Potential of ground based radar for the monitoring of deformation of volcanoes

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Potential of Ground Based Radar for the Monitoring of Deformation of Volcanoes

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Abstract. The ground based radar presented here is a new tool for volcano deformation monitoring. With respect to other systems it has various advantages: operational by any weather (rain, fog, aerosols), high frequency sampling capability (10 a few tens of seconds), possibility of monitoring surfaces not equipped with reflectors. It can be used to monitor unstable and dangerous parts of volcanoes (craters, lava domes, ...). The all weather capability and the high frequency sampling rate are crucial on volcanoes where activity can change within a few hours or less. We present the system and show an application for range measurements on corner reflectors. Then, we present the results obtained in the Pyrénées mountains (France) on a natural surface not equipped with reflectors. We analyze the evolution of the coherence of the reflected signal as a function of the nature of the terrain and elapsed time.

1. Introduction

The monitoring of volcanoes and the forecasting of eruptions and/or flank instabilities are based on the combination of geophysical and geochemical analysis. The measurement of ground deformations is one of the geophysical techniques more often used for this purpose [*Van der Laat*, 1996]. There are several reasons for this : volcanoes almost always deform during the eruptive cycle and especially prior to eruptions; ground deformation is a parameter relatively easy to interpret in comparison to other monitored data; the deformation gives direct constraints on the volume and rate of lava transport; there are several ways to measure the deformation and most of them can be automated.

Classical non automatic methods for measuring the deformations of volcanoes include all the traditional geodetic techniques (leveling, triangulation, trilateration, airborne-photogrammetry). Classical automatic methods include tilt measurement (there is a large number of sensors designed to be fixed on the ground and that allow to measure locally tilts with a high level of accuracy) and extension measurements (in boreholes using 1D, 2D or 3D strainmeters or across fractures using extensometers). *Agnew* [1986] gives a detailed review of those techniques. In the last ten years several new techniques extended the available tools for repeated as well as continuous monitoring. The most important one is the Global Positioning System (GPS) that can be used by any weather and without the need of reciprocal visibility between stations and that can be easily automated. Another is based on automated total station (combination of an automated theodolite and an electronic distance measurement -e.d.m.- device). Under favorable weather conditions, the instrument can measure with a millimeter accuracy distances to a few tens of small inexpensive optical corner-reflectors up to 3-5 km [*Briole et al.*, 1998]. Finally the interferometry on synthetic aperture radar images (InSAR) that has given spectacular images of ground deformations on volcanoes [*Massonnet et al.*, 1995] as well as in the epicenter area of large earthquakes is a technique also usable by any weather conditions and not too sensitive to the tropospheric contain [*Delacourt et al.*, 1998]. However, for volcano monitoring purpose, it is limited by the long repeat time of satellite passes and the relatively large ground resolution (typically 200 m).

The ground based radar that is presented in this paper complements the other available techniques. Its main advantage is the fact that it is the only one to combine the three following characteristics: capability of monitoring a non equipped area, monitoring by any weather, monitoring at high temporal and spatial sampling rates. However, unlike the satellite systems (GPS or InSAR) the path of the electromagnetic waves of the ground based radar is entirely located in the boundary layer of the troposphere where the refractive index is more unstable than in the highest layers and generates artifacts in the range measurements. As this is also the case when using automated EDM, this problem is partly solved by working in differential mode (one corner reflector or one part of the image used as reference for the estimation of the motion on the rest of the area). The width of the monitored area is typically of one to a few hundred meters for a distance of measurement of a few kilometers. This is lower that what is feasible using an automated EDM, and for some applications it should be necessary to mount the system on a rotating platform. In the first part of this paper, we present the technique used for high accuracy microwave range measurement on unstable slopes equipped with corner reflectors (like for e.d.m. measurements, the ground base radar was primarily designed to accurately monitor the range to corner reflectors). In the second part, we present a method developed for the detection and characterization of the deformation on unstable slopes non equipped with corner reflectors. This application is important on

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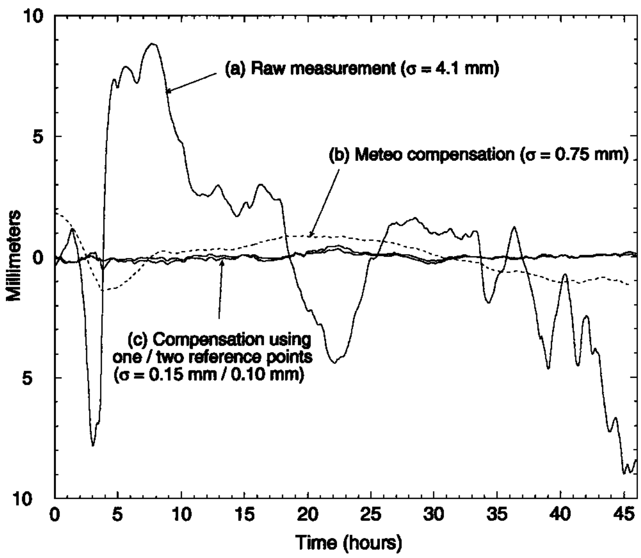

Figure 1. Range measurement on a passive corner reflector located 1.5 km away from the radar. The variations are due to temporal changes of the refractive index of the troposphere along the wave path. Curve (a) displays raw range data and shows relatively large distance fluctuations (4.1 mm r.m.s.). Curve (b) was obtained using local meteorological data collected close to the radar. Curves (c) were obtained by compensating the raw data assuming one or two reference points in the scene. This method integrates the refractive index variations along the wave path and gives better results (0.15 mm and 0.10 mm r.m.s. respectively).

volcanoes where access to the active area is sometimes difficult or dangerous.

2. Range measurement on slopes equipped with corner reflectors

We use a wide-band radar centered on the 26 GHz frequency (25-27 GHz band). The system is using classical radar techniques [*Hovanessian*, 1985; *Skolnik*, 1970]. It was described in detail by *Lemaître* [1995] and *Lemaître and Laffourcade* [1996]. Short pulses of a few centimeters are synthetized and data processing allows to remove ambiguities of distance. The phase information is thus exploited to give the final accuracy. Using corner reflectors of 40cm edge, a duration of observation of a few leads to comfortable signal to noise ratios at a distance of a few kilometers. The advantage of the corner reflectors is that they back-scatter a much stronger signal than the natural Earth surface does. The phase measurement is converted into an accurate range measurement (a phase variation of 360 degrees corresponds to a half wavelength range variation) of less than one tenth of millimeter. The main limitation is due to the fluctuations in the time and the space of the refraction index of the troposphere along the wave path. The tropospheric delay constitutes a source of range error of several tens of parts per million (p.p.m.) equivalent to several centimeters at one kilometer. This error can be reduced by carrying out differential measurement on targets located in the same scene, one of them being taken as reference for the others. In the case of slow deformations, another way to reduce the tropospheric effect is to average over periods of one to several hours. Figure 1 displays the results obtained on an experimental site using several techniques of compensation : calculation of the index from measured tropospheric parameters, direct measurement of a pseudo-index on one or several reference points (assumed as fixed). The typical accuracy of a differential range measurement at a distance of 1500 m is one tenth of a millimeter. It is about one millimeter in absolute mode with compensation of the atmospheric effects based on measurement of the local tropospheric parameters and a long enough observation time.

3. Measurement on areas non equipped with corner reflectors

Most of the active volcanoes are not directly accessible in their summit area. This can be due to the difficulty of access or to the volcano activity. To apply the radar technique there, we have assumed that the unstable area cannot be equipped with corner reflectors (or that existing corner reflectors have been destroyed or buried by the assumed volcano activity). We have tried to extract from radar observations some relevant information allowing to characterize the changes of the monitored area. During one month, we carried out measurements on various areas with a constant sampling rate. The experimentation was carried out during the summer 1997 at La Mongie, a mountainous site in the Pyrénées, France (Figure 2). From two given back-scattered responses of the same area, we calculate the inter-correlation of the impulse responses. This gives a measure of the apparent radial displacement (a.r.d.) and a measure of the degree of correlation of the two sights. As for the application with corner reflectors (section 2), the broad band capacity of the radar is used to remove phase ambiguities. Like in the case of corner reflectors, the a.r.d. is affected by the difference in refraction index from one scene to another. However, using the radar in differential mode, and comparing

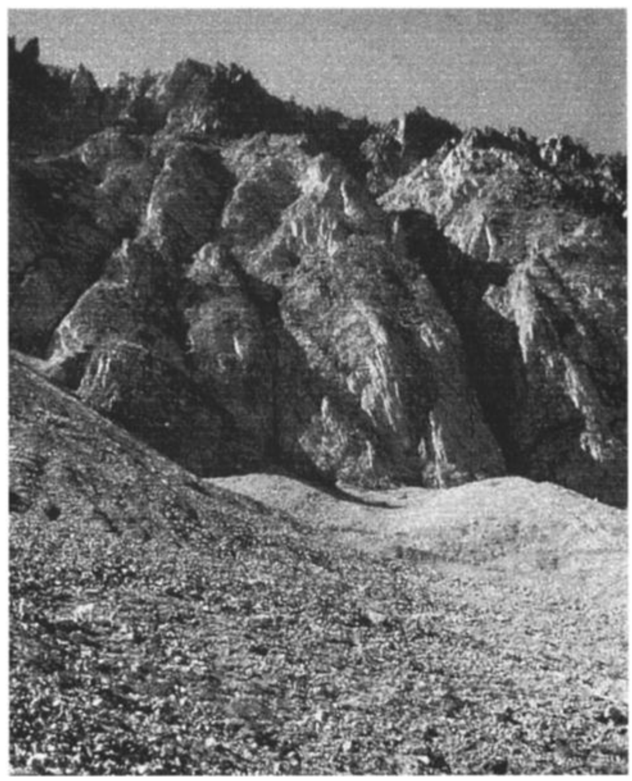

Figure 2. Photography of the area used as test site for the measurements on non equipped surface. This site located in La Mongie (Pyrénées, France) was chosen because of its scarce vegetation which allows to maintain the radar echo stability.

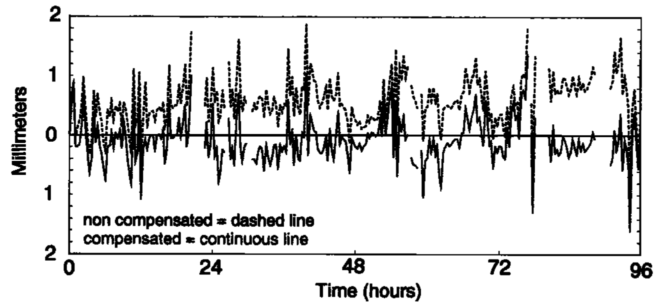

Figure 3. Four day time series of differential ground based radar measurement on non equipped surfaces. The two targets observed in differential mode are located 1 km away from the radar and separated by 40 m along the line of sight. The dashed line indicates the raw range difference. Atmospheric delays, almost similar for both wave paths, are almost completely removed. The absolute range variation on one of the two areas gives an information on the evolution of the integrated refractive index during the record. This data is used for compensating the atmospheric effect over the 40 m wave path separating the two targets. The continuous line is obtained after this common-mode correction. The residual variations are centered around zero and below the 1 mm peak-to-peak level.

the a.r.d. of two areas located in the same azimuth close one to the other, the atmospheric effects are almost completely eliminated (Figure 3). It is thus possible to detect subtle differential displacements of two close areas located at different distance from the radar. For a given area, the correlation of two sights temporally separated is a measurement of the topographic changes which occurred during this period. The natural de-correlation of an area depends on its nature and indicates the time scale on which a relevant information on its deformation can be recovered. Figure 4 and Figure 5 show 3D (time, time,

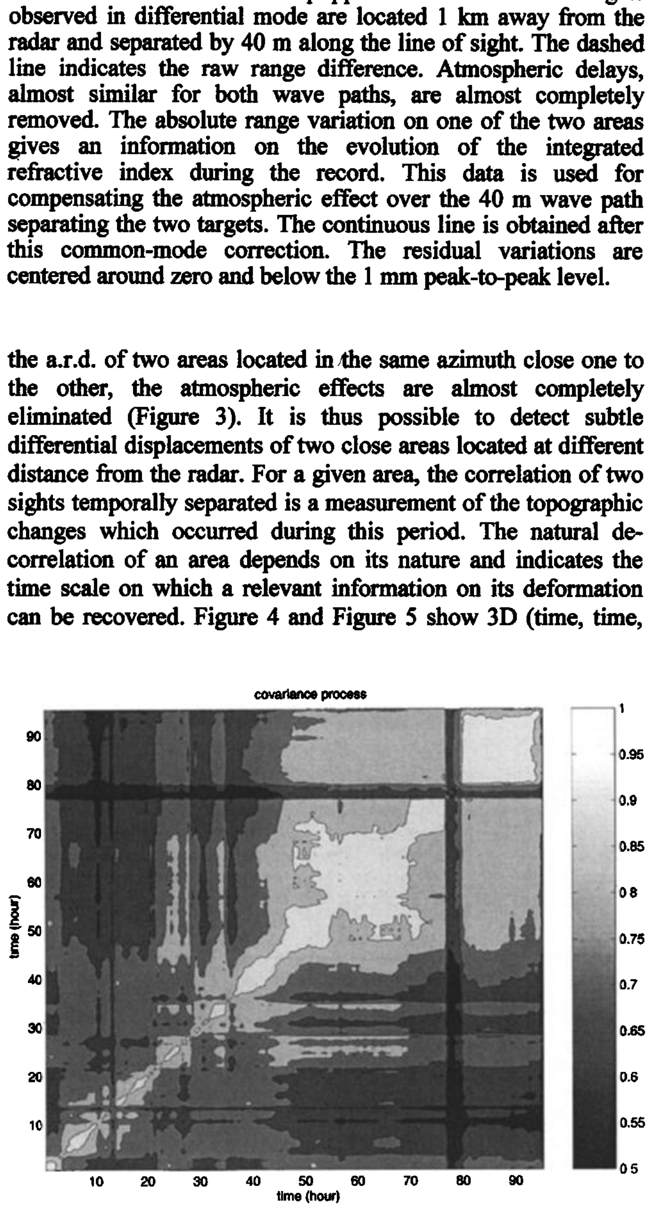

Figure 4. Time-time representation of the natural de-correlation of a rock fall area (bottom of Figure 2). This figure as well as the following ones displays results obtained on different areas using a covariance process: each temporal sample is compared to all others to calculate a correlation index (here ranging from 1 to 0.5). For a rock fall area, the instability of the surface induces a quick decrease of the correlation factor in the four days period. Reversible evolutions, caused by rains which temporarily modify electromagnetic scattering properties of the soil, are visible, particularly at t=11, 13 and 79.

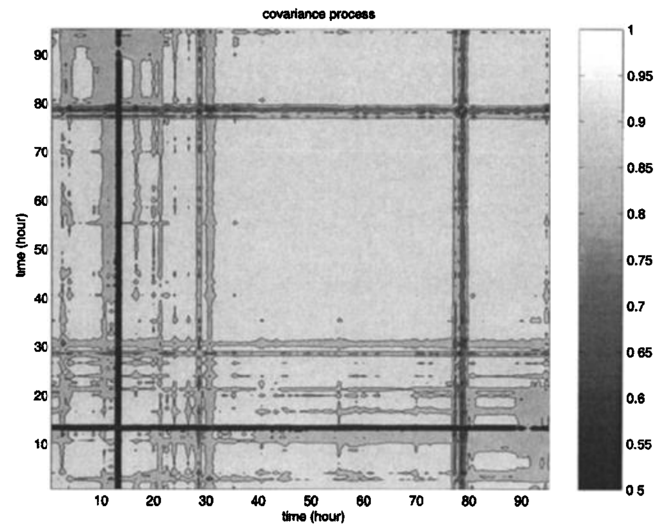

Figure 5. Time-time representation of the natural de-correlation of a stable cliff (top of Figure 2). With respect to the result obtained on the rock fall area (Figure 4), a low decrease of correlation with time is observed, except when meteorological events (like rain) occur. Over periods of time of a few days, the de-correlation is mainly a reversible process. Geometrically stable areas can be used not only to monitor deformations over periods of time of days (possibly months) but also to calibrate the meteorological disturbances and apply them to less coherent areas.

covariance) representations of the experimental results on a 40 m x 40 m rock-fall area and a stable rocky area. The diagrams show reversible modifications (moisture of surface in the early morning) as well as irreversible ones (de-correlation due to increase of the elapsed time between the two sights). The rocky area, which is structurally more stable, de-correlates slowly. The value of correlation after the four days experiment shown in Figure 4 is still high and this area would probably remain enough coherent (for differential measurements) during several weeks. On the opposite, the rock-fall area de-correlates more quickly. In order to quantify the volumes of material involved to produce a given level of de-correlation, an operator artificially generated abrupt changes in the area of rock-fall, by crossing it at regular interval. The 3D representation of Figure 6 shows the changes induced by these walks across. On a volcano, the high level of sensitivity of the radar would allow it to detect subtle surface changes such as deposits of rocks or ash, and it would probably be possible to quantitatively relate the de-correlation to the thickness of the deposit. One of the limitations of the radar technique is related to the presence of vegetation that usually produces fluctuating signals, not correlated with topographic changes. Although it might be a matter of concern on the flanks of several volcanoes, this limitation is not critical for the monitoring of the active top of the volcanoes (craters, domes) not covered by any vegetation.

4. Limitation due to the propagation through the troposphere and effect of aerosols

For microwaves and millimeter waves water vapor is the main cause of the variations in the refractive index and then it produces fluctuations in the phase measured by the radar. This sensitivity is lower in the optical domain where temperature variations become dominating factor. The tropospheric effects can be considered as the sum of two components:

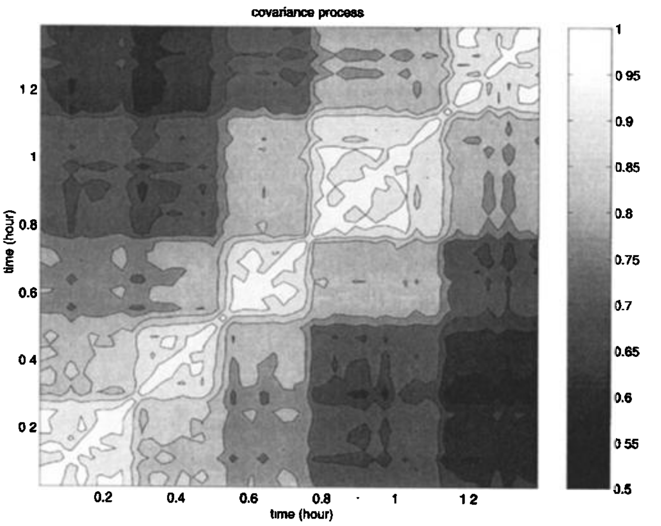

Figure 6. Time-time representation of an artificial de-correlation of a 50 50 m^2 rock fall area. An irreversible and gradually increasing de-correlation was created by a person walking across the illuminated area every 20 minutes. The operator modifies more quickly the soil structure than the nature does. The de-correlation index variation could be quantitatively associated to the modification amplitude.

1) at a relatively large scale, slowly varying effects which can be corrected by meteorological measurements or better by using range measurements to some reference points,

2) at a smaller scale, rapidly changing effects caused by atmospheric turbulence which can be efficiently reduced by temporal averaging [*Laffourcade*, 1998].

Finally, since the radar has to be all-weather operational we have investigated the possible effects of volcanic ash clouds after a powerful eruption. We have thus studied attenuation and phase shift induced by the presence of aerosols on the link. We have shown that microwaves are not very sensitive to dense ash clouds even for high concentration [*Lemaître and Laffourcade*, 1998].

5. Conclusions

Compared to the other existing techniques, the application of ground based radar to geophysics presents several innovative characteristics. For the range measurement on corner reflectors, this method allows to measure distances by all weather conditions with coverage and accuracy comparable to the optical instruments. Compared to the Global Positioning System (GPS) the interest of the radar is its capability of continuously measuring ranges on a large number of passive and inexpensive reflectors. Compared to Interferometry by Synthetic Aperture Radar (InSAR) from satellite, which gave several spectacular results in the last few years, the ground based radar presents the advantages of smaller space scale (a few tens meter instead of hundreds meters) and a higher rate of information refreshment (a few seconds instead of one to several days). A ground based radar has recently been integrated in the monitoring network of the Sechilienne landslide, close to Grenoble (France) and it is expected to be used for temporary test measurements on Etna (Italy) and Merapi (Indonesia) volcanoes.

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