Chapter

Close-Range Sensing of Alpine Glaciers

Daniele Giordan, Niccolò Dematteis, Fabrizio Troilo, Valerio Segor and Danilo Godone

Abstract

Glacial processes can have a strong impact on human activities in terms of hazards and freshwater supply. Therefore, scientific observation is fundamental to understand their current state and possible evolution. To achieve this aim, various monitoring systems have been developed in the last decades to monitor different geophysical and geochemical properties. In this manuscript, we describe examples of close-range monitoring sensors to measure the glacier dynamics: (i) terrestrial interferometric radar, (ii) monoscopic time-lapse camera, (iii) total station, (iv) laser scanner, (v) ground-penetrating radar and (vi) structure form motion. We present the monitoring applications in the Planpincieux and Grandes Jorasses glaciers, which are located in the touristic area of the Italian side of the Mont Blanc massif. In recent years, the Planpincieux-Grandes Jorasses complex has become an open-air research laboratory of glacial monitoring techniques. Many close-range surveys have been conducted in this environment and a permanent network of monitoring systems that measures glacier surface deformation is presently active.

Keywords: Mont Blanc, monitoring, remote sensing, data integration, glacial hazards

1. Introduction

Mountain glaciers represent the main source of fresh water for human activities of the surrounding regions [1, 2]. Furthermore, glaciological processes (e.g. ice break-offs, glacier outbursts, snow/ice avalanches) can threaten population, urban areas and infrastructures [3]. In densely populated areas, such as the European Alps, the interaction between glaciers and anthropic activities is very frequent and it is of crucial importance to study the glaciers to understand their evolution and response to climate change, which is expected to reduce their area coverage and increase their instability [4].

Long-term monitoring of glaciological processes is often complicated and expensive, especially in remote areas and inaccessible terrains, which are common in mountain environment [5]. A practical approach is the adoption of remote sensing apparatuses that allow observing glacial processes with minimal risk for scientists and technicians. In recent years, the free availability of data acquired from satellite platforms has largely improved the possibility to observe wide areas from remote with relatively high spatiotemporal resolution. Nevertheless, satellite surveys suffer complex geometries and the revisit time might be not adequate to measure fast processes. Therefore, the use of close-range remote sensing systems is often the most effective solution for glacier monitoring [6].

Section 2 presents a substantial list of close-range remote sensing techniques that can be adopted to measure glacier surface deformations. Section 3 is devoted to the Planpincieux and Grandes Jorasses glaciers (Mont Blanc massif) case study (**Figure 1**). In recent years, such a glacial complex has become an open-air laboratory where innovative and experimental monitoring systems have been developed [6–12]. Several practical examples of close-range remote sensing surveys will be described therein.

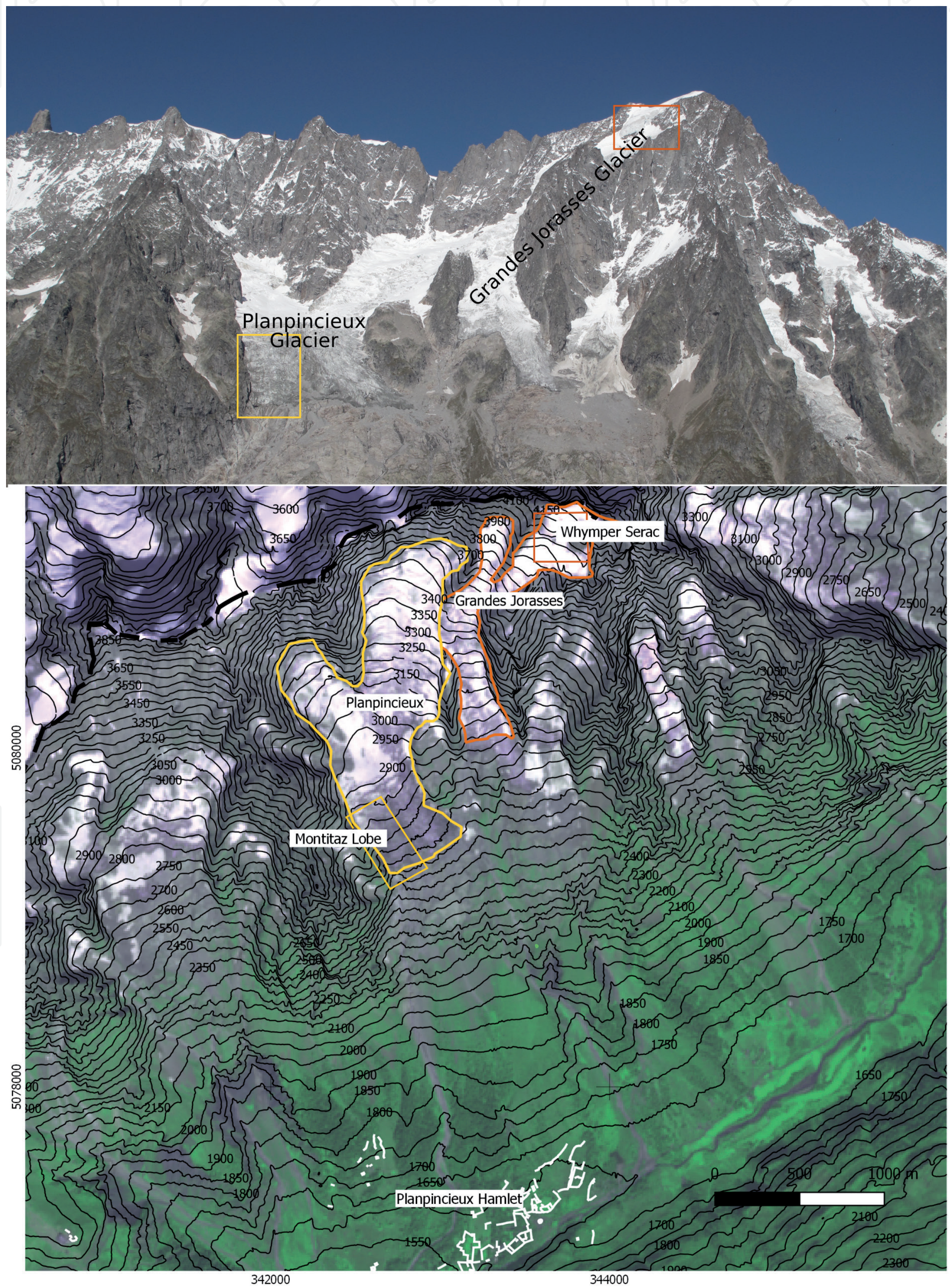

Figure 1.
*Overview of the Planpincieux and Grandes Jorasses glaciers (upper tile) and area of study (lower tile). Yellow and orange rectangles indicate respectively the Montitaz Lobe and the Whymper Serac framed by the time-lapse cameras (**Figure 2**).*

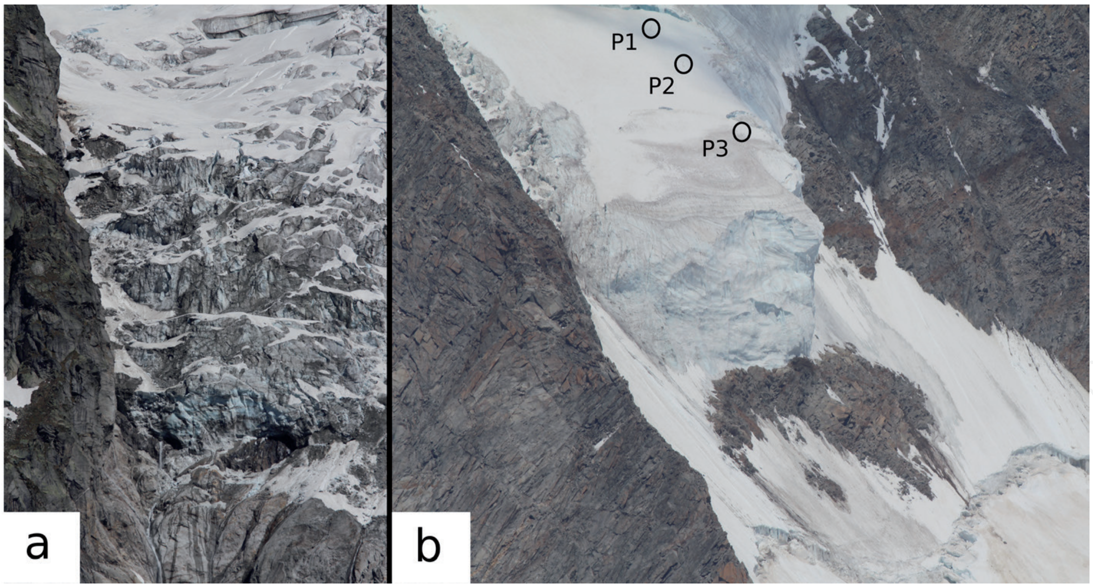

Figure 2.
(a) Image of the Montitaz Lobe of the Planpincieux Glacier monitored by a monoscopic time-lapse camera. The terminus width is approximately 100 m. (b) Image of the Whyper Serac acquired by monoscopic time-lapse camera. The serac face is approximately 40-m high. The black circles indicate the prism positions onto the serac surface in 2019.

2. Close-range remote sensing techniques

The study of the Planpincieux and Grandes Jorasses glacier surface deformations has been conducted following different approaches: (i) volumetric changes have been evaluated with point clouds and digital elevation models (DEMs). Such measurements have been obtained with laser scanners or structure from motion (SFM) processing. (ii) Surface kinematics maps of specific displacement components, which have been provided by monoscopic time-lapse camera and terrestrial interferometric radars. (iii) 3D displacements measured in specific points with a robotised total station (RTS). Furthermore, helicopter-borne ground-penetrating radar (GPR) campaigns have been conducted to investigate the glacier internal structure and thickness (**Table 1**).

2.1 Point clouds for surface generation

Three-dimensional point clouds are crucial tools in glacier monitoring; the main survey techniques to obtain them are LiDAR [13], terrestrial laser scanner (TLS) [14] and aerial and terrestrial photogrammetry, particularly structure from motion (SfM) approach [15]. LiDAR and TLS are based on a sensor, terrestrial or airborne, capable of emitting laser pulses at high frequency and measure their 'time of flight' in order to compute the position of each echo. The absolute position of each point is calculated from the emitter centre, geocoded by a GNSS coupled with an inertial measurement unit [16]. Besides its coordinates, each point can be characterised by the intensity of the echo in order to detect the nature of the target [17]. By the exploitation of laser beam divergence, it is also possible to discriminate and analyse multiple echoes or even the full waveform, thus obtaining multiple measurements of different object hit by the same pulse [18].

Concerning SfM, it is a technique originating from computer vision, which, by processing multiple images from different points of view of the same target object, generates a three-dimensional point cloud. The algorithm matches common

Glacier	Survey	Dates	References
Planpincieux	GPR	2/4/2013,	
		2019	
	DIC	August 2013-in	[8]
		course	
	TRI	9/8/2013-	[9, 42]
		10/8/2013	
		7/8/2014-	
		8/8/2014	
		1/9/2015-	
		14/10/2015	
		13/6/2016-	
		19/6/2019	
		26/9/2019-in	
		course	
	LiDAR	9/6/2014	
	TLS	2/10/2015	
	Helicopter-	2017	
	borne SFM	28/10/2018	
		20/9/2019	
		1/10/2019	
		5/11/2019	
	Drone SFM	24/7/2019	
Grandes	RTS	2010-in course	[11, 12]
Jorasses			
	DIC	2016-in course	
	GPR	4/6/2010	
		2/4/2013	
	Helicopter-	July 2010	
	borne SFM		
	Drone SFM	July 2019	

Table 1.
List of the surveys conducted in the Planpincieux and Grandes Jorasses glaciers since 2010.

features in the images and reconstructs the three-dimensional coordinates of the matching points and of the cameras. Resulting points are then collected in the cloud [19]. Images can be captured by various kinds of sensors including cameras, smartphones and drones [20].

2.2 Punctual topographic displacement measurements

Robotised total station (RTS) is a topographic apparatus that measures the sensor-to-target range and the azimuth and zenith angles, which allow determining the target position in a 3D coordinate system whose centre corresponds to the

RTS itself. Typical measurement sensibility of best-quality RTS is of 1.5 mm and 0.5 arcsec, depending on the distance. The RTS is composed of a laser rangefinder and an electronic theodolite that measures respectively distance and angles. The RTS targets retroreflector prisms installed both in and outside the moving area. The latter ones serve as control points for measurement calibration and data corrections.

Since it is required to install prisms within the investigated area, the RTS cannot be considered a remote sensing device in a strict sense. Nevertheless, such installation is needed just once; thereafter, the RTS provides measurements from remote, strongly reducing human and financial costs for accessing the surveyed area. This holds especially when the RTS works in automatic target recognition (ATR) mode, with which it carries out autonomously the measurements. In geosciences, the RTS is widely used for gravitational slope phenomena, such as landslides [21, 22], volcanos [23] and glaciers [11, 12, 24].

2.3 Glacier surface kinematics maps

Spatially distributed data are a relevant tool in glaciological studies because they allow to analyse the surface kinematic patterns and to identify possible different kinematic sectors. In the Planpincieux-Grandes Jorasses glacial complex, two main remote sensing systems have been applied to measure surface kinematics maps: digital image correlation (DIC) and terrestrial radar interferometry (TRI).

2.3.1 Digital image correlation

With the advent of digital cameras, time-lapse imagery has become popular since the beginning of the 2000s in glaciology, where it has been applied to survey polar ice flow [25–28] and mountain glaciers [6, 8, 29–33].

DIC is an image analysis technique that is applied to a pair of images to obtain spatially distributed maps of the two displacement components orthogonal to the line-of-sight (LOS). In classical DIC processing, a reference template out of the master image is searched for in an investigated larger area of the slave image. The cross-correlation (CC) is calculated for every possible template of the investigated area and the position of the maximum correlation coefficient corresponds to the displacement of the master template. Alternatively, the CC can be calculated in the Fourier domain according to the convolution theorem. Fourier CC is computationally efficient but it is more prone to outliers.

The main DIC advantages concern the low-cost hardware and its high portability even in harsh environments. Nevertheless, it suffers adverse meteorology and it strongly depends on the visibility conditions.

2.3.2 Terrestrial radar interferometry

In the last two decades, TRI revealed to be a valuable tool to monitor glaciers [9, 34–42]. TRI concerns the analysis of the phase difference between two radar acquisitions, which is directly related to the target displacement component parallel to the LOS. Typical radar apparatuses can provide spatially distributed displacement data in an area of several square kilometres with an operative range of a few kilometres. Radars are active sensors, as such, TRI can be applied during the night and severe meteorological conditions. Moreover, TRI measurements have sub-millimetre sensibility in an optimal context. However, the processing is not trivial and it requires high computational costs. Particularly complicated is the phase wrapping solution, which depends on the phase 2 periodicity and which is related to the sensor-to-target range. Moreover, TRI is quite sensitive to possible morphological change of the scattering surface and that causes signal decorrelation and extreme atmospheric conditions can heavily affect the measurements [43, 44]. In glaciological contexts, long distances, morphological surface changes and severe meteorology are common and TRI processing must be handled carefully.

2.4 Glacier internal structure

GPR has been widely used as a geophysical method for the study of internal glacier properties. A variation in electrical permittivity creates dielectric interfaces and subsequent reflections that can be analysed. GPR can be used for the definition of firn-ice transition, the detection of subglacial cavities and the ice thickness [45]. GPR systems include a transmitter and a receiver antenna. Typical operating frequencies vary between 10 and 15 MHz, for the investigation of glaciers having depths of hundreds of meters, to 400–600 MHz, for shallow investigations. Different factors can limit the effectiveness of the technique, such as debris cover of the ice surface or highly crevassed areas that can create scattering or absorption phenomena that reduce the possibility of investigation of the glacier sub-surface. Processing of radar data normally implies many steps, which include (i) low-frequency filtering, caused mainly by surface reflection; (ii) selection of a time gain to correct for the amplitude divergence; (iii) temporal and spatial filtering for improving the signal-to-noise ratio; (iV) deconvolution and (v) migration [46].

GPR apparatuses are usually lightweight and compact and they can be easily transported by walking or snowmobile, which allows at acquiring a large number of 2D radar profiles. However, helicopter-borne surveys provide the most versatile platform and they have been used for detecting glacier thickness [47, 48], intraglacial features [49] and snow accumulation [50].

2.5 Data integration

Spatially distributed deformation data provide wide information on the investigated process. Nevertheless, common remote sensing apparatuses only provide specific displacement components or punctual measurements and the integration of different sensors is necessary to obtain spatially distributed 3D data.

Dematteis et al. [6] proposed an innovative solution to obtain 3D displacement using DIC and TRI data integration. DIC and TRI provide different and complementary displacement components that can be coupled to obtain a three-dimensional representation of the surface kinematics. The necessary conditions to couple the different data are that their maps must have the same spatial resolution in the same coordinate system (CS). Therefore, a geometric transformation is required to represent both data in the same CS, which is usually associated with a georeferenced DEM.

A different approach of data integration entails the merging of DIC and RTS data. RTS provides 3D displacement in specific points, while DIC can measure spatially distributed data. Therefore, their integration allows obtaining the displacement direction and versus using RTS data, while the DIC results give the spatial distribution.

3. Case study: Planpincieux-Grandes Jorasses glaciers

The Planpincieux and Grandes Jorasses glaciers form a unique polythermal glacial complex located on the Italian side of the Grandes Jorasses peak (Mont

Blanc massif), in the Ferret valley (**Figure 1**). The glaciers have approximately a South-East aspect and the elevation ranges from 2600 m asl to 4200 m asl. The accumulation area of the Grandes Jorasses Glacier is formed of two 45° steep cirques, which merge in an icefall at 3500 m asl. In the left cirque is located the Whymper Serac, whose front is at an elevation of 3800 m asl (**Figure 2b**). According to Pralong and Funk [51], this portion is classified as an unbalanced hanging glacier. As such, the serac progressively increases its volume and when its shape reaches unstable geometry, the serac collapses. This cycle follows an irregular periodicity and the time between the break-offs ranges from a few years to more than a decade. Usually, the unstable ice chunk has a volume of the order of 105 m^3, which can collapse at once or in several pieces. The instability dynamics is driven only by the geometry and it is not linked to temperature or water percolation. Therefore, the fracture can also occur during the cold season, when the collapse might easily trigger a large snow avalanche that would seriously threaten the underlying buildings and the road at the valley bottom. The last events happened in August 1993, June 1998 [11] and September 2014 [12]. The first one caused the fatality of eight mountaineers, but the ice avalanche did not cause further damages for the absence of snow.

The Planpincieux Glacier topography presents three distinguished zones: the accumulation area, 3000–3500 m asl, is formed of two steep cirques that merge in a wide plateau at 2900–3000 m asl, and two lobes constitute the ablation area. The right lower lobe (**Figure 2a**) is 32° steep on average and it is quite crevassed. Its terminus ends in correspondence of a bedrock cliff that causes frequent calving. In the past, several collapses occurred and, in a few cases, they endangered the bridge of the Montitaz stream that originates from the glacier snout. Further information on the Planpincieux Glacier can be found in Giordan et al. [7].

3.1 Monitoring campaigns

In the last decades, the Planpincieux-Grandes Jorasses Glacier complex has become an open-air laboratory where innovative remote sensing techniques have been developed to monitor the glacier activity [6–12].

The Planpincieux Glacier is observed by two monoscopic time-lapse cameras placed in the opposite side of the Ferret valley, at a distance of 3800 m from the glacier. The monitoring station is equipped with two solar panels and an electric cell for power supply. It is remotely controlled by a Raspberry Pi 3 connected to the server of the Geohazard Monitoring Group (GMG) of the Research Institute for Geo-Hydrological Protection (IRPI), in Torino, Italy. A robotised webcam has been installed in 2018 to survey the station functioning. The system is active since August 2013 and it acquires images at hourly frequency. In the period August 2013–December 2019, it collected more than 35,000 images and it is probably the longest continuous series of hourly images in the European Alps. The images are processed with the DIC technique to estimate the surface glacier kinematics.

The Grandes Jorasses Glacier is being monitored since 2010 by an RTS installed in the Planpincieux hamlet at a distance of 4800 m. The RTS measures every 2 h the position of the prisms installed onto and in the vicinity of the Whymper Serac (**Figure 2b**). Due to the extreme meteorological conditions and the exceptional sensor-to-target range, the prisms are not always visible and gaps in the measurement series are frequent, especially during the cold season. Snowfalls and strong wind occasionally cause the loss of some prisms and the intervention of Alpine guides it is necessary for the installation of new targets. Moreover, the Whymper Serac is continuously monitored by a 4800-m-far monoscopic camera. This survey is active since 2010 and the serac surface displacement is estimated with feature tracking of the hourly photographs.

Besides these continuous monitoring systems, in the past, several measurement campaigns have been conducted to increase the glacier understanding and to develop new monitoring techniques of glaciological close-range remote sensing. In **Table 1**, the complete list of the surveys conducted since 2010 is presented and the related references are reported when available.

3.1.1 Point cloud analysis

DEMs obtained during LiDAR and TLS surveys and from photographic SfM acquired by drones and helicopter-borne cameras allow monitoring the morphology evolution of the glacier surface. In addition, the DEM of difference (DoD) calculation permits to estimate the surface elevation changes and the possible ice mass loss. From the DoD obtained with the DEMs acquired in October 2019 and June 2014 (helicopter-borne SfM and LiDAR respectively), one can observe the glacier thinning of more than 10 m on average (**Figure 3**). In the considered period, the terminus retreated by several tenths of metres and the bedrock remained exposed. In this part, the DoD shows a thickness loss of 30–40 m approximately, which corresponds to the glacier thickness in 2014.

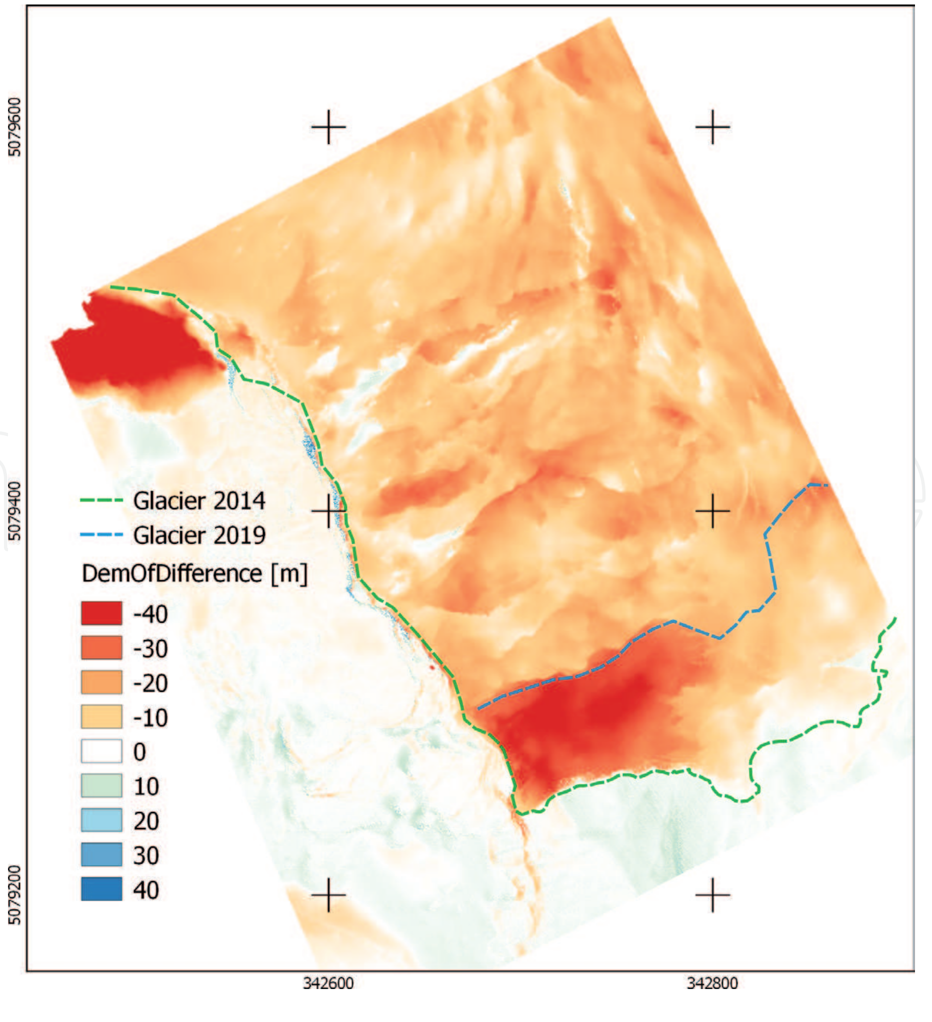

Figure 3.
DEM of difference (DoD) of the Montitaz Lobe. The DoD is calculated as the difference between the DEMs acquired on 1/10/2019 and 9/6/2014. The glacier outlines in both years are represented as dashed lines.

3.1.2 RTS applications

RTS measurements are continuously active since 2010 to monitor the surface velocity of the Whymper Serac. The survey is conducted with a Leica TM30 that operates in ATR mode. The prism network is composed of several stakes installed into the unstable portions, while a few prisms placed in the surrounding bedrock serve as reference points. Complete acquisition of the entire network lasts approximately 45 min and it is conducted every 2h. The sensor-to-target distance is of 4800 m on average, which is beyond the instrument operating limits declared by the manufacture in ATR mode (https://w3.leica-geosystems.com/downloads123/zz/tps/tm30/brochures-datasheet/tm30_technical_data_en.pdf). In addition, extreme atmospheric conditions linked to the high-mountain elevation occur frequently. This situation makes the Whymper Serac a critical scenario for RTS measurements and a robust processing method has been developed ad hoc [11]. However, the RTS data allowed forecasting 10 days in advance the serac break-off of 22/10/2014 [12]. The RTS data acquired before such an event are shown in **Figure 4**.

3.1.3 Time-lapse camera applications

The surface kinematics of the Planpincieux Glacier right lobe has been deeply investigated with image analysis of 6-year-long time-lapse monitoring. The data analysis allowed characterising the terminus dynamics and classifying the instability processes that cause break-offs: (i) disaggregation, (ii) slab fracture and (iii) water tunnelling [7]. Disaggregation is the progressive toppling of small ice pieces caused by the movement of the terminus beyond the frontal bedrock cliff. It is the most frequent process and it involves break-offs of limited size, usually lower than 1000 m^3. Slab fracture instability is caused by the aperture of a crevasse orthogonal to the motion direction, located in correspondence to the maximum tensile stress line. When the fracture reaches the bedrock, it triggers a large break-off of an ice lamella that can assume a volume of 104–105 m^3. Water tunnelling refers to the formation of R-channels [52] where a large amount of

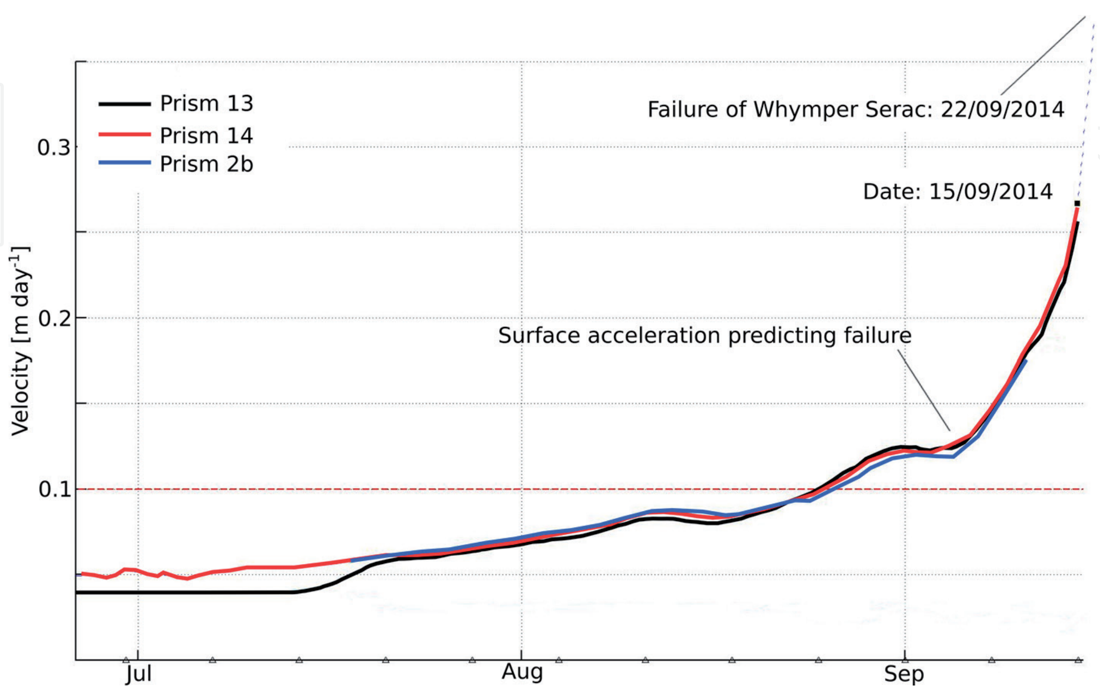

Figure 4.
RTS measurements of prisms 13, 14, and 2b before the failure of 22/09/2014. Using these data, the break-off was predicted 10 days in advance.

water can accumulate. The water produces a strong pressure on the frontal cliff that can provoke failure of the terminus. Moreover, the empty tunnels increase the instability and they can collapse themselves.

Besides the visual photographic interpretation, DIC in the Fourier domain was applied to the hourly images, obtaining surface displacement maps at daily resolution. During the monitoring period, the surface displacement pattern was composed of four distinct kinematic domains, which were characterised by different velocity regimes. The presence of kinematics domains indicates the action of high strain rates localised at the domain limits, where large fractures appear (**Figure 5**). The behaviour of the frontal sector is noteworthy, because it reveals the occurrence of a few speed-up periods per year, which culminate with large break-offs (**Figure 6**). These kinematic fluctuations were characterised by well-defined thresholds of initial velocity ($v_0 \geq 30$ cm day^{-1}) and acceleration ($a \geq 3$ cm day^{-2}). Moreover, a monotonic relationship (rank correlation coefficient > 0.7, p-value < 0.02) between the velocity peak and the collapsed volume has been observed.

DIC in the spatial domain was applied to the images of the Whymper Serac to measure the displacement in July 2019 (**Figure 7a**, **b**). The available images presented rototranslation that had to be compensated with robust coregistration. Moreover, the smooth texture and low chromatic contrast of the scene lowered the signal-to-noise ratio (i.e. the correlation, see **Figure 7**) and hence many artefacts were present in the displacement maps. Therefore, a robust outlier correction method was applied [53]. The results showed a slight acceleration during July, which was confirmed by RTS measurements.

3.1.4 TRI applications

The Planpincieux is probably the unique glacier where TRI surveys were conducted using four different terrestrial interferometric radar models, namely: GPRI™ (Gamma Remote Sensing, https://www.gamma-rs.ch/rud/microwave-hardware/gpri.html), IBIS-L™ (IDS Georadar, https://idsgeoradar.com/products/interferometric-radar/ibis-fl), FastGBSAR-S™ (MetaSensing, https://www.geomatics.metasensing.com/fastgbsar-s) and GBInSAR LiSALab™ (LiSALab, http://www.lisalab.com/home/default.asp?sez=6).

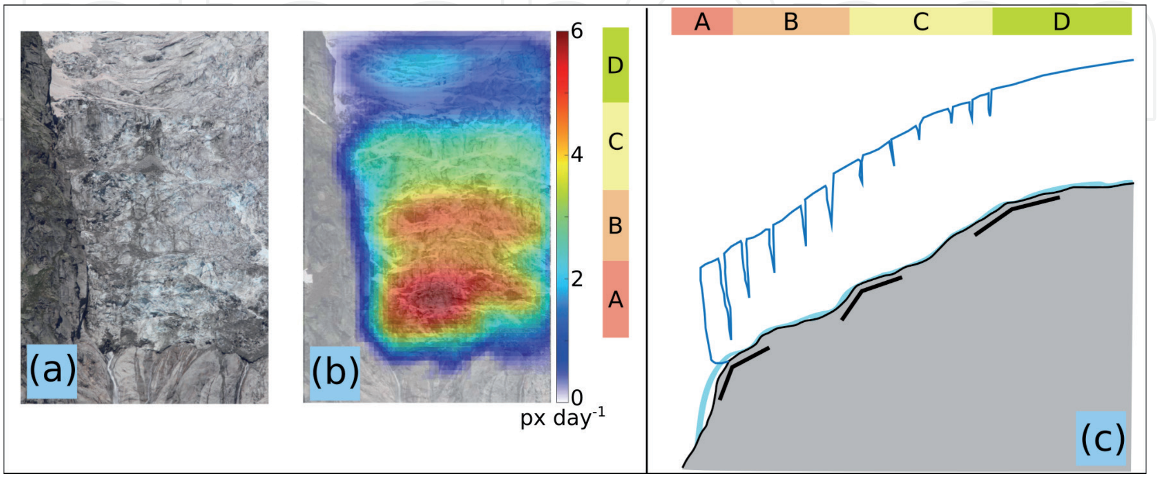

Figure 5.
(a) Image of the Montitaz Lobe acquired by the monoscopic time-lapse camera. The terminus width is approximately 100 m. (b) Surface deformation map. Different velocity regimes clearly identify the four kinematics domains. (c) Longitudinal conceptual scheme of the glacier lobe (not in scale). The black lines indicate bedrock discontinuities that correspond to the kinematic domain limits. Modified from Giordan et al. [7].

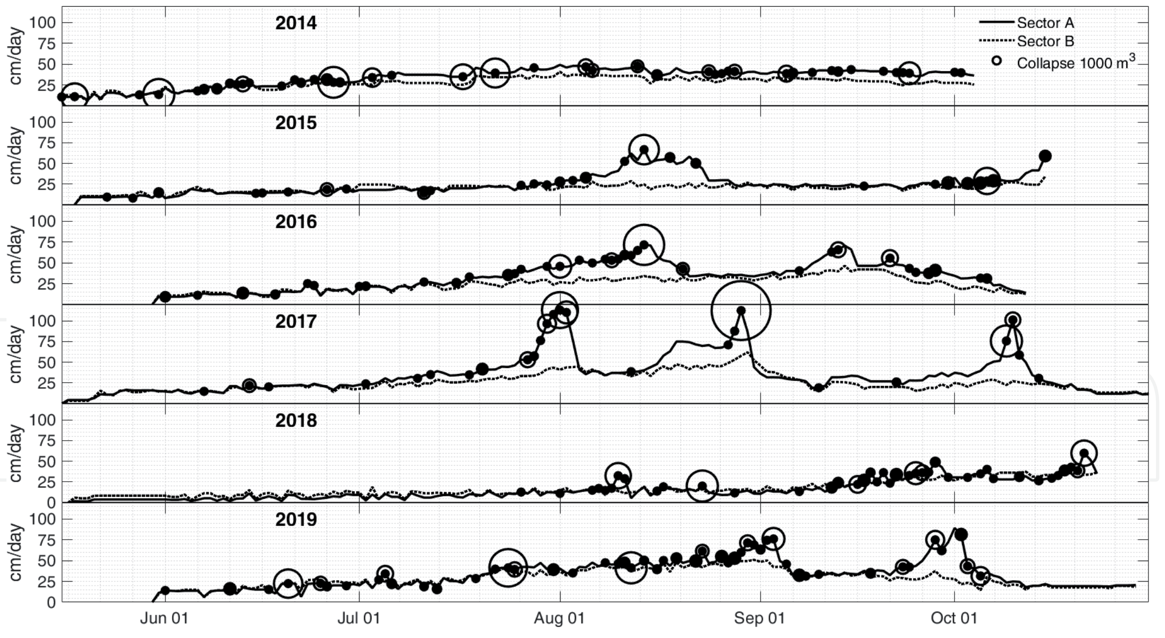

Figure 6.
Time series of the daily velocity of sectors A and B (see ***Figure 5****) in the years 2014–2019 (from top to bottom). The break-off occurrence is depicted in black dots, while the white circle size is proportional to the volume.*

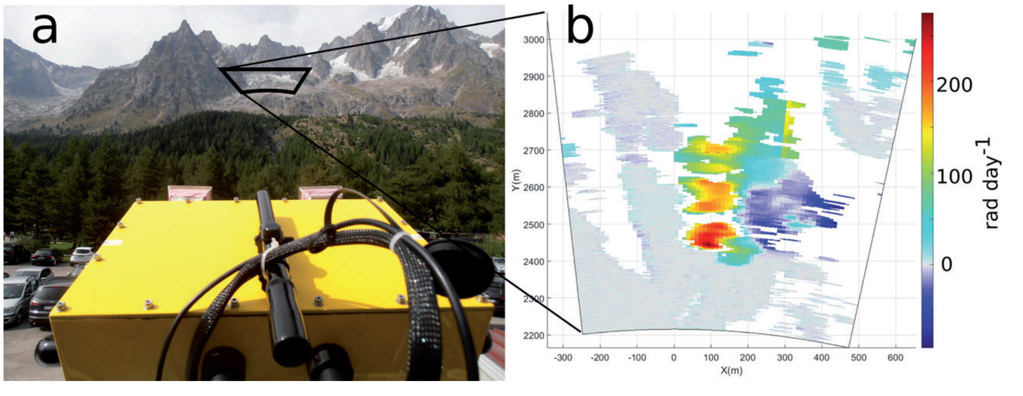

Figure 7.
(a) IBIS-L GBSAR surveyed the Planpincieux Glacier area, delimited in black. (b) The cumulative sum of the interferograms acquired in the period September 4, 2015 to October 14, 2015.

The surface kinematics of the glaciers was surveyed in five TRI campaigns, in 2013, 2014, 2015, 2016 and 2019 (**Table 1**). The first two were conducted using the GPRI™ real-aperture radar (RAR) in Ku band that surveyed the glacier from the valley bottom and the valley ridge opposite to the glaciers. Both campaigns lasted for 2 days and they were able to detect the displacements of the lower portions of the Planpincieux and Grandes Jorasses glaciers, which were approximately 25 cm day^{-1} and 50 cm day^{-1} respectively. Instead, the following surveys were conducted using Ku-band ground-based synthetic aperture radars (GB-SAR). The campaign of autumn 2015 (IBIS-L™) lasted much longer and hence it was possible to recognise the different kinematic domains of the Montitaz Lobe (**Figure 8**). During the campaign, the meteorological conditions were severe and the radar acquisitions were affected by strong APS. To solve the issue, a polynomial APS model that was a function of the topography was developed [9, 42]. In 2016, FastGBSAR-S™ measurements with an acquisition frequency of 10 s were carried out; thereby, the atmospheric disturbance was minimised. Fully polarimetric measurements were experimented, but the very long distance did not allow exploiting the potentiality of such a technology. The last campaign (GBInSAR LiSALab™) began at the end of September 2019 for civil protection and it is still active during the writing of the present chapter.

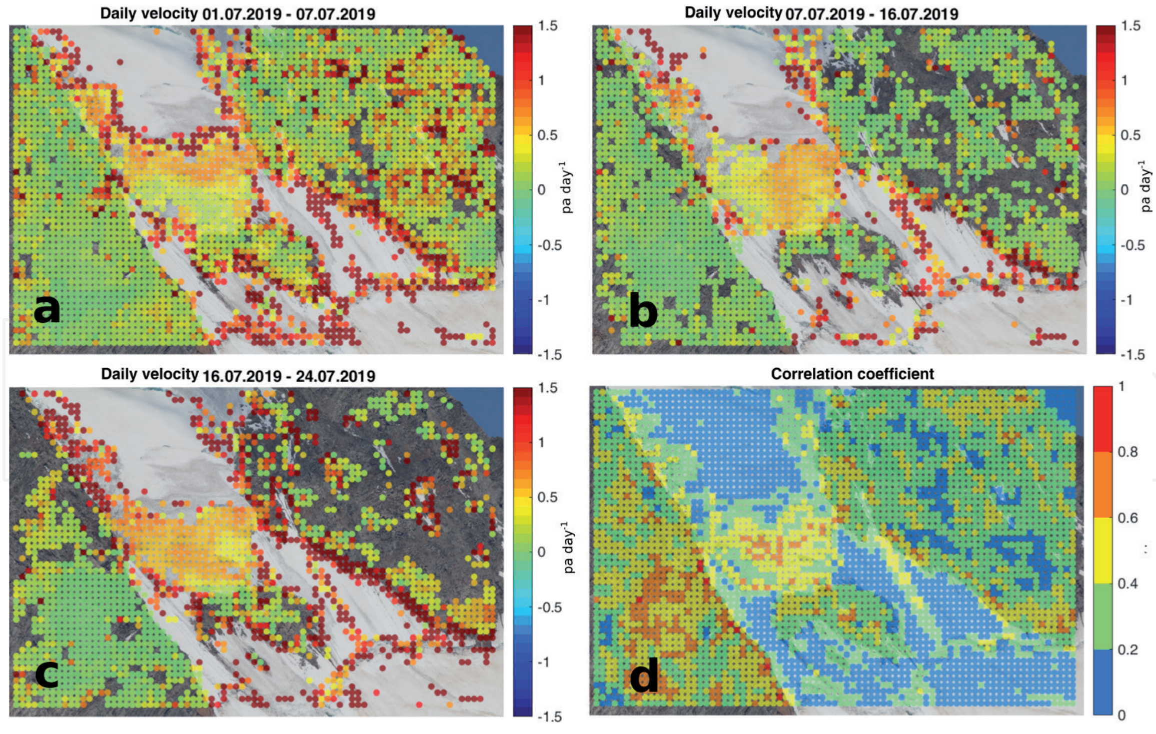

Figure 8.
(a-c) Surface displacement maps of the Whymper Serac of the periods July 1, 2019 to July 7, 2019, July 7, 2019 to July 16, 2019 and July 16, 2019–July 24, 2019. (d) Map of the mean correlation coefficient, which displays low values because of the texture smoothness of the snow surfaces. The serac face is approximately 40 m high.

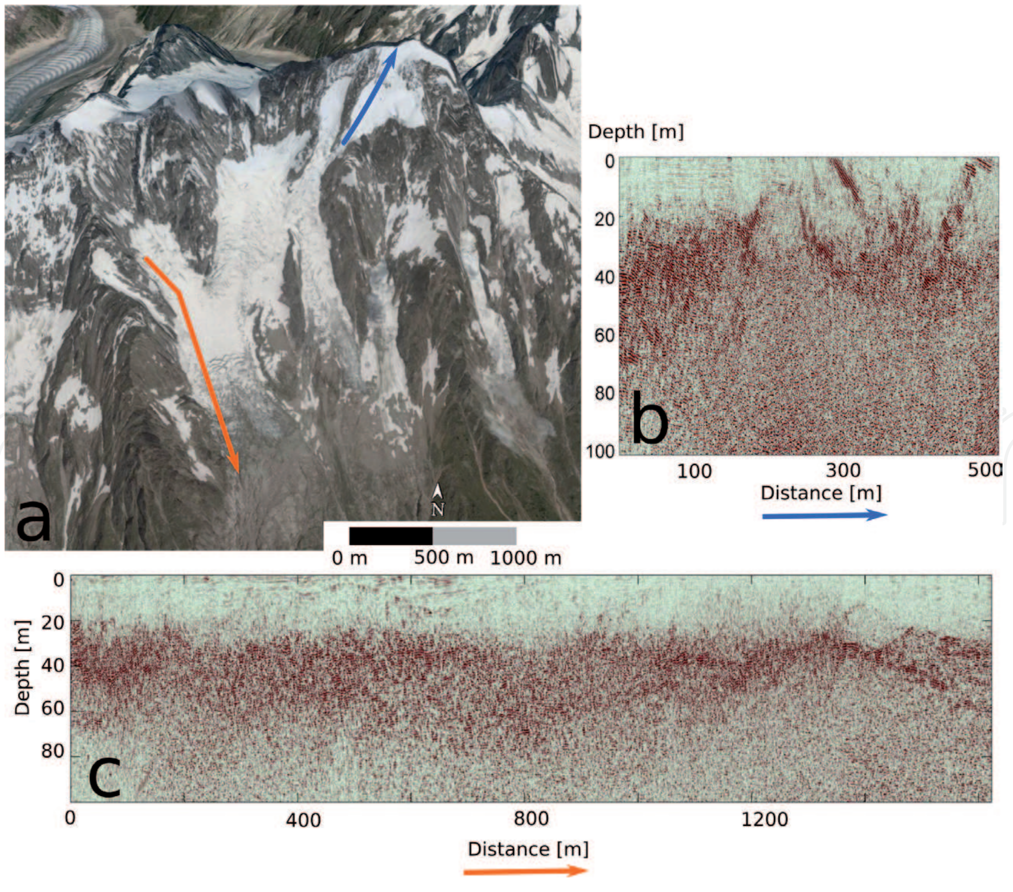

Figure 9.
(a) GPR traces of the Planpincieux (orange line) and Grandes Jorasses (blue line) glaciers. (b-c) GPR profiles of the Whymper Serac and Planpincieux Glacier respectively. The white-red boundary indicates the ice thickness.

3.1.5 GPR applications

A helicopter-borne 65-MHz GPR survey was conducted in the Planpincieux-Grandes Jorasses glacial complex in April 2014, when 16 GPR traces homogeneously distributed on the glaciers' surface were acquired (**Figure 9**). The noise of the radar data was quite high, because the numerous crevasses caused bounds of the electromagnetic waves and produced echoes and artefacts. Nevertheless, it was possible to estimate the glacier thickness, which was in the range 20–40 m in the Planpincieux Glacier and lower than 20 m in the Whymper Serac.

3.1.6 Data integration

In September 2015, time-lapse photography and terrestrial radar campaigns were conducted simultaneously to measure the Planpincieux Glacier surface kinematics. The actual three-dimensional surface kinematics was obtained by coupling DIC and TRI results. **Figure 10** reports the mean daily velocity map, where the colour represents the velocity module and the arrows indicate direction and versus. The 3D displacement can be obtained only in the areas visible by both the sensors. In the right lobe, the displacement vectors are not uniformly parallel to the surface, because the seracs move downstream as a single body and the ice is subjected to internal deformation. This result is not trivial, as the most common approach to estimate 3D displacement is to project the single movement components along the local slope obtained from the DEM, but this assumption might be misleading in specific cases.

The permanent monitoring system of the Whymper Serac is composed of RTS and time-lapse imagery. In July 2019, the data of the two sensors were integrated and represented in an informative bulletin [54, 55], shown in **Figure 11**. Such integration allows evaluating the versus and direction of the principal movement (with the RTS data) and the distribution of the strain rates (with the DIC results).

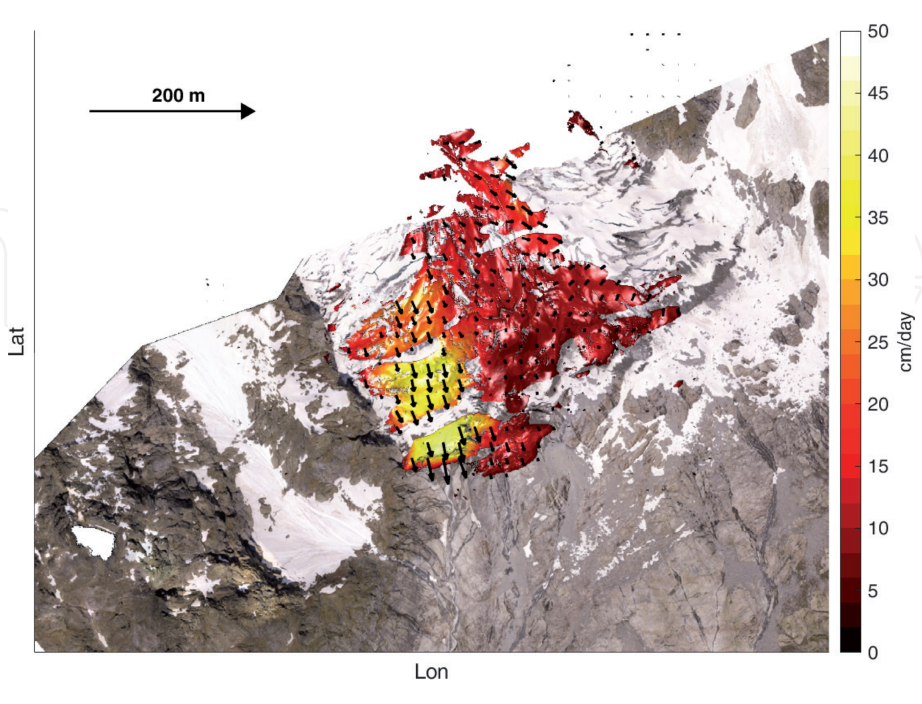

Figure 10.
Velocity field of the surface kinematics of the lower Planpincieux Glacier obtained with the integration of DIC and TRI measurements. Colours and arrows represent velocity module and direction respectively. Modified from Dematteis et al. [6].

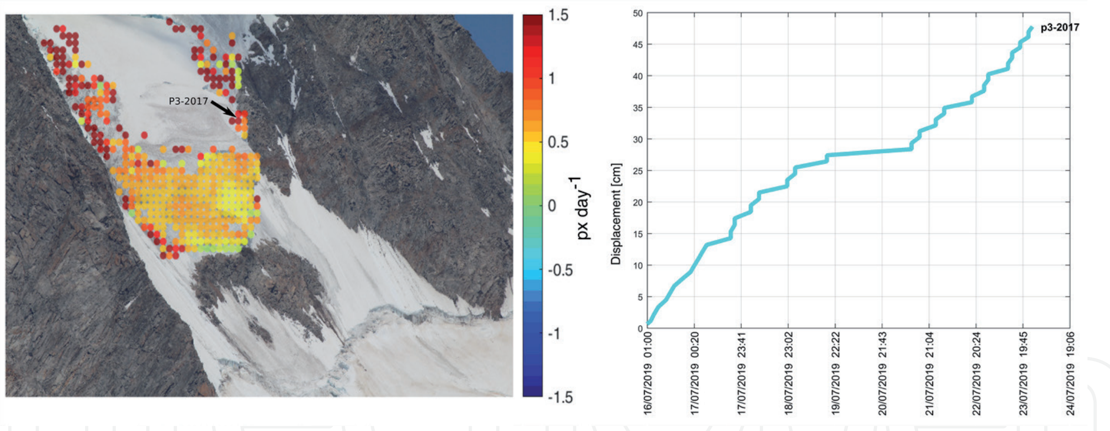

Figure 11.
Data integration of DIC and RTS measurements. The image depicts the spatially distributed daily deformation of the Whymper Serac front (coloured dots) and the surface displacement direction measured by the TRS in correspondence with the prism P3-2017. The right plot reports the displacement trend provided by the RTS.

4. Summary

In-depth knowledge of glacier behaviour is fundamental for glaciological risk evaluation and management and it permits to develop mitigation and adaptation strategies against the cryosphere change provoked by global warming. To achieve this aim, data collection about the current glacier state is of primary importance, but the harsh mountain environment makes the survey activities difficult. Measurements from aerospace platforms are affected by complex geometries and might not provide sufficient spatiotemporal resolution, especially when high acquisition rates (i.e. minutes to hours) are necessary. Therefore, ground-based systems are often the most suitable solution. Nevertheless, impervious areas where glaciers are usually located entail the use of high financial and human efforts, as well as potential risks to access the investigated area. Therefore, remote sensing systems represent the best cost-benefit ratio and they are commonly adopted for glacier monitoring. Considering the possible adverse conditions (e.g. extreme meteorology, steep slopes, long sensor-to-target distance, natural hazards) that can occur during the survey activities, ad hoc technologies and methods must be developed. The glacial complex formed of the Planpincieux and Grandes Jorasses glaciers represents an outstanding site where different close-range remote sensing approaches have been experimented, in a heterogeneous Alpine glacier environment. Here, the combined use of multiple sensors proved to be a valuable tool to collect complementary information that allowed improving the understanding of the current state and recent evolution of the glacial area.

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References

[1] Barnett TP, Adam JC, Lettenmaier DP. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature. 2005;**438**:303-309. DOI: 10.1038/nature04141

[2] Hock R, Jansson P, Braun LN. Modelling the Response of Mountain Glacier Discharge to Climate Warming. In Global Change and Mountain Regions (A State of Knowledge Overview). Dordrecht: Springer; 2005. pp. 243-252. DOI: 10.1007/1-4020-3508-x_25

[3] Kääb A, Huggel C, Fischer L, Guex S, Paul F, Roer I, et al. Remote sensing of glacier- and permafrost-related hazards in high mountains: An overview. Natural Hazards and Earth System Sciences. 2005;**5**(4):527-554. DOI: 10.5194/nhess-5-527-2005

[4] Deline P, Gruber S, Delaloye R, Fischer L, Geertsema M, Giardino M, et al. Ice loss and slope stability in high-mountain regions. In: Snow and Ice-Related Hazards, Risks, and Disasters. Academic Press; 2014. pp. 521-561. DOI: 10.1016/B978-0-12-394849-6.00015-9. ISBN: 9780123964731

[5] Kenner R, Phillips M, Limpach P, Beutel J, Hiller M. Monitoring mass movements using georeferenced time-lapse photography: Ritigraben rock glacier, western Swiss Alps. Cold Regions Science and Technology. 2018;**145**:127-134. DOI: 10.1016/j.coldregions.2017.10.018

[6] Dematteis N, Giordan D, Zucca F, Luzi G, Allasia P. 4D surface kinematics monitoring through terrestrial radar interferometry and image cross-correlation coupling. ISPRS Journal of Photogrammetry and Remote Sensing. 2018;**142**:38-50. DOI: 10.1016/j.isprsjprs.2018.05.017

[7] Giordan D, Dematteis N, Allasia P, Motta E. Classification and kinematics of the Planpincieux Glacier break-offs using photographic time-lapse analysis. Journal of Glaciology. 2020;**66**(256):188-202. DOI: 10.1017/jog.2019.99

[8] Giordan D, Allasia P, Dematteis N, Dell'Anese F, Vagliasindi M, Motta E. A low-cost optical remote sensing application for glacier deformation monitoring in an alpine environment. Sensors. 2016;**16**(10):1750. DOI: 10.3390/s16101750

[9] Dematteis N, Luzi G, Giordan D, Zucca F, Allasia P. Monitoring Alpine glacier surface deformations with GB-SAR. Remote Sensing Letters. 2017;**8**(10):947-956. DOI: 10.1080/2150704X.2017.1335905

[10] Dematteis N, Giordan D, Allasia P. Image classification for automated image cross-correlation applications in the geosciences. Applied Sciences. 2019;**9**(11):2357. DOI: 10.3390/app9112357

[11] Margreth S, Faillettaz J, Funk M, Vagliasindi M, Diotri F, Broccolato M. Safety concept for hazards caused by ice avalanches from the Whymper hanging glacier in the Mont Blanc Massif. Cold Regions Science and Technology. 2011;**69**(2-3):194-201. DOI: 10.1016/j.coldregions.2011.03.006

[12] Faillettaz J, Funk M, Vagliasindi M. Time forecast of a break-off event from a hanging glacier. The Cryosphere. 2016;**10**(3):1191-1200. DOI: 10.5194/tc-10-1191-2016

[13] Wehr A, Lohr U. Airborne laser scanning—An introduction and overview. ISPRS Journal of Photogrammetry and Remote Sensing. 1999;**54**(2-3):68-82. DOI: 10.1016/S0924-2716(99)00011-8

[14] Godone D, Godone F. The Support of Geomatics in Glacier Monitoring: The Contribution of Terrestrial Laser Scanner. Rijeka: IntechOpen; 2012. DOI: 10.5772/33463

[15] Westoby MJ, Brasington J, Glasser NF, Hambrey MJ, Reynolds JM. "Structure-from-Motion" photogrammetry: A low-cost, effective tool for geoscience applications. Geomorphology. 2012;**179**:300-314. DOI: 10.1016/j.geomorph.2012.08.021

[16] Baltsavias EP. Airborne laser scanning: Basic relations and formulas. ISPRS Journal of Photogrammetry and Remote Sensing. 1999;**54**(2-3):199-214. DOI: 10.1016/S0924-2716(99)00015-5

[17] Glennie CL, Carter WE, Shrestha RL, Dietrich WE. Geodetic imaging with airborne LiDAR: The Earth's surface revealed. Reports on Progress in Physics. 2013;(8):24-76. DOI: 10.1088/0034-4885/76/8/086801

[18] Chauve A, Mallet C, Bretar F, Durrieu S, Pierrot-Deseilligny M, Puech W, et al. Processing full-waveform Lidar data: Modelling raw signals. In: Proceedings of the International Archives of Photogrammetry Remote Sensing and Spatial Information Sciences. 2007. pp. 102-107

[19] Fonstad MA, Dietrich JT, Courville BC, Jensen JL, Carbonneau PE. Topographic structure from motion: A new development in photogrammetric measurement. Earth Surface Processes and Landforms. 2013;**38**:421-430. DOI: 10.1002/esp.3366

[20] Cignetti M, Godone D, Wrzesniak A, Giordan D. Structure from motion multisource application for landslide characterization and monitoring: The champlas du col case study, sestriere, north-western Italy. Sensors (Switzerland). 2019;**19**(10):2364. DOI: 10.3390/s19102364

[21] Manconi A, Allasia P, Giordan D, Baldo M, Lollino G, Corazza A, et al. Landslide 3D surface deformation model obtained via RTS measurements. In: Landslide Science and Practice. Berlin, Heidelberg: Springer Berlin Heidelberg; 2013. pp. 431-436. DOI: 10.1007/978-3-642-31445-2_56

[22] Allasia P, Baldo M, Giordan D, Godone D, Wrzesniak A, Lollino G. Near real time monitoring systems and periodic surveys using a multi sensors UAV: The case of Ponzano landslide. In: IAEG/AEG Annual Meeting Proceedings, San Francisco, California, 2018-Volume 1. Springer International Publishing: Cham; 2018. pp. 303-310. DOI: 10.1007/978-3-319-93124-1_37

[23] Langbein JO. Deformation of the Long Valley Caldera, California: Inferences from measurements from 1988 to 2001. Journal of Volcanology and Geothermal Research. 2003;**127**(3-4):247-267. DOI: 10.1016/S0377-0273(03)00172-0

[24] Nainwal HC, Negi BDS, Chaudhary M, Sajwan KS, Gaurav A. Temporal changes in rate of recession: Evidences from Satopanth and Bhagirath Kharak glaciers, Uttarakhand, using Total Station Survey. Current Science. 2008;**94**(5):653-660

[25] Ahn Y, Box JE. Glacier velocities from time-lapse photos: Technique development and first results from the Extreme Ice Survey (EIS) in Greenland. Journal of Glaciology. 2010;**56**(198):723-734. DOI: 10.3189/002214310793146313

[26] Dietrich R, Maas HG, Baessler M, Rülke A, Richter A, Schwalbe E, et al. Jakobshavn Isbræ, West Greenland: Flow velocities and tidal interaction of the front area from 2004 field observations. Journal of Geophysical Research: Earth Surface. 2007;**112**(3):F03S21. DOI: 10.1029/2006JF000601

[27] Brinkerhoff D, O'Neel S. Velocity variations at Columbia Glacier captured by particle filtering of oblique time-lapse images. arxiv.org; 2017

[28] Schwalbe E, Maas HG. The determination of high-resolution spatio-temporal glacier motion fields from time-lapse sequences. Earth Surface Dynamics. 2017;**5**(4):861-879. DOI: 10.5194/esurf-5-861-2017

[29] Benoit L, Dehecq A, Pham HT, Vernier F, Trouvé E, Moreau L, et al. Multi-method monitoring of Glacier d'Argentière dynamics. Annals of Glaciology. 2015;**56**(70):118-128. DOI: 10.3189/2015AoG70A985

[30] Messerli A, Grinsted A. Image georectification and feature tracking toolbox: ImGRAFT. Geoscientific Instrumentation, Methods and Data Systems. 2015;**4**(1):23-34. DOI: 10.5194/gi-4-23-2015

[31] Fallourd R, Trouvé E, Roşu D, Vernier F, Bolon P, Harant O, et al. Monitoring temperate glacier displacement by multi-temporal TerraSAR-X images and continuous GPS measurements. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing. 2011;**4**(2):372-386. DOI: 10.1109/JSTARS.2010.2096200

[32] Vernier F, Fallourd R, Friedt JM, Yan Y, Trouvé E, Nicolas J-M, et al. Fast correlation technique for glacier flow monitoring by digital camera and space-borne SAR images. EURASIP Journal on Image and Video Processing. 2011;**1**:11. DOI: 10.1186/1687-5281-2011-11

[33] Evans AN. Glacier surface motion computation from digital image séquences. IEEE Transactions on Geoscience and Remote Sensing. 2000;**38**(2 II):1064-1072. DOI: 10.1109/36.841985

[34] Allstadt KE, Shean DE, Campbell A, Fahnestock M, Malone SD. Observations of seasonal and diurnal glacier velocities at Mount Rainier, Washington, using terrestrial radar interferometry. The Cryosphere. 2015;**9**(6):2219-2235. DOI: 10.5194/tc-9-2219-2015

[35] Luzi G, Pieraccini M, Mecatti D, Noferini L, Macaluso G, Tamburini A, et al. Monitoring of an alpine glacier by means of ground-based SAR interferometry. IEEE Geoscience and Remote Sensing Letters. 2007;**4**(3):495-499. DOI: 10.1109/LGRS.2007.898282

[36] Noferini L, Mecatti D, Macaluso G, Pieraccini M, Atzeni C. Monitoring of Belvedere Glacier using a wide angle GB-SAR interferometer. Journal of Applied Geophysics. 2009;**68**(2):289-293. DOI: 10.1016/j.jappgeo.2009.02.004

[37] Riesen P, Strozzi T, Bauder A, Wiesmann A, Funk M. Short-term surface ice motion variations measured with a ground-based portable real aperture radar interferometer. Journal of Glaciology. 2011;**57**(201):53-60. DOI: 10.3189/002214311795306718

[38] Voytenko D, Dixon TH, Werner C, Gourmelen N, Howat IM, Tinder PC, et al. Monitoring a glacier in southeastern Iceland with the portable terrestrial radar interferometer. In: Proceedings of the International Geoscience and Remote Sensing Symposium (IGARSS). 2012. pp. 3230-3232. DOI: 10.1109/IGARSS.2012.6350736

[39] Voytenko D, Stern A, Holland DM, Dixon TH, Christianson K, Walker RT. Tidally driven ice speed variation at Helheim Glacier, Greenland, observed with terrestrial radar interferometry. Journal of Glaciology. 2015;**61**(226):301-308. DOI: 10.3189/2015JoG14J173

[40] Xie S, Dixon TH, Voytenko D, Holland DM, Holland D, Zheng T. Precursor motion to iceberg calving at Jakobshavn Isbræ, Greenland,

observed with terrestrial radar interferometry. Journal of Glaciology. 2016;**62**(236):1134-1142. DOI: 10.1017/jog.2016.104

[41] López-Moreno JI, Alonso-González E, Monserrat O, Del Río LM, Otero J, Lapazaran J, et al. Ground-based remote-sensing techniques for diagnosis of the current state and recent evolution of the Monte Perdido Glacier, Spanish Pyrenees. Journal of Glaciology. 2019;**65**(249):85-100. DOI: 10.1017/jog.2018.96

[42] Luzi G, Dematteis N, Zucca F, Monserrat O, Giordan D, López-Moreno JI. Terrestrial radar interferometry to monitor glaciers with complex atmospheric screen. In: Proceedings of the International Geoscience and Remote Sensing Symposium (IGARSS); Vol. 2018, July. 2018. pp. 6243-6246. DOI: 10.1109/IGARSS.2018.8519008

[43] Caduff R, Schlunegger F, Kos A, Wiesmann A. A review of terrestrial radar interferometry for measuring surface change in the geosciences. Earth Surface Processes and Landforms. 2015;**40**(2):208-228. DOI: 10.1002/esp.3656

[44] Monserrat O, Crosetto M, Luzi G. A review of ground-based SAR interferometry for deformation measurement. ISPRS Journal of Photogrammetry and Remote Sensing. 2014;**93**:40-48. DOI: 10.1016/j.isprsjprs.2014.04.001

[45] Pellikka P, Rees W. Remote Sensing of Glaciers: Techniques for Topographic, Spatial and Thematic Mapping of Glaciers. Boca Raton, USA: CRC Press; 2009. ISBN: 978-0-415-40166-1

[46] Daniels DJ. Ground Penetrating Radar: Theory and Applications. 2nd ed. The Institution of Electrical Engineers, London; 2004

[47] Macheret YY, Zhuravlev AB. Radio echo-sounding of Svalbard glaciers. Journal of Glaciology. 1982;**28**(99):295-314. DOI: 10.1017/S0022143000011643

[48] Damm V. Ice thickness and bedrock map of Matusevich Glacier drainage system (Oates Coast). Terra Antart. 2004;**11**(1-2):85-90

[49] Arcone SA, Yankielun NE. 1.4 GHz radar penetration and evidence of drainage structures in temperate ice: Black Rapids Glacier, Alaska, USA. Journal of Glaciology. 2000;**46**(154):477-490

[50] Machguth H, Eisen O, Paul F, Hoelzle M. Strong spatial variability of snow accumulation observed with helicopter-borne GPR on two adjacent Alpine glaciers. Geophysical Research Letters. 2006;**33**(13). DOI: 10.1029/2006GL026576

[51] Pralong A, Funk M. On the instability of avalanching glaciers. Journal of Glaciology. 2006;**52**(176):31-48. DOI: 10.3189/172756506781828980

[52] Röthlisberger H. Water pressure in intra- and subglacial channels. Journal of Glaciology. 1972;**11**(62):177-203. DOI: 10.3189/s0022143000022188

[53] Hart DP. The elimination of correlation errors in PIV processing. In: Proceedings of the 9th International Symposium on Applications of Laser Techniques to Fluid Mechanics; Volucella. 1998. pp. 13-16

[54] Giordan D, Wrzesniak A, Allasia P. The importance of a dedicated monitoring solution and communication strategy for an effective management of complex active landslides in urbanized areas. Sustainability. 2019;**11**(4):946. DOI: 10.3390/su11040946

[55] Wrzesniak A, Giordan D. Development of an algorithm for automatic elaboration, representation and dissemination of landslide monitoring data. Geomatics, Natural Hazards and Risk. 2017;**8**(2):1898-1913. DOI: 10.1080/19475705.2017.1392369