MULTI-TEMPORAL BLOCK ADJUSTMENT FOR AERIAL IMAGE TIME SERIES: THE BELVEDERE GLACIER CASE STUDY

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ABSTRACT:

While considering monitoring actions aimed at natural hazards management, an historical research about the investigated phenomenon is mandatory, in order to acquire those data necessary to understand its dynamics and to forecast possible evolutions. In this paper, some results referred to an experience of multitemporal aerial triangulation are presented, with the purpose of demonstrating accuracy improvements in stereo model orientation. The case study is the Belvedere Glacier that belongs to the Monte Rosa east face (Italian Western Alps) and since 1868 has been being interested by superglacial lakes outbursts, ice avalanches and surge-type movements, awakening the interest of the scientific community in studying these phenomena and generally to consider a glacier monitoring. Approaching the multitemporal analysis of the geometric features of moving surfaces, the most critical factor is always the planimetric coherence between the oriented stereo models of the different periods. This work tries to give a preliminary answer to this problem. Two digitized aerial stereo-pairs (years 2001 and 2003) acquired at different scales were used for the tests . Three Aerial Triangulation approaches were considered and compared: a) a traditional *Single Block Bundle Adjustment* (*SBBA*) ; b) a *Single Block Sequential Bundle Adjustment* (*SBSBA*); c) a *Multi-temporal Block Bundle Adjustment (MTBBA)*. Statistical parameters referring to some Check Points sited in no-moving areas demonstrate that MTBBA produces a better co-registration among blocks, guaranteeing a better coherence between measurements and consequently a higher precision in determining displacements measured at the ground level. The declared intention of testing the results in an operative context, suggested to carry out image orientation exploiting existing data for the identification of the Ground Control Points. Even if the image mean scale suggests the use of high precision Ground Control Points, a faster approach was chosen, measuring: a) their planimetric coordinates on the available orthoimages having a nominal scale of 1:10.000; b) extracting the elevation values from the Piemonte Region Digital Elevation Model. According to the selected Check Points, resulting coordinate differences were successively compared and statistical parameters were calculated. The stereo models, oriented according to the *MTBBA* approach, were then employed in the computation of a map describing glacier surface variations, aimed to the description of its dynamics in the referring period (2001-2003).

1. INTRODUCTION

This work is mainly aimed at demonstrating that the relative accuracy that affects the geometric comparison of multi-temporal photogrammetric images can be increased by a bundle adjustment performed using all the images referring to the considered different periods. Furthermore, it is also aimed at showing how the accuracy (relatively speaking) of the comparison process between the multi-temporal photogrammetric blocks is just weakly conditioned by the metric quality of the Ground Control Points (GCPs) used for the Exterior Orientation of images. In fact, during the presented tests, poor quality GCPs were used: their planimetric coordinates were derived by available aerial ortho-images, and their height was measured on a Digital Elevation Model (DEM). Both these map data types will be described later.

Tests refer to three different approaches in the calculation of the image Exterior Orientation, as described in paragraph 4. They clearly show that a multi-temporal block adjustment (MBAT) determines a appreciable increasing of the relative accuracy of the occurred changes in images. According to MBAT the available two blocks (years 2001 and 2003), showing the Belvedere Glacier, were oriented and two DSMs (*Digital Surface Model*) of the glacier surface were generated in an automatic way. These, were successively compared by matrix subtraction to map and measure occurred changes in the considered period.

2. STUDY AREA: THE BELVEDERE GLACIER

The Belvedere glacier represents a quite singular situation in the Alpine context; in fact it is characterized by specific dynamics that are typical, today, of the Himalayan area (Mercalli, 2002). The glacier has been always showing a high dynamicity as the Monterin tables (1922) demonstrate for the period 1826-1922. Further bibliographical contributions (Fantoli, 1928) confirm such trend, referring about important glacier movements occurred since 1868. The Belvedere glacier was described for the first time at the end of the 18^{th} century by De Saussure (1779-1796) and Amoretti (1817). They qualitatively referred about the huge dimension of the glacier. Successive scientific missions (Porro, 1917; Porro & Somigliana, 1917) promoted by the Italian Glaciological Committee were organized to rigorously survey (glaciology and topography issues) the Belvedere. Terrestrial photogrammetric surveys were also carried out at that time. Some further researches were addressed to the characterization of the peri-glacial vegetation (Negri, 1917).

In 1922 the Glacier performed its maximal size and a third tongue appeared. In table 2 a summary is given about the on-field surveys made at the beginning of the 20th century (Monterin, 1922; Sacco, 1930); table 3 shows the glacier displacements as they can be measured considering existing historical maps.

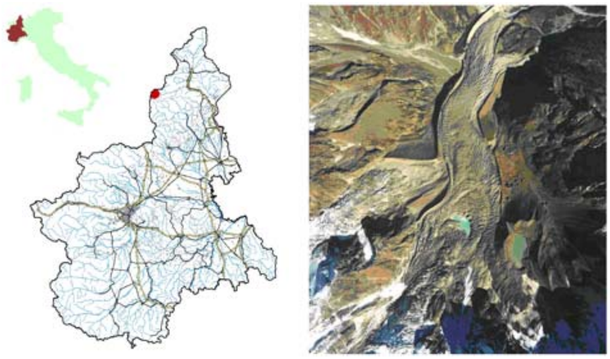

Figure 1. Belvedere Glacier area (left); Belvedere Glacier aerial image (right).

Glacier increasing periods	Glacier decreasing periods
1826	1826 – 1842
1842 – 1859	1859 – 1878
1878 – 1893	1893 - 1913
1913 - 1922	

Table 1. Belvedere Glacier dynamics in time (Fantoli, 1928).

During the International Geophysical Year (July 1957-December 1958) many investigations of the glacier were promoted. For the first time an aerial photogrammetric survey (E.I.R.A., 1961) was effectuated and a 1:5000 scale map was produced by stereoplotting. In the last twenty years the glacier has been increasing its dynamics both in time frequency and in size. Some of the occurred events have brought to the attention of the scientific community the possibility of generation of risky situations both for things and people (Diolaiuti et al, 2003; Tamburini et al, 2003; Kaab et al, 2004). The Italian political institutions have taken into consideration such potential risky situation in some official publications (eg. ordinance of the President of the Ministries Council – 4th July 2002). At the moment the most critical issues regarding the glacier dynamics are its volume increasing (an opposite behaviour respect to the common decreasing trend of the most of the alpine glaciers) and the speed augment of the displacements, observed since 2001. Haeberli et al (2002) assume a *surge* phenomenon as possible motivation of such behaviour.

Year	Right tongue		Median tongue		Left tongue	
1914	Front position (equal to 1901)		Tongue formation		Front stationary	
	Horizontal displacement	Vertical displacement	Horizontal displacement	Vertical displacement	Horizontal displacement	Vertical displacement
1915	7 m	33 m				
1916				44 m	27.50 m	21 m
1917	49 m					
1918			112		50 m	
1919	62 m	42 m			50 m	
1920	60 m			62 m	62.30 m	53 m
1921	26 m				28.70 m	
1922	12 m	4 m	Front stationary		12 m	11 m

Table 2. Belvedere Glacier surveys in the past.

Year	Maps	Left tongue elevation	Vertical trend	Right tongue elevation	Vertical trend	Median tongue elevation	Vertical trend
1851	Schlagintweit	1611 m	/		/	/	
1885	I.G.M.	1725 m	- 114 m	1812 m	/	1800 m	-
1915	Monterin	1712 m	+ 13 m	1783 m	+ 30 m	1800 m	-
1918	Porro e Somigliana	1691 m	+ 21 m	1750 m	+ 33 m	1756 m	+ 44 m
1921	Somigliana e Monterin	1638 m	+ 53 m	1708 m	+ 42 m	1694 m	+ 62 m
1922	Monterin	1627 m	+ 11 m	1704 m	+ 4 m	1695 m	Stationary

Table 3. Planimetric and altimetric displacements as resulting from historical map comparison.

The *surge* can be considered a sort of "*glacial flood*" (Mercalli et al, 2002; Hooke, 2005), that is a sudden and fast movement of the Glacier nor related to an increasing of the snow supply nor to a decreasing of the ice melting process.

3. AVAILABLE DATA

3.1 Aerial images

Tests that produced the results object of this work, were carried out using 2 aerial stereo-pairs acquired respectively in the years 2001 e 2003. Field surveys demonstrate that in this period important movements have interested the glacier and its surface has suffered from great deformations.

Table 4 shows the technical features of the available images.

Stereopair	Image Mean Scale	Relative Flight Height (H)	Base (B)	Calibrated Focal Length (mm)	Expected σ_Z (m)
2001	≈ 1:20.000	≈ 3000 m	≈ 750 m	151.946	≈ 1.5
2003	≈ 1:12.000	≈ 1750 m	≈ 550 m	152.815	≈ 0.6
	Camera Type		Lens. N°.	Date of calibration	
2001	WILD RC5 15/4 UAG		407	16.12.2000	
2003	WILD RC20 15/4 UAGA-F		13128	05.01.2000	

Table 4. Technical features of the available aerial stereo-pairs.

Images were supplied as scanned images of hardcopy printings. They therefore represent a low quality product, that is a good benchmark to test the methodology here proposed. The scanning resolution of 800 DPI (*Dots per Inch*) determines a physical pixel size of 31.75 μm. Expected accuracy of the height coordinate, measured through a stereo-plotting approach, can be easily calculated supposing an accuracy of the X parallax measurement equals to half a pixel (16 μm), according to (1).

$$\sigma_z = \frac{H}{B} \cdot \frac{H}{f} \sigma_x \qquad (1)$$

Where *H* is the Relative Flight Height, *B* is the base of the stereopair, *f* is the Focal Length of the camera, σ_x the accuracy of the X parallax measurement.

The calibration certificates were available for both the cameras..

3.2 Reference map data

The exterior orientation (E.O.) parameters of the images were estimated, through a bundle adjustment approach, by using an opportune number of Ground Control Points (GCPs); their planimetric coordinates were measured on an available aerial orthoimage dated 2000 (nominal scale of 1:10.000, 1 m Ground Sample Distance); height coordinate was derived by the Digital Elevation Model (DEM) produced by the Piemonte Region, having a grid size of 50 m and a declared height accuracy of 2.5 m. The chosen projected reference system is the WGS-84/UTM 32N. There are two main motivations that suggested, for this work, to consider poor quality GCPs, directly measured on existing data map:

- to evaluate how much the map reference data accuracy can condition the relative accuracies between the multi-temporal image blocks to be compared;

- to suggest to technicians the adoption of such methodology to face, in a very economical and fast way, the problem of the geometric features change detection. Immediate answers, produced without any programmed field survey, can be considered an excellence while dealing with monitoring problems involving risky situations.

3.3 Photogrammetric Software

Tests were carried out using the *Leica Photogrammetric Suite* 9.1 (LPS).

4. EVALUATED AT APPROACHES

In order to evaluate if and how a Multi-Temporal Block Bundle Adjustment (MTBBA) could improve the relative accuracy in the measuring operations regarding geometry changes occurred in the compared periods, 3 Aerial Triangulation strategies were considered:

- the **S**ingle **B**lock **B**undle **A**djustment (SBBA);
- the **S**ingle **B**lock **S**equential **B**undle **A**djustment (SBSBA);
- the **M**ulti-**T**emporal **B**lock **B**undle **A**djustment (MTBBA).

During the collimation process of the GCPs needed for the Aerial Triangulation, great attention was paid to ensure that some of them (11) were common to all the available images (both the years). However, for each stereo-pair some further GCPs were selected to improve the performance of the bundle adjustment in the single period.

12 Check Points (CHKs), rigorously common to the two stereo-pair, were then identified to evaluate the resulting accuracies as obtained by the different adjustment strategies.

4.1 Single Block Bundle Adjustment (SBBA)

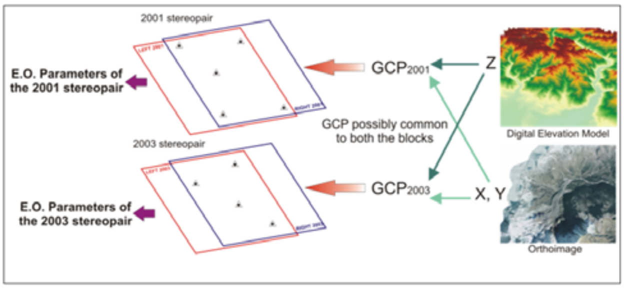

Figure 2. The Single Block Bundle Adjustment concept.

According to this approach each single block (2001 and 2003 stereo-pairs) was adjusted separately. Where possible the same GCPs were used during this operation.

4.2 Single Block Sequential Bundle Adjustment (SBSBA)

The here defined SBSBA is an intermediate approach in the triangulation strategy. According to it, one stereo-pair, chosen as reference, has to be adjusted using some GCPs. All the other stereo-pairs belonging to the time series, are then adjusted using GCPs extracted (possibly in a stereoscopic way) directly from the already oriented reference model.

The choice that states which must be the first block to be adjusted can be based on two alternative criteria:

- in order to maintain the accuracy of the GCPs, to be identified in the second step of the process, as higher as possible the stereo-pair to be firstly oriented should be the one acquired at the lowest flight height;
- in order to ensure that GCPs, needed to adjust all of the blocks of the time-series, can cover the whole area of each image, the stereo-pair to be firstly oriented should be the one that guarantees the widest coverage (highest flight height).

In this work, driven by the objective difficulty of recognizing GCPs in a mountain context (very few manmade objects exist), the second criterium was adopted. Thus, the 2001 pair was firstly oriented, while the exterior orientation of the 2003 one was solved by using GCPs coming from a 3D collimation operated on the 2001 photogrammetric model.

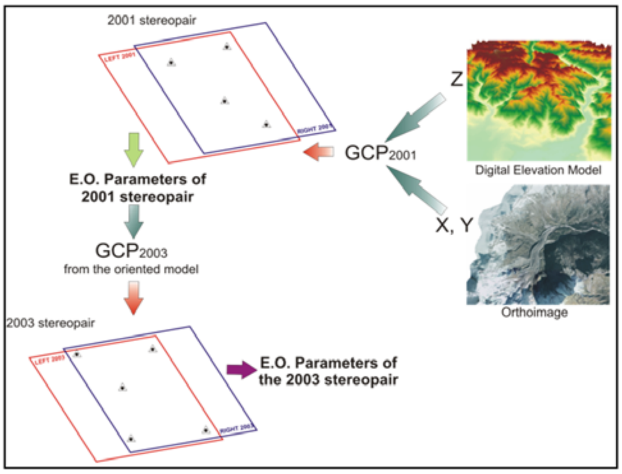

Figure 3. The Single Block Sequential Bundle Adjustment concept.

4.3 Multi-Temporal Block Bundle Adjustment (MTBBA)

This approach is the one the authors intend to demonstrate the effectiveness of in geometric change detection applications. It states that all the stereo-pairs of the considered time series must be adjusted simultaneously using a certain number of common GCPs. The basic idea is that, such operation can improve the relative homology of the resulting images, guaranteeing a better correspondence between terrain surfaces to be measured from the oriented stereo models. GCPs used during the Bundle Adjustment should be possibly selected checking for their existence over all the images participating to the Aerial Triangulation.

As far as Tie Points are concerned, some preliminary tests carried out during this work (not presented here) demonstrate that they are, obviously, needed for the single stereo-pair; but in the most of the cases they do not generate any improvement of the solution of the Bundle Adjustment if selected to link different time image blocks. Further investigations are, at the moment, being made by the research group in this direction. Accepting this consideration, for this work, Tie Points were collected just between images belonging to the same stereo-pair, but no between the different ones.

The result of the MTBBA is a one-step estimation of the

Exterior Orientation Parameters of the images belonging to the blocks. The effect is the absorption of the most of the relative errors between the blocks themselves (see chapter 5).

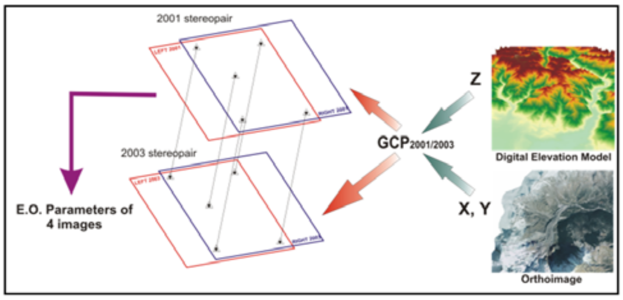

Figura 4: the **M**ulti-**T**emporal **B**lock **B**undle **A**djustment concept.

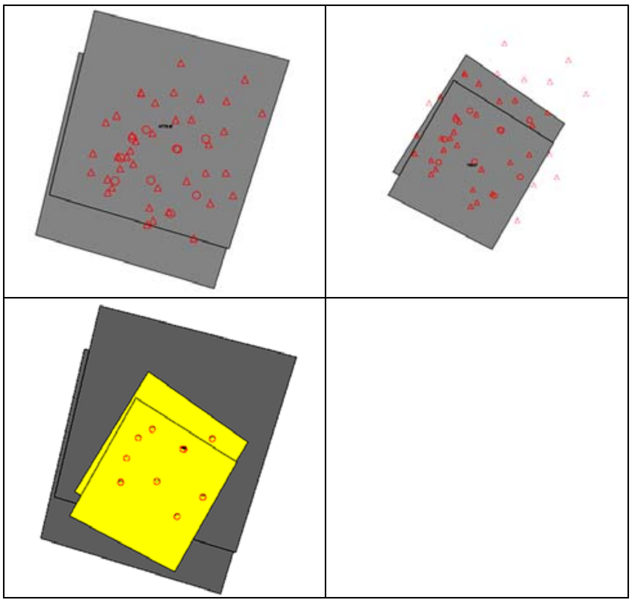

Figure 5. *Upper Left*: 2001 oriented model footprint; *Upper right*: 2003 oriented model footprint; *Lower Left:* 2001 and 2003 blocks, with the only CHKs overlayed. *Triangles* = GCPs; *Circles* = CHKs.

In figure 5 are shown the footprints of the oriented 2001 and 2003 blocks, where it is possible to see the effect of their different mean scale and the distribution of the used GCPs (triangles) and CHKs (circles). Please note how some GCPs are not common to both the stereo-pairs. Their presence is anyway favorable to better fit the coverage of each single block.

Furthermore, it has to be noted how the GCPs and CHKS spatial distribution is quite irregular. This is a common situation while operating with GCPs and CHKs collected on existing reference data map (especially in mountain regions), without a before-flight programmed survey.

5. RESULTS

All of the presented results are referred to some tests made considering the 3 approaches of Aerial Triangulation previously presented. The set of points (GCPs, CHKs, and TP) used to generate all of the statistics were rigorously maintained the same during calculations. Their basic requirement is to be common to all of the images and to be referred to points that did not change in time.

5.1 Accuracy tests

Evaluation is aimed:

- at defining the relative accuracy in the measurement of the three spatial coordinates (with particular regard for the Z one) of objects considered stable in time (not changing);
- at comparing the relative accuracy with the absolute one (that i respect to the reference map data) to demonstrate how a medium quality of the GCPs, just lightly conditions the accuracy of the relative measurement made between multi-temporal blocks.

As relative accuracy, here is intended the standard deviation of a sample of differences of spatial coordinates (CHKs and GCPS) as measured from the different oriented multi temporal blocks (statistics are available for all of the three compared approaches). Three types of coordinate differences sample were considered while producing statistics:

- the sample represented by the joined residuals (ΔEast, ΔNorth, ΔH) calculated from both the GCPs and CHKs common to the two blocks;
- the sample represented by the only CHKs residuals;
- the sample represented by the only GCPs residuals.

This strategy for evaluation was chosen to better investigate the capability of the exterior orientation parameter estimation to generalize the solution. The calculated statistics are:

- as far as the planimetric coordinate residuals are concerned:
  - mean: it quantifies the eventual systematic (traslational) error resulting by the adjustment;
  - standard deviation: it quantifies the residual accidental error affecting the CHKs and GCPs coordinate estimations;
- as far as the height coordinate residuals are concerned, the RMSE (*Root Mean Square Error*) was also calculated (it doesn't separates the systematic and accidental contribution to the global error).

Figures 7-8-9 show such results. Their interpretation can drive to answer the problem of the relative accuracy between blocks. Graphics adopt the following conventional color codification:

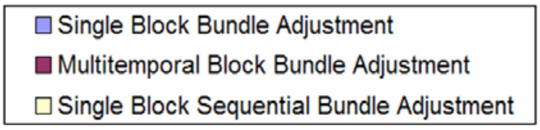

Figure 6. Conventional colors used for the interpretation of the graphics in figure 7, 8, 9.

Figure 10, instead, shows the RMSE values calculated for all of the three spatial coordinates (CHKs and GCPs are considered together). RMSE is obtained comparing the coordinates of the points as measured from the adjusted blocks with their expected value (the one derived by the reference data map). Results refer to 12 Check Points and 11 GCPs common to all the images.

All the bundle adjustment were performed weighting the observations with the declared precision of the reference data (2 m for planimetric coordinates and 2.5 meters for height).

The number of the Tie Points, linking the images of each stereopair, varies between 30 and 60 according to the performance of the autocorrelation process inside LPS, to the presence of shadow areas and to the extension of the area common to the images belonging to the considered stereopair.

Further investigations are, at the moment, ongoing to verify the degree of variability of the exterior orientation parameters estimations obtained through the three different adjustment methods.

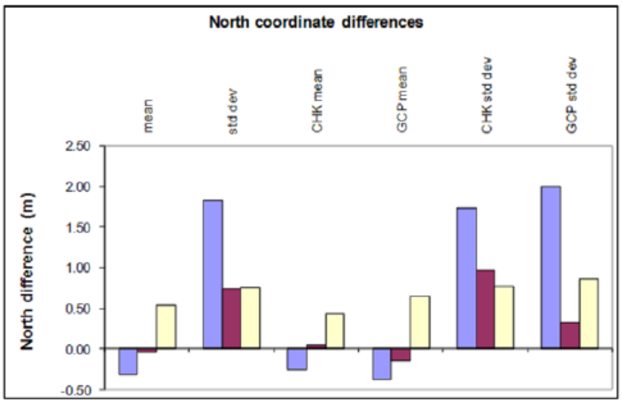

Figure 7. Statistics (relative accuracy) regarding the North coordinate differences (N_{2003}-N_{2001}) measured on the two blocks oriented according to the three proposed methods.

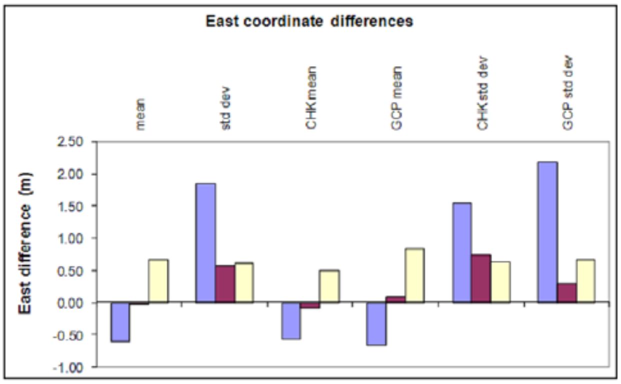

Figure 8. Statistics regarding the East coordinate differences (E_{2003}-E_{2001}) measured on the two blocks oriented according to the three proposed methods.

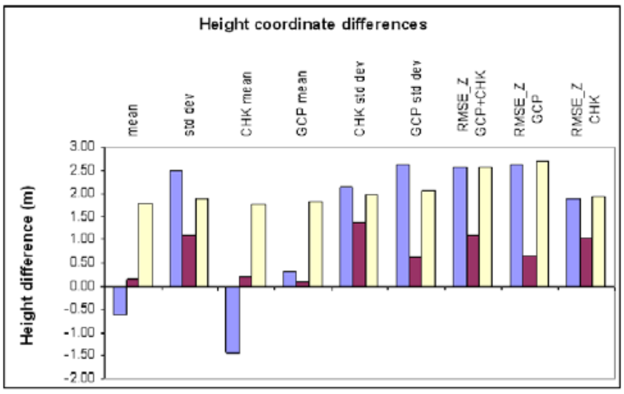

Figure 9. Statistics regarding the Height coordinate differences (Z_{2003}-Z_{2001}) measured on the two blocks oriented according to the three proposed methods.

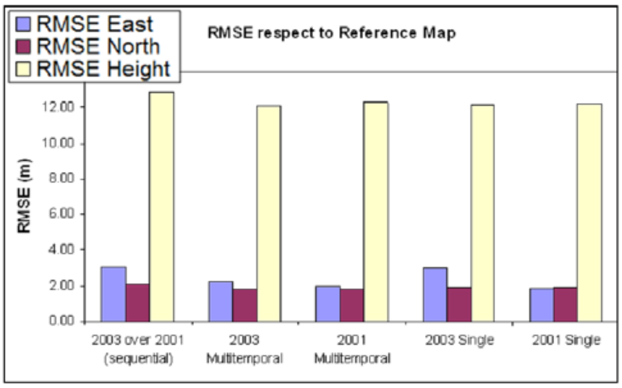

Figure 10. RMSEs globally calculated for the joined set of points CHKs + GCPs. Results refer about the difference between the coordinates of the points as estimated by each single oriented model and the reference ones (as measured on the reference map data). Estimations are labelled (X-axis) according to the adopted adjusting method used.

5.2 Change detection of the Belvedere Glacier surface in the period 2001-2003

According to the operational indications coming from the previous steps, selecting the adjustment approach based on the MTBBA, was possible to orient the two available stereo-pairs and to proceed to the automatic extraction of two Digital Surface Models, DSM, (one per each period) of the glacier surface. DSMs were generated with a geometric resolution of 1 m, considering the estimated accuracy for the planimetric coordinates. The adoption of an automatic point extraction procedure can be considered reasonable because the surface of interest (the glacier) is not covered by shadows nor by vegetation that, usually, represent limiting factors for the autocorrelation performance. Furthermore, the particular texture of this glacier guarantees that a sufficient number of geometric discontinuities are present as favorable element in the process.

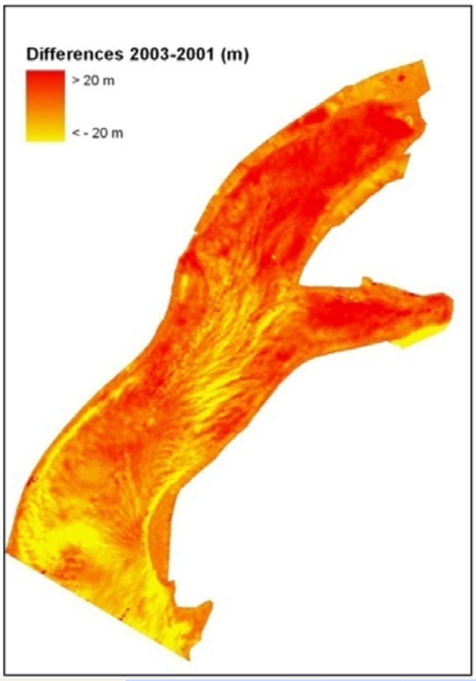

Figure 11. Glacier surface change map. It refers about what happened in the period 2003-2001 and it must be read as “after minus before”.

Once the two DSMs of the two investigated periods were generated in a grid format, they were compared by matrix subtraction (2003 – 2001) in order to evaluate the occurred deformations. The previously results regarding the accuracies of the measurements are useful for correctly reading the produced surface change map (figure 11). It's interesting to note that an important height improvement occurred in the front and median part of the glacier (especially concentrated in the two tongues), while in the very end of it an appreciable decreasing is evident.

Such result confirms that the glacier is not interested by an ordinary supply of material coming from the slopes around, but it suffers from an anomalous mass transfer downward respect the valley.

6. CONCLUSIONS

A first type of conclusions is a general evaluation (independent from the adopted adjustment method) regarding the real relative accuracy (that is the accuracy in appreciating the differences in the spatial coordinates of the object points) that can be obtained comparing DSMs produced through a photogrammetric process. Results demonstrate that the accuracy must not be deduced from a direct comparison with the reference map data, but, on the contrary, it must be quantified considering some check points assumed as stable in time. Such comparison, especially taking into consideration the Z coordinate (compare figure 9 and figure 10), allows to reduce the expected accuracy from 12 meters down to 2.5 meters (in the worst situation). This is a very encouraging fact that is not strictly related to the aerial triangulation method, for technician monitoring surfaces changes.

A second type of conclusions regards the improvement of the relative accuracy obtainable by using a MTBBA approach. It is worth to note that such improvement is important just for the Z coordinate (figure 7,8,9). Same figures show that the classical photogrammetric approach (SBBA) is always the worst performing, while the mixed approach (SBSBA) perform well just for the planimetric coordinate estimation, but, in all the situation, suggests to be affected by some systematic error (mean and standard deviation values are comparable).

A third type of conclusions is pertinent to the presented application. In fact surveys carried out in the period 2001-2003 demonstrate that the glacier surface changes as measured by the photogrammetric approach are coherent with the ones coming from the field.

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