Physical analysis of atmospheric delay signal observed in stacked radar interferometric data

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***Abstract*— The main limiting factors for deformation measurements using repeat-pass satellite radar interferometry are temporal decorrelation of the scattering characteristics of the earth and atmospheric delay phase contributions to the interferometric phase. Ferretti et al.[1] showed that using a multitude of radar acquisitions over the same site—a time series approach—reflections can be identified with a stable phase behavior in time, thus allowing deformation behavior to be estimated. The model of observation equations consists of m phase observations for a specific pixel and n unknown parameters describing surface deformation, elevation, and trend. Atmospheric delay is an important error source in these observations, but since it is temporally uncorrelated (while spatially correlated) it can be approximated per pixel per interferometric combination.**

This approximation requires a heuristic decision on which part of the temporal behavior of the interferometric phase is due to unmodelled deformation (e.g., non-linear deformation if the model estimates only linear deformation), and which part is due to uncorrelated atmospheric signal. Second, the residues attributed to atmosphere for all selected points within a single interferogram are expected to show spatial correlation, following a specific power law behavior (Hanssen, 2001). This results in a second decision on dividing atmospheric contribution and phase noise. Although the assumptions on which these two decisions are based are reasonable and results of previous studies show estimations of deformation and topography which are very likely, there is no independent means of control for the approach followed.

In this paper, we will investigate the atmospheric signal estimated from a stack of 70 radar images acquired over Berlin, Germany. The estimated signal will be statistically parameterized and physically compared with meteorological data such as visual, infrared, and water vapor images from meteorological satellites and synoptic data. We will draw conclusions on the likelihood of the assumptions underlying the isolation of atmospheric signal, resulting in an increased reliability of the estimated parameters.

I. INTRODUCTION

During the last years InSAR has been widely used for the study of deformation and topography. Compared with other techniques, InSAR has the advantage of having an extraordinary spatial coverage with relatively fine resolution. Furthermore it also has day and night imaging capabilities and is able to operate in cloudy weather conditions. Nevertheless there are also some problems affecting this technique. It is based on the exploitation of the phase difference as the result of the complex conjugate product of two electromagnetic waves. Coherent signals are thus needed. Consequently, one of the main problems affecting InSAR is the temporal variation of the physical scattering properties within a resolution cell. In order to circumvent this effect and to be able to use a time span of several years, a reference network of points which have limited temporal decorrelation has been used based on the *Permanent Scatterers* (PS) technique.

The second main problem affecting InSAR images is related to the atmosphere. It acts over the electromagnetic wave by bending and delaying the signal due to the refractivity distribution, mainly due to the water vapor in the lower part of the troposphere [2]. For InSAR this last one is the main problem.

The atmospheric signal is cannot yet be modeled in a deterministic way and might be source of important errors when analyzing the interferometric phase, for example for accurate deformation monitoring. An incorrect estimation of the atmospheric delay may lead to important inaccuracies in the measurements. Therefore a reliable mathematical model that describes stochastically the atmospheric delay behaviour is necessary if an increased reliability of the estimated parameters is required. This paper presents an approach to achieve this goal and improve understanding and statistical characterization of the atmospheric signal.

II. ATMOSPHERIC SIGNAL

First we will briefly review the most important characteristics of atmospheric signal.

A. Properties

First of all it is convenient to bear in mind that due to the relative character of an interferogram absolute signal delay measurements are not possible to measure. Secondly, orbit errors can also add up a linear trend over the whole interferogram which is difficult to distinguish from that of the atmospheric signal delay trends. They can be carefully removed using some residual flattening. Thirdly the amount of atmospheric signal within an interferogram is highly variable in time. Therefore it is assumed that temporally it is uncorrelated (two states of the atmosphere can be very different in just a day time span). However it is spatially correlated and

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consequently it is expected to show some kind of characteristic behaviour in space.

B. Power-law model

Assuming 3D isotropic turbulence in Kolmogorov theory, the spatial variation of the refractivity N is given by the following structure function [3]:

$$\begin{aligned} D_N(\rho) &= E\{[N(\vec{\rho}+\vec{r_1}) - N(\vec{r_1})]^2\} \quad (1) \\ &= \begin{cases} C_N^2 \rho^{2/3} & \text{for } l_i \ll \rho \ll l_o \\ C_N^2 l_i^{2/3} (\rho/l_i)^2 & \text{for } \rho \ll l_i \end{cases} \end{aligned}$$

with C_N^2 the structure coefficient and l_i and l_o the inner and outer scales of turbulence which can range from a few millimeters for optical wavelenghts to several kilometers for radio wavelengths for the outer scale, called also effective height or tropospheric thickness. The coefficient $2/3$ is a measure of the rate at which the refractivity decorrelates with increasing distance. The theoretical structure function of the signal delay can be derived from (1) if ones uses also the relation between the refractivity distribution $N(\vec{r}, t_i)$ and the one-way signal S^{t_i} delay for the acquisition time t_i and resolution cell j:

$$S_j^{t_i} = 10^{-6} \int_0^H \frac{N}{\cos\theta_{inc}}\, dh. \quad (2)$$

with θ_{inc} the incidence angle and H the height of the satellite above the position of the scatterer. Combining (1) and (2) and with a few transformations [4] the theoretical structure function of the signal delay $D_S(\rho)$ is given by:

$$D_S(\rho) = C_S^2\ \rho^{\frac{5}{3}} \quad (3)$$

where C_S^2 is the structure coefficient of the signal delay. Assuming isotropy it is expected that the atmospheric signal here studied follow within certain scale the stated $5/3$ power law. Further studies (Hanssen 2001) suggest dividing the atmospheric signal in several regions in which different power coefficients apply to the signal.

The power–law variogram model, as the one in (3), is the only one which has the property of being scale invariant [5] as are our observations expected to be within a certain range. These processes can be parametrized through the fractal dimension D, which characterizes its behaviour. Its relation with the coefficient β of the power law model is given by:

$$\beta = \begin{cases} 5 - 2D_1 & \text{for } 1D \text{ signal} \\ 7 - 2D_2 & \text{for } 2D \text{ fields} \end{cases}$$

If $1 < D_1 < 2$ (or $1 < \beta < 3$) the process is a self–affine fractal. These sort of fractals have the same behaviour in all dimensions and are by definition isotropic. If our observations agree with other works, the atmospheric signal should show the behaviour of a self-affine fractal.

III. Methodology

A stack of 70 ERS-1/2 acquisitions over the area of Berlin are available in this study. The total span of the perpendicular baseline is 2100 m. and that of the time is 8.5 years, from May 1992 to November 2000.

A. PS processing to isolate atmosphere

The aim of the *permanent scatterer* processing is to find sparsely distributed points with limited temporal decorrelation, and to estimate DEM error and linear deformation at these points using a time series approach [6].

1) Firstly the selection of a master has been performed from the stack of the images. The criterium followed has been to choose the master as that one whose mean coherence was the highest as if that SLC would be master of the stack of images. The magnitude of all SLC images are calibrated for processor gain factors, range spreading loss and antenna pattern. Once the master was selected 7 interferograms of the stack were discarded as they presented a Doppler Centroid frequency too large compared with the selected master.
2) The amplitude time series is used to select a large number of points that are most likely to possess a coherent phase in time. These points that present a large amplitude and a small amplitude dispersion are expected to have a relatively small standard deviation. Nearly 100.000 points were selected.
3) The phase of the selected points are first used to correct for global phase trends over the inteferograms caused by orbit errors. The corrected data are then analyzed with the PS network approach [1].
4) The model of observation equations relates a random vector $\underline{y}$ of m phase observations with a vector $\underline{x}$ of n unknown parameters, according to:

$$E\{\underline{y}\} = Ax; \quad D\{\underline{y}\} = Q_y, \quad (4)$$

where the matrix Q_y is the variance-covariance matrix (Teunissen 2000). The dominant parameters affecting the interferometric phase are topographic height H_j, deformation in slant direction D_j, slant-atmospheric delay during the first acquisition $S_j^{t_1}$, slant-atmospheric delay during the second acquisition $S_j^{t_2}$ and an integer ambiguity number w_k. Fortunately these components have different spectral properties which enables us to separate them. The topography is a linear function of the perpendicular baseline, and the velocity can be assumed to be a linear function of temporal baseline. Orbit errors are linear functions of the range and azimuth coordinates. The atmospheric phase is spatially correlated, but uncorrelated in time. Noise is considered high frequency in all domains. It is our first goal to obtain the unwrapped 'atmosphere plus noise' matrix by stepwise removing the other phase components, and then to remove the noise by spatial filtering with an averaging kernel.

5) The phase difference of nearby points is used to compute DEM error differences and linear velocity differences between points. A least squares adjustment and hypothesis testing step is then performed to obtain reliable estimates for the DEM error and linear velocity at these points, with respect to an arbitrary reference point. The phase is corrected for the estimated DEM errors and linear deformation, yielding the residual phase of atmosphere plus noise. Finally this phase has been unwrapped on a sparse grid.

B. Variogram estimation

Under the previously stated assumptions and at this point, a matrix containing atmospheric signal plus noise has been isolated. The atmospheric phase can be analysed in different ways, such as the power spectrum, the covariance function or the structure function or variogram [4]. Since the PS technique does not provide a regular grid of points available, a power spectrum can not be conveniently calculated through the 1-D Fast Fourier Transform. No restrictions in the preliminary estimation of the mean or regarding stationarity is necessary to use the structure function. It can be applied to a network of sparsely distributed point as in our case, giving us a useful quantitative expression for the variance of the difference in atmospheric delay between two points separated by a distance ρ. Moreover it is also useful for the quality description.

The variogram of the stack of interferograms has been calculated using a smaller number of coherent Permanent Scatterers available. The initial number N of almost 100.000 permanent scatterers available requires a large number of computations due to the large number of possible combinations among permanent scatterers. This implies a long processing time. Hence, a pre-step for data reduction results necessary. As criterium we have chosen here to select a reduced but statistically representative n subset of points. They have been randomly selected between the whole group N based on their mean. The histogram of the atmospheric phase per interferogram after the unwrapping processing shows in all the cases a very approximate Gaussian distribution. The expected value for the phase will be thus the mean value. We have applied an algorithm looking for convergence to the mean of the group of N permanent scatterers. In the moment the mean of a subset of n number of PSs is equal to that of N the process stops. Following this procedure it was found that the convergence to the mean of N was quite fast and with a number of 3000 randomly selected PSs the time computing decreases extraordinary. Moreover there are enough points to obtain smooth variograms.

IV. Results

The mean atmospheric residual phase has been substracted for every interferogram, i.e, the master atmospheric phase screen (APS). Figure 1 shows an example of an atmospheric phase screen over the test area Berlin, Germany. Thus the variogram of every acquisition has been computed. Figure 2 shows the superposed variograms for the 62 acquisitions:

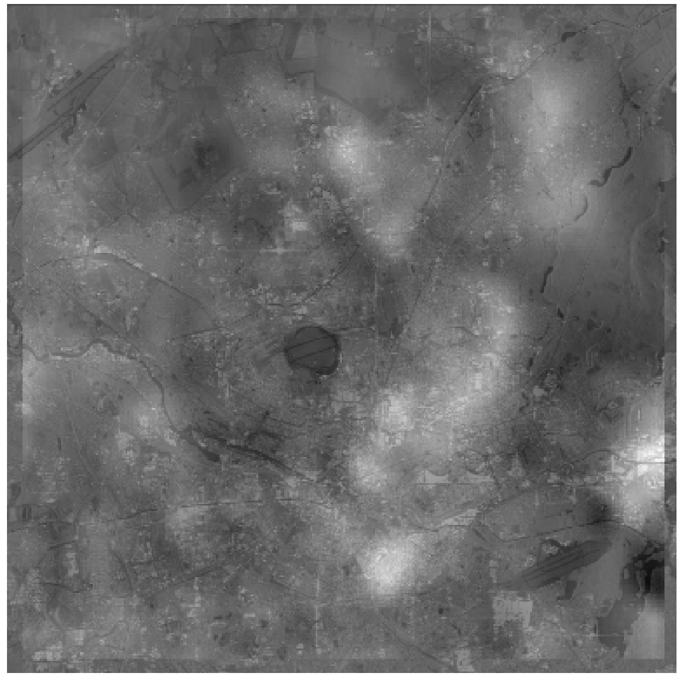

Fig. 1. Example of atmospheric phase screen retrieved over Berlin

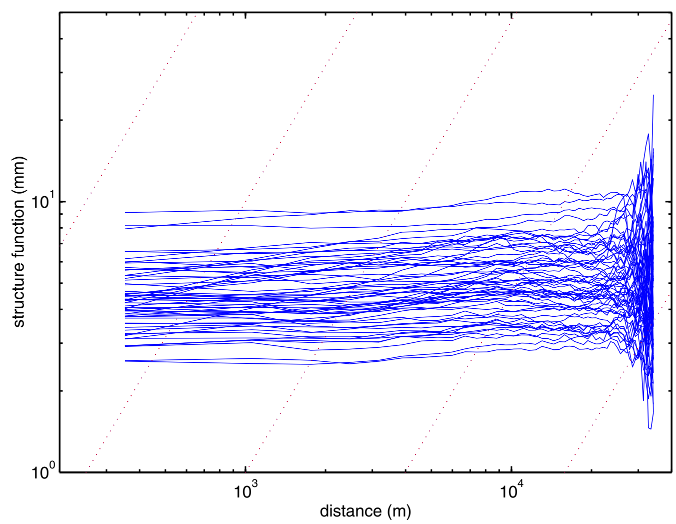

Fig. 2. Variograms of the stack of images

The structure function has been converted to millimeters by taking its square root for easier interpretation. All the variograms show the same structure but ranging in standard deviation of the difference in the atmospheric delay from 2 to $11mm$. Overlapped to the variograms it is depicted for comparison in red-blue the theoretic $\beta = \frac{5}{3}$ power law predicted in (4). The variograms do not fit at all this power law, in fact the curves appear to be quite flat. Further detailed observation of the figure allows split the variograms in several regimes as theoretically has been described. The first area for distances between points up to 2 km. Making the assumption in this area that curves follow a linear relation, it is obtained a slope of $1/15$. A second area can be appreciated with distances ranging from 2 km to approximately 25 km, with a slightly higher slope. In this case the slope obtained is $1/12$. The third area for longer distances does not show any sort of pattern and unlikely to have atmospheric origen. This can be a sign of the decorrelation of points which large distances, here more than 30 km. With the previous coefficients obtained we cannot conclude that the process has self-affine behaviour, as the coefficient β is in each case smaller than 1.

Another important feature of the atmospheric signal can be visualized when representing the histogram of the variance of the atmospheric delay for a particular distance between points for all the acquisitions. Figure 3 shows an histogram belonging to each of the three previous mentioned areas.

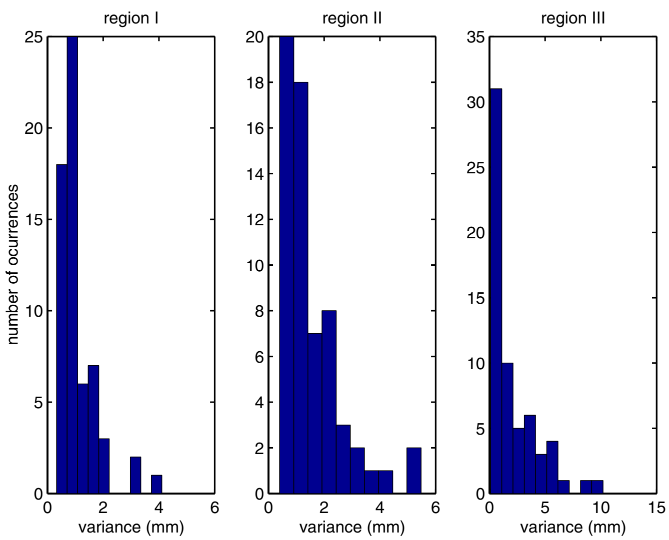

Fig. 3. histograms of the atmospheric delay for three regions in figure 2

For all the distances the histogram of variances shows a sort of Gaussian skewed left distribution. It means that whereas relatively small variability occurs often, large variability is presented in a few cases, as the right side of every histogram has just a few occurrences. Large variabilities may be linked to unstable weather situations. In following studies we will focus on the relation of the variability in atmospheric signal delay with the state of the atmosphere at the time of the acquisition. It is expected that those variograms with the relatively largest variations are linked with episodes of large amount of atmospheric variability or unstable states of the atmosphere. On the other hand those ones who relatively display the smallest variances are expected to be in anticyclonic situations. Maps of the region and synoptic data will be used.

V. CONCLUSIONS

The PS technique allows the determination of the APS of an interferogram or an acquisition when removed the mean atmospheric residual. It adds up the advantage of using temporal series on stable points and therefore capable of using a large spatial and time span to isolate the atmospheric signal from topography and deformation. Since the atmospheric signal is spatially correlated it shows a characteristic behaviour as depicted in figure 2. However and based on these results here presented, we cannot conclude that the unwrapped phase matrix, corrected for topography and deformation for the acquisitions, shows just atmospheric signal. The theoretic atmospheric model predicted by (3) is far from the $1/12$ and $1/15$ power coefficients obtained. This study is still ongoing, but these preliminary results turn our attention to the hypotheses taken. Among them the assumption taken with regards to a linear-model for the velocities of the PSCs might not be accurate and non-linear model should be introduced. The technique loses reliability as the distance between points gets large as the points become uncorrelated. In this case the atmospheric signal shows no characteristic behaviour and the noisy high-frequency phase domain over the atmosphere.
The structure function is a way to show quantitatively the difference in atmospheric signal delay between two points and therefore are relative measures. From figure 2 we can conclude that this stated difference range from 2 to 10 mm, addressing large values likely for that unstable atmospheric situations. We expect to draw further conclusions when compared the variograms and histograms with sinoptic data and meteorologic maps of the day of the acquisitions.

REFERENCES

[1] A. Ferretti, C. Prati, and F. Rocca, "Nonlinear subsidence rate estimation using permanent scatterers in differential SAR interferometry," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 38, no. 5, pp. 2202–2212, Sept. 2000.

[2] B. R. Bean and E. J. Dutton, *Radio Meteorology*. New York: Dover, 1968.

[3] V. I. Tatarski, *Wave propagation in a turbulent medium*. New York: McGraw-Hill, 1961, translated from Russian.

[4] R. F. Hanssen, *Radar Interferometry: Data Interpretation and Error Analysis*. Dordrecht: Kluwer Academic Publishers, 2001.

[5] J.-P. Chilès and P. Delfiner, *Geostatistics: modeling spatial uncertainty*, ser. Wiley Series in Probability and Statistics. New York: John Wiley & Sons, 1999.

[6] B. M. Kampes and N. Adam, "Velocity field retrieval from long term coherent points in radar interferometric stacks," in *International Geoscience and Remote Sensing Symposium, Toulouse, France, 21–25 July 2003*, 2003.