MEASUREMENT OF GLACIER VELOCITY FIELDS USING VERY PRECISE MULTITEMPORAL CORRELATION ON HIGH RESOLUTION SPOT5 IMAGES

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ABSTRACT:

Monitoring of ice velocity field is one of the key issues to glacier dynamics understanding. Surface velocity fields can provide useful information on phenomena such as glacier surges or ice fall. They can also reflect the effect of global warming on the dynamic of ice masses.

Although the surface displacements of glaciers can be monitored locally with ground GPS points, this solution is difficult in terms of both implementation and cost.

We show how glaciers displacements can be accurately measured using correlation of sequential high resolution optical satellite images. The advantages of this technique are first its potential temporal resolution, depending on the re-visit period of the satellite system, second its large spatial coverage, and third its resolution, proportional to the image resolution.

The availability of a very high resolution remote sensing satellite like SPOT5 opens the way for such application. Due to its unique compromise between a 2.5m resolution and a 60 km swath, this satellite is potentially very useful for accurate measurement of terrain displacement, over large areas like glaciers.

We present the methodology developed to measure glaciers surface displacement by image correlation. An example is shown over the French Alps. The paper addresses methodological issues: images co-registration, geo-referencing, glacier distortion measurement, velocity field computation. We also discuss coherence issues. This method is finally compared to SAR interferometry. We show how, as for SAR interferometry, it can be applied to a wide range of geophysical phenomena, such as earthquakes or landslide.

RESUME:

Le suivi des champs de vitesse des glaciers est l'une des clés pour la compréhension de leur dynamique. Les vitesses de surface peuvent donner des informations sur les phénomènes tels que les crues glaciaires et les chutes de sérac. Ils peuvent aussi être des indicateurs de l'impact du réchauffement global sur la dynamique des masses de glace.

Bien que les déplacements de surface puissent être mesurés localement en utilisant des balises GPS, cette solution demeure lourde et coûteuse.

Nous montrons ici comment les déplacements peuvent être mesurés finement par corrélation d'images spatiales haute résolution. Les avantages de cette technique sont sa résolution temporelle potentielle, qui dépend du temps de revisite du système satellitaire, sa grande couverture spatiale, et sa précision, qui est proportionnelle à la résolution des images elles-mêmes.

La disponibilité d'un satellite de type SPOT5 ouvre la voie à de telles applications. Son compromis résolution (2.5m) – fauchée (60km) le rend très intéressant pour les mesures de déplacement de terrain sur de larges zones.

Nous présentons ici la méthodologie développée pour mesurer les déplacements de la surface des glaciers par corrélation d'image. Un exemple est présenté sur les Alpes. Le papier détaille la méthodologie employée : co-registration des images, geo-référencement, calcul des champs de déplacement. Nous traitons aussi du problème de la cohérence. Finalement, nous comparons cette méthode avec l'interférométrie radar. Nous montrons comment, comme pour l'interférométrie, elle peut être appliquée à une grande variété de phénomènes géophysiques, tels les déplacements de terrain provoqués par les tremblements de terre ou les glissements de terrain.

1 GLACIER DISPLACEMENTS MEASUREMENT

Glaciers surface displacements can be monitored by different ways: the traditional technique, still used today, consists into placing reference points on the glacier surface, and measuring their position at different times of the year. Today, with the use of differential GPS (D-GPS), one can achieve very precise measurement (a few centimetres error), yet limited to a few points in the accessible part of the glaciers.

This kind of field campaign is costly and may be difficult. Glaciers might be more or less accessible, and weather conditions might be bad in altitude. Snow might also cover some of the reference points.

Aerial or satellite imagery may be used for such displacement measurement. Their main advantage is their spatial coverage, potentially the whole glacier. Satellite radar interferometry has been used for precise ice velocity measurement since 1993 (Goldstein, 1993), and this technique is very adequate for measuring small displacements (up to a few tens of cm), on cloud covered areas. Therefore, this method has proved to be adequate to follow glaciers displacements over a few days.

However, on longer time intervals, interferometry is no more adequate.

On the other hand, precise sub-pixel correlation techniques have already been used (Vadon, 2000), but not yet in the field of glaciers displacement. The following study is an ongoing work of OMP and CNES, using high resolution (SPOT5 THR) image correlation for displacement measurement.

2 DISPLACEMENT FIELD MEASUREMENT BY CORRELATION: METHODOLOGY

2.1 Introduction

The general principle of offset computation by correlation is the following: around every reference image point, for which one wants to compute the local offset with a secondary image, a so-called rectangular "vignette" is constituted, centered on the reference point. Having a rough knowledge of the local offset, we can center the search on the secondary image around the estimated position. We iteratively build a small vignette on the secondary image, which has the same size as the primary one, and which travels through an area called "research area" (Figure 1). The size of this research area is related to the uncertainty on the position in the secondary image.
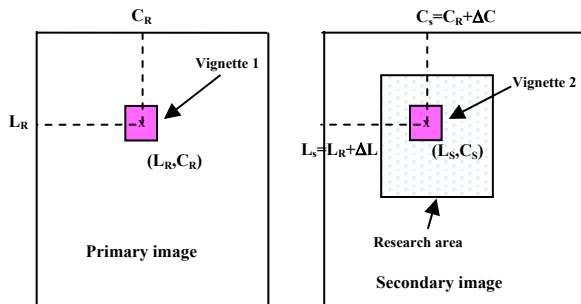

Figure 1: Correlation windows principle
(L and C refer to line and column in the images)

First, correlation rates are computed for every vignette position in the research area. The best correlation corresponds to the position in the research area of the secondary image that maximizes the radiometric resemblance between the two vignettes.
For sub-pixel search, the principle is similar, except that the second image is re-sampled in the vicinity of the position computed at the previous step. Second loop is performed at +-0.5 pixel in line and column, third loop at +-0.25 pixel around the previous position, and so on. Process stops when the required localization accuracy is reached.

This principle is general to all offset computation between images. Specific to glaciers is the fact that the surrounding slopes are stable, whereas the glaciers themselves have moved. Therefore, it is important that the software allows a variable search window size: very small research area on the glacier surroundings, and large one on the glacier itself. As a matter of fact, research area must always be as small as possible, because secondary correlation picks are one of the limiting factors of the method.

The conditions for an accurate offset computation are:

- Well sampled, aliasing free images. This is the case for SPOT5 THR images, thanks to its two quincunx arrays of detectors (Latry, 1995).
- Similar radiometry: this implies minimum time delay between the two acquisitions.
- Similar geometry: this implies acquiring images from the same viewpoint or at least as similar as possible viewpoints (similar incidence angles). In the case of SPOT5, the best configuration is a time interval multiple of 26 days, the orbital cycle.

2.2 Geometrical model

Before computing the local offsets between reference and secondary images, it is important to resample the secondary image, in order to make it as close as possible geometrically to the reference one. Correlation assumes a local radiometric linear relation between the two vignettes (y = ax + b, where y is the secondary radiometry and x the reference radiometry), and this relation can only be true if the geometry of the secondary image is very close to the one of the reference.

This resampling process requires an accurate geometrical model. Starting with initial system variables, ephemeris and attitude data, provided with the images, geometrical modeling is achieved by automatic bundle block adjustment. We obtain a refined geometrical model (refined attitude biases and first order derivatives).

The process requires a Digital Elevation Model (DEM) of the region. At this stage, it is not necessary to have a very good quality DEM, because the process is global. Typically, a DTED level 1 DEM is sufficient. The process of relative bundle block adjustment does not require ground control points. However, in our study area, we made two different computations, with and without ground control points (GCPs), in other words with absolute and relative geometrical modeling.

The inputs to the bundle block adjustment are homologous points, issued from a first correlation between the two raw images. The process models the impact of attitude (roll, pitch and yaw) biases and derivatives, and tries to minimize the residuals on the non-glacier areas. This method, which uses the physical attitude models, is better than the classical one, which tries to make a polynomial fit of the residual on the offset grids themselves (Figures 3 and 4).

At the end of this first step, we are able to resample the secondary image to the geometry of the reference one, in such a way that the non-glaciated areas are superposable. Therefore, all measurements done over the glaciers are now absolute: they represent the movement only, without any orbital and attitude residual.

2.3 Offsets computation by correlation

Glaciers, at least over one summer season, have proved to correlate quite well: their texture is adequate at the scale we are working (2.5m resolution), even when considering the fact that they partially melt in surface. However, one must be careful with year to year correlation: crevasses are stationary, and the measured displacements could be found to be almost null over one year!

Glaciers surface might have moved a lot during the acquisition interval. Dependant of the image resolution, the

motion might reach tens of pixels. Therefore, it is important to adjust the research area size to the expected maximum offset, or, if one can model the movement, to provide the correlation process with the estimated offset value. In the latter case, the research window may remain small, because the estimated position of the homologous points in the secondary image is accurate enough.

2.4 Conversion into latitude and longitude and geo-coding

Now that we have computed the offsets in line ΔL and in columns ΔC in the reference image, for a given set of points (usually a regular grid of points), we must convert them into ΔLat and ΔLon on the ground, or their equivalent ΔX and ΔY if we use a map projection. At this stage, we must be careful not to simply multiply the offset by the average satellite image pixel size (2.5m in the case of SPOT5 THR), because the pixel size is variable inside the image, in particular in mountainous areas. To be precise, we proceed the following way

- Project the reference point on the ground
- Project the secondary point on the ground
- Deduce by difference the horizontal displacements ΔLat and ΔLon. The difference in altitude is only due to the local glacier slope.

At this stage, we have converted the initial offset grids, in pixel unit and in reference image geometry, into offsets in meter or degrees, in the two directions North and East. A final transformation, using the geometrical model of the reference image, allows the geocoding of the two offset grids.

We now have 2 grids of offsets, one in the North/South direction, and the other in the East/West one, directly interpretable: they are hopefully null (or almost null) outside the glaciers and they represent absolute motion on the glaciers.
From those grids, we can extract profiles of highest velocity fields, or simply read displacement of reference geographical points. We may separately consider the two directions, or compute the total horizontal displacement:

$$\Delta Horizontal = \sqrt{\Delta X^2 + \Delta Y^2}$$

2.5 Measurement accuracy

The different errors which might affect the process are

- Global image geometrical distortion residuals
- Local geometrical residuals, due to local DEM error
- Local offset computation errors, on the glaciers themselves.

We can give an upper bound to the first error, computing the residuals outside the glaciers. Average residual is null (we refined the image geometrical models in order to minimize the residuals, by bundle block adjustment, which usually presents a null residual average), and standard deviation provides us with an information about the quality of this process. However, due to the low gain of the images, glaciers correlate much better than general landscape: the rms error on the glaciers is expected to be lower than the one outside the glaciers.

The second error mainly depends on the stereoscopic baseline between the two acquisitions. The closest the two local acquisition angles, the less sensible the results to relief errors. Even if an accurate DEM is not available everywhere on the 60km x 60km SPOT5 scene, one should try to have a good DEM at least on the glaciers themselves.

The third error is mainly due the radiometric dissemblance between the two images, provided the resampling processes are all performed with an adequate filter, like the apodized cardinal sine (Carfantan, 2001). This radiometric dissemblance may be related to surface changes between the two acquisitions, or may be a consequence of different acquisition incidence angles. In the case of time interval, one must not forget that, even if the images are acquired at the same hour of the day, different sun angles will lead to different shadows. This is particularly true in mountainous areas, but in our case, we found it more visible outside the glaciers than on the glaciers themselves, because glaciers were not on the areas of steepest slopes in the image. Quantifying this error is possible: computing the glacier motion on a given profile (for example on the steepest slope line), and then on a different one, close to the first one, can provide a good approximation of the accuracy.

3 TEST CASE: THE ALPS, SUMMER 2003

Glaciers of the Mont Blanc range have been selected for a first application of the methodology. The two main glaciers in this area are the "Mer de glace" and the "Argentière". They are well known, easily accessible and we have a good knowledge of their past velocities. A field campaign has taken place last summer, at about the same time as SPOT5 images were acquired. Ground truth could therefore be gathered, which allowed us to validate our methodology.

3.1 Images

Four images were acquired by SPOT5 (Figure 2) on this region in the summer 2003, forming the following two pairs:

- 19 July / 19 August: incidence angles -23.6° and -15.2°, 31 days interval
- 23 August / 18 September: same local acquisition angle: 16°, 26 days interval (one SPOT5 orbital cycle)
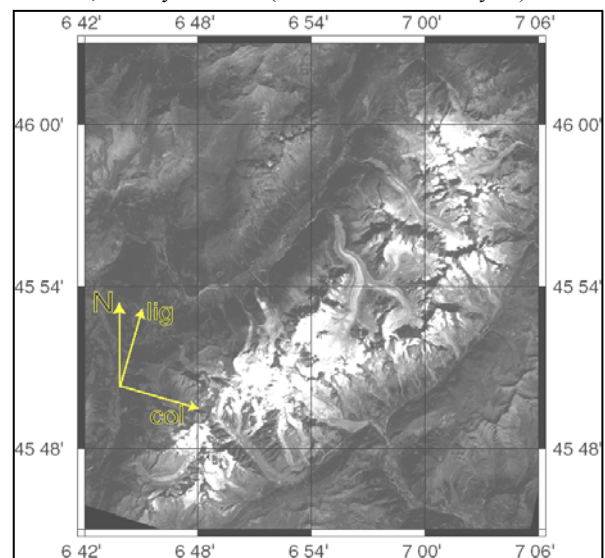

Figure 2: SPOT5 image on the Mont Blanc range (detail, geo-referenced). Lig and Col represent image direction.

3.2 Digital Terrain Model

Outside the glaciers, the SRTM DEM (1200^2 pts / degree) has been used. Such a DEM is already available for free everywhere on earth, or will be very soon. Its quality is sufficient for the global image bundle block adjustment.

On the glaciers themselves, the SRTM DEM has been improved by using the 2nd and 3rd SPOT5 THR images, which, with a 31° incidence angle difference, and a time interval of 4 days, were the most favorable images for DEM computation.

3.3 Results

After the first step of the method, the bundle block adjustment, displacement image exhibits only very small residuals outside the glaciers (Figure 4). Note that the results are very similar with or without GCPs. We have computed the residual errors outside the glaciers, using GCPs, and they happened to be of the order of 0.5m (rms). Figures 3 and 4 show how system level bundle block adjustment improves the global image quality, hence the measurement accuracy of the glaciers motion.
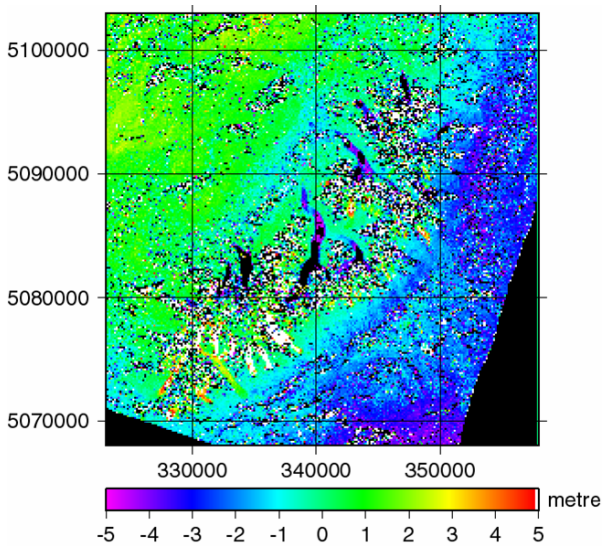

Figure 3: Offsets in longitude, no resampling, direct geo-coding without bundle block adjustment
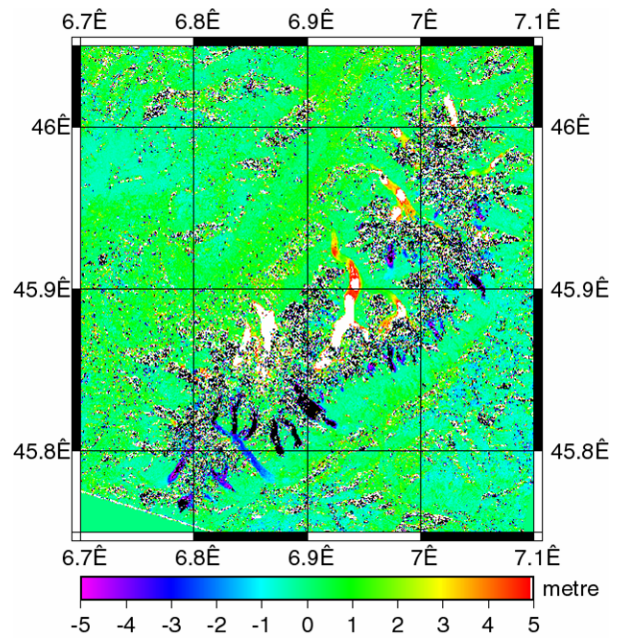

Figure 4: Offsets in longitude, obtained after secondary image resampling and bundle block adjustment

From the geocoded motion maps (Figure 4 and its equivalent in latitude), we can extract the profiles passing through the GPS probes, and check the consistency with the motion derived from the ground measurements. Of course, we take into account the time interval between the D-GPS measurements, and keep the same scale when comparing all measurements (for example we express all in cm/day).

Figure 5 shows a detail, over the glaciers, of the total horizontal displacement map, from 23 August to 18 September. This map is easily deduced from the two computed maps, in latitude and in longitude. Black dots represent the GPS measurements, and the black line the line of interest. The work of comparison between the measurements in still on-going, but seems very promising, showing a good consistency between motion computed from the SPOT5 images and motion computed from the D-GPS measurements.

Next work will consist into comparing the results obtained independently from the two image pairs. It is assumed that the glaciers surface velocity is rather stable. The first pair being less favorable for the acquisition conditions (different incidence angles), we will be able to measure the impact of such conditions on the results.
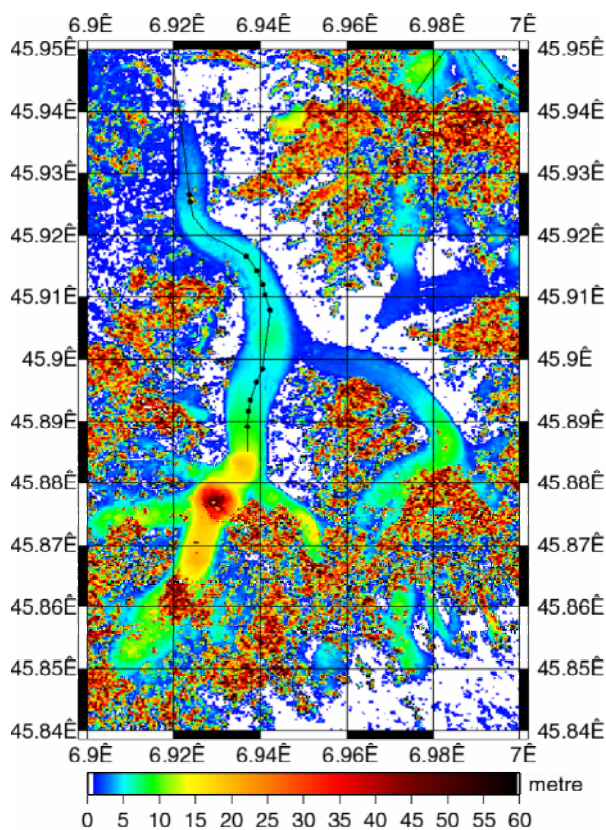
Figure 5: Total horizontal displacement map,
23 August/18 September 2003

4 COMPARISON WITH RADAR INTERFEROMETRY

If we compare the optical images correlation technique with radar interferometry, for the monitoring of glaciers surface motion, we can notice some similarities: being both based on space images, they potentially cover the whole area of interest, and provide complete maps of measurement instead of point measurement, which is a key issue for global monitoring. They also share the same limitation: both are limited by the surface temporal coherence loss. Note that this temporal coherence loss is only a few days for InSAR and a few months for optical images of glaciers.

But there are major differences between the two techniques: it may be difficult or even impossible to measure large terrain movement by interferometry because, one fringe representing half the wavelength of displacement -2.8 cm in the case of ERS and Envisat-, the number of fringes in the interferogram can rapidly become very high, making unwrapping impossible. In the case of optical image correlation, the measurement is proportional to the image resolution. For example, a 5m glacier motion will represent 178 fringes (impossible to unwrap) in the interferogram, whereas it will appear as a 2 pixels offset (easy to measure) if we correlate two 2.5m resolution optical images. However, the resolution of the optical images is a key factor, because the accuracy of our measurement is directly proportional to the image resolution, which is not the case in interferometry where the accuracy is proportional to the wavelength, in all cases around the centimeter (Massonnet, 1998).

Another difference with radar interferometry is the fact that optical correlation provides us with the two horizontal components of the motion, whereas interferometry only provides us with the motion projection along the line of sight. A displacement along the track, for example, would never be measurable in interferometry.

5 APPLICATION OF THE METHODOLOGY TO OTHER GEOPHYSICAL PHENOMENA

Our methodology has been developed on glaciers but its field of application is much wider. Any geophysical phenomena, which signature is a surface horizontal terrain displacement, on a scale compatible with the satellite image resolution and spatial coverage, is a potential candidate for the method, provided the geophysical event does not make the surface totally losing its coherence.

In particular, the same methodology can be applied to the measurement of other earth surface movements such as landslides or earthquakes.

6 CONCLUSION

This work, still ongoing, seems very promising for glacier surface motion monitoring. Acquiring regularly high resolution images on glaciers, one can expect being able to follow, year after year, the variation of their velocities. Images should better be acquired during the summer, snow falls being a problem because they induce coherence losses.

The interest of glacier monitoring from space images is high, if one considers the difficulty of field campaigns in such a harsh mountainous environment. Regular acquisitions should be programmed, if one considers the probability of cloud coverage and the problem of coherence loss on long time periods for such surfaces.

We have explained the general methodology applied for displacement computation, and we have shown preliminary results on the Alps. The same methodology might directly be applied to glaciers from other mountain ranges. Future work will consist into trying to extract other useful information, such as ablation values.

References

Carfantan H, 2001, Estimation non biaisée de décalages subpixelaires sur les images SPOT. GRETSI Proceedings, Sept. 2001

Goldstein RM, 1993. Satellite radar interferometry for monitoring ice sheet motion: application to an Antarctic ice stream, Science, 262 (5139)1525-1530

Latry C, 1995, French patent. « Procédé d'acquisition d'une image par balayage pousse-balai ». Patent n° 95 09242

Massonnet D, 1998. Radar interferometry and its application to changes in the earth surface. Review of Geophysics, 36(4), 441-500

Vadon H, 2000: «Earthquake displacement fields mapped by very precise correlation. Complementarity with radar interferometry". IEEE International Geoscience Remote Sensing Symposium, 2000.