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The Support of Geomatics in Glacier Monitoring: The Contribution of Terrestrial Laser Scanner

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1. Introduction

Worldwide glacier monitoring was initiated more than a century ago and it is now integrated into global climate-related observation systems. Glacier mass changes have been clearly recognised as high-confidence climate indicators with respect to early detection strategies of greenhouse effects on climate (Hoelze et al. 2003).

Combinations of in-situ observations with remotely sensed data, traditional measurements with new technologies, are an integrated and multi-level strategy applied to the worldwide glacier monitoring within major climatic zones by the international institution of the Global Terrestrial Network for Glaciers (GTN-G) and Global Terrestrial Observing System (GTOS) (Haeberli et al., 2005).

Many examples of successful applications of space-borne synthetic aperture radar interferometry (InSAR) are available in the scientific literature of the last decades applied to detection of ground surface deformations (induced by seismic or volcanic activities) and for monitoring of glacier motion (Wasowski & Gostelow, 1999; Massonet & Feigl, 1998)

The applications of Ground Remote Monitoring techniques (Ground Based - Synthetic Aperture Radar (GB-SAR) and Terrestrial Laser Scanner (TLS) for extraction of topography and flow properties of glaciers are less frequent.

As reported by Sailer et al. (2005), the observational parameters include "accurate topographic data of the observed target and its surroundings, as well as of the terrain that may be affected down-streams of a glacier by floods or avalanches. Depending on the size and accessibility of the area to be observed and on the repeat interval, satellite-borne, airborne or ground based imaging sensors or scanners (InSAR, photogrammetry, GB-SAR, terrestrial laser scanner - TLS) are the preferable observational tools".

Even in the above mentioned work, three types of basic observational requirements for each of the glacial hazard type are mentioned:

- base maps (extent of glaciers, glacial lakes, surface morphology);
- topographic data (DEM);
- surface motion (of glacier and/or moraine).

This chapter shows the methodology and application results of the Terrestrial Laser Scanner for the extraction of topographic data and surface motion at the Belvedere Glacier, in Italian Alps.

The monitoring campaigns have been performed in Summer/Autumn 2006 and 2007 and they consist on measurements of the central/lower part of the glacial body, of the glacier snout and measurement of a landslide (the Locce landslides), affecting the terminal moraine of the Locce Glacier, tributary on the right side of the Belvedere Glacier.

2. The Belvedere glacier

The Belvedere Glacier (WGI code I4L01211009) is located in the Anzasca valley, Macugnaga (45°58′ N, 7°58′ E), in the north-eastern sector of Piemonte (Italy).

It is a rock covered glacier (Mazza, 1998) situated at the base of the gigantic Monte Rosa east face. According to the Glaciorisk database (GRIDABASE http://www.nimbus.it/glaciorisk/gridabasemainmenu.asp) the glacier elevation ranges from a maximum of 4520 m a.s.l. to a minimum of 1760 m a.s.l., its length is about 6 km and its maximum width is up to 500 m, with an average surface of 5.58 km². It's oriented at 45° north with an average slope of 10°. The glacier main body is connected, in its upper part, with the Northern Locce, Signal and Monte Rosa Glaciers and it ends with a forked snout.

The glacier has been subject of scientific studies and expeditions from the end of the 18th century, when its magnitude has been firstly described and highlighted (De Saussure, 1779 - 1796).

At the beginning of the present century - since 1999, according to Mazza (2003) - the glacier has undergone a remarkable increase in horizontal displacement speed and surface elevation. According to the displacement rate measurement, carried out by remote sensing techniques, the speed of the glacier has increased from 32 – 43 m per year, recorded in the last 5 years of the 20th century to 92 – 112 m per year (02/09/1999 – 06/09/2001); in the autumn of the same year the speed had still increased to its maximum of 100 – 200 m per year (Kaab et al., 2005).

According to the definition of Haeberli et al (2002) the Belvedere glacier has been subject to a "surge-type movement", currently a unique phenomenon in the Alps; conversely Mazza (2003) have explained the phenomena with the kinematic waves theory due to the reduced horizontal displacement speed, the lack of the formation of a terminal moraine and the absence of the typical block-flow movement; in fact, due to the high displacement speed, the glacier is unable to keep a viscous flow and breaks into small ice blocks. Moreover, the kinematic wave theory is supported by previous events, though characterised by reduced magnitudes, occurred between 1984 and 1985 and at the end of 1992 (Mazza, 2003).

The surface elevation has shown a similar trend, with an increase in ice thickness of up to 20 m reaching the level of the Little Ice Age moraine (Mortara et al., 2003), with the consequent

appearance of large crevasses on the whole glacier. Due to the described phenomena the formation of a new moraine has been observed. Contemporarily, in the upper part, the glacier surface has shown an opposite state, by lowering its elevation and in the originated depression a supraglacial lake has been observed. The lake has been identified as the "*Effimero Lake*" (Figure 1).

The lake has undergone different fillings until reaching its maximum volume of $3 \cdot 10^6$ m^3 and a 57 m depth with evident risk of GLOF (Glacial Lake Outburst Flood) or *jökulhlaup* due to termokarst processes or rockfall from Monte Rosa East Face. During the most critical phase the lake level has been rising with a rate of 1 m/day so an overflow event was also evaluated (Mercalli et al., 2002; Mortara et al., 2003; Mortara and Mercalli, 2002; Tamburini and Mortara, 2004).



Fig. 1. The "Effimero lake", in the left of the image the "Locce lake" (Photo G. Mortara)

In the past, similar events have been observed in Belvedere glacial basin. Due to intense precipitation, the consequent outbursts of a water pocket inside the glacier have provoked different collapses in the lateral moraines and the consequent trigger of debris flows (1868, 1896, 1904, 1922) as reported by Haeberli et al (2002).

Since 1990 (Fischer et al., 2006; Fischer et al, 2011) the Monte Rosa east face has also been involved in several episodes of ice and rock avalanches, due to the permafrost degradation in high mountain slopes caused by the increase of 0° C isotherm altitude (Beninston, 2003; Carrasco et al., 2005).

Permafrost and ice play a key role in high mountains slope stability, the presence of ice in discontinuities improves the bond between rocks by its adhesion effect. Melting results in the loss of this factor and in the increase of flowing water, increasing the pressure in joints and, consequently, lowering the shear strength (Davies et al., 2001). Unfortunately such

events have been observed in the rest of the Alps in the last years (Deline et al., 2002; Deline et al., 2004a; Giani et al., 2001; Godone et al., 2007).

In the last years two main events have been observed: on 25 August 2005 a massive ice avalanche has fallen down from the Monte Rosa east face with a total volume of up to $1.1 \cdot 10^6$ m³; on 21 April 2007 a similar event has happened (Figure 2), with nearly halved volume involved (~500000 m³) (Cat Berro et al., 2008). In every occasion, the debris has covered the upper sector of Belvedere and due to its mixed composition, rocks and ice, can be considered as a contribution in glacier mass balance (Federici et al., 2008).



Fig. 2. The 2007 ice avalanche deposit (photo G. Mortara)

Both phenomena, the changes in surface dynamics and the supraglacial lake, have triggered a civil protection procedure in order to reduce risk related to the explained events for the inhabitants of Macugnaga (Mercalli et al., 2002; Mortara et al., 2003; Mortara and Mercalli, 1999). Fortunately the lake has ended, by itself, the emergency state by two endoglacial outbursts, due to the improvement in subglacial drainage system, finished without consequences (Tamburini and Mortara, 2004; Tamburini et al., 2003). The two episodes occurred on 19 and 20 June 2003 with a discharge of, respectively, 14 and 9 m³/s; among them a marked discharge reduction has been observed, probably due to a temporary obstruction in the drainage system.

3. Materials and methods

The traditional measurements carried out using GPS and ablatometric stakes provide only punctual evaluations of the phenomena. In glacier monitoring an extensive approach could be preferred in order to obtain a complete description of the surveyed object. According to this statement, different Terrestrial Laser Scanner campaigns have been planned at different sites of the glacier surface, in order to evaluate the most interesting geodynamical phenomena during their evolution. The measurements includes the central body of the glacier, the snouts and a landslides affecting the frontal moraine of the Lago delle Locce and the right side of the Belvedere Glacier in its upper part (Figure 3).

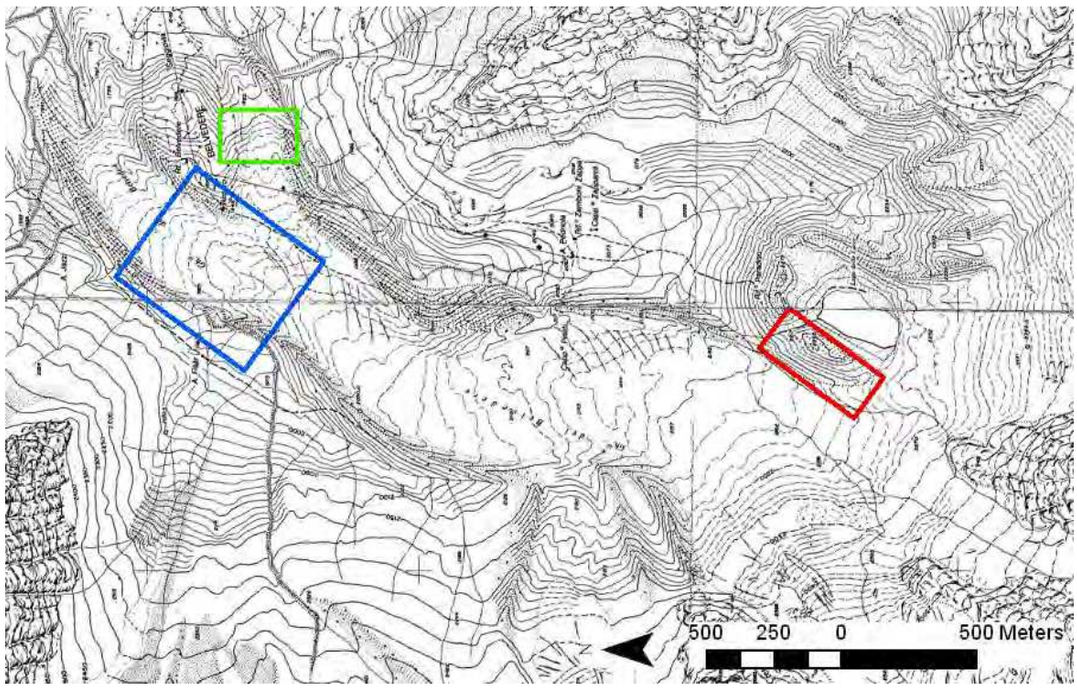


Fig. 3. Terrestrial Laser Scanner survey sites: right snout (green square), Locce landslide (red square) and glacier surface (blues square). Regional Technical Map (original scale 1:10000) in background



Fig. 4. The Optech ILRIS-3D laser scanner during a field masurements (photo P. Federici)

The Laser Scanner work as a range finder, projecting thousands of laser pulses towards the survey target and through the reflected beams is capable of reconstructing its geometry; moreover, by measuring the object from different points of views it's possible to complete the description avoiding shadow effects, induced by object features.

The instrument employed in the following experiment was the Optech ILRIS-3D™ (Figure 3). The laser is characterised by a quite long range, according to target reflectivity, and it assures safe operational conditions according to laser safety standards, as reported in the following table (Table 1).

Dynamic scanning range	3 m - 1500 m to an 80% target
	3 m - 800 m to an 20% target
	3 m - 350 m to an 4% target
Data sampling rate (actual measurement rate)	2500 points per second
Beam divergence	0.00974°
Minimum spot step (x and y axis)	0.00115°
Raw range accuracy	7 mm @ 100 m
Raw positional accuracy	8 mm @ 100 m
Laser wavelength	1500 nm
Laser class (IEC 600825-1)	Class 1
Digital camera	Integrated digital camera 6 Mpixel (CMOS sensor)
Scanner field of view (ILRIS-3D)	40° x 40°

Table 1. ILRIS-3D technical characteristics (www.optech.ca/i3dtechoverview-ilris.htm)

The laser is built in a robust metal case, allowing its employment in fieldwork conditions, moreover, thank to a special backpack the instrument is fully portable (Figure 5). The complex weight is up to 13 kg and with the aid of a second operator carrying the battery pack and the tripod is fully operational without further equipments.



Fig. 5. ILRIS-3D mounted on tripod and the special backpack employed in instrument transport (left) and ILRIS-3D interface control - red squares represent surveyed areas, the green one is the area under measurement (right)

At the beginning of the survey, the instrument acquires a picture of the object with its incorporated digital camera, and displays it on the controller screen. This enables the operator to decide the area, or the areas – e.g. the objects and targets - of the picture to be scanned by simply drawing rectangular selection windows and by specifying acquisition parameters for each one.

The aim of the whole experiment was the comprehension of glacier dynamics in time, so a multitemporal approach has been adopted when planning the surveys. In order to maximize the productivity and avoid risks for the operators, the employment of targets placed on the object has been strongly limited. One advantage of the laser scanner is to work without contact with the surveyed objects, so allowing to measure dangerous or inaccessible places, too. This peculiarity has already been employed in landslide and volcanoes monitoring (Hunter et al., 2003; Oppikofer et al., 2008).

For each area under observation, two scan sessions have been executed with the aim of measuring changes in glacier features; during the third test on the central body of the glacier also measurements of some targets have been used in order to make a comparison with ablation stakes measurement accomplished with GPS, thus obtaining co-registered data.

The acquisition strategy has been planned with the aim of measuring an overlapping sector among adjacent scans and to include stable areas external to the survey object. Overlapping parts have been used while collecting tie points (Figure 6) to join scans into a single point cloud and stable areas have been employed for the alignment of multitemporal scans, as reference areas.

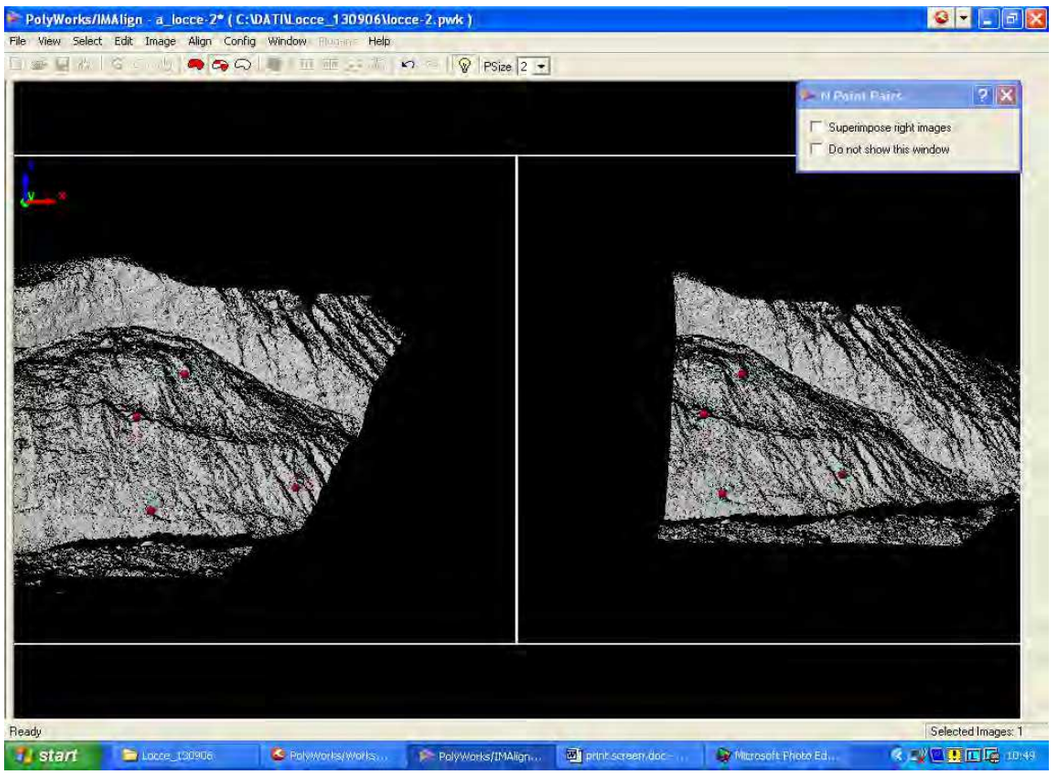


Fig. 6. Scans co-registration though common feature collimation (red points)

Data processing have been performed using Innovmetric Polyworks™, the software is subdivided in modules specifically designed for the different work phases. The ImAlign module is dedicated to the alignment of different scans into a unique reference system, in the described experiment this goal has been achieved by homologous feature collimation; using an interactive closest point algorithm (Beinat, 2006; Besl and Mc Kay, 1992; Chen and Medioni, 1992), the matching has been achieved with good results in alignment accuracy by employing only few couples of selected points.

The point cloud is not really modified by the operation, as the software compiles a rototranslation matrix used in locating the original data in the three dimensional reference system. By comparing multitemporal matrix parameters a computation of object displacement can be achieved, too.

The module allows also performing manual object removal and data cleaning in order to obtain an essential point cloud without minor details such as trees or buildings. By selecting different sectors of a point cloud the software allows to separate stable and unstable areas with the purpose of using them, respectively, in multitemporal alignment and comparisons (Figure 7).

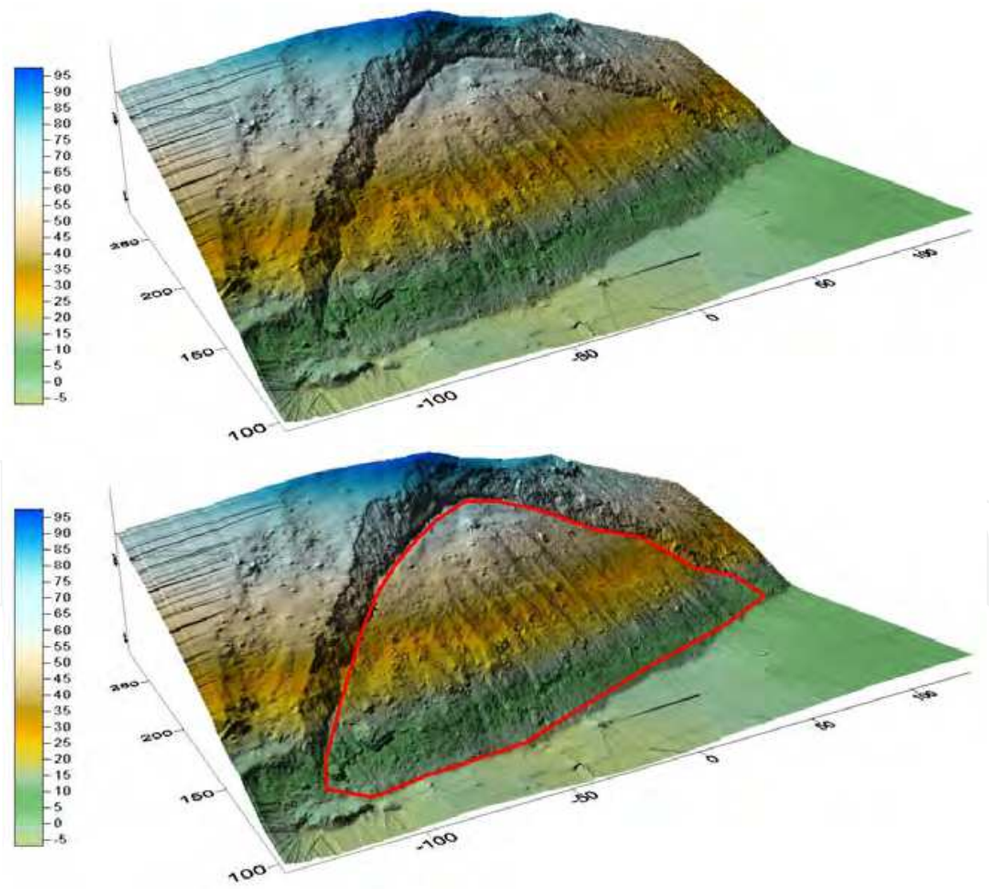


Fig. 7. Triangulated surface of the Locce landslide and selection on the moving/stable areas (red line) for the alignment and movement determination.

The software processes 3D data according to their reference system so when a complex or huge amount of data needs to be aligned, the operator may select only the usable sectors and perform the alignment; then by applying the rototranslation matrix to the whole dataset, the software computes the alignment parameters achieving the final results and reducing computational time and efforts.

At the end of the alignment procedure, the software opens the second module, ImMerge, where the point cloud is transformed into triangulated surfaces. Surfaces are computed according to the Delaunay triangulation (De Smith et al, 2007) thus generating triangular networks (Lambers et al, 2007). The meshing process is necessary as the comparison algorithm need to compute differences between two continuous surfaces and not on point clouds; the second option is however feasible but computation time is quite longer and the success in the process conclusion is not guaranteed.

The computed surface may be edited in the following module, ImEdit, where volume calculation and cross section extraction may be executed, too.

On the other hand the surface comparisons are carried out in the ImInspect module. This one is dedicated to the inspection of meshes and the analysis of differences between them according to predefined directions e.g. along one axis, along the shortest distance or along a user specified vector.

The inspection could also be carried out manually, by vector plotting on homologous features in two different, multitemporal, meshes. In this module the mesh georeferencing is also achievable by assigning coordinates to point picked on the surface; the software has a series of functions, that help the operator in finding the centre of the target by interpolation algorithms, as usually target coordinates are referred to the target centre.

3.1 Moraine survey

The Locce Landslide has been measured according to the same approach adopted in the snout survey, explained in details in the next paragraph; the first survey has been carried out on 01/08/2006 and the second one on the 13/09/2006. Also in this experiment the object has been measured by various scan positions.

Each scan session has been accomplished with a 7 cm resolution obtaining up to 9 million of 3D points (see again figure 7).



Fig. 8. Panoramic image of Belvedere right snout

3.2 Terminus survey

The right snout of the Belvedere Glacier (Figure 8) has been surveyed in two separated sessions on the 02/08/2006 and on the 14/10/2006. Each session (Figure 9) has been subdivided in different scan positions, in order to completely measure the glacier snout and to include, in sessions, the mountainside and the Little Ice Age moraine, with the purpose of employing their feature as reference areas.

As showed in the figure 9, reporting the instrument interface, the scans have been executed with a 20 cm resolution collecting up to 11 millions of points in the first session and 14 millions in the second one.

Data has been downloaded in a folder and then processed in the previously explained mode. The comparison between the two scan sessions has been carried out by the assessment of differences, between surfaces along the z axis, in order to quantify the ablation, in the snout zone. Moreover, by manual object recognition a few boulders have been determined in both surfaces and their locations have been linked by a vector, in order to analyze the main snout displacement direction.

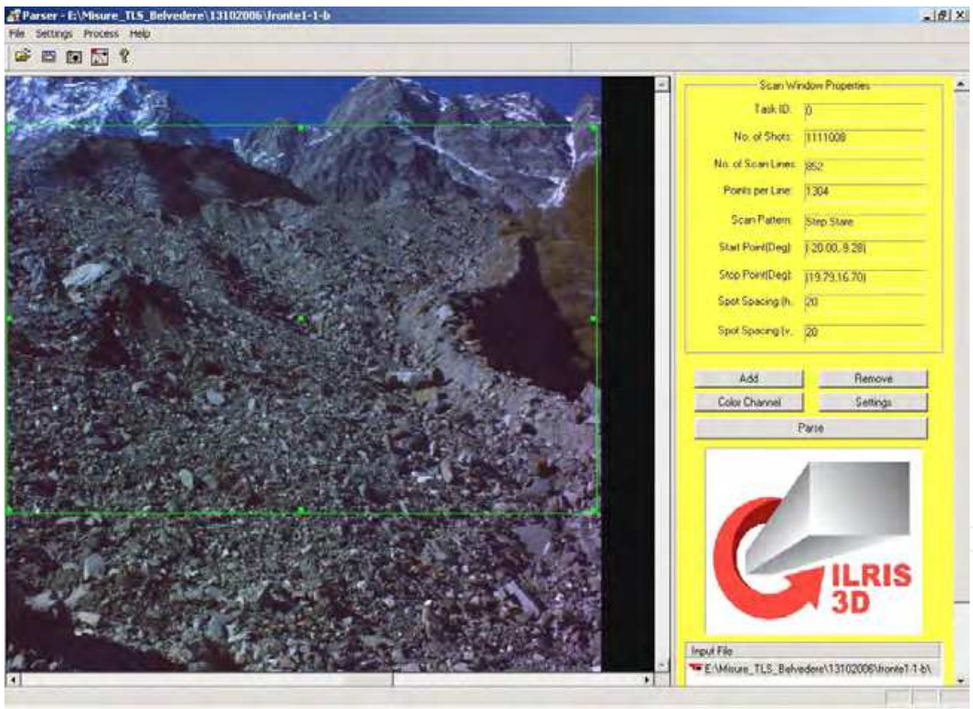


Fig. 9. ILRIS-3D interface during snout survey

3.3 Glacier surface survey

The survey of glacier surface has required a more complex procedure as the georeferencing of the final result was necessary.

During a survey campaign five targets have been placed on the glacier and their position has been measured employing the differential GPS, as in stake positioning (Figure 10). The

coincidence of the two measurements has been repeated during the second laser survey in order to have the same time span covered by two kinds of survey methods.

Target coordinates have been processed as well as the one belonging to stakes and stored in an ASCII file in order to be used in surface georeferencing.

The laser measurement has then been executed, during the survey different resolutions have been chosen when scanning the glacier (7 cm resolution) or targets (1 cm resolution). According to these parameters, during the first session the glacier surface has been measured by 14 millions of 3D points and by 19 millions in the second session.

The data obtained from the first scan has been aligned in one overall point cloud and then georeferenced by the employment of targets coordinates. The triangular meshes obtained from the two scan sessions have then been co-registered on reference areas i.e. the lateral moraines.

The surface has then been compared along the z axis in order to evaluate the ablation and manually processed in order to find boulders or other homologous features on both sessions.

Boulders have been processed by computing their rototranslation matrix (from session 1 to session 2), with the purpose of obtaining vectors parameters and evaluating glacier displacement.

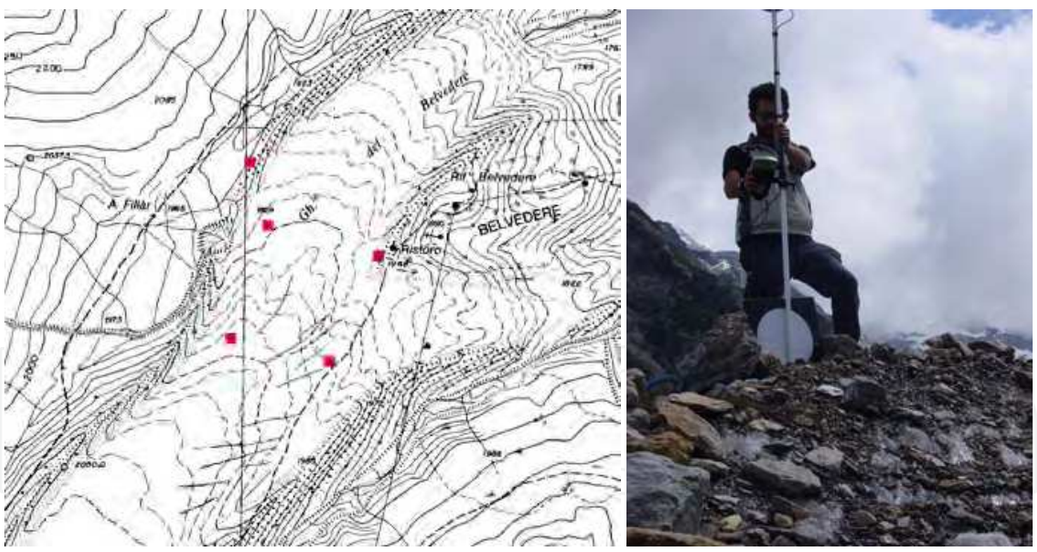


Fig. 10. Targets location (Regional Technical Map, original scale 1:10000, in background) and survey (Photo P. Federici)

3.3.1 Comparison with ablatometric stakes

Thank to the availability of georeferenced laser scans, an independent check of the results of multi-temporal point cloud comparisons, could have been carried out with punctual ablation stakes surveys carried out in the same monitoring campaigns (Godone et al., 2010). In early June 2006 ablation stakes have been installed on the Belvedere Glacier surface and stakes

measurements have been repeated regularly during 2006 and 2007 ablation seasons (figure 9). Stakes were introduced in ice up to a depth of 8 meters, after perforation of ice by means of a stream driller, as shown in figure 11, and periodically checked with differential GPS measurements. At the same time the ablation rate was measured at each point.

This procedure has been employed in order to evaluate laser scanning reliability in glacier monitoring in comparison with a well-established technique.

Ablation and displacement data obtained from both methodologies have been statistically compared, by Student's *t* test, in order to evaluate results differences and comparability, and moreover to highlight critical aspects.



Fig. 11. Installation of an ablation stake using a stream driller and D-GPS measurement (Photo P. Federici)

4. Results and discussions

The laser scanner approach allows to extend the survey and analysis to an entire object, or a portion of it, and not to narrow only on discrete locations as in traditional surveys, e.g. GPS, topographical surveys.

Moreover the analysis tools available in data processing software allow the accomplishment of several investigations and testing with the purpose of extending the comprehension of the analysed phenomena.

The accuracy obtained in pre-processing (scans alignment) allowed to execute the comparisons. In the last experiment it has been computed as decimetric and centimetric in the other two tests

4.1 Moraine landslide survey

The measurement of the Locce landslide allowed, although not directly, the understanding of the global dynamic of the glacier. The survey approach was the same of the other two cases with multiple and multitemporal (01/08/06 and 13/09/06) scans.

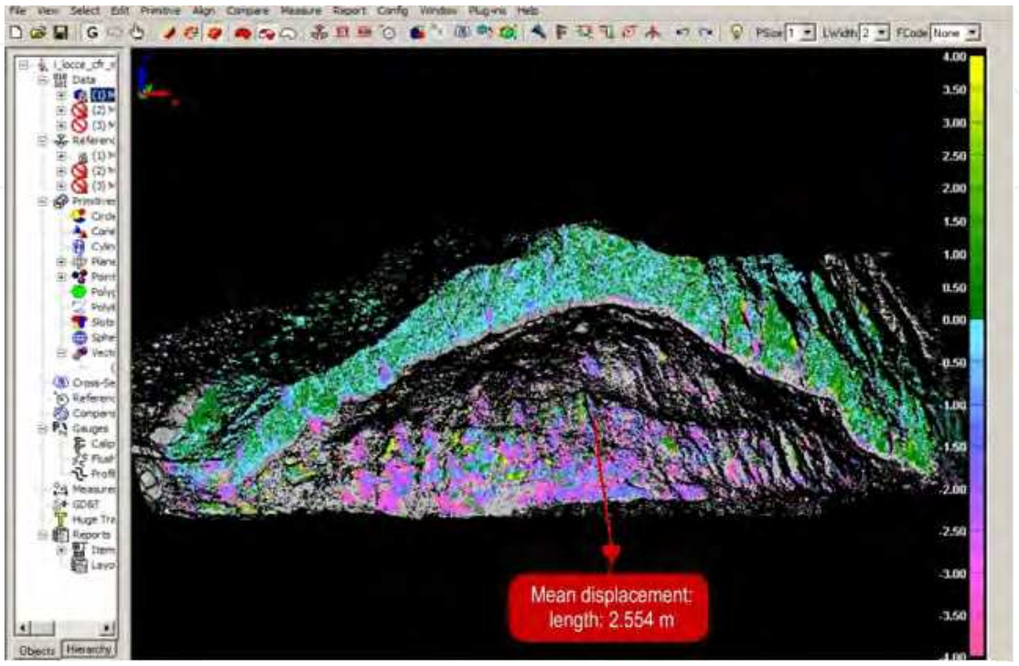


Fig. 12. Map of landslide collapse computed by subtracting the two multitemporal surfaces along the average displacement vector

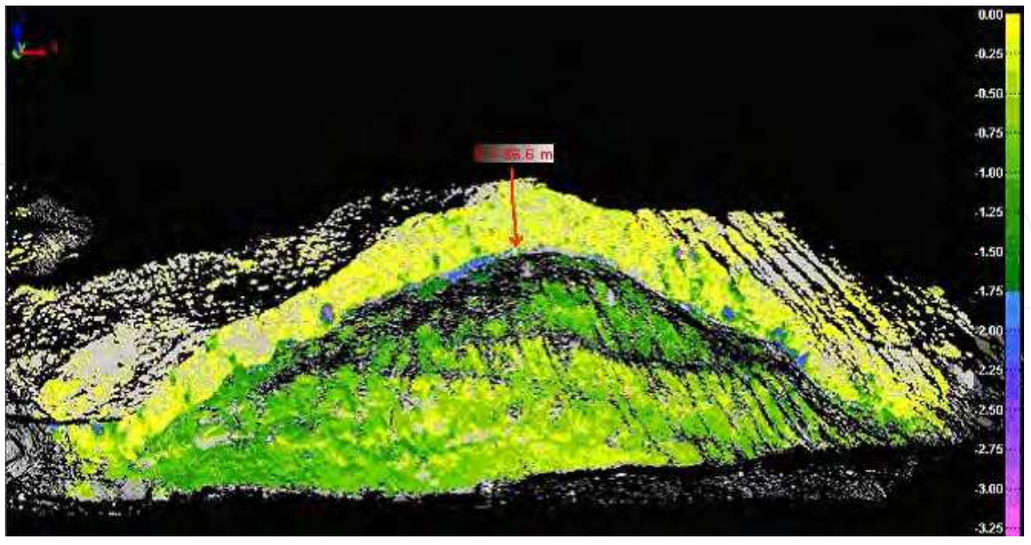


Fig. 13. Measure of the total displacement of the landslide from its edge

The surface comparison gave an average measure of landslide movement of over 2 m (Figure 12) with an average rate of 0.05 m/day and in addition, through manual

measurement, the total vertical shift of the landslide mass has been estimated in 36.62 m since the trigger of the event (Figure 13).

In this experiment the accuracy reached in the alignment phase was centimetric.

4.2 Terminus survey

The right snout has been measured on the 02/08/06 and on the 13/10/06 with multiple scans, point clouds obtained from the measurement have than been separately merged into a unique surface and then compared, after the alignment according to fixed features. The alignment processes have been accomplished obtaining centimetric accuracy allowing the execution of the next measurements.

The comparison has been carried out in two ways, automatic and manual. Firstly the data comparison has been performed by assessing the differences between the two surfaces along the z axis (Figure 14), by evaluating an estimate of the front ablation of about 4 m and then by manually plotting vectors linking the same feature represented in both point clouds, usually large boulders, in order to estimate the displacement (Figure 15). At the end of the process up to six vectors have been measured (Table 2), obtaining an average displacement of 6.93 m and a rate of 0.09 m/day.

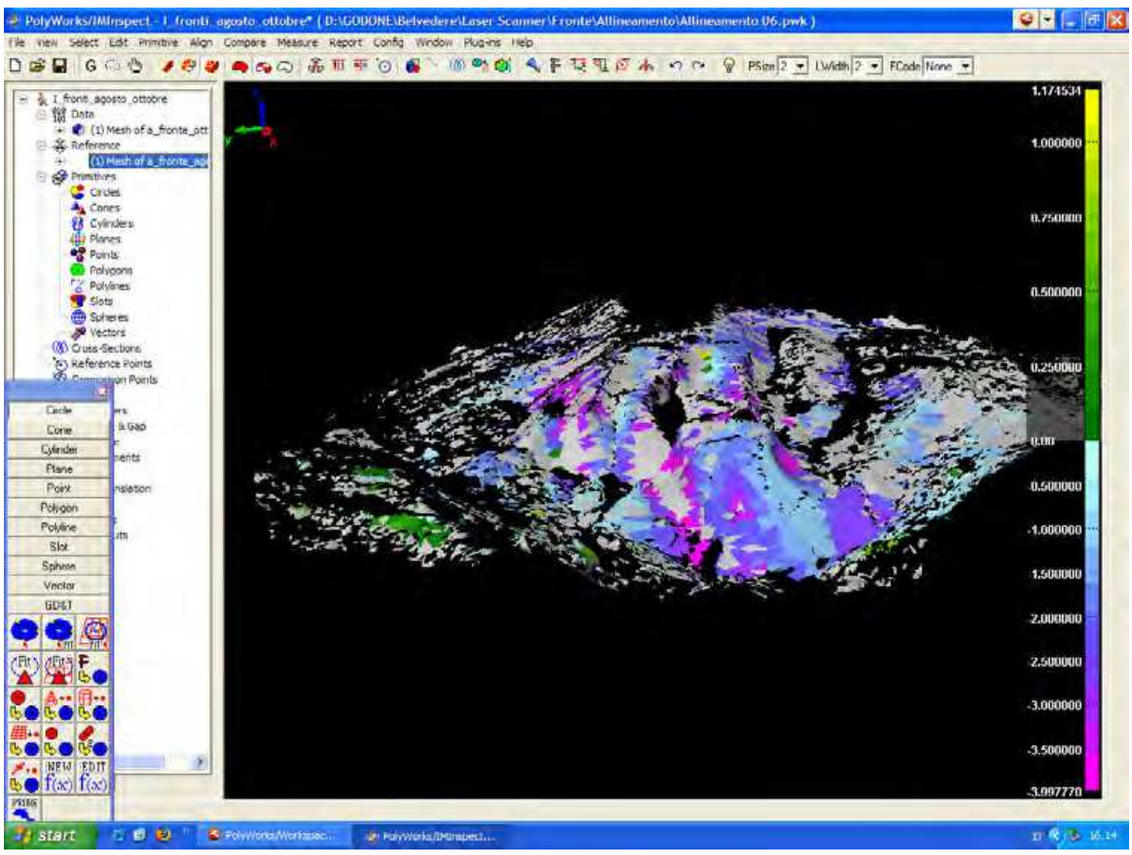


Fig. 14. Map of snout ablation computed by subtracting the two multitemporal triangulated surfaces along z axis

Vector	x	y	z	rx	ry	rz	Length
1	112.76	54.55	53.88	-0.89	0.02	-0.45	11.03
2	163.03	85.88	67.58	-0.93	0.04	-0.37	5.73
3	162.13	37.35	79.50	-0.54	-0.79	-0.30	8.06
4	93.01	-6.80	39.29	-0.71	-0.44	-0.55	6.05
5	73.65	1.53	33.70	-0.87	-0.22	-0.44	4.92
6	59.15	17.04	30.14	0.00	-0.75	-0.66	2.40

Table 2. Vectors measured from natural benchmarks (vectors 1, 2, 4 and 5 have been employed in snout displacement computation)

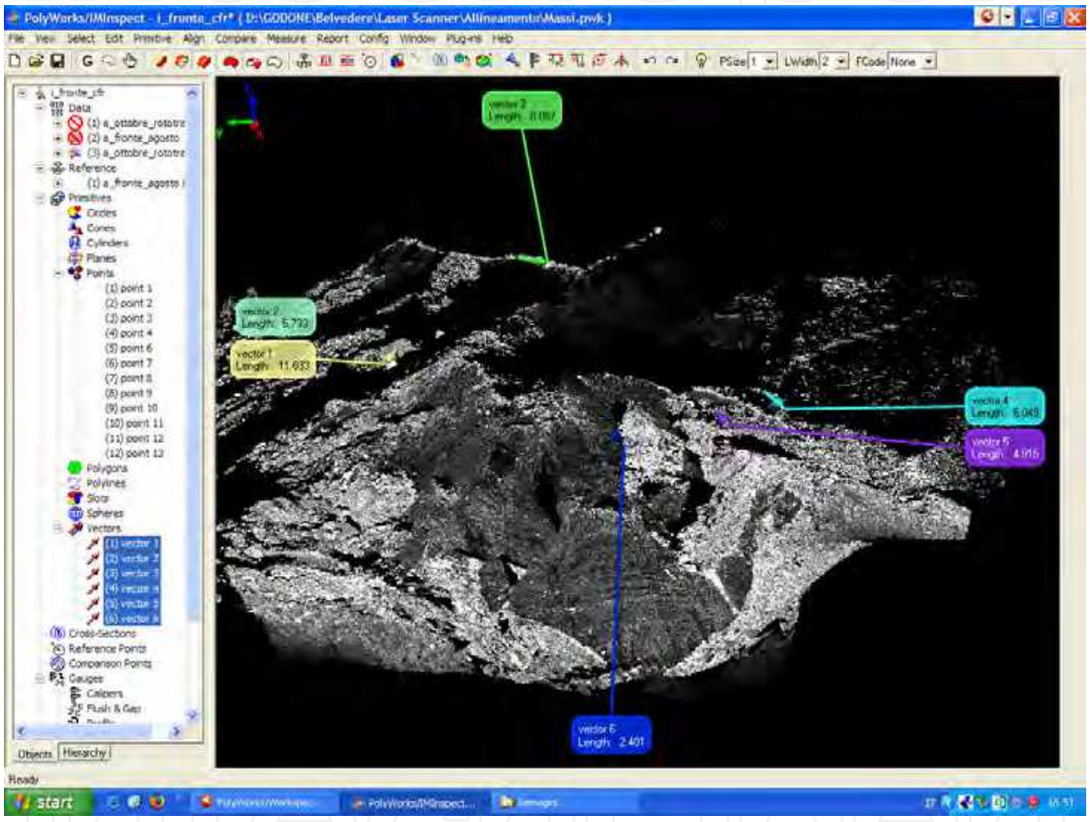


Fig. 15. Vectors plotted on the glacier 3D point cloud

4.3 Glacier surface survey

The multitemporal survey (29/06/2007 – 01/09/2007) of the Belvedere surface has provided a global overview of glacier dynamic, and despite the traditional approach, i.e. stake measurement, results are widespread to the whole surface investigated and not only related to the position of every single stake.

4.3.1 Data alignment and calibration

The georeferencing of the first surface, through target alignment, has assured enough accuracy in order to continue the comparison process. The two multitemporal surfaces have

been aligned using the "natural benchmark" approach; in other words employing natural features such as boulders and rocks on glacier cover, with an accuracy of ± 0.2 m (Figure 16).

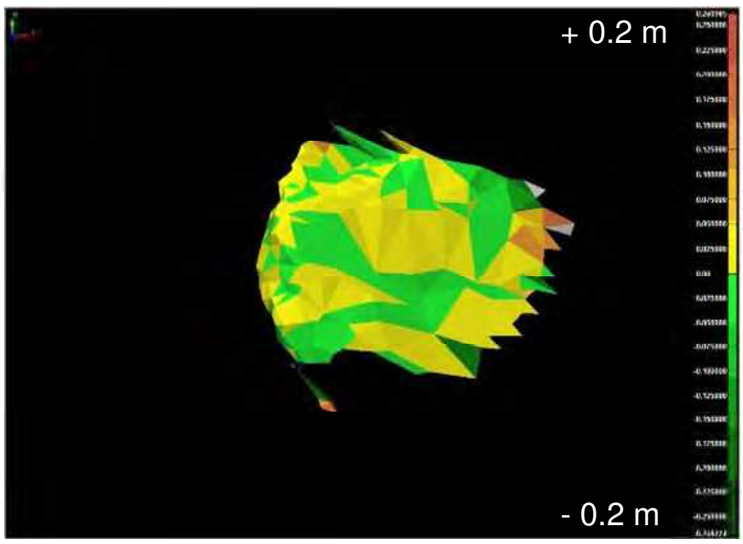


Fig. 16. Residuals of the alignment of the two surfaces computed on natural benchmarks

4.3.2 Displacement

The analysis executed on "natural benchmarks" on the surface of the glacier has allowed identifying up to 40 boulders, usable for displacement vectors computing (Figure 17, Figure 18). The calculation carried out on the rototranslation matrices has provided a displacement measurement ranging from 0.436 to 7.615 m, with an average rate of 0.059 m per day

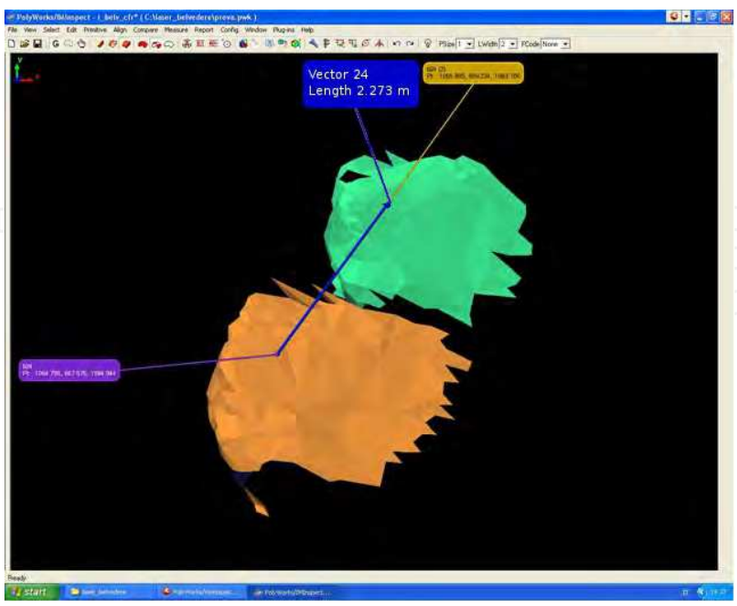


Fig. 17. Measurement of displacement vector on two multitemporal positions of the same boulder

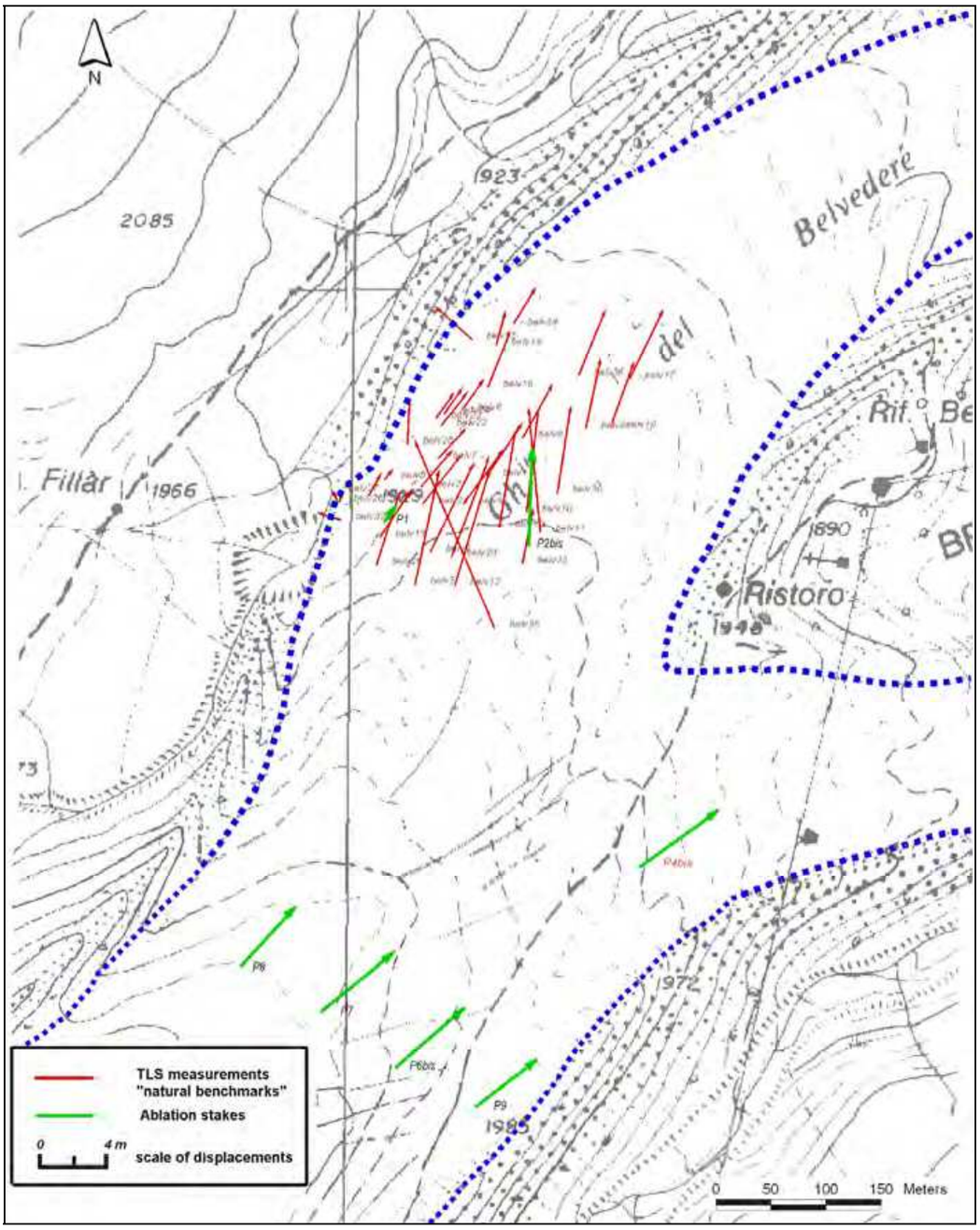


Fig. 18. Displacement measured with TLS on "natural benchmarks" (in red) and from ablation stakes positions (green)

4.3.3 Ablation

The difference of surfaces' elevation, computed along the z axis, has resulted as the measure of the ablation of the investigated portion of the glacier. The ablation ranges from a minimum value of 2 m to a maximum of 8 m (Figure 19). The average ablation rate is 0.048 m/day; the rate measured with traditional method in the same period – 65 days – is 0.028 m/day.

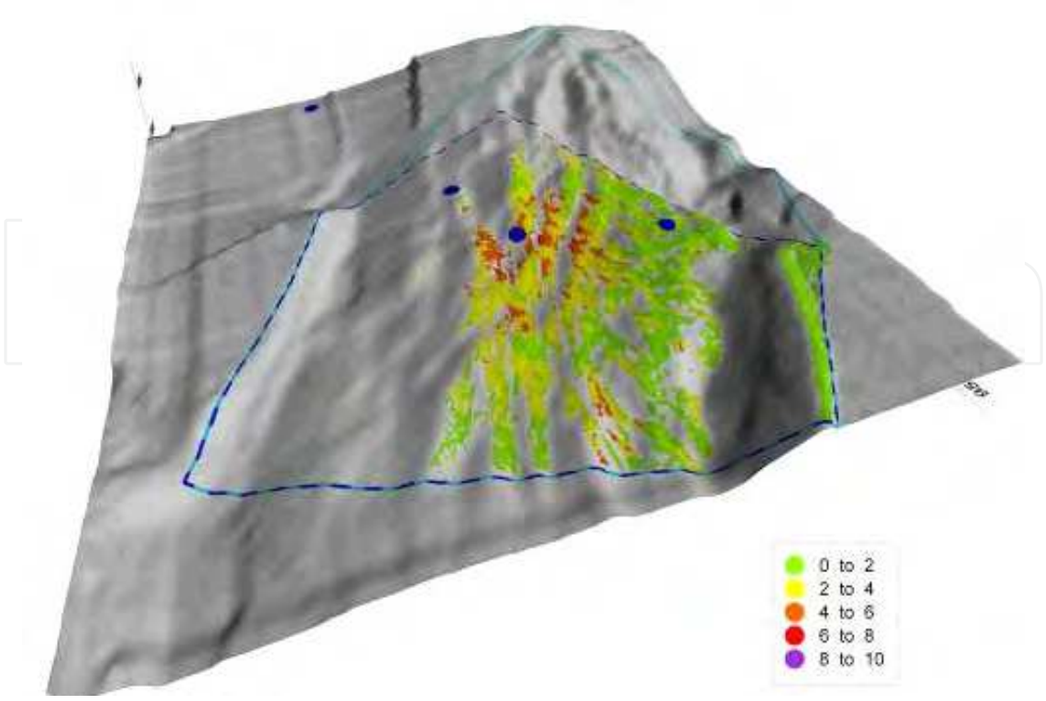


Fig. 19. Ablation map computed by subtracting two multitemporal surfaces

5. Discussion

The terrestrial laser scanner measurement has been highly experimental, as currently is hard to find extensive experiments on glacier carried out with this technology, e.g. the Miage lake (Mont Blanc Massif) survey (Deline et al., 2004b).

Compared with GPS, total stations and other field instruments, the laser is more difficult to handle and carry during the way to measuring station but the high speed survey and final results anyway encourage its employment.

The opportunity of completely reconstruct the surveyed object is highly valuable in glaciology, as it allows to carry out measurement otherwise impossible or highly dangerous to operators. The resolution and the achievable accuracy (Figure 20), let to perform, not only global but also detailed measurements and analysis and moreover through a multitemporal approach change detection investigations are possible, with meaningful results.

Considering the glacier or its portion, the survey has always been subdivided in two or more measuring sessions; in the post processing phase the scan were aligned according to homologous feature common to two o more scans. In the first and the second case showed, feature measured, and employed for the alignment, has been selected in areas outside the analysis sector, and considered stable, such as the mountainside surrounding the survey target. This method is useful when the georeferencing of the object is not mandatory and a relative analysis is the objective. When needed, as in the last experiment, a set of target placed on the glacier and georeferenced has been used in order to align, and put in map coordinates, the scans. It's necessary to state that, sometimes, the second methodology is not

achievable; due to the impossibility to reach the survey object for safety reasons, as in the second and, particularly, in the first experiment.

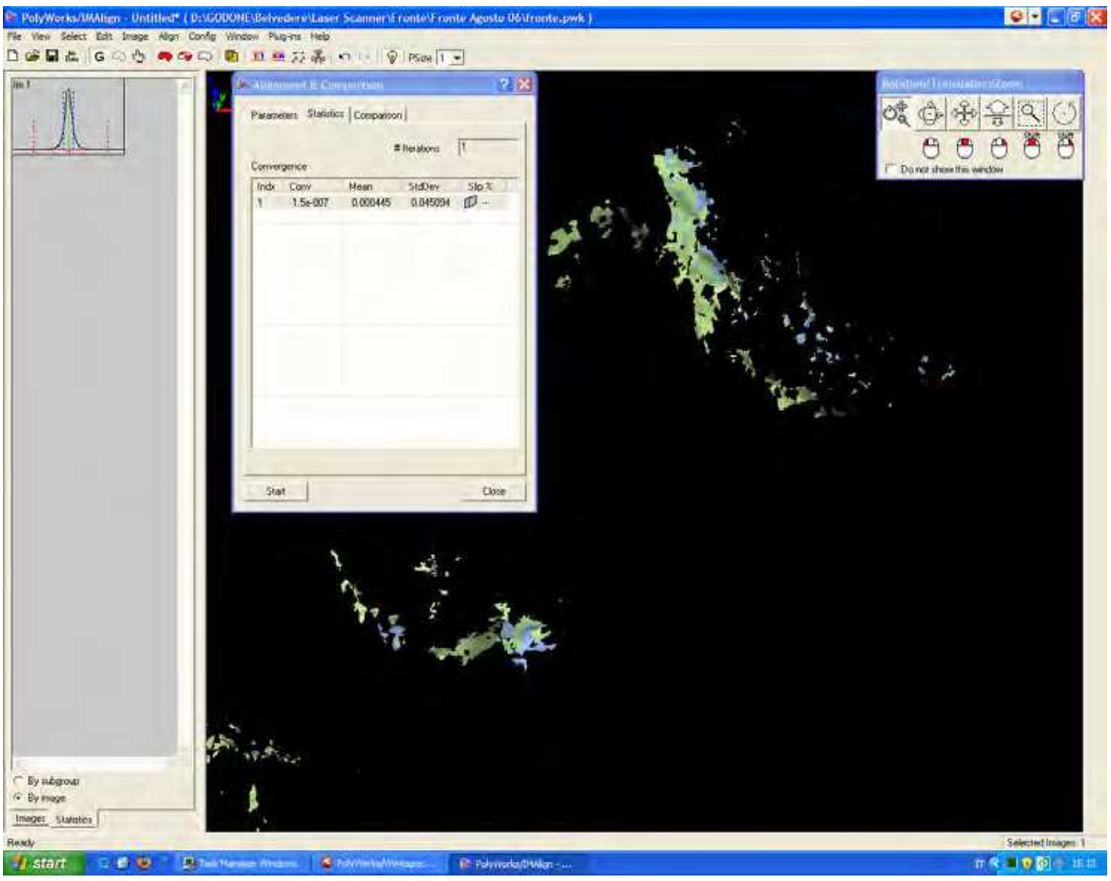


Fig. 20. Alignment accuracy assessment

5.1 Moraine survey

The survey of the Locce landslide has two goals, to monitor the process of the landslide in time and to give contributing factors to Belvedere dynamic comprehension.

As the following experiment, the measurements have been carried out with the change detection approach. The results obtained from the first analysis show the landslide trend to move towards the glacier surface (Figure 21). This fact may be partially explained by the pressure of the uphill lake, called "Lago delle Locce" that exerts a pressure on the surrounding moraine, including the landslide sector.

On the other side, however, there is the glacier surface and according to the recent dynamics, has been characterized by a sudden mass movement down valley, without the contribution of upper glaciers and without particularly abundant snowfall in the previous seasons. This flow has caused an increase of surface elevation in the lower sector of the glacier, and a consequential decrease in the upper part, including the Locce moraine sector (Haeberli et al., 2002; Kamb et al., 1985; Mazza, 2003; Miller, 1971).



Fig. 21. Evolution of the landslide from 01/05/2005 (upper left) to 26/06/2005 (upper right), year 2006 (lower left) and 2007 (lower right) (Photo courtesy: L. Schranz, A. Tamburini)



Fig. 22. Upper edge of the Locce landslide with evidences (red line) of further collapses (Photo G. Mortara)

The evidences, of these dynamic, are evident also on the top of the Locce moraine, where the main ridge is still collapsing and a rotational movement is clearly recognizable (Figure 22).

The terrestrial laser scanner has allowed studying the phenomenon as it prevented the operator to stay close to the object during measurement and provided a complete reconstruction in order to perform every kind of analysis requested, in a virtual environment. Due to the need of relative evaluations, the scans have been aligned on common features in stable areas of the survey, in order to avoid target placement in dangerous places. Notwithstanding the dimension of the landslide, every survey has been completed in one day, with multiple scans, assuring an accurate and detailed description of the site.

The analysis has been carried out both automatically and manually, highlighting the flexibility of the methodology when studying such events.

The magnitude of the phenomenon deserve further studies and deepening, as the Locce sector has been already involved in several lake outbursts in '70 (Mortara and Mercalli, 2002) and the current trend of the landslide is not leading to a safe and stable situation, if considering Belvedere glacier reduction, too.

5.2 Terminus survey

Measurement of glacier front, usually, are based on repeated surveys (often along predefined bearings) from a reference point placed at a certain distance form the glacier, in order to measure fluctuations in time (Bonardi et al., 2006). Obviously, this approach tends to excessively simplify the complexity of the front, with a single or discrete representation, however this approach is highly convenient as it requires cheap instrumentations. It is really fast to perform, but results are only referred to few point measured on the glacier. On the other hand, the employment of laser scanner requires skilled operators and the availability of such equipment, but the results are nearly impressive both under visual and geometrical point of view.

With terrestrial laser scanner, not only displacement evaluation have been executed, also ablation data are available after the scans alignment, by differentiating the obtained surface, a global evaluation is feasible; another advantage of this technique. In this case is more appropriate to refer the measurement to the snout rather than to the simple front.

The entire measurement has been completed in two session of one day duration, including the reaching of the site. As explained above, the snout has been measured from three different positions in order to scan the entire ice cliff and the surrounding mountainsides. The post processing phase has been subdivided in three phases; at the beginning the scans have been aligned, reconstructing the front in the two epochs, then the two surfaces have been aligned thank to external features and then, finally, the multitemporal analysis has been carried out. The two surfaces have then been compared globally along the z axis with the aim of obtaining an estimate of the ablation in the front sector. These data, compared with those measured in the, traditional, stake approach, in the same period, have shown similar values ($p = 0.380$) confirming the reliability of the method.

The ablation estimation has been carried out in a completely automatic way; on the contrary the measure of glacier displacement needs to be performed manually, as it is based on object

recognition on both surfaces. In order to measure the displacement on the two surfaces, features common to the two multitemporal scan have been searched. When a rock or a boulder was recognized, in both scans, was then used to manually generate a displacement vector, linking the two objects in the two scans.

Moreover the vector obtained needs to be checked in order to exclude those characterized by anomalous directions, probably due to falling of rocks and not strictly related to glacier displacement

Due to the 2.5 month period, only 6 vectors were traced and, among them, only 4 were then used in order to compute the displacement speed. The selection has been carried out based on vector direction in comparison with the glacier main flow direction. The methodology has allowed measuring glacier surface displacement rate, without risks for the survey operators, but due to the time span between the two surveys the number of available features on the glacier was nearly scarce, in order to measure the displacement in a more detailed way, measurement should be repeated at an interval never greater than one month. The proof of this advice is in the result of the first analysis; in the global evaluation of the front ablation, positive values have been found in the bedrock close to the ice cliff, this can be explained by the accumulation of boulders, fallen, from the surface due to the high displacement speed, as shown in the next figure (Figure 23), highlighted by white ellipses.

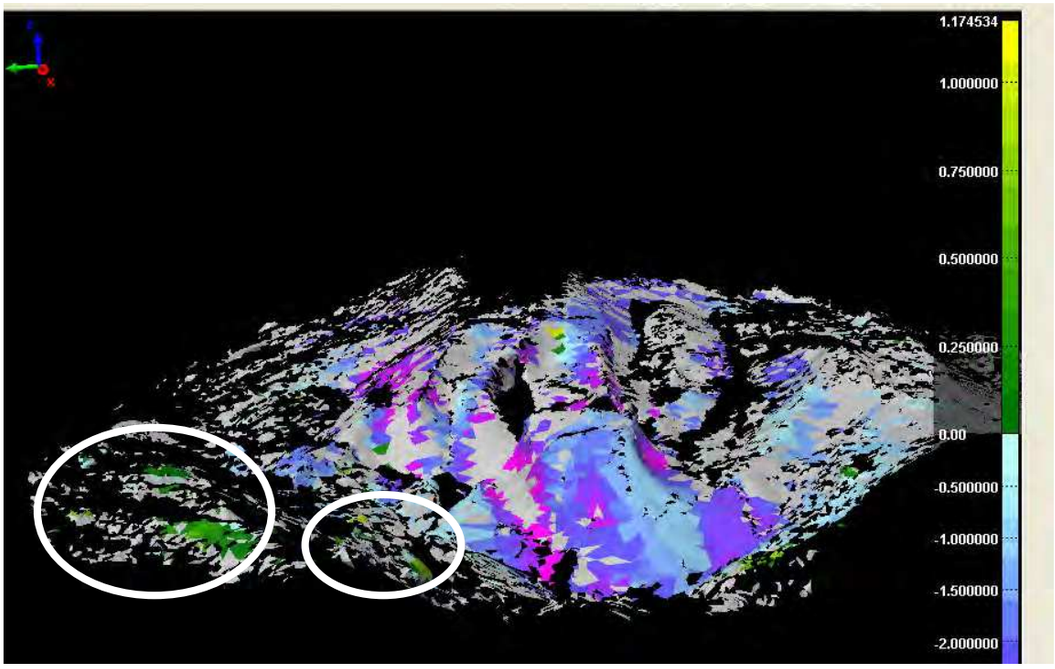


Fig. 23. Snout ablation map, accumulation of rocks, fallen from the glacier surface, are highlighted by the white ellipses in the lower left part of the image

5.3 Glacier surface survey

The survey of the surface has been the most complex field activity in the whole experiment. From the logistic point of view, the laser instrument, equipped with tripod and batteries had

to be transported to a raised position, over the glacier surface, and due to the location of the measuring station the entire equipment has been moved only by instruments operators.

The survey has also been georeferenced, in order to analyze glacier displacement according to its bearing and to compare it with stakes measures. In order to accomplish the georeferencing, 4 targets have been placed on the glacier during the first survey and their positions have been measured with differential GPS. In order to optimize the stake and target survey, one GPS campaign has been performed with both aims.

The employment of targets comprises additional tasks to achieve, in fact every single target need to be measured in a separate scan session; this detail suggest that targets should be used only when strictly needed as they require quite a lot of operational time, to spend in measurement of their position, in their scanning and computational time in data processing.

5.3.1 Data alignment and calibration

Every measurement has been characterized by multiple scans in order to survey the largest part of the glacier, each scan has been then aligned thank to targets.

The alignment, between the two surveys, has been performed easily as in previous experiments. In this one, the "natural benchmark" approach has been used in a twofold way; during the alignment phase, as already described in the two previous tests, the two scans have been aligned on features tracked down in glacier surroundings; and during the analysis phase as described below.

5.3.2 Displacement

The glacier displacement has been measured according to the new approach, already tested on Liligo Glacier, Karakoram, Pakistan (Diolaiuti et al., 2003) and on Belvedere snout, which considers as reference points boulder and rocks placed on glacier surface. By recognizing the relative positions of these "natural benchmark" a vector computation is possible, allowing measuring local glacier displacements, limited only by the number of recognizable features. In spite of the scarce results obtained on the right snout of the glacier, in this experiment up to 40 features, and consequently, displacement vectors have been computed with a highly detailed analysis of the phenomenon (Figure 18). Displacement data, compared with those measured by GPS at stakes positions are comparable with no significant differences ($p = 0.245$) and similar variances ($p = 0.323$), as shown in the same figure.

5.3.3 Ablation

Laser data offers also the chance to measure the glacier ablation in the scanned area. In this case the automatic comparison of the two surfaces along z axis, as already performed on snout experiment, have proven its effectiveness providing a fast and accurate measurement extended to the entire scanned area. The comparison between laser data and stake measurement has provided an unexpected result: the two datasets have shown significant differences in variances ($p = 4.700 \cdot 10^{-3}$) and highly significant differences in their values ($p = 7.000 \cdot 10^{-4}$), according to *t* test. The analysis have been repeated, by comparing laser data with the glacier elevation losses, measured with GPS at stake locations; in this second test

the two datasets have shown non significant differences (p = 0.751). This different test results suggest the importance of the correct interpretation of the laser survey results, due the high complexity of a glacier system, several factor (e.g. debris cover or bare ice…) should be taken into account before identifying the correct meaning of a new technique results.

6. Conclusions

The cryosphere is characterized by undoubtedly remarkable phenomena with meaningful magnitudes. Hazards related to these events may endanger human life and settlements, as already stated by different authors (Huggel, 2004; Rott et al., 2005). The monitoring of these phenomena should assure enough accuracy as they have to describe complex phenomena and their potential hazards. Contemporarily, they should be characterised by a handy employment and management due to the difficult environment of application.

The geomatic methodologies employed in the monitoring and analysis of cryospheric phenomena has provided a satisfactory response to the briefly listed requirements.

GPS and Terrestrial Laser Scanner have confirmed their effectiveness in the research. The ease in their field employment has allowed the execution of fast and reliable surveys.

The Terrestrial Laser Scanner, thank to its high acquisition frequency, provides a complete description of the glacier surface in short time. The output point cloud is immediately ready to process and allows the extraction of geometrical features of the object.

As a remote technique, the accessibility of the survey object is not needed so measurement of unsafe areas is feasible (Biasion et al., 2005). When the object georeferencing is not requested also the target positioning is not necessary, point cloud processing and comparison may be executed in a relative approach, with no loss in the final accuracy. The proposed "natural benchmark" approach has proved its applicability introducing a new method in the processing of data.

In both cases the accuracies obtained by the two techniques has assured their applicability to cryosphere monitoring reaching the requirement specified for this kind of measurements (Rott et al., 2005).

The fast execution of measurement has allowed completing a survey session in few hours enabling their repetition during the season. A high frequency monitoring is highly recommendable in these events in order to achieve the maximum number of information on the phenomenon dynamics. Moreover, due to the phenomena complexity, multidisciplinary approaches are recommendable (Zublin et al, 2008) in order to achieve the maximum detail in the survey object reconstruction and consequent analyses.

The measurements are still in progress as the explained phenomena deserve a continual monitoring to deepen the comprehension of their dynamics.

Other techniques are developing, like the GB-SAR (Ground Based Synthetic Aperture Radar), in cryosphere monitoring and the integration with the other methodologies is highly recommended in order to obtain data from different sources, integrate and cross validate them. This multi disciplinary approach should lead to the definition of the optimal method in the monitoring of these phenomena.

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Laser scanning technology plays an important role in the science and engineering arena. The aim of the scanning is usually to create a digital version of the object surface. Multiple scanning is sometimes performed via multiple cameras to obtain all slides of the scene under study. Usually, optical tests are used to elucidate the power of laser scanning technology in the modern industry and in the research laboratories. This book describes the recent contributions reported by laser scanning technology in different areas around the world. The main topics of laser scanning described in this volume include full body scanning, traffic management, 3D survey process, bridge monitoring, tracking of scanning, human sensing, three-dimensional modelling, glacier monitoring and digitizing heritage monuments.

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