day on average over the 5 ice-free validation locations) which reflects an appropriate processing since the area of interest is moving a factor 5 to 50 faster. The observed patterns of glacier surface velocity are also in accordance with a higher velocity at the center of the glacier than on the edges (compare e.g. the velocity in TH3 and TH5), and a higher velocity at steep parts of Grenzgletscher than on the flat tongue of Gornergletscher (compare e.g. TH2 and CM5 to CM1). Finally, the velocities derived from UAV compare well with independent data collected by differential GNSS measurements a few hundred meters upstream of the area of interest (points GO01, GO02 and GO03 in Fig 5). The higher velocity measured at the locations monitored by GNSS (points GO01-G003) compared to the neighboring locations monitored by UAV (points TH1-Th3) is coherent with the increase of glacier velocity at the steeper upstream part of Grentzgletscher (approx. 13.5 % at GO02 compared to 7.5 % at TH2). Finally, the trend of deceleration over the course of the summer recorded by GNSS is in good agreement with the UAV-based velocities throughout the glacier.

5 Data and code availability

5.1 Structure and availability of the dataset

All the data presented in this dataset are available in the following repository (Rep): https://zenodo.org/record/1487862, with

5   the following DOI: https://doi.org/10.5281/zenodo.1487862 (Benoit et al, 2018).

The results of the photogrammetric processing, i.e. the orthomosaics and the DEMs, are available in the compressed folder Rep\Photogrammetric_Products.zip. Within this folder, the products are grouped in sub-folders by acquisition date using the following standard: 2017_mm_dd with mm the month and dd the day of acquisition. Finally, these sub-folders contain the

10   following files:

- 2017_mm_dd_orthomosaic.tiff: Contains the orthomosaic.

- 2017_mm_dd_dem.tiff: Contains the DEM.

- 2017_mm_dd_report.pdf: Contains the processing report (generated by Pix4D Mapper) that summarizes the quality of the photogrammetric processing for the date of interest.

The Matching Maps are stored in the compressed folder Rep\Matching_Maps.zip. Within this folder, the individual maps are grouped in sub-folders named according to the acquisition date of the pair of subsequent orthomosaics used to generate the Matching Map: 2017_mm_dd_2017_nn_ee with mm (resp. dd) and nn (resp. ee) the acquisition months (resp. days). These sub-folders contain the following files:

20   - 2017_mm_dd_2017_nn_ee_disp_Eastward: Contains the Matching Map of Eastward displacements.

- 2017_mm_dd_2017_nn_ee_disp_Northward: Contains the Matching Map of Northward displacements.

- 2017_mm_dd_2017_nn_ee__disp_mask: Contains the mask of reliable displacements after filtering: 1 if the location corresponds to a reliable displacement, 0 otherwise.

5.2 Code availability

25   The photogrammetric processing has been carried out using the proprietary software Pix4D Mapper, commercially available at: https://pix4d.com/ (last access 2018/11/16).

The Matching Maps have been computed using Matlab routines written by Mathieu Gravey. The related utilities are freely available on the following repository: https://github.com/GAIA-UNIL/MatchingMapMaker.

6 Conclusion

The present dataset compiles ten UAV surveys of the Gornergletscher carried out during summer 2017. A careful photogrammetric processing leads to a set of 10 cm resolution orthomosaics, DEMs and glacier displacement maps for each acquisition date. This dataset can be used for almost any glacier mapping task, and in particular to investigate glacier surface
5   dynamics at high temporal and spatial resolution.

Author contributions

AG, FH and GM designed the experiment.

AG, RV, II, BL, GP and LB carried out the acquisitions.

AG, RV and LB performed the photogrammetric processing.

10 MG, LB and AG computed the Matching maps.

DG recorded differential GNSS data used for validation.

LB wrote the manuscript with inputs from all authors.

Competing interests

The authors declare no competing interests.

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