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## Seasonal flow variability of a temperate glacier in the Mont Blanc massif observed by GPS

**Fanny Ponton (1), Andrea Walpersdorf (1), Michel Gay (2), Emmanuel Trouvé (3), Jean-Louis Mugnier (1), Nathalie Cotte (1), Laurent Ott (2) and Jonathan Serafini (1,4)**

(1) *ISTerre, CNRS, Université Joseph Fourier, Maison des Géosciences, BP 53, 38 041 Grenoble Cedex 9, France (fanny.ponton@ujf-grenoble.fr; andrea.walpersdorf@ujf-grenoble.fr; Jean-Louis.Mugnier@univ-savoie.fr; Nathalie.Cotte@ujf-grenoble.fr), (2) GIPSA-lab, INPG, Université Joseph Fourier, 961 rue de la Houille Blanche, 38402 Saint Martin d'Hères, France (michel.gay@gipsa-lab.grenoble-inp.fr; laurent.ott@gipsa-lab.grenoble-inp.fr), (3) LISTIC, Polytech Annecy-Chambéry, BP 80439, 74944 Annecy-le-Vieux cedex, France (emmanuel.trouve@univ-savoie.fr), (4) now at GePaSud, Université de Polynésie française, B.P. 6570, 98702 FAA'A, Tahiti - Polynésie Française (jonathan.serafini@upf.pf).*

### ABSTRACT

We present four years of GPS data acquired continuously on the Argentière glacier in the Mont Blanc massif, France. Our local permanent GPS network is composed of two stations on the glacier at altitudes of 2441 m and 2770 m, and two stations in static places, one in the valley of Chamonix at an altitude of 1121 m and the other on a rock outcrop near the glacier at the altitude of 2835 m. The measurements yield average displacement rates of about 13 cm/day for the upper glacier station (2770 m) and 17 cm/day for the lower site (2441 m). Moreover, we observe an annual variability of the displacement rates of up to 28 %, with fastest flow in late summer. The continuous monitoring of the Argentière glacier flow over several annual cycles can now be used to determine the correlation with climatological parameters such as temperature and cumulated precipitations.

### 1. INTRODUCTION

The study of the Argentière glacier in the Mont Blanc massif in France by continuous GNSS measurements is part of the EFIDIR project (Extraction and Fusion

of Information for ground displacement measurements with Radar Imagery). EFIDIR is funded by the French ANR from 2008 to 2011 to develop methodologies for improving the precision of radar imagery for displacement measurements. The project brings together researchers in different domains as signal processing, space geodesy and geophysics. The Argentière glacier has been selected as one of the EFIDIR targets representative for a fast moving geophysical object. Satellite radar images have been collected from TerraSAR-X and Radarsat2 satellites since the end of 2007 (for coverage see Fig. 1). Several corner reflectors have been set up to create well defined points in the radar images. Continuous GPS measurements in the same region, in particular on the Argentière glacier will be used for two different aims. First, the GPS stations on the glacier provide the ground truth for displacement measurements by radar imagery. One of the stations located close to a corner reflector helps establishing the spatial correlation between successive images. Second, the GPS network will be used to provide in situ measurements of the tropospheric delay that affects both the GPS and the radar imagery in the same way. While tropospheric delay remains one of the major error sources in satellite radar imagery, the analysis of GPS data permits to quantify this highly variable delay precisely (e.g. [1, 2]). The development of an optimal use of this precise but localized information provided by the GPS network to correct radar images is one of the goals of the EFIDIR project.

Sub-products of the GNSS instrumentation on the Argentière glacier are the times series of positions of two stations installed on the ice sheet. The relative continuous time series will help to identify not only an average flow velocity but also a seasonal flow variability. This is new information for temperate glaciers where altitude, climatic conditions and difficulties to access limit the possibilities to obtain continuous and numerous datasets. These new observations on the Argentière glacier flow could be linked with climatic conditions and temperate glacier flow models.

The glacier of Argentière in the Mont Blanc massif has a length of about 10 km from the edge of the tongue at the altitude of 1600 m to the top part at the altitude of 3400 m (Fig. 2). In 2003, it covered a surface of 12.4 km<sup>2</sup>. In the framework of the EFIDIR project, we developed a local GPS network to monitor this glacier and the overlying troposphere. The network is composed of 4 stations installed at different altitudes. To provide ground truth for the

surface ice flow velocities to be measured by radar satellites, two of them are installed on the ice, at 2770 m and 2441 m of altitude (ARGG and SERA). The upper one is close to the line of balance between snow accumulation and melt of the glacier, where also one of the corner reflectors is installed. Two more stations are located outside of the glacier, one on rock outcrops near the Argentière mountain hut at 2835 m (ARGR), and one in the close by town of Chamonix at 1121 m (CHMX) (Fig. 1 and 2). In this work, we present the GPS data analysis leading to a consistent position time series for the upper glacier station, ARGG. The analysis of the second glacier station, SERA, is still under work. Only the very first data from October 2008 have already been analyzed in the framework of the MSc thesis of J. Serafini at ISTERre [3]. We cite these results here in the meanwhile for completeness (last line in Tab.1).

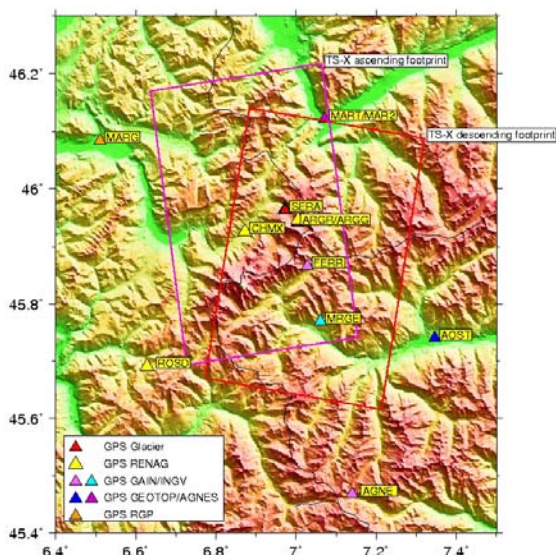


Figure 1. Map of the local GPS network. The color code indicates the original networks of the stations (RENAG, RGP, INGV (RING), AGNES). The frames show the surface covered by the Terra-SAR X and Radarsat 2 images.

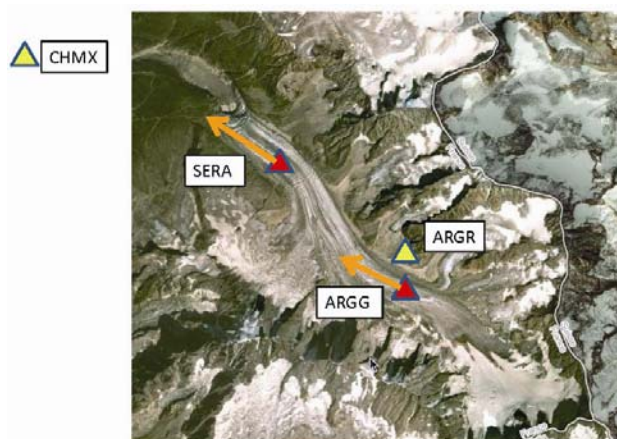


Figure 2. Local view of the Argentière glacier with locations of dedicated GPS stations. The average flow velocities of the two glacier stations ARGG and SERA are indicated schematically, evaluated to 13.3 cm/day (in this work) and 16.8 cm/day [3].

## 2. GPS DATA AND DATA ANALYSIS

The local GPS network provides data since spring 2007 (ARGG since 06/2007, ARGR and CHMX since 07/2007 and SERA since 11/2008). The first glacier station ARGG was initially installed on the edge of the corner reflector. Re-orientations of the corner reflector for specific satellite overflows caused several discontinuities in the coordinate time series. Although the corner reflector was anchored in the ice, differential ice melting in summer probably tilted the corner reflector and created motions of the GPS antenna that cannot be attributed to glacier flow. To obtain more consistent position time series, the antenna was finally mounted on a wooden mast at a few meters distance from the corner reflector. This mast is about 6 m long with 2.5 m fixed in the ice at the time of installation (Fig. 3). Ice melt in summer of 1 – 2 m necessitates regular re-installations of the mast. These different manipulations of the antenna setup led to discontinuities in the coordinate time series that have to be taken into account when establishing average flow velocities. The SERA station was mounted on a mast from the beginning. Due to the larger amount of ice melt in the lower part of the glacier, this station setup had to be manipulated even more often than for the ARGG station. The GPS equipment used are Topcon GB1000 receivers with PG-A1 antennae for ARGG and SERA, Trimble NetRS with a Zephyr antenna for ARGR and Ashtech ZXII with a Dorne Margolin choke-ring antenna for CHMX.



Figure 3. Photo of the ARGG GPS station.

The GPS data analysis was done with MIT's GAMIT/GLOBK software version 10.4 [4]. Average positions are evaluated over 6 hour sessions. This duration seems the most appropriate for the large glacier displacements, without weakening too much the positioning precision for the stable sites. The network analyzed is composed of the 4 local GPS stations, 34 stations from the regional or national networks RENAG (<http://webrenag.unice.fr>), RGP (<http://rgp.ign.fr>), AGNES (<http://www.swisstopo.admin.ch>) and RING (<http://ring.gm.ingv.it>), and 13 stations from the international IGS network (<http://igsceb.jpl.nasa.gov>). In the analysis of the 6 h sessions, the troposphere is modeled using the tropospheric mapping function VMF1 [5] and its pressure and temperature values as a priori values for each station, to estimate one zenith delay parameter every 2 hours and one horizontal tropospheric gradient per 6 h session. Atmospheric and ocean loading are modeled according to [6] and by the FES2004 model [7]. Resulting average position time series are represented in the ITRF 2008 reference frame [8], thanks to the IGS stations included in the analysis.

The resulting time series for the glacier stations contain several gaps and discontinuities, due to power failures and the above mentioned antenna setup manipulations. We estimated and corrected for the displacements due to manipulations by extrapolating the antenna motion from the last position using the average flow rate of the data segments before and after any discontinuity (jump or gap), and evaluating the “manual” displacement by the difference of this extrapolated position and the first position of the succeeding segment (see schematic representation in Fig. 4).

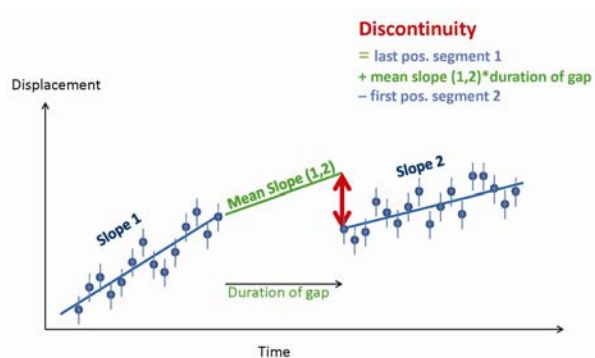


Figure 4. Schematic representation of the strategy used to correct for offsets in the position time series due to manipulations of the antenna setup.

For applying this strategy, 15 continuous data segments have been identified and the average flow velocities have been determined (Tab. 1). The extrapolation between successive segments showed that only 4 manipulations could be clearly identified and related to interventions on site (e.g. installation and re-installations of the mast). The 4 offsets (usually of several meters) have been corrected for in the position time series shown hereafter (Fig. 5 and 6).

### 3. POSITION TIME SERIES

The position time series of the ARGG station are shown on Fig. 5. An average displacement rate has been evaluated by component, with 6.0 cm/day toward the north, 11.9 cm/day toward the west and a downward motion of 1.1 cm/day. The flow direction is well aligned with the direction of the glacial valley (Fig. 2). With respect to these large linear displacements, any residual motion is hardly visible. To highlight any additional accelerations and decelerations, the average displacement rate has been subtracted from the three position components, with the resulting de-trended time series shown in Fig. 6. Seasonal variations of the glacier flow are now clearly visible. In particular, a regular annual signal seems to be dominating since 2008, while the 2007 data are less coherent, maybe due to the antenna mount on the corner reflector. The largest flow velocities are found rather simultaneously on the three components, in north, west and downward direction, around the months of August and September each year. The amplitudes of the position variations are about 80 cm on the North component, about 140 cm on the East component and 40 cm on the vertical. These differences in amplitude correspond to the direction of motion with a large west component, a smaller north component and a

relatively tiny downward motion. Eventually, in addition to the annual variation, another pluri-annual signal is superposed in the time series that has to be confirmed by a longer measurement span.

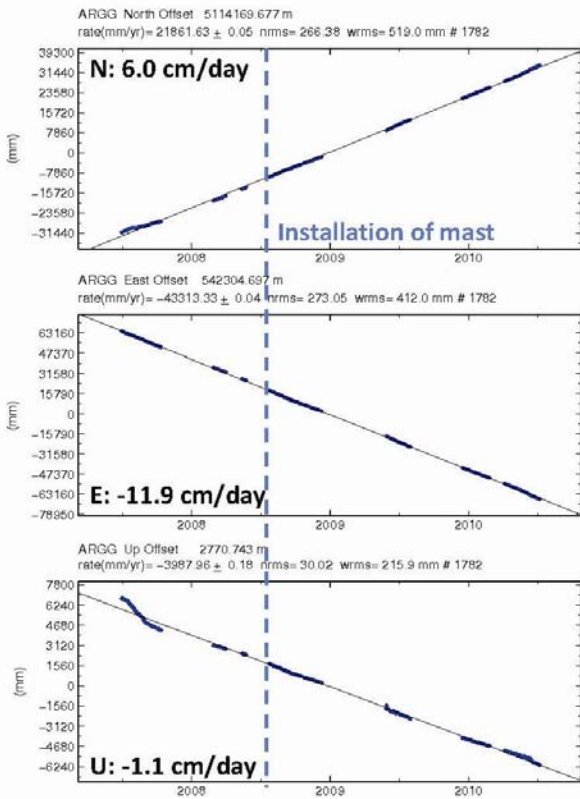


Figure 5. Position time series of station ARGG with respect to ITRF 2008. The three boxes show the North, East and Up component, respectively. Average flow rates are indicated for each component. The dashed vertical line indicates the moment when the antenna was un-mounted from the corner reflector and installed on the measurement mast.

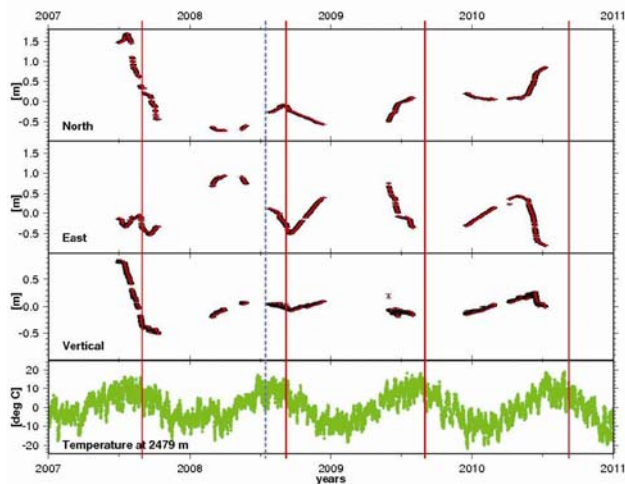


Figure 6. Detrended position time series of the ARGG station. The dashed blue vertical line highlights the installation of the mast. The red vertical lines indicate

the approximate location of an annual maximum of flow velocity. The lower box shows the temperature evolution of a close by weather station at 2479 m of altitude.

#### 4. DISCUSSION

One methodological test highlighting the coherence of the GPS measurements and their significance for monitoring the glacier flow is the comparison of the horizontal flow velocity with the simultaneous vertical motion. Indeed, if the experimental setup is well adapted (and the motion of the GPS antenna representative for the glacier motion), the relation between horizontal and vertical displacements should correspond to the slope of the glacier at the place of the GPS station. The evaluation of the slope of the motion has been done for each continuous data segment (Tab. 1). The limitation is the low vertical displacement rate, with the vertical position being less well constraint by the GPS measurements, due to the large elevation masks by the mountain ranges around the GPS station. However, the average vertical displacement rate is still determined to better than 1 mm/day for each of the segments. For comparison, the uncertainty of the horizontal average velocities is 0.3 mm/day. The slopes evaluated for each segment vary from 13 to 2 degrees, while the average velocities over the whole observation span yield a slope of 5 degrees. Indeed, high slopes are observed in the beginning of the experiment, in summer 2007, when the GPS antenna was still mounted on the upper edge of the corner reflector. A tilt of the corner reflector could explain the too large downward motions at this epoch. Since 2008, and in particular since the antenna setup on the mast in July 2008, the slopes for each data segment yield very coherent values of 4-5 degrees, while the total velocities vary by 4.2 cm/day. This shows that the measurement of the velocity variations is significant.

The average flow velocity at the ARGG station at 2770 m altitude should be compatible with annual measurements of several profiles across the Argentière glacier presented by [9]. One profile situated at 2730 m is close to ARGG station so that velocities can be compared. According to [9], the flow velocity at this altitude has been rather stable over the last 25 years, around 55 m/yr with variations of  $\pm 5$  m/yr correlated over several years. In particular, the annual rate decreased between 2000 and 2007 from 58 to 50 m/yr, corresponding to 15.9 to 13.7 cm/day. Our measurement of an average

velocity from 2007 to 2010 of 13.3 cm/day is coherent with these former results. As the GPS station is at an altitude 40 m above the profile, the GPS flow velocity should be slightly lower than the velocity at the profile. This could indicate that the flow velocity probably did not decrease since the last date published in [9]. The indication of an eventual long term variation that starts to be visible in the GPS time series is also in agreement with the pluri-annual variability shown by [9].

Our continuous GPS measurements resolve for the first time the short term variability of the Argentière glacier flow. As shown above, we can provide evidence for an annual signal, with a maximum velocity at the end of summer. The departure from

mean velocity reaches 28 % in our observation interval (Tab. 1). The comparison with the variability of ground temperature in the study zone (Fig. 6 bottom) shows that this maximum is reached at the end of the period of maximum temperature in summer (mid-September). Unfortunately, until now, only in 2008 this summer period is continuously measured, but the change in flow velocity seems to take place instantaneously after the drop of ground temperature. The amplitude of the seasonal variations as well as the particular signature of the variations are new observations that could be exploited for improving glacier flow models.

Table 1. Velocities per data segment

	N	E	U	total	slope	epoch	# obs.
ARGG	[cm/day]				[° ]	[yr]	[days]
<b>total</b>	<b>6.0</b>	<b>-11.9</b>	<b>-1.1</b>	<b>13.3</b>	<b>5</b>	<b>2007.49</b>	<b>446</b>
<b>seg. 1</b>	6.3	-12.1	-2.5	13.9	10	2007.49	33
2	3.6	-11.6	-2.8	12.4	13	2007.58	22
3	5.3	-15.7	-3.6	17.0 (+28%)	12	2007.65	10
4	3.9	-11.4	-1.4	12.1	7	2007.68	35
5	5.4	-10.3	-0.4	11.7 (-12%)	2	2008.16	16
6	6.0	-11.3	-0.8	12.8	4	2008.20	16
7	6.9	-13.5	-1.0	15.2	4	2008.36	10
8	6.2	-12.3	-1.2	13.8	5	2008.56	5
9	5.9	-13.1	-1.3	14.4	5	2008.58	57
10	5.5	-10.7	-0.9	12.1	4	2008.74	20
11	5.6	-10.7	-0.9	12.1	4	2008.81	35
12	7.5	-14.4	-1.4	16.3	5	2009.41	25
13	6.4	-12.4	-1.2	14.0	5	2009.47	38
14	5.8	-11.2	-0.9	12.7	4	2009.95	47
15	6.9	-13.4	-1.1	15.1	4	2010.26	79
SERA	9.5	-13.8	-0.3	16.8	1	2008.81	14

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