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Article

Assessment of using ASTER-derived DTM for Glaciological Applications in the Central Andes, Mt. Aconcagua, Argentina

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Keywords: ASTER, DTM, glacier volume change, Mt. Aconcagua

Summary: Monitoring glaciers has recently gained more attention, as efforts to better model climate changes are intensifying worldwide. This paper presents a feasibility study on the implementation and performance assessment of digital terrain models (DTMs), derived from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) optical imagery, in order to determine the altimetric and volumetric changes on Las Vacas and Horcones Superior glaciers, located at 32° 41' S and 69° 57' W in the Mt. Aconcagua area, Mendoza, Argentina. The DTMs were created from ASTER images from 2001 and 2008 in a standard satellite digital photogrammetry environment. To assess the absolute vertical accuracy of the DTMs, GPS data was used, and the results indicated a 24 ± 10 m RMSEz, in topographically complex scenarios and with slopes greater than 30°. To obtain a robust matching as well as to minimize the residuals between DTMs, a 3D conformal transformation was applied to co-register them. To calculate the differences between DTMs, the approach of computing the differences along surface normal vectors was proposed. Next, the changes happened to the glaciers were identified, resulting in −3.15 m/a and −0.92 m/a for Las Vacas and the Horcones Superior, respectively. Finally, the results were tested using the 3D control deformation in order to determine the degree of uncertainty in the estimation of changes in the thickness and volume of glaciers.

Zusammenfassung: *Untersuchung zur Eignung von Höhenmodellen aus ASTER-Daten für glaziologische Untersuchungen in den Zentralanden am Aconcagua, Argentinien.* Das Gletschermonitoring hat an Bedeutung gewonnen, weil weltweit die Bemühungen um eine bessere Modellierung der Klimaveränderung gestiegen sind. Dieser Artikel stellt eine Machbarkeitsstudie zur Nutzung von ASTER-Daten (Advanced Spaceborne Thermal Emission and Reflection Radiometer) zur Bestimmung von Höhen und Volumenveränderungen am Beispiel der Gletscher Las Vacas und Horcones Superior vor (32° 41' S, 69° 57' W, Aconcaguamassiv). Als Datengrundlage dienten zwei ASTER-Szenen von 2001 und 2008. Mit den GPS-bestimmten Bodenpunkten wurde eine Höhengenauigkeit (RMSEz) von 24 ± 10 m in topographisch stark bewegtem Gelände mit bis zu 30° Hangneigung nachgewiesen. Die beiden Höhenmodelle wurden mit einer 3D-Helmerttransformation zusammengeführt, um dann die Unterschiede entlang der Oberflächennormalen zu bestimmen. Daraus ergab sich ein Abtrag von −3.15 m/a beim Las Vacas und −0.92 m/a beim Horcones Superior Gletscher. Abschließend wurde die Genauigkeit der Bestimmung an Kontrollpunkten verifiziert.

1 Introduction

Glaciers play a significant role in controlling downstream water supply in arid or semiarid regions, where precipitation is minimal. Therefore, it is crucial to understand the temporal and spatial behaviour and volume changes of glaciers in those regions. During the late 20th and early 21st centuries, glaciers have suffered a global recession. This sustained de-

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cline of ice covered areas is one of the most reliable indicators of global warming (Haeberli 2005, IPCC 2007). A parallel trend is that the demand for fresh water has increased sharply in recent decades. Therefore, research on analysing and quantifying changes in glacier processes has become an important subject, since knowledge of the evolution of glaciers is essential to make future decisions regarding their conservation and/or protection.

Considering that glaciers are usually located in difficult to access areas with complex topography and extreme weather conditions, their monitoring from the ground is a rather complex task. Consequently, remote sensing represents an attractive approach to map glaciers.

To monitor glacier volume changes, digital terrain models (DTMs) represent the ideal data, as from DTMs, acquired at different epochs, both deformation and movements can be detected (Barrand el al. 2009). Nowadays, DTMs are one of the most common products in mapping practice and come in a broad range of spatial resolution and accuracy. Historically, stereo image based surface extraction by photogrammetry used to be the primary source to create digital terrain models (DTMs) until active sensors, such as light detection and ranging (lidar) and synthetic aperture radar interferometry (InSAR) technologies, were introduced. Presently, lidar technology provides a powerful tool for high-density and high-accuracy three-dimensional terrain point data acquisition, and one of the advantages is the direct availability of three-dimensional coordinates of points in object space (Shan & Toth 2008). As an active remote sensing technology, airborne lidar data are practically free of shadows, a major advantage compared to photogrammetric methods where the shadows are a big problem, in particular in areas of complex topography or in glacier areas. Lidar from airborne platforms could provide the most accurate elevation information for glacier surfaces, but its cost is high, and, in fact, prohibitive in many earth science applications. InSAR is a powerful technique to monitor land surface changes from space and air with good quality. The limiting factors in mountainous terrain are occlusions, the difficulty of decorrelation, and the SAR image geometry. Restrictions to the spatial coverage arise from decorrelating snow-covered areas, such as glaciers over forested areas, and shadowing caused by the very rugged topography (Franceschetti & Lanari 1999). Photogrammetry generally falls behind in terms of performance, but is much more affordable from both airborne and satellite platforms. Another important issue is that InSAR and photogrammetry are dependent on ground control, but lidar without GCPs is not more exact than photogrammetry. Despite of the recent dominance of active sensors, optical image-based DTM extraction by photogrammetry has seen significant improvements recently, and provides a less accurate yet very inexpensive alternative to lidar and SAR techniques.

The objective of this study is to investigate the feasibility of using DTMs derived from ASTER imagery to estimate glacier changes in the complex topographic areas of the Mt Aconcagua. The use of satellite image-based digital photogrammetric method represents the first implementation and use of DTMs in that region. While ASTER imagery is very inexpensive, its use presents a challenge due to its coarse resolution and modest georeferencing accuracy. The ASTER product level 1A has the stereo pairs 3N and 3B that permit the generation of topographic mapping products, such as digital elevation models (DEMs), digital terrain models (DTMs) and orthophotos (Iwasaki & Fujisada 2005). Stereo ASTER imagery has been frequently used to monitor glaciers, since it is available at low cost with worldwide coverage (Etzelmüller & Sulebak 2000, Vignon et al. 2003, Rivera 2004, Miller et al. 2009, Bolch et al. 2011).

To get a better understanding of the behaviour and the accuracy of DTMs of different types of relief, it is relevant to make an assessment. DTM errors vary with relief types and elevation. Typical accuracies above 2000 m above sea level (ASL) range between ± 15 to 30 m at the 68 % confidence level, while for the worst case, at 5000 m ASL, the error could reach ± 60 m at the 68 % confidence level (Kääb et al. 2002, Racoviteanu et al. 2007, Schneider et al. 2008). Kääb et al. (2002) showed that the errors increase with the complexity in the topography, and the best elevation accuracy found for a scenario with moderate topography was ± 18 m. Lang & Welch (1999), Hirano et al. (2002), Toutin (2008), and others found that RMSEz values generally fall between 10 m and 50 m. In the Mt. Everest region, Pieczonka et al. (2011) found data that defies the overall trend, where RMSEz values are 45 m below 5000 m ASL and 37 m above 6000 m ASL. This may be due to the difficulty of validating the elevation data at higher altitudes. Their study also confirmed that for slopes steeper than 50°, the error could be more than ± 105 m.

This investigation is focused on accuracy estimation and assessing the capability to monitor the evolution of glacier surfaces in the Mt. Aconcagua region. A novel component is that the proposed method calculates the elevation difference along surface normal vectors, resulting in better volume difference estimation. The next two sections describe related work and the methodology used for the extraction of the DTMs, including a study on the accuracy of the DTMs using reference fields surveyed by GPS. The computation and analysis of the differences between DTMs, made before and after a robust surface matching, based on a conformal transformation, is discussed in the fourth section. To better identify the changes produced by the glaciers, a test for 3D control deformation is used to assess to what extent the results correspond to noise due to the method, including error budget of the data and algorithmic limitations in resolution, or due to the actual changes by the ice bodies. Finally, the fifth section discusses the results of comparing ASTER DTMs from 2001 and 2008, including the glaciological analysis of the changes found in glaciers during that period.

2 Related Work

DTMs are approximations of the land surface that have inherent inaccuracies that should be taken into account when are used for comparative evaluation in order to ensure the maximum reliability (Nuth & Kääb 2011, Pieczonka et al. 2011).

There are a large number of studies, introducing various methods to analyse and/or minimize the height differences between DTMs in areas with variable topographic complexities to obtain more reliable results to model glaciers. Vignon et al. (2003) conducted tests in the Rio Santa Basin, Peru, with the goal of estimating the local displacement. They selected the calibration area in a region with no spatial changes in time, and thus, obtained unbiased absolute differences in elevation. Berthier et al. (2007) works in the Spiti/Lahaul region in the Himachal Prades, India, and their approach is based on a correction in the glacier elevation changes between DTMs made by subtracting the bias in the ice-free areas. Racoviteanu et al. (2007), working in Nevado Coropuna, Peruvian Andes, computed the vertical differences by subtracting two DTMs on a cell by cell basis. Kääb (2008) studied the glaciers on the Svalbard archipelago, Norway. He selected ice-free areas in the vicinity of and rock outcrops within the ice-caps as reference sites to compare two and more ASTER DTMs. Later, contour models were derived. The average elevation differences were expressed as a function of the elevation, e.g., 4 m by 100 m elevation, and this representation appears to reduce the influence of noise and errors in the mean change in the ice thickness. Miller et al. (2009) were also studying the Svalbard archipelago, Norway, and proposed an algorithm, where the vertical difference between points located on the matched and the reference surfaces is minimized. Nuth & Kääb (2010) focused on regions with characteristics of alpine glaciers. Nuth & Kääb (2011) relate the height differences to the slope and the aspect.

3 Study Area

The study area is located within the Parque Provincial Aconcagua, Mendoza, Argentina, a protected nature reserve, located around 32° 41’ S and 69° 57’ W (Fig. 1). The characteristics of the relief in the study area are topographically complex with an elevation ranging from 3200 m to 6969 m ASL. The annual precipitation rate for the area at 4000 m ASL is above 600 mm (Minetti & Corte 1984). The mean annual air temperature at Cristo Redentor (32° 50’ S, 70° 05’ W) at 3832 m ASL during the period of 1961–1980 was −1.6 °C (Estadísticas Meteorológicas 1986, Trombotto 1991). The Las Vacas glacier is located to the north of Mt. Aconcagua and has an area of 19.4 km^2 (February 2007). Its orientation is towards the east with an altitudinal range between 3700 m and 5500 m ASL. This is a typical cirque calving glacier with three arms coming together downstream in a big Seracs cascade up to the front. The Horcones Superior glacier is located at the west foot of Mt. Aconcagua where Plaza de Mulas camp is at 4370 m ASL. The orientation is southeast with an area of 5.6 km^2 in February 2007, and its maximum altitude is 5400 m ASL. Fig. 1 also shows the slope map of the study area with the maximum value of 48° in the south wall of Mt. Aconcagua; also, the elevation histograms of both glaciers are shown.

4 Data and Methods

4.1 *Data Sources*

Images: To support this study, two ASTER scenes were selected. The characteristics of level 1A stereo pairs (3N and 3B) are listed in Tab. 1. The images from the TERRA Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor have a geometric resolution ranging from 15 m to 90 m depending on the bands with an area coverage of 60 x 60 km^2. The ASTER sensors were designed to produce detailed maps of the temperature, reflectance, elevation and emissivity of the earth surface. The three ASTER telescopes VNIR (visible and near-infrared), SWIR (short wavelength infrared), and TIR (thermal infrared region) can be oriented in the cross track direction, rotating the camera in the ± 24° range. Therefore, ASTER has the ability to generate stereoscopic images through two telescopes, a nadir-looking (3N)

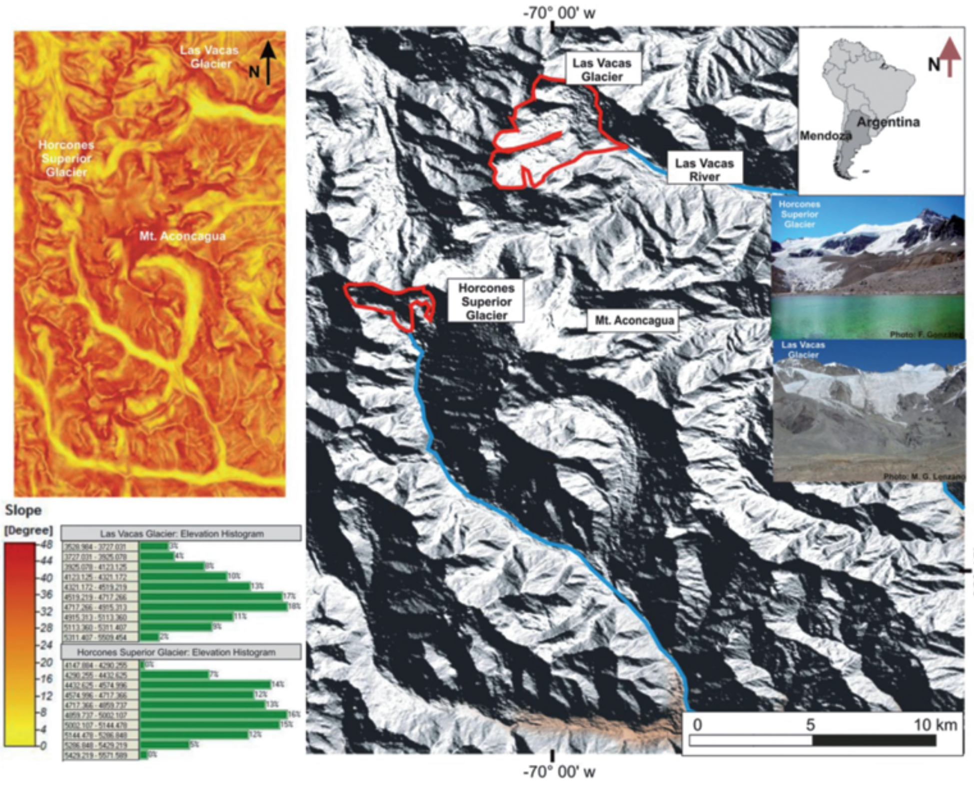

Fig. 1: Map of the study area: upper left: slope map of the study area; lower left: elevation histogram of both glaciers; centre: right shaded relief of the studied terrain; upper right: the location in Argentina; right: Horcones Superior glacier; lower right: Las Vacas glacier.

Tab. 1: Characteristics of images used.

Satellite Sensor	ID	Date	Resolution
TERRA ASTER	AST_L1A_00301132001150259	01/13/2001	15 m
TERRA ASTER	AST_L1A_00301012008145101	01/01/2008	15 m

and a backward-looking (3B) telescope. Both ASTER images were acquired during midsummer. The images show scarce snow cover and the maximum cloud percentage of 20 % has a limited or no affect over the glacier areas.

GNSS data: GCPs and checkpoints based on GPS surveys were established in the field with respect to a base station located at Horcones lake using the DGPS (differential GPS) static positioning method. This base point is part of the geodetic network of Mendoza province in the framework POSGAR98 (Posicionamiento Geodésico Argentino) (Cimbaro & Lauria 2007, Lauria 2009), and linked to the Permanent Station (PS) network SIRGAS (Sistema de Referencia Geocéntrico para las Américas) (Fortes et al. 2006). The base station at Horcones lake was established by using three PSs, including MZAC in the city of Mendoza, SANT, in Santiago de Chile, and CFAG in the province of San Juan. The receiver installed at the base was a double-frequency receiver, Trimble 5700, and the receivers used as rovers were single-frequency Geo-Tech models. The data processing was based on commercial software, using fixed solutions at the 95 % confidence level. The RMSEs (root-mean-square error) for GCPs were: RMSEx = 0.19 m, RMSEy = 0.22 m, and RMSEz = 0.35 m. This accuracy of the coordinates was satisfactory for this type of investigation.

A reference profile was surveyed along the road from the entrance to the Aconcagua Provincial Park on Lake Horcones through Horcones River to camp Plaza de Mulas (Fig. 5). This profile was used to evaluate the accuracy of the DTMs. The survey was done by kinematic GPS processing (Trimble R3, single-frequency), resulting in errors of RMSEx = 0.37 m, RMSEy = 0.21 m, and RMSEz = 0.36 m.

4.2 *Digital Terrain Model (DTM) Extraction*

Image orientation is solved by the addition of GCPs to optimize the quality (Etzelmüller & Sulebak 2000). The use of GCPs is important to obtain precise georeferencing for the stereo models, as they assure accurate elevation as well as planimetry in the reference frame (Wolf & DeWitt 2000). In this study, 11 GCPs were surveyed by GPS and projected into the Argentine GK2 local mapping frame. To improve the image georeferencing, and subsequently increase the reliability of the DTMs, additional 25 secondary GCPs were derived from the cartographic database of IGN (Instituto Geográfico Nacional, República Argentina) at 1:50,000 scale. Finally, approximately 100 tie points per scene were used to form strong stereo models. The DTMs with a grid size of 45 m were extracted by the digital photogrammetric software Photomod 4.4 (Rózycky & Wolniewicz 2007, Liba & Jarve 2009).

During the relative orientation, the y-parallax value for the 2001 and 2008 stereo models was 1.1 and 1.2 pixels RMSE, respectively. After performing the absolute orientation, the residuals at GCPs for both models are shown in Tab. 2. According to Toutin (2008), these results range between the acceptable limits of accuracy, given the geometric resolution of the ASTER imagery.

From the two datasets acquired in 2001 and 2008, the first one, DTM_{01}, was considered as the base or reference in the subsequent analysis, i.e. the DTM_{08} was compared to DTM_{01} with the objective to minimize the residual errors produced by the photogrammetric transformation (Vignon et al. 2003).

The surface of the glaciers is represented by TIN structures (triangulated irregular network). In addition to automatically created surface points, topographic discontinuities,

Tab. 2: Residuals of GCPs in the 2001 and 2008 stereo pairs, respectively (RMSE = root-mean-square error, STD = standard deviation).

		Res X (m)	Res Y (m)	Res Z (m)
2001	RMSE	19.0	20.1	21.8
	Mean	15.3	14.8	18.6
	STD	11.3	13.6	11.4
	Max	39.7	46.8	40.6
2008	RMSE	13.1	12.6	23.8
	Mean	10.5	9.6	20.7
	STD	7.3	8.2	11.7
	Max	34.6	29.1	37.8

Tab. 3: Differences between DTM_{01} and DTM_{08} respectively.

Glacier	Mean $\Delta XY_{01\text{-}08}$ (m)	Mean ΔZ_{01-08} (m)
Las Vacas	27.3 ±15.5	15.3 ±13.0
Horcones Superior	15.7 ± 9.3	34.7 ±13.2

through manually measured breaklines and points were modelled, improving the relief forms in areas with complex landscape (MARZOLFF & POESEN 2009).

4.3 *DTM Differencing*

The difference between DTMs was assessed based on using a variety of topographic features, such as rocky outcrops that are assumed to be static in the proximity of the glaciers under study. Based on comparing 100 points, the RMSEz found for ΔH_{01-08} was 26 m, see Tab. 3. The Fig. 2 shows the places where the relative differences between the DTMs were taken.

Results shown in Tab. 3 may indicate that the mathematical model needed to adequately describe the surface differences could be quite complex, as the definition of the shift between two glacier surfaces is not a simple task. Regardless of the model complexity, the approach is based on minimizing the differences between the two surfaces in a least squares sense. Assuming that the surface shape changes slower than the movement of the glacier, a 3D conformal transformation was selected to model the surface changes. If this assumption does not hold for a complete area, then the area can be segmented to smaller sub-areas that should be independently processed. In this study, a robust matching was achieved by using a large number of outcrops as references as well as other surface features of the glaciers (BERTHIER et al. 2007, KÄÄB 2008). The 7 parameters of the 3D conformal transformation are three rotations (ω, φ, κ), three translations (X, Y, Z) and a scale factor (s). Tab. 4 shows the adjusted values for both glaciers. The results from the calculation of the parameters reflect the relative accuracy of ASTER models; the rotations angles are considerably larger in ω, φ due to the shape of the scenes, while the shifts in X, Y, and Z are generally in the order of a half pixel. Note that the transformation produced an improvement in the accuracy of both models. Fig. 3 shows a profile of DTM_{01} overlaid on DTM_{08} before and after applying the 3D conformal transformation. Errors decreased between 14 % and 77 %. The location of this profile (A) is shown in Fig. 5.

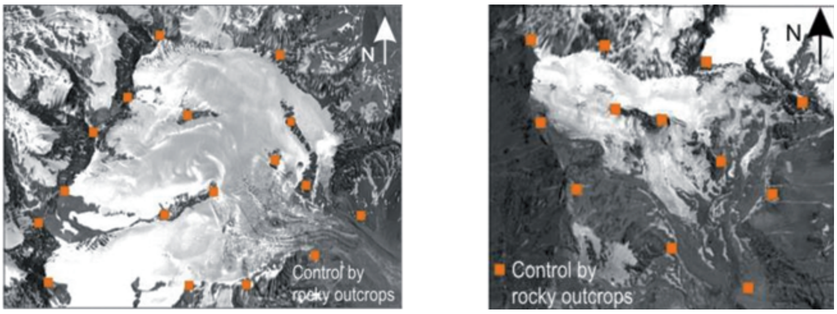

Fig. 2: Location of rocky outcrops around the glaciers: a) LV (Las Vacas), b) HS (Horcones Superior).

Tab. 4: Transformation parameters for both glaciers.

Glacier	ω(°)	φ(°)	κ(°)	X (m)	Y (m)	Z (m)	scale	Number of iterations
Las Vacas	0.416	0.130	0.008	7.78	−5.71	2.69	0.999	4
Horcones Superior	0.455	−0.221	0.124	−7.08	11.69	5.66	1.000	4

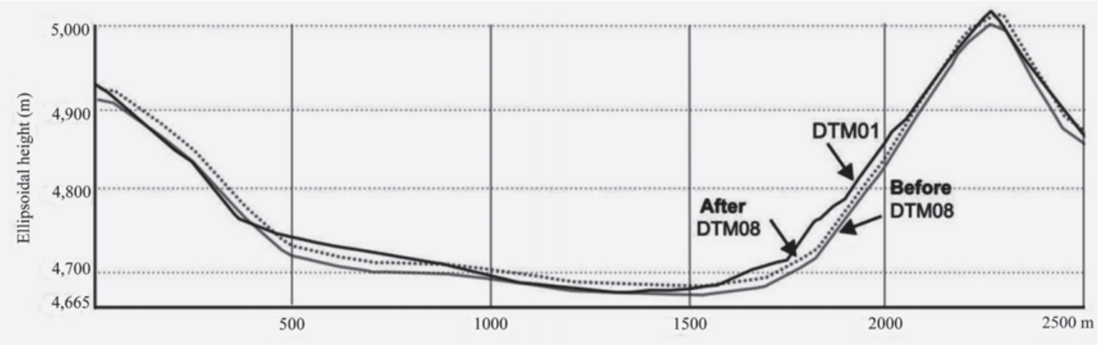

Fig. 3: Profiles before and after applying the transformation.

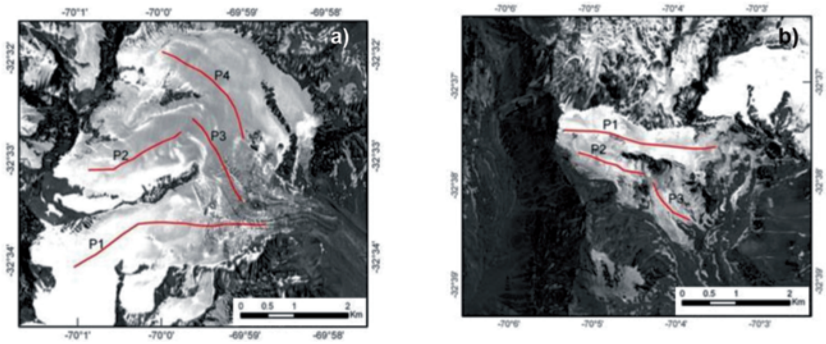

Fig. 4: Profiles overlaid on the glaciers (ASTER image 2001): a) LV (Las Vacas), b) HS (Horcones Superior).

4.4 *Glacier Surface Changes (2001–2008)*

The areal changes, ΔA_{01-08}, in the period of 2001–2008 were derived from ASTER orthorectified images by manually delineating glaciers. This process was repeated several times to determine the deviation of the manual method. The surfaces were expressed per convention as surfaces projected to the ground reference plane.

Profiles on the glaciers were generated by manual delineation, following the line of the ice central flow on 3D surfaces, and the elevation differences (ΔH_{01-08}) were computed along them. Fig. 4 shows the location of the profiles over the glaciers. The elevation differences were taken as normal differences between both surfaces. By comparing DTM_{01} and DTM_{08}, the volumetric changes (ΔV_{01-08}) of the glaciers were determined. The volumetric changes were estimated using an iterative method that re-triangulates a new surface based on points from both surfaces, and then calculates the new surface elevations based on the difference between the elevations of the two surfaces.

4.5 *Testing Changes in the Glaciers*

Since deformations introduced during the generation of DTMs substantially impact the final quality of any derived products, it is important to quantify the distortion and noise introduced in the models, and determine the degree of uncertainty in the estimation of changes in ice volume (Koblet et al. 2010). In this study, the method of *testing 3D displacement vectors by confidence ellipsoids* (Sutti & Torok 1996) was implemented which basically mean applying tests to the profile changes of the glaciers. The significance of a statistical hypothesis test allows for deciding whether a point movement can be considered as a physical deformation, a displacement, or random measurement errors (noise). In this work, only the elevation change (ΔH_{01-08}) along the profiles was analysed using single variable-based deformation assessment.

In this study, the noise coefficient T_k (1) was calculated based on the test with respect to the d_k vector as threshold. Note that d_k is defined by the distance between points of the corresponding 2001 and 2008 data. The vector d_k was taken at 50 m spacing along of the profiles of both glaciers. In the study all measurements were taken with the same weight. The vector d_k provides information about the movement between two periods. Values that are above the T_k thresholds imply that there have been actual changes of the glaciers. If the d_k value is less than T_k, it means noise or no deformation.

$$\left|T_k\right| = \sigma_0 \sqrt{Q_{hk} F_{1-a}} \tag{1}$$

Where

σ_0: average standard error of the profile in each epoch $\dfrac{\sigma_1^{\,2} + \sigma_2^{\,2}}{2}$

σ_1, σ_2: average standard error of the profile in each epoch

Q_{hk}: is a function of the measurements weights

F_{1-a}: coefficient which is extracted from the Fisher-Snedecor table (Forbes et al. 2011).

Fig. 5: GPS checkpoints (green) and profile B (red) used for the validation of the DTMs, and profile A (black) used for evaluating the robust surface matching (ASTER image 2001).

5 Results

5.1 *DTM Accuracy Assessment*

The investigated area represents an extreme scenario, as the elevation range is between 3800 m and almost 7000 m ASL and the average height is 5000 m ASL. To assess the absolute accuracy of the DTMs, the elevation data, H, extracted from the 3D models, were compared with seven fairly evenly distributed GPS checkpoints, independent of the GCPs (Fig. 5). The vertical accuracy between ASTER and GPS data was 24 ± 10 m RMSEz, and 28 ± 12 m in planimetry. Furthermore, a GPS transect from the entrance to the Parque Provincial Aconcagua through the Horcones River valley until the Plaza de Mulas camp was acquired. Using that GPS profile, the RMSEz for $\Delta(H_{GPS}–H_{DTM})$ was 44 ± 9 m for DTM_{01}, and 52 ± 11 m for DTM_{08}. Fig. 5 shows the distribution of GPS check points in green colour and the profile in red colour.

5.2 *Area, Volume and Mass Changes*

The 2D areal variations of the glaciers during the 2001–2008 period were as follows: the Las Vacas and Horcones Superior glaciers diminished by 9 % and 12.4 %, respectively (Tab. 5).

The elevation changes ΔH through the comparison of the different profiles extracted from the DTMs during the 2001–2008 period were computed. Tab. 5 shows the elevation mean values for every profile in each glacier, free of noise, and the computed T_k threshold values. T_k coefficients in both glaciers show a variation between 28.2 m and 29.5 m, and therefore, values above these are considered as changes of the glacier surface by the co-registration. Based on that, all profiles had deformations except for the LV-2 on the Las Vacas glacier.

Tab. 5: Mean elevation variations in glaciers and T_k values.

Glacier	Noise coefficient T_k (m)	Profile	Mean $\Delta H_{01\text{-}08}$ /a
Las Vacas	29.5	#1	0.87 ± 1.4
		#2	estimation failed
		#3	−7.1 ± 1.1
		#4	−1.5 ± 1.4
Horcones Superior	28.2	#1	0.63 ± 0.8
		#2	0.16 ± 0.06
		#3	−3.56 ± 1.9

The profiles were analysed by this test for a change of the elevation and, as a result, on average 31 % of the cases were due to the loss of glacial ice. In the case of Las Vacas, based on the LV-1, LV-3 and LV-4 profiles examined, the glacier lost mass with an average decline of −4.3 m/a. Only the LV-1 profile shows a modest gain of mass. Since this profile is oriented from west to east, many of its points are in the accumulation zone. In addition, due to the shape of the valley more precipitation is caught than elsewhere. Hence, $\Delta H_{01–08}$ has positive values, while the other points, at the ablation zone have negative $\Delta H_{01–08}$ values. The LV-3 profile points, north-south oriented and situated in the ablation zone of Las Vacas glacier, give negative $\Delta H_{01–08}$ values. The profile LV-4, north-south oriented, having a few points in the accumulation zone, has also negative $\Delta H_{01–08}$ values.

The Horcones Superior glacier (HS) is northwest – southeast oriented. Fig. 4 shows its profile HS-1, located in the accumulation zone. The results of profiles HS-1 and HS-2 show positive values for ice elevation change with an average rate of 0.35 m/a, while those of profile HS-3, located in the HS glacier ablation zone, show mass loss with an elevation change rate of −3.5 m/a.

The Las Vacas glacier shows a volume gain of +0.062 km^3 while the Horcones Superior glacier experienced a loss of −0.011 km^3. Tab. 6 shows areal and volumetric changes for both glaciers.

Tab. 6: Volumetric and areal variations in the glaciers in 2001–2008 period.

Glacier	Gain (km^3)	Loss (km^3)	$\Delta V_{01\text{-}08}$ (km^3)	$\Delta A_{01\text{-}08}$ (km^2)
Las Vacas	0.20	−0.147	0.053	−1.5
Horcones Superior	0.04	−0.055	−0.015	−0.55

Since these results are based only on 31 % of the profiles points, the use of independent references is essential to estimate the performance of the proposed approach. In this study, we analysed a relatively short period of time, and therefore, the author decided to extend it to a longer lapse to confirm the behaviour of the DTMs. Thus, a similar methodology was used to estimate the changes in ice elevation in the Piloto glacier in the 1974–2001 (ΔH_{74-01}) period. This glacier is located at the end of Quebrada de Matienzo (Fig. 5), in the upstreams of the Las Cuevas River, next to the Horcones valley. The Piloto glacier has been monitored with direct measuring methods for the past 30 years, thus providing a reliable annual mass balance series (Leiva 1982, Leiva et al. 2007). The DTM was created from a contour line model from 1974 (CLM_{74}), made by the Photogrammetry Department of the National University of San Juan through a photogrammetric data compilation, based on aerial photos from 1974 (1:10000 scale, 10 m contour interval). The elevation change in the glacier was calculated from (CLM_{74}) with respect to ASTER DTM_{01}, and compared with the values obtained from the Piloto glacier mass balance in the 1979–2001 period. According to Leiva et al. (2007), the accumulated balance in the Piloto glacier eastern tongue (PE) between 1979 and 2001 is −9.79 m of water equivalent (water equivalent (w.e.) considers a standard ice density of 850 kg/m^3), which yields an average rate of −0.44 m/a w.e. per year. The PE glacier mean ice elevation change (ΔH_{74-01}), calculated by the comparison of DTM_{01}-CLM_{74} gives a result of –15.40 m, which represents – 13.09 m w.e., giving an average rate of −0.48 m/a w.e. per year, a rather good match.

The difference between both rates of mass loss calculations is almost negligible considering the errors of the mass balance determination by the glaciological method, and thus supports the applicability of the photogrammetric approach.

6 Discussions and Conclusions

This study demonstrates that the generation of DTMs from ASTER optical images in areas with high topographic complexity, such as the Mt. Aconcagua region, is feasible and the quality of the DTM is adequate to estimate elevation and volumetric changes in glaciers. The proposed method produced acceptable results in difficult to access areas, which cannot be observed effectively and rapidly with conventional methods, and thus are rarely investigated. The validation of the DTMs through GPS checkpoints and profiles provided valuable information about the accuracy of derived products and how the slope can contribute to deformations and errors on DTMs.

The relative errors between the DTMs were minimized through a robust matching by a 3D conformal transformation, using segments of smaller sub-areas independently processed with parameters adjusted using stable points, such as rocky outcrop areas around the glaciers. Applying the transformation to co-register the two DTMs, the quality of the final results has improved, as shown in Fig. 3.

The glaciers showed a net ice mass loss for the 2001–2008 period even though the LV-1 profile and the HS-1 and HS-2 profiles, located at the accumulation zone of the glaciers, gave a small ice mass gain and simultaneously a decrease of their area. Another relevant issue is the differences between the results at both sites. This may be explained by the different orientation that is west–east in the case of Las Vacas and northwest–southeast in Horcones Superior, and also the different size, LV has a 19.4 km^2 while the HS has 5.6 km^2.The behaviour of a big glacier could be different compared to the small one. Another aspect could be the local conditions of each valley, the bedrocks, slope, the winds in the upper zone, drifting and accumulated snow in other areas. Therefore, it is important to take the non-photogrammetric aspects in subsequent studies into account, including shape of the cirque glacier, the winds patterns and temperatures.

Because only 31 % of the profile points passed a test for 3D deformation comparing ASTER imagery has certain limitations. To independently assess the performance potential of the introduced method for a longer period of time, a comparison with the results of mass balance on the Piloto glacier, where direct measurements provided reliable mass balances, lead to good results. Future work will further investigate the optimization of the residuals and consider the cross performance evaluation of data obtained by different sensors.

As a final remark, it is important to note that the geodetic balances give acceptable results which can be adjusted and controlled from direct field data. However, the photogrammetric method has the advantage to easily cover places, even large areas with difficult access on the ground. Also, regular studies by direct mass balance measurements are significantly more expensive than the here proposed approach.

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