MULTI-TEMPORAL AND MULTI-SENSOR GLACIER MONITORING

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ABSTRACT:

Glaciers are subject to drastic mass loss in the last decades and their importance as an environmental and hydrological resource requires regular monitoring. Geomatics techniques are the ideal tool to survey these complex and remote areas, with different remote sensing platforms and sensors to choose from depending on the scale and accuracy to be monitored.
In this case study, the Broulè glacier (Valpelline, Aosta Valley, Italy) was monitored for several years using a DJI Phantom 4 RTK UAV, an airborne PhaseOne camera, and a very high-resolution images Pléiades satellite stereo pair to estimate the glacier's melting and to investigate the possibility of carrying out monitoring campaigns limiting in-situ surveys. A comparison of the 3D models and cartographic products obtained from the different sensors made it possible to estimate the accuracies achievable and check them on rocky areas around the glacier considered to be invariant over time. Although the orography of the area and the poor accessibility did not allow a balanced distribution of Ground Control Points (GCPs) and Check Points (CPs), the RMSE in the photogrammetric models was a few centimetres. An altimetric comparison between the photogrammetric DSMs allowed us to estimate the error at -1.6 m, which is strongly influenced by the altimetry of the terrain.
Therefore, although it is impossible to rely solely on satellite imagery for a centimetric survey, it seems possible to continue the multi-temporal monitoring over the years using remote sensing (aerial and satellite) with a previous good cartographic base supported by good field campaigns.

1. INTRODUCTION

Glaciers are often seen as 'sentinels' of climate change and European mountains are considered ‘water towers’. These masses of ice cover up to 10% of the Earth's surface (Bednar-Friedl B., 2022) are the habitat of a variety of fragile ecosystems, and represent one of the most important components of terrestrial water storage.

Under different pathways, current projections show the likelihood of an increase of 1.5°C above pre-industrial levels that is already strongly modify the glacier’s environment. The impact on mountain regions will be severe, both for people and the environment, and implies the need for surveying and monitoring (Viviroli, 2011). The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) reinforces the consequences for people and ecosystems. Reduced snowfall and shorter snow cover will not reverse the strong summer ablation, especially at lower altitudes, leading to a reduction of glacier mass at lower altitudes and a significant reduction of glaciers at higher altitudes.

Environmental monitoring with remote sensing techniques has been done with different goals, risk monitoring (Buill, 2016), detecting geomorphological changes (Błaszczyk, M, 2022), and coastal change monitoring (Mills J., 2005). The glacier environment is mainly monitored with UAV (Belloni et al, 2022) and satellite stereo pairs (Paul F., 2007; Giulio Tonolo F., 2020).

Moreover, different techniques, aerial and terrestrial are often integrated to perform high-resolution multitemporal analysis.
Although the use of airplanes or helicopters for surveying is expensive, UAVs and on-site measurement campaigns often force the use of numerous resources and movement through risky terrain.

The aim of this paper is to compare the different methods used to monitor a mountain and a fairly inaccessible environment and to highlight the difference in the accuracies achievable and their limitations.

2. CASE STUDY

Valpelline is a long valley that stretches from Aosta to Switzerland, located in the north-western part of Italy, in the Aosta Valley region. The Valpelline is a valley that is still little explored and little affected by tourism. The valley is crossed by the Buthier stream, which acts as a basin for the meltwater from the surrounding glaciers and flows into the Place Moulin artificial dam, the most important hydropower plant in the region.

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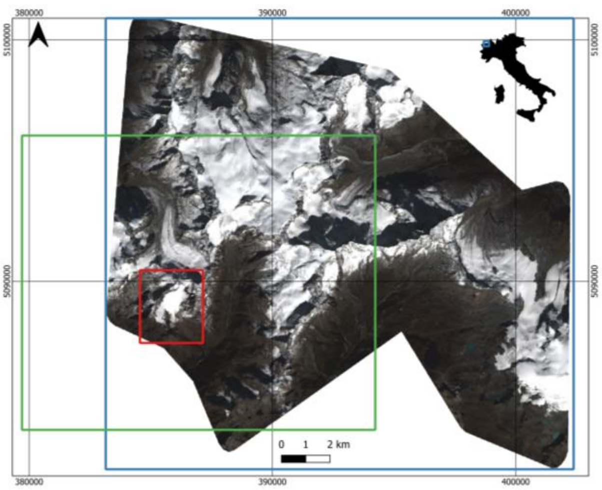

Figure 1. Satellite Pléiades © CNES 2022 and AIRBUS DS (blue), aircraft (green), drone (red) footprints over Broulè glacier on the satellite orthophoto. Coordinate System: ETRF2000 UTM32N

In Valpelline the glacier examined is the Mont Broulè glacier (Figure 1). The mount Broulè reaches 3538 m asl under the Pennine Alps in Valpelline, along the Italian-Swiss border. The small glacier can only be reached by helicopter or on foot via a steep path from the Place Mulin dam (1969 m asl).
It is also called Mont Brulè, a name that seems to derive from "braulé" or "Breuil", terms of Celtic origin meaning marshy plain.

The orography of the Valpelline, with narrow valleys and high peaks, makes the area very inaccessible, with few mountain refuges, and surveying in these areas is inconvenient and very difficult. For these reasons, surveys in mountainous areas generally rely on remote sensing, particularly satellite and airborne.
In the case study, photogrammetric measurements were carried out at the following scales:

- single glacier (Mont Broulè with an extension of about 2 km^2) with UAV and centimeter resolution;
- entire basin (about 20 km^2) with aerial photogrammetry and decimetric resolution;
- valley and surrounding areas (about 40 km^2) with satellite photogrammetry and sub-metric resolution.

The multiresolution analysis will therefore be performed only on the Mont Broulè glacier where all different datasets are available.

3. MATERIALS AND METHODS

3.1 Measurements Campaigns and GCP

Glacier monitoring starts with in situ measurement campaigns. In this case study two different campaigns were carried out: the first on the 29th and 30th of September 2020 around Valpelline, and, roughly one year later, the second on the 20th of October 2021 only on the Broulè glacier. The campaigns aimed to measure some points in the surveyed area, and place 1 m x 1 m yellow geolocalised markers measured with GNSS (Global Navigation Satellite System) RTK (Real Time Kinematic) and centimetric accuracy. During both UAV campaigns DJI Phantom 4 RTK drone surveys were carried out over the Broulè glacier area. On these occasions, some Ground Control Points (GCPs) were measured on cartographic points (e.g. well-recognizable natural points, rock edges) or by placing and measuring different sizes of sheet markers on the ground. Only the 1 m x 1 m yellow geolocalised markers were fixed on the ground to use in the following years' surveys.

3.2 Aerial and UAV flights

In July 2020, a photogrammetric flight by Digisky company has been made over Valpelline Valley within the activities of the Glacier Lab of the DIATI, Politecnico di Torino. The onboard PhaseOne camera model is the iXM-RS150F with 151.3 MP resolution, placed under the aircraft wing; the aircraft is also equipped with a GNSS (Global Navigation Satellite System) antenna and an IMU (Inertial Measurement Unit) of low accuracy. Unfortunately, the GNSS antenna and the camera shots are not synchronized, so the position of the cameras at the time of the shot is not acquired. In October 2022, in collaboration with ARPA Valle d’Aosta a second flight with the same camera was carried out in the Valpelline Area, again flying over the Mont Broulè glacier.

At the end of the 2019/2020 and 2020/2021 hydrological years, (October 2020 and 2021 respectively), two measurement campaigns were carried out on the glacier and the surveys with the DJI Phantom 4 RTK drone were performed, with a FC6310R camera equipped with 1" CMOS camera equipped with 20 MP sensor. The hydrological necessity of monitoring melting required the installation of hydrometers at the front of the glacier.

3.3 Satellite imagery

A very high-resolution stereo pair acquired on 21st September 2017 (Pléiades © CNES 2022 and AIRBUS DS) at 10:41:08.6 UTC with 0.7 m GSD resampled by the data provider at 0.5 m covering an area of around 245 km^2 between the Italian and Swiss border was also considered in the dataset. The Pléiades imagery acquired in Near Infrared (NIR) and visible spectral bands has a spatial resolution of 0.7 m for the panchromatic and 2.8 m for the multispectral spectral bands.
A summary of the characteristics of all the imagery acquisitions is reported in Table 1.

	Date	Average flight height agl (above ground level)	GSD [m]
Satellite Plèiades	22/09/2017	698 km	0.5
Aerial Digisky flight	09/07/2020	800-1000m	0.09
UAV DJI PH4 RTK flights	30/10/2020	80-120m	0.04
UAV DJI PH4 RTK flights	20/10/2021	80-120m	0.04
Aerial Digisky flight	03/10/2022	800-1000m	0.09

Table 1. Surveys over Broulè glacier

3.4 Data processing

3.4.1 Photogrammetric images: Both the aircraft and drone images acquired were processed as a photogrammetric block through AgiSoft Metashape Professional v 1.8.3.

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Aerial photogrammetry follows the same steps both for drone and aircraft images. The images were imported and aligned and georeferenced matching the markers in the images with the relevant 3D coordinates measured during the campaign. For all the models the coordinate reference system used is ETRF2000 UTM 32 N (EPSG: 6707).

From the sparse point cloud is generated the dense cloud, the drone ones, 405.054.228 and 170.350.995 points, for 2020 and 2021, respectively, and 956.804.204 and 1.118.954.341 points for 2020 and 2022 aerial photogrammetric flight, respectively. DSMs and medium-resolution orthophotos were generated from the dense clouds.

The drone has an onboard GNSS RTK system and an IMU active during image acquisition, which allows the position of the cameras to be georeferenced in real time with centimetric accuracy during the survey. The acquisition is in ellipsoidal height, so the camera coordinates datum is converted to orthometric height with the Italian ConveRgo software and VERTO approach (CICIS).

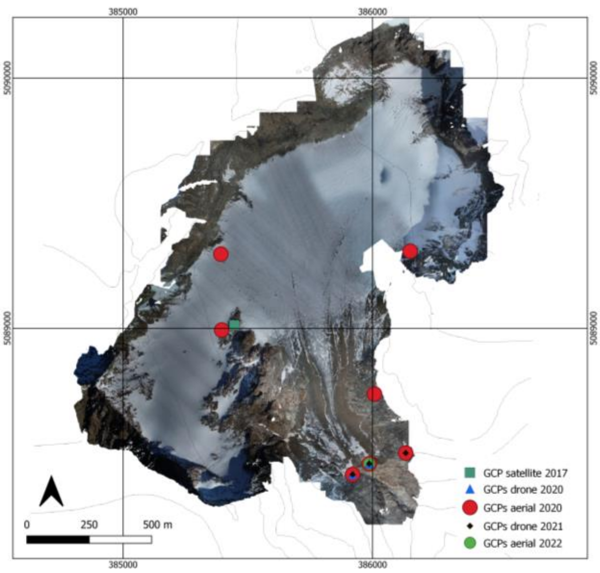

Figure 2. GCPs on drone 2021 orthophoto Broulè glacier with contour lines GSD = 0.04 m; Coordinate System: ETRF2000 UTM32N

3.4.2 Satellite imagery: The satellite stereo pair were processed with OrthoEngine Geomatica Banff 2019 edition with RFM, Rational Function models (or RPC, Rational Polynomial coefficients). The images are pan-sharpened to obtain a very high-resolution image combining the multispectral low-resolution image and the panchromatic one. For satellite imageries, different configurations were tested with a variable number of automatically extracted GCPs both with an aerial orthophoto base and without any support (Eisank, 2015). From the comparison of residual errors and validation with previous products, it was decided to continue with a single collimated GCP manually, due to the difficulty of automatic matching points.

After the model calculation, the epipolar images were generated to proceed with the DSM extraction. In the end, from the DSM using the math model the images are orthorectified to generate the two orthophotos.

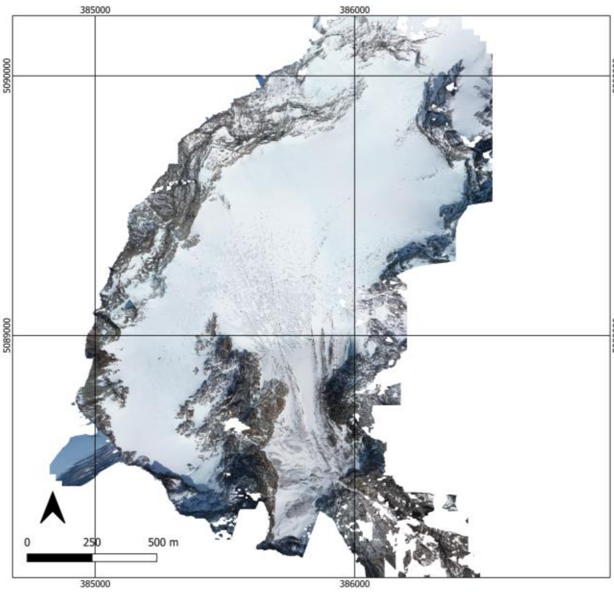

Figure 3. Drone 2020 orthophoto Broulè glacier GSD = 0.05 m; Coordinate System: ETRF2000 UTM32N

4. RESULTS

4.1 Cartographic products

The cartographic products extracted are orthophotos and DSMs (Digital Surface Models).

From the Pléiades stereo pair are obtained 2 orthophotos with 0.5 m of resolution and 1 DSM with 0.5 m of resolution covering an area of 245 km^2; from the aerial flight 2020 images are obtained 1 orthophoto with 0.09 m of resolution and 1 DSM with 0.37 m of resolution covering an area of 88.3 km^2. From the UAV 2020 are obtained 1 orthophoto with 0.05 m of resolution (Fig. 3) and 1 DSM with 0.09 m of resolution covering an area of 4.3 km^2; from the UAV 2021 are obtained 1 orthophoto with 0.04 m of resolution and 1 DSM with 0.15 m of resolution covering an area of 4.1 km^2. Finally, from the aerial flight 2022 images are obtained 1 orthophoto with 0.08 m of resolution and 1 DSM with 0.38 m of resolution covering an area of 78 km^2;

A summary of the resolution of all the models is reported in Table 2.

	GSD Orthophoto[m]	GSD DSM [m]
Satellite Plèiades constellation 2017	0.50	0.50
Aerial Digisky flight 2020	0.09	0.37
UAV DJI PH4 RTK flights 2020	0.05	0.09
UAV DJI PH4 RTK flights 2021	0.04	0.15
Aerial Digisky flight 2022	0.08	0.38

Table 2. GSD of cartographic products

4.1.1 Residual errors GCPs comparison: Due to the different geometric resolutions, 3D models derived from the UAV, airbone and satellite platforms show different accuracies, both planar and vertical.

A summary of the GCPs RMSE of all the models is reported in Table 3 and shown in Figure 2.

	N. GCP	Tot RMSE [m]
Satellite Plèiades constellation 2017	1	/
Aerial Digisky flight 2020	18	0.07
UAV DJI PH4 RTK flights 2020	2	0.05
UAV DJI PH4 RTK flights 2021	3	0.05
Aerial Digisky flight 2022	14	0.36

Table 3. N. GCPs and total RMSE

For the drone models are also reported in Table 4 the average camera location error estimated.

	Tot RMSE [m]
UAV DJI PH4 RTK flights 2020	0.04
UAV DJI PH4 RTK flights 2021	0.02

Table 4. Average camera locations error

Although the number of GCP of the aircraft flight models is discrete, their layout is poorly distributed over the entire overflown territory, planarly but especially altimetrically, on the area covered outside the Broulè glacier. The orography of the territory, in fact, has considerable elevation changes between valleys and peaks, areas that are mostly inaccessible for the materialization of GCPs. In the glacier considered the models have only one GCP in the central part.

Accuracies remain centimetric and always below the pixel.

4.2 DSM comparisons

To assess a multi-temporal analysis by using DoD – Difference of DSMs approach, in addition to 5 models elaborated, the 2008 Geoportale LIDAR dataset with 2 meters of spatial resolution has been considered (Aosta Vally Geoportale, official regional DSM coverage).

The evaluation of the DSMs allowed a comparison of the accuracy of the models on stable areas, generally rocky sectors, considered time independent and an assessment of glacial melting during the time period considered.

In QGIS v. 3.16.1, the ‘Raster calculator function’ is used to compare the models; they have been subtracted from the 2020 UAV model which is considered the most reliable due to both GCPs and RTK camera locations.

To assess the possibility of carrying out monitoring totally relying on satellite images and the accuracy, the only stable areas (reported as ‘zonal statistics’ in Fig. 4) next to the glacier and present in all models were evaluated.

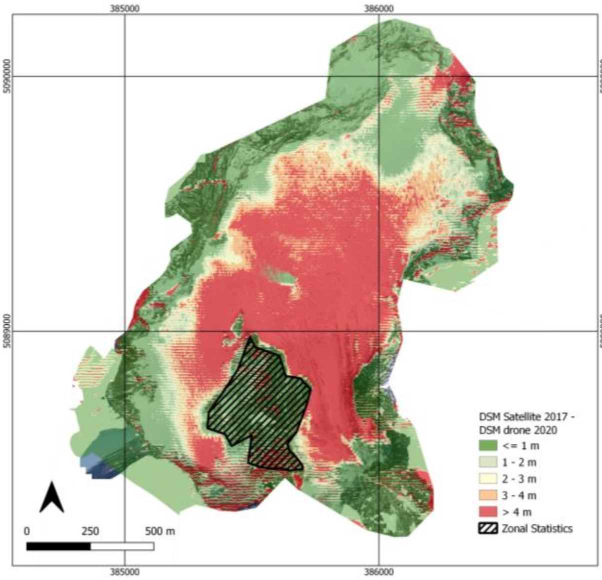

Figure 4. DSM Difference: Satellite 2017- Drone 2020 and area considered for zonal statistics overviewing the 2020 drone orthophoto; Coordinate System: ETRF2000 UTM32N

The 2017 DSM satellite was subtracted from the 2020 UAV DSM. In Figure 4 the red area enhanced the snow melting of the glacier between 2017 and 2020. The green area above 1 meter characterizes mainly the rocky areas around the glacier that remain at a constant high during the years.
To assess the reliability of the model obtained from satellite images the statistical parameters of mean and standard deviation between the differences were calculated and reported in Table 5.

	Mean [m]	Standard deviation [m]
DSM Difference: Pleiades satellite 2017- UAV DJI PH4 RTK 2020	-1.61	2.0

Table 5. Zonal statistics in a stable area

The average height difference between the two models is -1.6 m, and shows a standard deviation between the two DSMs of around 2 meters.

5. DISCUSSION

The different sensors enhance the limitations and difficulties of the survey in a glacier environment. Although an increase in support points is desirable, especially for aircraft models, the accuracy achieved is such that they can be compared.

The accuracy of the models is highly dependent on the orography and slope of the area, especially by sudden changes in altitude. While there is an agreement between the different models in flat areas, the error increases as the slope increases and is highly dependent on the ground surface.

It is also important to note that, as this is a high mountain area, even the rocky areas, which are supposed to be time-invariant, may have undergone partial changes due to landslides and instabilities.

The choice was made to compare the reference model with the satellite model because the use of satellite images would allow the possibility of limiting or avoiding complex field work. For the estimation of annual glacier mass balances, the accuracy obtained from single point satellite imagery is sufficient, whereas appropriately supported photogrammetric flights are needed to support hydrological activities.

The three reported cross sections (Figure 5) show qualitatively the agreement of the models on the stable areas and the glacier area changes (ice melted and mass transferred) between 2008 and 2022. The lower central part of the glacier had lost around 50 meters of thickness and around 20 in the upper part.

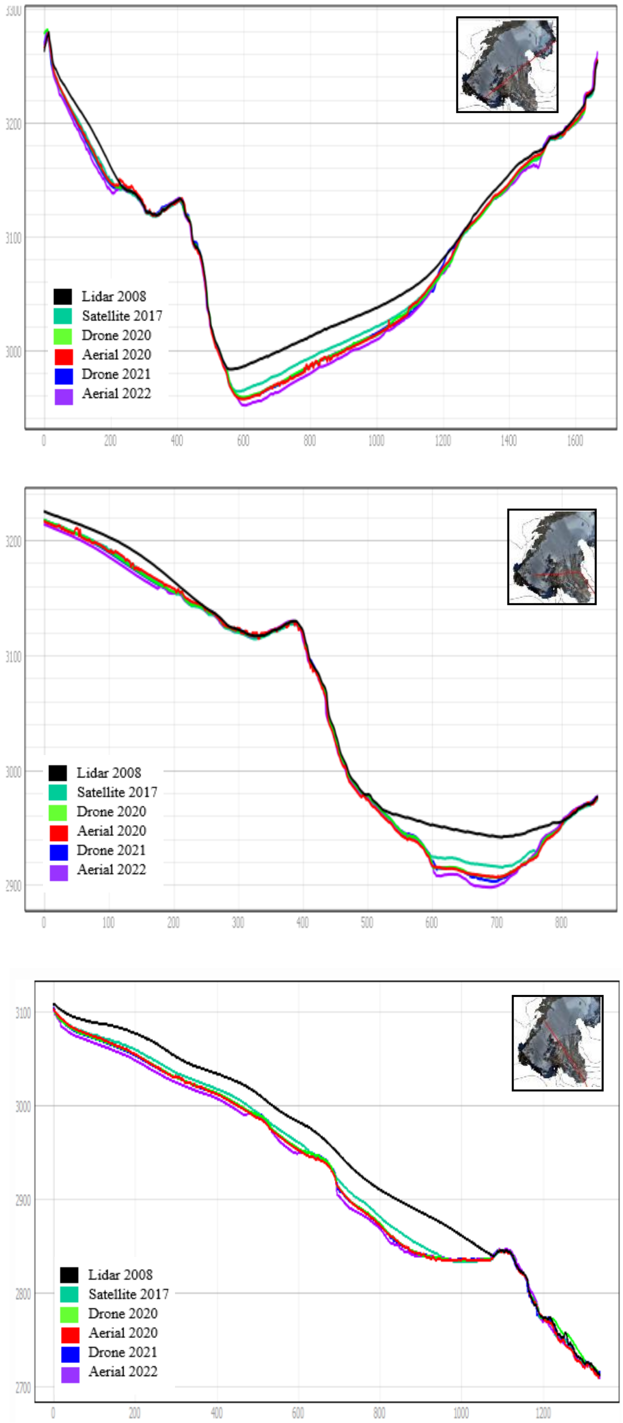

Figure 5. Cross sections on the glacier area, three examples on both rocky areas and snow

From the DSMs produced with different techniques, it is possible to evaluate the melting volumes of the Mont Boulè glacier. Different periods are compared here starting from the DSMs generated, as described above, over the years:

- 2008 (DSM Region VdA)
- 2017 (DSM Satellite Pléiades)
- 2020 and 2021 (photogrammetric DSM from drone)

Table 6 shows the areas considered and the differences obtained in millions of m^3. the acceleration of the fusion processes is evident, especially in recent years.

Period (Years)	Area [km^2]	Melted volume [Mm^3]
2008-2020 (Fig. 7)	3.1616	6.8912
2017-2020 (Fig.4)	3.3641	2.5558
2020-2021(Fig.6)	3.5633	1.4365

Table 6. Melted volume on the Mont Broulè glacier

Finally, it is important to underline that the possibility of increasing GCPs and the use of CPs would allow for an increase in the accuracy of the model and a better evaluation of it. If in the UAV flights, we had geo-tagged images and measuring more CPs would have given us a more robust estimation of the accuracies, otherwise, for the aerial flight, the images were not geo-tagged. Although this is the aim, the layout of the points is heavily influenced by the inaccessibility of some areas. Increasing the GCP on photographic points is being considered, but it is not easy to identify natural points that are visible and stable over time. In addition, the unresolved problem with aerial images was the lack of image geotagging, so although we measured a lot of GCPs, they were not sufficient to deal with the large differences in elevation.

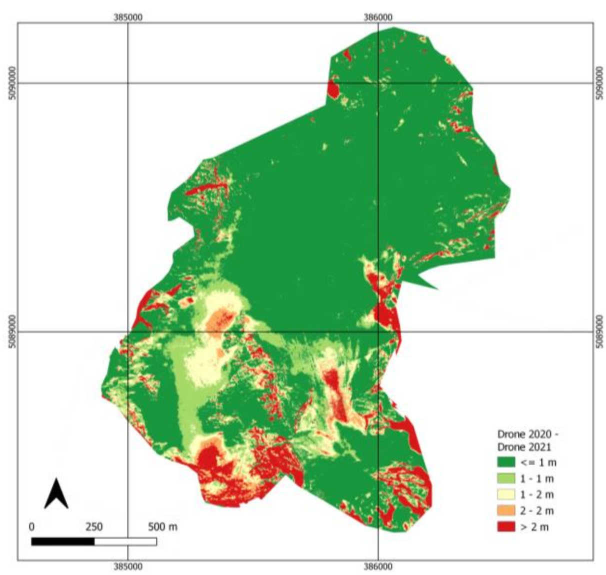

Figure 6. DSM Difference: Drone 2020 - Drone 2021
Coordinate System: ETRF2000 UTM32N

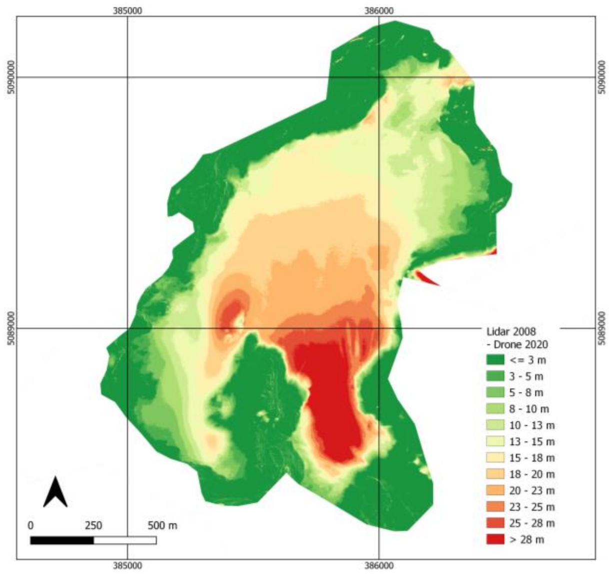

Figure 7. DSM Difference: Lidar 2008 - Drone 2021
Coordinate System: ETRF2000 UTM32N

6. CONCLUSIONS

In this work, the monitoring of the Broulè glacier is considered approaching three different sensors over several years.
The use of satellite imagery makes it possible to monitor a large area without costly and risky measurement campaigns. It is important to emphasize that these campaigns involved dozens of people, requiring several days of measurement each, and needed helicopters to be able to move equipment to areas otherwise difficult to reach. The use of aerial photogrammetry allows us to achieve centimetric resolutions, but both aircraft and UAVs require measurement campaigns, the former for the need to measure GNSS reference points and the latter for surveying. In these areas, the need for geotagging the images was evident because is not possible to set up a regular and adequate GCPs network. After all, this requires involving many people.

Moreover, given the results, those proposed are all valid options but, as far as satellite images are concerned, they give us outputs at resolutions of a few decimetres if not metric. In the case of scientific analyses or operational purposes requiring greater detail, centimetric results from aerial acquisitions can be exploited: in the case of the aircraft, they allow us to cover a vast area, but with high costs and a very large amount of data that could be difficult to manage. As for the drone, although it is probably the one that has given us the best results (in terms of accuracy and resolution), we have to consider its operational constraints: weather conditions (rain and wind), travel time to reach the take off area, flight and scenario limitations (distance and altitude take off point) and limited battery life due to cold temperatures.

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