Monitoring Alpine glacier activity by a combined use of TerraSAR-X images and continuous GPS measurements – the Argentière glacier experiment

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Abstract

The monitoring of Alpine glacier activity is one of the applications which require the combined use of ground measurements and SAR data. It should become feasible thanks to the new generation SAR satellites (ALOS, TerraSAR-X, Cosmo-SkyMed and RadarSAT-2) and the high precision GPS measurements. This paper presents the early results of an experiment which started in 2007 on Argentière glacier (Mont-Blanc area) and includes a moving corner reflector (CR) oriented for TerraSAR-X acquisitions, SAR images where this CR is visible and 3 continuous GPS stations providing the CR position and information on the tropospheric path delay corrections.

1 Introduction

The monitoring of temperate glacier fast evolution is an important issue for economical and security reasons and as an indicator of the local effects of global climate change. Compared to sparse terrestrial ground measurements, remote sensing is expected to allow regular observations of glacier activity and to provide dense measurements of physical parameters which are necessary to detect significant changes and to constrain glacier flow models. High resolution optical images can be used to measure the glacier topography and summer displacement [1]. However, snow makes optical correlation most of the year impossible, and especially at glacier accumulation areas around the year. SAR data are a complementary information source which can be used in the cold season where reduced surface changes make SAR interferometry feasible [2]. The high spatial resolution images (3 m in range) and the relatively short repeat cycle of TerraSAR-X (11 days) will allow new investigations over moving glacier surfaces made of ice, firm, snow and rocks. Surface motion analysis will benefit from the higher resolution or the dual polarization for feature tracking approaches and from the increased interferometric potential to obtain displacement fields by differential SAR Interferometry (D-InSAR).

Nevertheless, several difficulties have to be solved in order to obtain reliable displacement measurements over the fast moving Alpine glaciers. The three main limitations which affect the D-InSAR approach are the coherence preservation, the atmospheric artefacts and the unknown phase unwrapping offsets when the moving surface cannot be connected to a non-moving area. In order to investigate these issues on Alpine glaciers, series of TerraSAR-X images are expected to be acquired over the Chamonix Mont-Blanc test-site which includes well-known glaciers such as the Mer-de-Glace glacier (the second European largest glacier complex) and the Argentière glacier (AG) which has been monitored and instrumented for several decades by different scientific teams. Moreover, a corner reflector (CR) provided by the DLR and a continuous GPS recording station (see **Figure 1**) have been fixed on the ice on the upper part of the glacier during the second E-SAR campaign performed over this test-site in February 2007 [3]. Two other non-moving continuous GPS stations have been installed, one near the glacier at 2700 m above msl height and one down in the Chamonix valley. Despite the difficulties to maintain this equipment on the moving and changing glacier surface, it allows to perform several experiments based on the detection of the CR in the SAR images and the knowledge of its position by the GPS data.

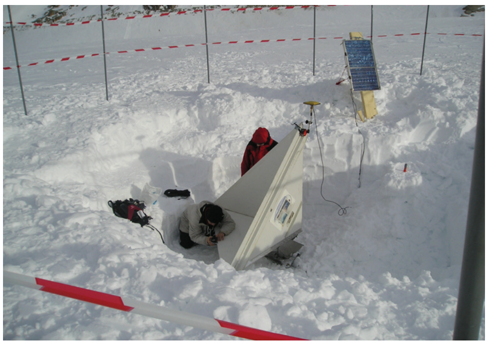

Figure 1 Corner reflector and continuous GPS moving with the Argentière glacier (Feb. 2007).

2 GPS measurements

2.1 Available data

To investigate the potential of a combined use of SAR images and GPS data for glacier activity monitoring, three continuous GPS have been installed in the Chamonix valley. **Figure 1** shows the GPS (Topcon GB1000) and the SAR corner reflector installed on the Argentière glacier in February 2007. The GPS system is alimented with three batteries and solar panels. The same material has been installed on the rock near Argentière refuge (2772 m) which is close to the glacier and in the Chamonix valley (1000 m) end of June 2007. The first data recorded by the continuous GPS fixed on the Argentière glacier and presented here cover 3 periods in 2007: 02/21-03/10, 03/27-04/13, 06/05-06/24.

2.2 Positioning analysis

The position of the GPS site on the Argentière glacier (AG) has been determined during 3 continuous measurement sessions over about 20 days using MIT's GAMIT software [4]. One set of station coordinates has been evaluated over 6 h of data, 4 times per day. The formal error of the horizontal and vertical coordinates of the AG station is 2-4 mm and 7-24 mm, respectively, and 1-8 mm and 5-14 mm on the horizontal and vertical components at the other, stable stations of the network. The increased uncertainty of the vertical component of the AG site is due to the high masks created by the mountains around the site limiting the number of satellite observations under low elevation angles. Moreover, the quantity of snow accumulating around the site creates time-varying additional masks.

The position time series of the site over the three observation spans are shown in **Figure 2**. For each continuous interval, a linear displacement rate has been evaluated with respect to the stable network using the Kalman filter GLOBK [4]. These velocities are listed in **Table 1**. The number of satellite observations under low elevation angles, reflecting the variable masks, are presented in **Figure 3** and can be related with the degree of noise in particular on the vertical component. The low angle observations are in fact critical to de-correlate the vertical position from the evaluation of tropospheric delay. **Figure 4** presents a comparison of the three quantities (observations under low elevation angle, vertical position and tropospheric parameters) for the first observation session. In the second and third session, low angle observations are continuously available and help reducing the noise on the vertical component, as seen by the narrower time series presented in **Figure 2**.

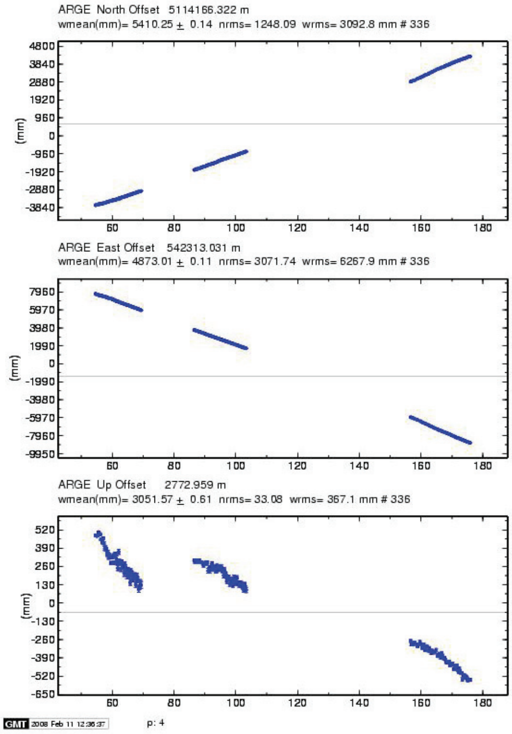

Figure 2. Position evolution of the AG station over the 3 sessions in February, April and June 2007.

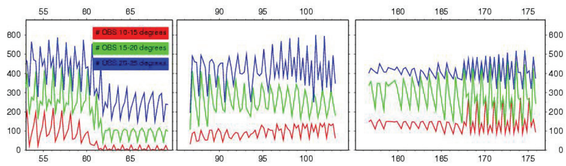

Figure 3. Evolution of the number of observations in elevation intervals 10-15°, 15-20° and 20-25° throughout the three measurement sessions.

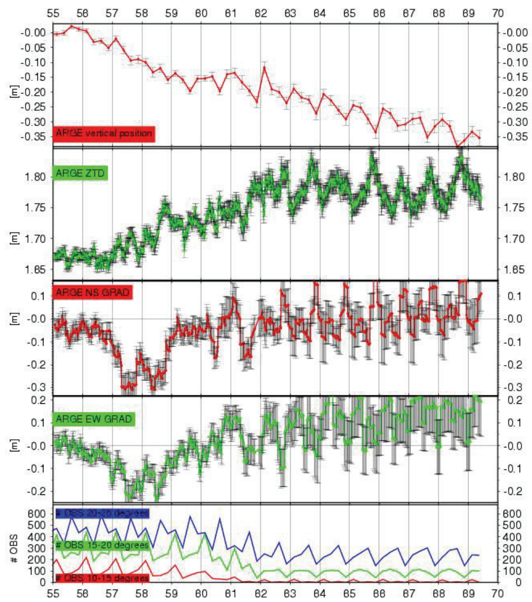

Figure 4. Correlation between noise on the Up coordinate time series (upper box in m), ZTD time series (second box in m), NS and EW gradients (third and forth box, in m) and number of observations in elevation intervals 10-15°, 15-20° and 20-25° (lower box).

dates	days	North v.	East v.	Up v.	total v.
23/02-10/03	55-69	5.1	-12.1	-2.4	13.4
27/03-13/04	86-103	5.9	-12.2	-1.2	13.6
05/06-24/06	156-175	7.1	-15.0	-1.5	16.7

Table 1. Average velocities (cm/day) for 3 observation sessions in 2007 (uncertainties < 0.1 cm/day).

2.3 Tropospheric parameter extraction

Most scientific GPS analysis softwares estimate nowadays two types of tropospheric parameters, Zenith Total Delay (ZTD) and horizontal tropospheric gradients (GRAD) in NS and EW direction. While the ZTD describes a troposphere with homogeneous density in horizontal layers, the gradients take into account a linear, asymmetric component. The mapping functions used in our analysis to constrain ZTDs and gradients are the VMF1 [5] for ZTD and the gradient mapping function from Chen and Herring [6]. These mapping functions take into account the observations of all satellites seen simultaneously to constrain one set of parameters. The data entering in the evaluation of the parameters are cumulated over a limited time span (e.g. 6 hours, 2 hours, 15 min…) according to the atmospheric variability and the aim of the analysis. Indeed, when focussing on precise positioning, the number of tropospheric parameters should be limited not to decrease the stability of the positioning solution. When tropospheric parameters are evaluated with high time resolution (e.g. 15 min), the precise station positions should be determined in a separate run and input as a priori positions in the analysis estimating many tropospheric parameters. In our analysis, we estimate one ZTD per station every 15 min and one couple of horizontal gradients per station every 30 min. Finally, as the tropospheric parameters are evaluated over a defined time interval, the first and the last few parameters in an analysis session suffer from the lack of continuous data (data before or after the time tag of the parameter missing). Therefore we apply a sliding window strategy, shifting 6-hour sessions by 3 hours and keeping only the middle 3 hours of each session to constitute the continuous tropospheric parameter time series. This means that one day of data is analysed in eight 6-hour sessions starting at 0, 3, 6, 9, 12, 15, 18 and 21 h. The resulting time series have smooth transitions between the individual analysis sessions as well as across the day boundary where distinct satellite orbit arcs also can create slight discontinuities.

The obtained ZTD and NS/EW gradients can be used with the same mapping functions as for the evaluation of these delays to reconstruct precise tropospheric delays along the line of view of over-flying satellites. The use of both types of parameters also permits the construction of precise delay maps with the gradients adding information for a better interpolation between stations in sparse networks.

At the time being, tropospheric parameters with high temporal resolution have been extracted for the first observation session on the Argentière glacier. The ZTD and gradient time series (**Figure 4**) highlight the necessity of low angle observations to obtain significant estimates. The tropospheric gradients are parameters of a higher order than the ZTDs and are therefore even more sensitive to a large satellite distribution. Significant gradients have been observed before the time of heavy snowfall at the days of year 060-061. After this time, the gradient evaluations seem to vary with the geometry of the remaining visible satellites repeated every 11 hours 58 min. As shown in **Figure 3**, the following observation sessions seem to be less perturbed by loss of low angle observations and provide better constrained tropospheric parameters.

3 SAR images

3.1 ENVISAT data

The first space borne SAR image of Argentière glacier with the corner reflector has been acquired by ENVISAT on Feb. 22, 2007. It was during the second airborne SAR campaign performed over this test-site [3] and the CR was oriented for E-SAR acquisitions with 46° in azimuth and 0° in elevation. The optimal orientation for ENVISAT IS6 descending images (40° incidence angle) would have been 10° in azimuth and 15° in elevation. Despite these differences, the response of the CR is clearly visible in the co-polar VV ENVISAT image (see **Figure 5**) and does not appear in the cross-polar VH image. A second ENVISAT image has been acquired almost 1 year later (Feb. 7, 2008) with the same line of sight. At that time, the CR was oriented with 10° in azimuth and 17° in elevation for TerraSAR-X descending acquisitions with 38° incidence angle. The CR is perfectly detectable with more than 10 dB difference between the CR and the mean glacier radiometry.

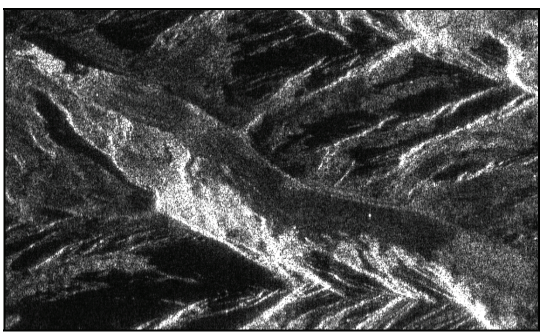

Figure 5 Argentière glacier and the corner reflector in ENVISAT Alt-Pol image (VV channel), Feb. 2007

These two images allow performing a first glacier motion measurement based on the corner reflector detection in space borne SAR images. The precise positions of the CR have been computed by correlating the image CR response with a theoretical “impulse response” to be observed in ENVISAT images. The registration of the two images has been performed by applying the same technique on a set of strong backscatters located on non-moving areas (rocks, building in the valley…). The resulting CR displacement measured in range and azimuth directions are respectively Δr = 4.915 pixel and Δa = -0.545 pixel (with 4 looks averaging from SLC images). The resulting 350-day displacement is 60.1 m which corresponds to a mean displacement of 17.4 cm/day. Compared to the ground measurements obtained by continuous GPS (**Table 1**) the SAR measurement is slightly higher. This can be explained by the fact that the ENVISAT images cover 1 year displacement, including the summer period where the glacier accelerates (more in the lower part, less in the upper part), whereas the GPS measurements go from February to June. This is also consistent with the GPS daily mean velocity which is higher in June (16.7 cm/day) than in February/March/April (13.5 cm/day).

3.2 TerraSAR-X data

The precision of the previous CR-based glacier displacement measurement will be improved by the higher resolution of TerraSAR-X images (about 3 m instead of 15 m with ENVISAT). The October 2007 acquisition, illustrated in **Figure 6,** confirmed that the CR is perfectly detectable in HH-VV dual-polarization images. More images (not yet available) are necessary to assess the displacement measurement performances using the corner reflector or natural targets such as big rocks moving with the glacier.

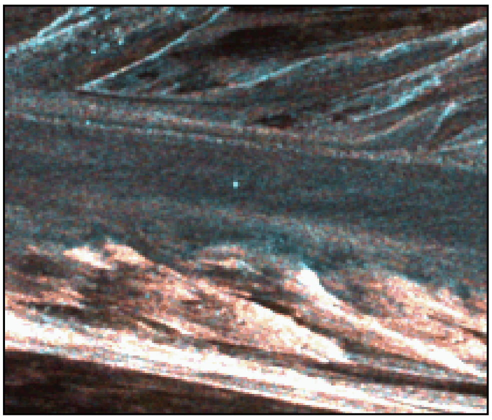

Figure 6 Argentière glacier and the corner reflector in TerraSAR-X dual-pol (HH-VV) image, Oct. 2007

4 Conclusions and perspectives

The early results of an original experiment started in 2007 over Argentière glacier have been presented. They show the feasibility and the potential of a combined use of continuous GPS, corner reflectors and satellite SAR images for glacier monitoring. This experiment opens new research axes to improve performances by combining these information sources.

With the GPS measurements, the availability of data from a second GPS site installed end of June 2007 on the rock close to the glacier site (~700 m distance) will greatly improve the interpretation and validation of the ZTD/GRAD measurements from the rapidly moving site on the glacier. Completed with a third site in the valley (in Chamonix) the 3-site-network will enable us to establish tropospheric delay maps using ZTD and gradients from the three sites. Extracting differences of delay with respect to a reference epoch or the average state over a long time span could be used to monitor “turbulent tropospheric perturbations” that reflect local departures from an isotropic atmosphere. The three stations can also be used to evaluate the total water vapour content or signal delay in the tropospheric layer between Chamonix and Argentière glacier (1000 m – 2700 m) to constrain an average topographic correction for InSAR images.

With the SAR images, TerraSAR-X images will be used to investigate important issues such as 11-day coherence preservation in X-band in winter over Alpine glaciers or the precision achieved by dual-pol amplitude correlation. The CR displacement will be used either as ground truth for performance assessment or as complementary data for solving D-InSAR phase unwrapping ambiguity. The combined use of SAR and GPS techniques seems the most promising to eliminate tropospheric artefacts in InSAR images.

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