TERRESTRIAL RADAR INTERFEROMETRY TO MONITOR GLACIERS WITH COMPLEX ATMOSPHERIC SCREEN

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ABSTRACT

This paper reports the results of two terrestrial surveys aimed at monitoring two Alpine glaciers located in Italy and Spain respectively, and carried out using a Ground Based SAR interferometer. Although the monitoring of glaciers based on this technique does not represent a novelty, these two case studies are peculiar, due to the characteristics of the Alpine glaciers among which the dominant role of the atmospheric phase screen (APS) on the radar signal propagation. These kind of glaciers, with their climate and geographical features, often demand a detailed analysis of the acquired data, at small temporal (less than an hour), and spatial (a few square meters) scale. The meteorological conditions, which affect the dynamics of the glaciers, deeply influenced the backscattering behavior, demanding a careful analysis of the amplitude of the radar signal, to characterize the surface, and of the interferometric phase, to evaluate the role of the APS. Only after the correction of the APS, a final accuracy of a few millimeters/day was attained in the daily velocity of the glacier in both cases.

Index Terms— GB SAR Interferometry, Glaciers, Atmosphere, Deformation.

1. INTRODUCTION

Terrestrial Radar interferometry mainly consolidated in the last decades for the monitoring of landslides, to estimate the deformation behavior of instable slopes, dams and mines [1]. One of the applications where the technique appeared a valuable tool is also the monitoring of glaciers: see for example [2], [3] [4] [5] [6]. One of the main reasons is that the alpine glaciers are often located on steep flanks, steep slopes and narrow valleys, often making spaceborne data not usable. In addition, the repetition times of satellite observations provide a too coarse temporal sampling for studying alpine glacier during the period of their maximum activity, when the air temperature daily fluctuates across zero Celsius degree, and instable cloud coverage makes also the sun radiation highly variable. In this paper we confirm that the Alpine glaciers, with surface areas of the order of a few square kilometers, despite the critical role of the Atmospheric Phase Screen (APS) can benefit from this technique (i.e., radar interferometry) in deformation retrieval. The results of two experimental campaigns carried out in Italy and Spain, monitoring the Planpincieux (Monte Bianco-Alps) and Monte Perdido (Pyrenees), are here investigated. In particular, amplitude and phase of the received radar signal have been both analyzed to separate glacier surfaces from stable rocks, whose radar backscattering can be similar, and to perform interferometric processing. The dispersion of amplitude and the coherence of a set of images acquired during some days are analyzed to finally reconstruct the glacier movement. These two parameters were also used to refine APS calculation, identifying stable points, and to finally provide estimates of the glacier deformation with an accuracy of a few centimeters.

2. THE MEASURING SYSTEM

The system used to acquire radar images is a commercial radar system the IBIS-L [6] based on a coherent continuous wave step frequency transceiver able to provide SAR images of a few square kilometers slopes moving along a two meters long rail. Its main parameters are listed in Table 1. SAR images were acquired in an almost continuous mode, with a time interval between image acquisitions of about 5 minutes, with the exception of some breaks caused by power supply interruptions. Raw data are focused in radar coordinates and

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then projected on the digital surface model DSM of the monitored area.

Table 1

Central frequency/wavelength	17.1 GHz/1.75 cm
Polarization	VV
Range resolution	0.43 m
Azimuth resolution (angular)	4.4 mrad
Azimuth resolution (linear)	10 m @ 2000m

Fig.1: View of the Planpincieux glacier with indicated: the glacier`s area (red dashed line), the positions of the radar (sky square), a weather station and an optical monitoring system.

Fig.2: View of the Monte Perdido glacier.

2. MEASUEREMENT CAMPAIGN

2.1. Planpincieux test site

The Planpincieux glacier is located approximately at 45.85°N 6.97°E, in the Aosta Valley Region (North-Western Italy). The glacier lies on the southern side of the Mont Blanc massif, towards the Ferret Valley, and it is part of the composite Grandes Jorasses-Planpincieux glacier, at an elevation between 2530-3700 m asl, covering approximately 1 km^2: in fig. 1 a view of the area with indicated the main locations is shown. The lower part of the Planpincieux glacier is intensely crevassed. The morphological analysis evidences that this part is separated in two different ice flows by a central ridge of bedrock. The radar system was positioned to optimize the parallel condition of the LOS to the estimated direction of the western flow, while the measurement of the eastern tongue that flows diagonally w.r.t. the LOS is handicapped. The mean distance of the glacier is about 2700 m with differences in elevation of 1200-1400 m. The radar images are georeferenced on a 1 m-resolution DSM: Terrestrial Laser Scanning (TLS) acquisitions have been carried out in late April or early May 2015s balance of the glacier. GB SAR data were collected between September 4 and October 14 2015

2.2 Monte Perdido test site

The glaciers in the Pyrenees are nowadays in a critical situation with clear evidence of very advanced stage of degradation; due to their small size, they are highly sensitive geo-indicators of the most recent climatic variations. The Monte Perdido Glacier is the third largest glacier in the Pyrenees and recent strong losses in glacier surface area have been reported; it is located in the Central Spanish Pyrenees (42°40′50″N 0°02′15″E) (see Fig. 2). The ice masses are north-facing, lie on structural flats beneath the main summit of the Monte Perdido Peak (3355 m) in the Ordesa and Monte Perdido National Park (OMPNP). The ice body is divided in three stepped ice masses connected by serac falls by the mid-20th century; the lower ice body disappeared during the 1970s. The upper and lower ice bodies have mean elevations of 3110 m and 2885 m. Despite the high elevation of the upper glacier, snow accumulation is limited due to the minimal avalanche activity above the glacier and its marked steepness (≈40º). According to recent measurements of air temperature (July 2014 to October 2017) at the foot of the glacier (2700 m a.s.l.) and slightly below the summit of the Monte Perdido peak (at 3295 m a.s.l.), the 0ºC is found to lie at 2945 m a.s.l., and the average summer (JJAS) temperature at the foot of the glacier is 7.3ºC. The mean distance of the glacier from the radar is about 1800 m with differences in elevation of 400-600 m. Radar images, acquired between July 15 2015 and 30 July 2015, are georeferenced on a 1 m-resolution digital surface model (DSM) derived from a terrestrial Laser Scanner campaign (September 2016). The monitoring here reported covers a seven days lapse, from 21h35m06s 2015.07.22 to 18h52m04s 2015.07.30, with an almost hourly repetition time, corresponding to 160 acquired images for seven days.

3. EXPERIMENTAL RESULTS

The same processing chain was used for the data sets acquired in the two experimental campaigns. The amplitude images are analyzed to distinguish the different areas of the glacier, and identify stable points to later carry out the APS calculation [6]. The critical parameters analyzed are the Mean amplitude, the amplitude dispersion (DA), defined as $D\mathrm{A} = \sigma_A / A$ where σ_A and A are respectively the standard deviation and the mean value of the measured amplitudes, and coherence. The processing includes first the application of a 2D unwrapping algorithm: unwrapping errors are mainly due to the high velocity and dielectric heterogeneity of the backscattering surface. To reduce possible errors, in this phase, interferograms with low coherence, which usually correspond to particular meteorological conditions (e.g. snow falls, zero air temperature crossing) are discarded and the displacement of the rejected interferograms is estimated with a linear interpolation between the previous and the subsequent interferogram. To correct atmospheric effects, a new APS-filtering model based on a 2D polynomial regression which takes into account the elevation was applied, for details see [6].

3.1. Planpincieux

The monitoring lasted more than one month: 3500 GB-SAR images were collected between September 4 and October 14 2015. In fig.3 the amplitude image, obtained with a coherent mean of the set of all the images, is shown. In general the signal, due to a low signal to noise ratio, does not allow at a first glance a clear distinguishing between the rocks, glaciers and shadowed area. On the other hand, coherence, shown in fig. 4, appears to be a fine mean to separate the different surfaces. A statistical analysis of the DA behavior, shown in fig. 5, supported a better understanding and a classification of the different surfaces, i.e. glacier, rock and shadow areas (noise). Rocks' DA decreases towards zero, maintaining greater than zero. The DA of the glacier is lower than noise only for a few hours. When the DA is computed for a longer period (>5-10 days) the DA of the glacier is higher than noise. At the end of this analysis, glacier points were selected with a Mean Amplitude threshold which appeared to be more reliable: a MA>1.5 is considered for the glacier area. As far as the APS is concerned, on the bases of the meteorological observations (air temperature and humidity), an empirical formula is applied, where a quadratic term is added, function of the elevation [6]. The final product of this procedure is a deformation map projected on the DSM of the imaged area which is shown in fig.6. Considering as error of the radar retrieval the standard deviation of the cumulative motion on the bedrock i.e. a stable area, we obtain for example, for the front sector a 29.2 ± 0.2 cm/day velocity, a relative error close to 1%.

3.2. Monte Perdido

In the Monte Perdido campaign the logistic was more complicated with respect to the Italian site. The powering was based on the use of solar panels, and this makes the image acquisition often discontinuous. Harsh weather conditions also affected the regular use of system. The processing procedure was the same. For the APS correction the same approach was used. In fig. 7 a mean amplitude map of the monitored area is shown. To distinguish the different areas, the same rationale used for the previous test site was applied. Fig. 8 shows the final product consisting in a deformation map, cm/day unit. A detailed analysis of single points temporal behavior is shown in fig. 9. As for the Planpincieux site, from these data we evaluated the accuracy of the achieved map, estimated through the residual cumulative displacement obtained in the fixed points (rocks) less than ±3 mm/day. Considering a typical value of the velocity for the glacier points around 2/3 cm/day, this accuracy can be considered satisfactory although worse than the previous case.

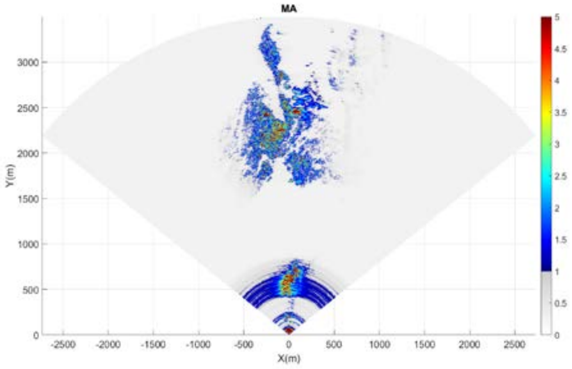

Fig.3: Mean amplitude in radar coordinates of the entire acquired area of the Planpincieux glacier; values in amplitude normalized to the clutter.

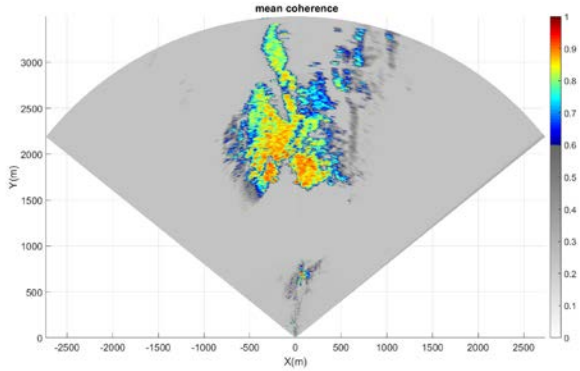

Fig.4: Coherence calculated for the Planpincieux area.

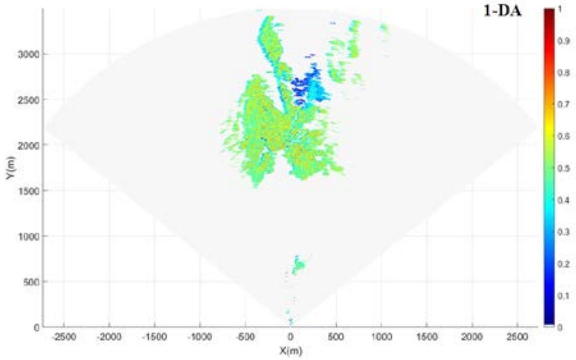

Fig.5: One's complement of amplitude dispersion $DA = \sigma_A / A$, calculated for the monitored area of the Planpincieux glacier.

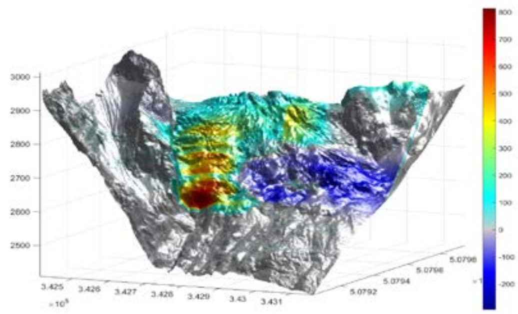

Fig.6: Cumulative deformation map of the Planpincieux glacier projected on the DSM. Displacements are in cm.

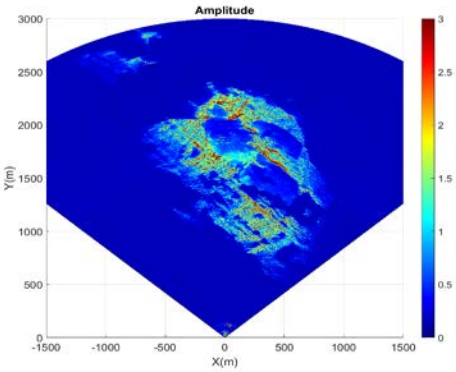

Fig.7: SAR Mean amplitude image of the Monte Perdido glacier. Values in amplitude normalized to the clutter.

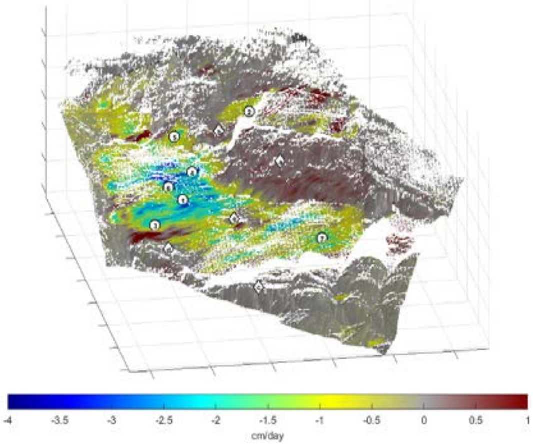

Fig.8: Deformation map of Monte Perdido with selected points; diamonds: stable pixels (letters); circles: glacier pixels (numbers).

4. CONCLUSIONS

Two survey campaigns aimed at estimating the surface deformation of two Alpine glaciers using a GB-SAR have been discussed. After the analysis of wrapping occurrence, and the role and the effects of the APS, deformation maps of the monitored area and glacier velocity of different sectors of the glaciers were estimated. The study confirmed that the GB-SAR technique can be successfully applied to the monitoring of Alpine glaciers, providing displacement map with adequate accuracy provided that atmospheric effect are carefully considered.

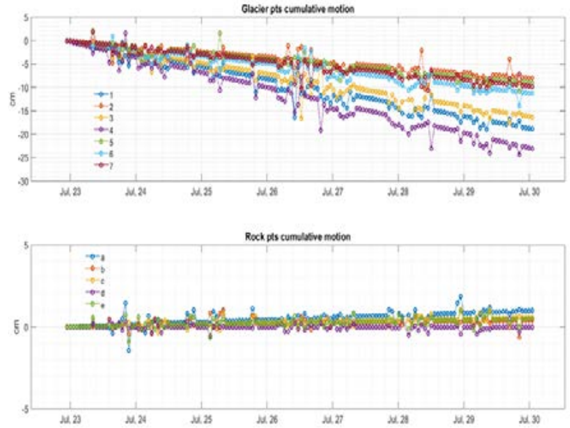

Fig.9: Cumulative motion for some points of Monte Perdido glacier; (see fig.8). Top: glacier points; bottom: stable rocks.

5. REFERENCES

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