# Ground Deformation Monitoring Exploiting SAR Permanent Scatterers

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***Abstract* – The detection of ground deformation phenomena exhibiting a time non-uniform behavior by means of the Permanent Scatterers technique is addressed in this presentation. Simple but effective models are discussed showing significant results obtained.**

## I. INTRODUCTION: PERMANENT SCATTERERS

The Permanent Scatterers technique is a fully operational tool for millimetric accuracy ground deformation mapping on a high spatial density grid of phase stable radar targets (the so-called Permanent Scatterers, PS).

Provided that long time series of SAR data are available (at least 25-30 images), the PS approach, allows to overcame the two most significant drawbacks of conventional Differential SAR Interferometry (DInSAR), namely decorrelation noise and atmospheric artifacts.

Since Permanent Scatterers are point-wise radar targets, they are only slightly affected by geometrical decorrelation even for large baseline values. On the sparse grid of Permanent Scatterers the various contributions to the differential interferometric phase (residual topography due to inaccuracies in the reference DEM, ground deformation, atmospheric signature and noise) can be discriminated. In particular, the atmospheric term (atmospheric phase screen, APS) can be estimated and subtracted from the original differential interferogram, provided that the PS spatial density is high enough (5-10 PS/km$^2$). Detailed descriptions of the main aspects of the PS approach can be found in [1], [2] and [3].

In this paper we assume to work on interferograms already compensated for atmospheric effects, in order to address the discrimination of deformation from residual topography and noise.

## II. PS PHASE ANALYSIS

In the framework of a PS analysis, N differential interferograms referred to a unique master image are created. The phase of pixel (*l,m*) in interferogram *i* is:

$$\phi_{l,m,i} = \frac{4\pi}{\lambda} r_{Ti} + \phi_{topo-res,i} + n_i$$

where $\lambda$ is the system wavelength, and $r_{Ti}$ the sensor-target distance ($\phi_{def}=4\pi/\lambda * r_{Ti}$ is, therefore, the phase contribution due to a varying $r_{Ti}$, i.e. surface deformation).

The phase terms can be separated by means of an analysis of their behavior along time and normal baseline dimensions.

- The topography phase term is proportional to the normal baseline. Assuming parallel orbits following well known expression is valid:

$$\phi_{topo-res,i} = \frac{4\pi}{\lambda r_M \sin\theta} \varepsilon B_{n,i}$$

  where $\varepsilon$ is the inaccuracy in the reference DEM relative to the image pixel at hand, $r_M$ is sensor-target distance in correspondence of the master acquisition, $\theta$ is the local incidence angle and $B_{n,i}$ is the normal baseline of image *i* with respect to the common master. On the other hand, the topographic phase term does not depend on the temporal baseline.

- The ground deformation[1] phase contribution is, conversely, strong correlated in time (temporal baseline) but does not depend on the normal baseline.
- Noise is, of course, uncorrelated both in time and acquisition geometry.

Assumed a particular model for ground deformation (depending on parameters $d_1, d_2, \ldots d_k$), the task we are facing for each PS is, therefore, the estimate of k+1 ($\underline{d}$,$\varepsilon$) parameters exploiting N phase data. Since phase values are wrapped, we are in front of a non-linear inverse problem. In the framework of the PS analysis the problem is usually solved scanning the parameter space seeking for the maximum of following quality function:

$$\gamma = \left| \frac{1}{N} \sum_{r=1}^{N} e^{jw_r} \right| = \left| \frac{1}{N} \sum_{r=1}^{N} e^{j\phi_r} \cdot e^{-j\phi_{def}(\underline{d},r)} \cdot e^{-j\phi_{topo-res}(\varepsilon,r)} \right|$$

where $w_i$ is the residual phase term, the model adopted is not able to take account for. If the model allows to fully describe the deformation occurring $w_i$ represents the noise (decorrelation and site effects).

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[1] With "ground deformation" we always mean the projection of the 3D deformation data along the sensor-target Line-of-Sight (LOS) direction.

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$\gamma$ is usually referred to as the single scatterer multi-interferogram coherence and is an *a posteriori* index of the effective phase stability of the radar target at hand, and, therefore, a reliability measure for the estimated parameters. As in conventional interferometry $\gamma$ values range from 0 (complete absence of coherence) to 1 (full coherence, absence of noise and deformation model perfectly fitting the data).

Of course, the higher the number of parameters used to model ground deformation, the more $\gamma$ is polarized towards 1 and the higher the risk of overfitting.

## III. SIMPLE MODELS FOR GOUND DEFORMATION

The simplest, but still extremely useful, model for ground deformation is time uniform displacement (i.e. constant LOS velocity as unique parameter):

$$\phi_{l,m,i} = \frac{4\pi}{\lambda} v_{l,m} T_i$$

where $v_{l,m}$ is the average LOS velocity of the PS in pixel (l,m) and $T_i$ is the temporal baseline (referred to the master image).

In many cases of real interest the constant velocity approach is sufficient, in particular for slow evolving phenomena whose non-linearity can be neglected at least in a first approximation (e.g. creeping, many cases of slip along active seismic faults, slow irreversible compaction of organic soil).

As discussed in [1], this model leads to a smart interpretation of the $\gamma$ based solution of the non-linear inverse problem we are facing, as the periodogam estimate of the position of a single tone peak $(v,\varepsilon)$, given a set of irregularly sampled observations in the $(B_n,T)$ domain.

Depending on the displacement phenomenon at hand other models can be adopted. In particular, the usage of higher order polynomials turns out very precious when facing sharp subsidence (induced by intense exploitation of groundwater resources or withdrawal of oil/gas) as well as ground deformation induced by mining activities and underground excavations, often causing rapid phenomena whose evolution is limited to the time span in which the originating activity takes place.

Finally, it is surely useful to take account of possible seasonal behaviors, especially in areas with a periodically varying groundwater level (dry summers and wet winters coupled with a differential exploitation of phreatic water for agricultural use and for supplying cities and industrial plants). The depletion and recharge of the aquifer system induces reversible ground deformation, sometimes even exceeding 2-3 cm [4].

The most simple and intuitive model taking account of both a time uniform and a cyclic (1 year periodicity) term is [5], [6]:

$$\phi_{l,m,i} = \frac{4\pi}{\lambda} v_{l,m} T_i + A_{l,m} \cos\left( 2\pi \frac{1}{\tilde{T}} (T_i - T_{0,l,m}) \right)$$

depending on the three parameters $(v,A,T_0)$.

In this section PS phases have been analyzed on a pixel by pixel basis. Of course available *a priori* information relative to the spatial correlation of deformation phenomena can be taken into account introducing space dependent parameters and processing jointly phase data relative to PS close enough [2].

## IV. RESULTS

Very interesting results have been obtained exploiting 56 ESA ERS-1/2 images acquired in the neighborhood of Metz (Lorraine, France) and covering the time span June 1995 – April 2000. The PS analysis, aimed at retrieving past deformation phenomena affecting villages in mining areas in Lorraine, was carried out by T.R.E. in the framework of the "Projet RESUM" founded by the French "Ministère de la recherche". Results are confidential and, therefore, all the names of locations have been omitted. In Figure 1, the position and average deformation rate of PS, whose deformation is time uniform, is depicted on a high radiometric quality multi-image reflectivity map. Several bright scatterers (we would expect behaving as PS) that with a constant velocity model do not show PS properties can be immediately recognized on the image. Assuming locally a polynomial model (4th order) for deformation, tens of PS affected by time non-uniform deformation (like the one in Figure 1.1) could be identified. Mining induced subsidence can achieve deformation rates of several centimeters/month, widely exceeding the 1.4 cm/35 days absolute limit imposed by the sampling theorem on ERS observations (as long as no *a priori* information are being used). As depicted in Figure 1.2, the PS analysis can still allow one to identify where and when deformation takes place but is no longer able (at least alone) to provide displacement measurements solved for the intrinsic ambiguity of phase data.

Further interesting results have been obtained exploiting 46 ERS-1/2 images gathered over the Santa Clara Valley in the time span May 1992 - November 2000. Seasonal ground deformation induced by the reversible compaction of the aquifer system (right beneath the city of San Jose) delimited by the Silver Creek and San Jose fault (~18 x 11 km$^2$) has been retrieved on a high density grid of Permanent Scatterers, in average 230/km$^2$ (Figure 2). The peak to peak amplitude of the displacement phenomenon involving coherently thousands of PS achieves 3 cm, in good agreement with what highlighted by other studies [4], [7].

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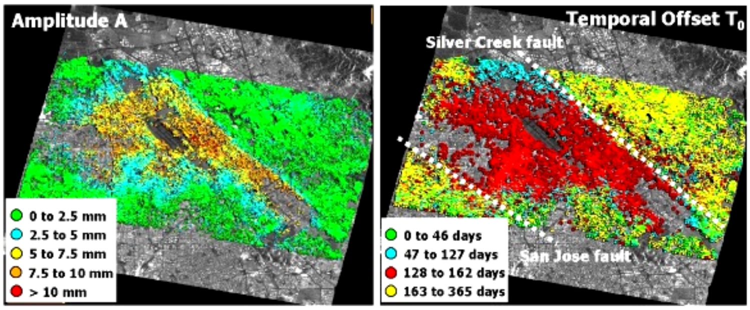

Figure 2: Reversible seasonal ground deformation beneath San Jose. Fitted amplitude and temporal offset.

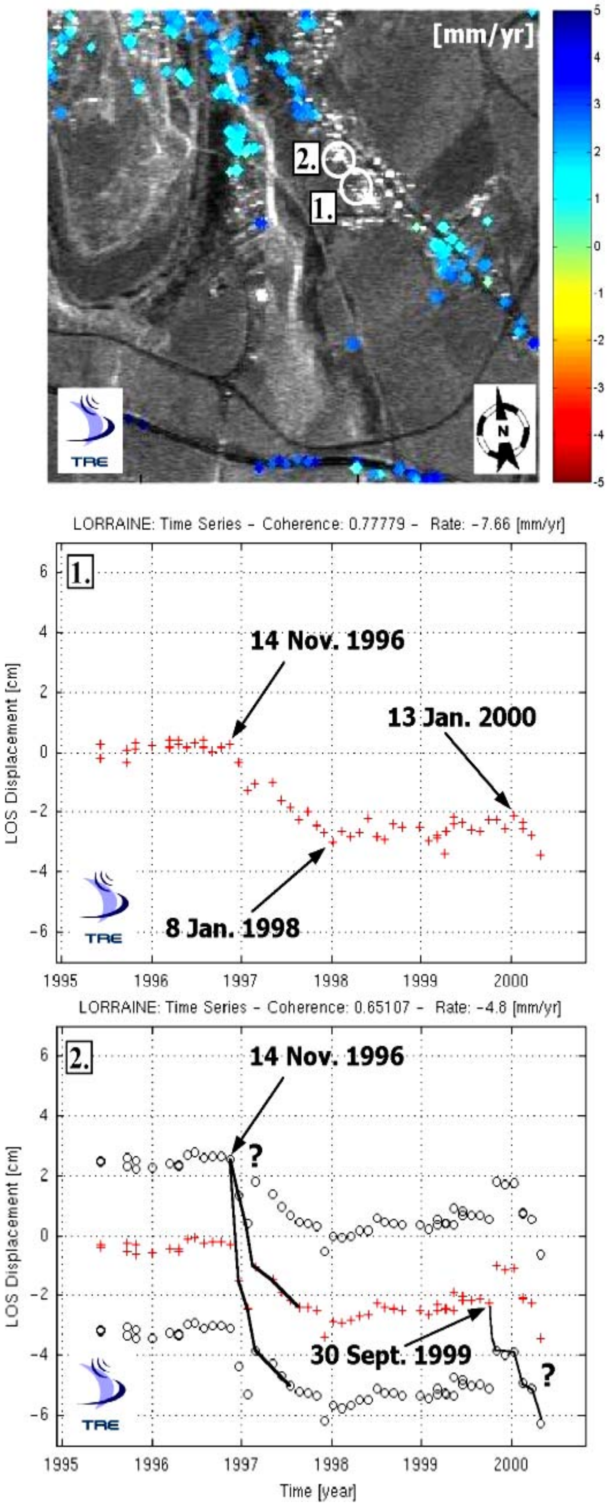

Figure 1: Time non-uniform deformation in Lorraine (France) detected exploiting a 4th order polynomial model for ground displacement.