Mitigation of atmospheric water-vapor effects on spaceborne Interferometric SAR imaging through the MM5 numerical model

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Abstract- Synthetic Aperture Radar (InSAR) imaging is a well established technique to derive useful products for several land applications. One of the major limitations of InSAR is due to atmospheric effects, and in particular to high water vapor variability.

In this work we make an experimental analysis to research the capability of Numerical Weather Prediction (NWP) models as MM5 to produce high resolution (1km-500m) maps of Integrated Water Vapor (IWV) in the atmosphere to mitigate the well-known disturbances that affect the radar signal while traveling from the sensor to the ground and back. Experiments have been conducted over the area surrounding Rome using ERS data acquired during the three days phase in '94 and using Envisat data acquired in recent years. By means of the PS technique SAR data have been processed and the Atmospheric Phase Screen (APS) of Slave images with respect to a reference Master have been extracted. MM5 provides realistic water vapor distribution fields that can be converted into electromagnetic slant delays. PSInSAR APS's have then been compared to MM5 IWV maps revealing interesting results. MM5 IWV maps have a much lower resolution than PSInSAR APS's: the turbulent term of the atmospheric vapor field cannot be well resolved by MM5, at least with the low resolution ECMWF inputs. However, the vapor distribution term that depends on the local topography has been found quite in accordance. In this work we will present experimental results as well as discussions over the adopted processing strategy.

1. INTRODUCTION

Water vapor is one of the most significant constituents of the atmosphere because its phase changes are responsible for clouds and precipitation, whose interaction with electromagnetic radiation is a crucial factor in atmospheric system regulation. Despite of its importance within atmospheric processes over a wide range of spatial and temporal scales, water vapor is one of the least understood and poorly described components of the atmosphere.

Current Numerical Weather Prediction (NWP) models can provide high spatial resolution able to reproduce realistic vapor distribution fields, but one of their most limiting factors is the poor resolution of the initial condition. On the other hand, from the point of view of SAR interferometric applications (e.g., earth motion monitoring), one of the biggest sources of noise for InSAR techniques is the delay caused by changes in the distribution of water vapor in the atmosphere [1]. By analyzing single interferograms, the water vapor delay contribution is practically indistinguishable from ground motion signal with amplitudes that can range from some millimeters up to several centimeters or even greater, leading to a real difficulty to detect ground deformations events. Several efforts have been spent to solve this problem [2], by developing methods to mitigate water vapor artifacts by reconstructing the most likely atmospheric scenario. Most known techniques tend to use observations, such as radiosondes, GPS receiver networks, ground or space based radiometers: the latter generally exhibit poor temporal or spatial resolution, and their accuracy may strongly depend on the surface (land/water) background over which the measurements are acquired [2]. Water vapor field, produced by NWP, can provide a good support to eliminate some of these problems. Meteorological model simulations, indeed, can be used to predict atmospheric delay to be subtracted from InSAR interferograms and to reduce noise on the geodetic signal.

In this paper, the preliminary results of high resolution water vapor field analysis are presented. The MM5 model version 3 [3] is used to produce high resolution water vapor fields to be compared with InSAR data, which have been processed with the Permanent Scatterers (PS) technique [4].

2. THE MM5 NWP MODEL

The fifth generation NCAR (National Center for Atmospheric Research) and Pennsylvania State University mesoscale model MM5 is used for this study; this is a non hydrostatic model at primitive equations with a terrain following vertical coordinates system and multiple nesting capabilities [3].

Four two-way nested domains are used to enhance the resolution over the urban area of Rome. The mother domain covers most of occidental Mediterranean area; it is centered at 41.5° N, 10.0° E and has a spatial resolution of 27 km. The nested domains run on Central Italy from a spatial resolution of 9 km for domain 2 to 1 km for the inner one; this last one covers the city area and its surroundings (Lazio region), greatly overlapping the ERS satellite swath.

Sensitivity tests and previous experiences [5] allowed us tailoring the optimal combination of physical parameterizations for the numerical experiments. All the numerical experiments last 24 hours, from 00:00UTC to the 24:00UTC of each chosen day of simulation. The European Centre for Medium-Range Weather Forecast (ECMWF) analysis at 0.25° for temperature, wind speed, relative humidity, and geopotential height are interpolated to the MM5 horizontal grid and to vertical levels to produce the model initial and boundary conditions.

3. COMPARISON METHODOLOGY

In order to compare SAR atmospheric phase screen (APS) and MM5 water vapor maps, some considerations have to be made.

- The two maps are required to be geocoded on the same grid in geographical coordinates. The MM5 grid has been taken as reference and the APS maps have been interpolated on it.
- The APS collects all spatially correlated noise in an interferogram. This means that also residual orbital errors can be included in APS maps. To get rid of such phase trends that can invalidate the comparison, a phase ramp has to be estimated in each interferogram and removed.
- To compare the two quantities, the electromagnetic delay has to be converted into height of integrated water vapor, by means of the well known formula [6]

$$ZWD \approx 6.4 IWV \tag{1}$$

- By considering that the water vapor map integrates along the vertical direction while the radar is looking with an incidence angle of approximately 23°, the cosine of the angle has to be accounted for to map the water vapor in the satellite line of sight.
- InSAR data is a differential measure: each estimated APS is the difference of water vapor delays in two different dates. All available APS's have been referred to a common date (as it is implemented in the classical PS processing chain [4]). In this way, all APS's are affected by a common trend deriving by the reference image. Simply by averaging all available APS's together, the delay map of the reference image can be estimated and removed.
- The tropospheric delay can be modeled as a function of two main terms: a turbulent term and a quantity proportional to the terrain height [7]

$$\alpha_i = \varepsilon_i + k_i q \tag{2}$$

where α_i is the tropospheric delay, ε_i the turbulent term, q the terrain height and k_i a proportionality constant.

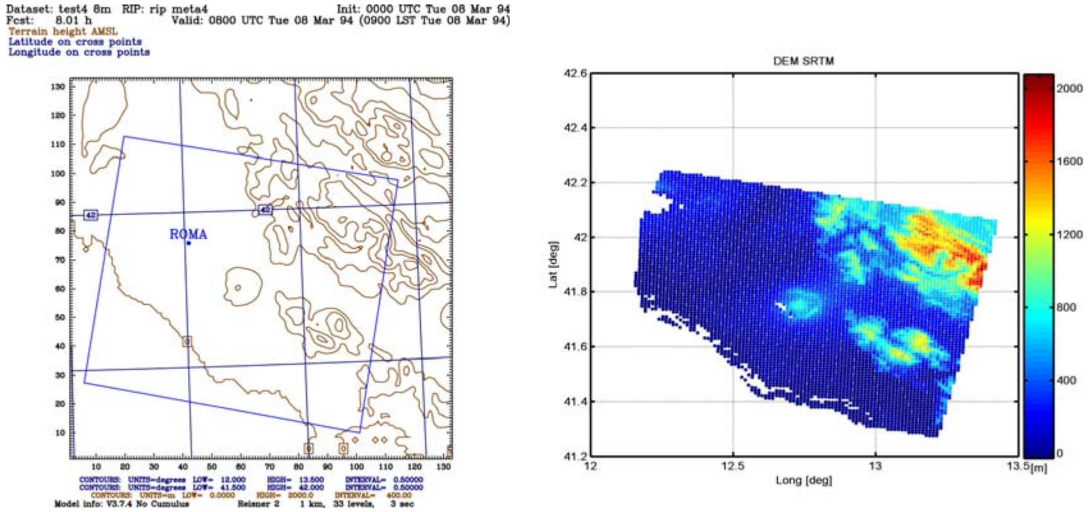

Figure 1. MM5 domain (left) and corresponding Digital Elevation Model (right) over the analyzed area in Rome.

The proportionality constant changes depending on the local atmospheric parameters (humidity, pressure and temperature) [8], but in any case the tropospheric delay decreases with the height. Thus we can write

$$k_i = k_0 + \delta k_i \tag{3}$$

where k_0 is a nominal value and δk_i takes into account the possible changes.

Thus, the APS of a generic image i referred to a common master M can be written as

$$\alpha_{i,M} = \varepsilon_i + k_i q - \left(\varepsilon_M + k_M q\right) = \varepsilon_i - \varepsilon_M + \delta k_i q - \delta k_M q \tag{4}$$

By averaging the stack of available APS's, it is possible to estimate just a differential component of the delay of the master acquisition,

$$\overline{\alpha}_M = \varepsilon_M + \delta k_M q \tag{5}$$

Thus, in order to compare "absolute" IWV maps to "absolute" APS maps, also the "nominal" IWV trend with height (the one linked to k_0), common in all IWV maps, has to be estimated and removed.

4. EXPERIMENTAL DATA AND RESULTS

The comparison between MM5 and InSAR maps has been conducted over an area of about 100km x 100km over Rome, as shown in Figure 1. In Figure 2 the corresponding digital elevation model is reported, spanning about 1600m. The data used in the experiment belong to 3 different datasets: the first one is composed by 27 ERS1 images, acquired between December 1993 and April 2004, during the so-called ERS1 3days phase. Second and third data-sets have been acquired by Envisat over the same area in descending and ascending passes (35 and 41 images respectively) between 2002 and 2009. MM5 available data in correspondence of the SAR acquisitions are 7, 20 and 10 runs.

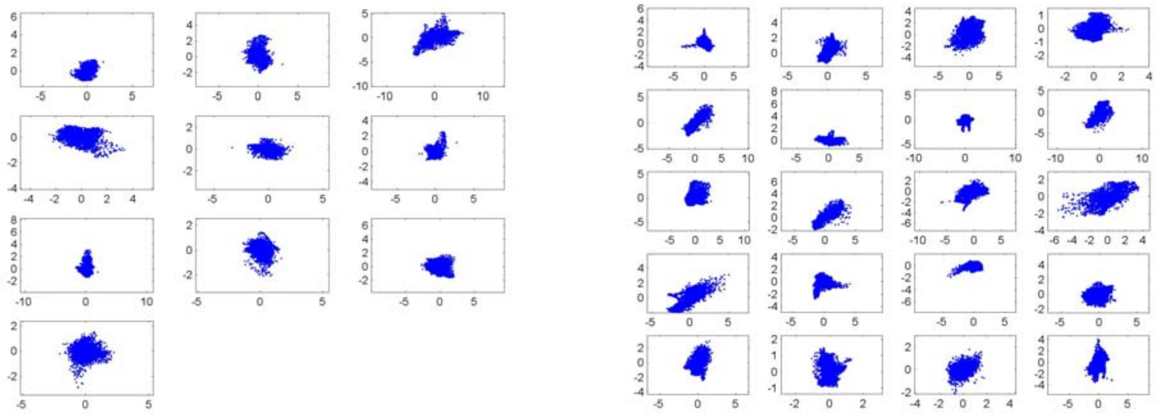

Figure 2. Scatter plot between InSAR (ordinate) and MM5 (abscissa) IWV in [mm]. Left descending, right ascending Envisat orbits over Rome.

	19940131	19940203	19940212	19940215	19940227	19940305	19940308
APS	.78	.67	.7	.28	.79	1.1	.4
APS-IWV	.64	.71	.53	.98	1.45	.9	.52

Table I. Standard deviation of the water vapor estimated by means of InSAR APS before and after compensating for the one estimated by MM5.

The main result of the first dataset can be summarized as in Table I, where the standard deviations of the APS maps are reported before and after compensating for the IWV estimates. As visible from Table I, in three cases out of seven, the water vapor estimated by the MM5 model is able to reduce the standard deviation of APS values. In other three cases the situation is strongly worsened. Just in one case (3rd February '94) the dispersion of water vapor is slightly increased. The reason can be further investigated by analyzing the trend of InSAR and MM5 maps with respect to the height: whenever the estimated trend is in accordance, MM5 is able to reduce the power of the atmospheric disturbances in InSAR data. On the contrary, when the turbulent term of the water vapor is predominant, MM5 is not able to predict the spatial features measured by InSAR.

Figure 3 shows the scatter-plot of IWV retrieved by means of InSAR and MM5 for Envisat data acquired along one descending (on the left) and one ascending (on the right) orbits. In particular in the ascending pass where the number of acquisitions is higher, it is evident a higher correlation between MM5 and InSAR measures. The better performance with respect to '94 ERS data can be explained by the higher accuracy of ECMWF data. Figure 4 shows in a compact form the results analysis. There the scatter-plot between the IWV-height trend (δk_i in eq. 4, in mm/m) estimated from MM5 and InSAR maps is shown. In the ascending orbit (image on the right) the two measures are quite well in accordance (dispersion of the scatter plot 0.7 mm/km for an InSAR δk_i dispersion of 1.3 mm/km). Moreover, the image shows in orange color those cases in which MM5 decreased the InSAR APS power, and in blue the other cases. Orange dots cluster in the upper and lower parts of the plot, i.e. MM5 succeeds in mitigating the atmospheric noise only when the IWV height dependent term is predominant (about 30% of cases in the ascending dataset). In the descending orbit (image on the left) the δk_i scatter plot is less accurate, and in only one case MM5 decreases the InSAR IWV power. It is interesting to observe at this point that ascending images are acquired around 9pm, whereas the descending passes are at about 9.30am, when the turbulent mixing of the atmosphere is higher.

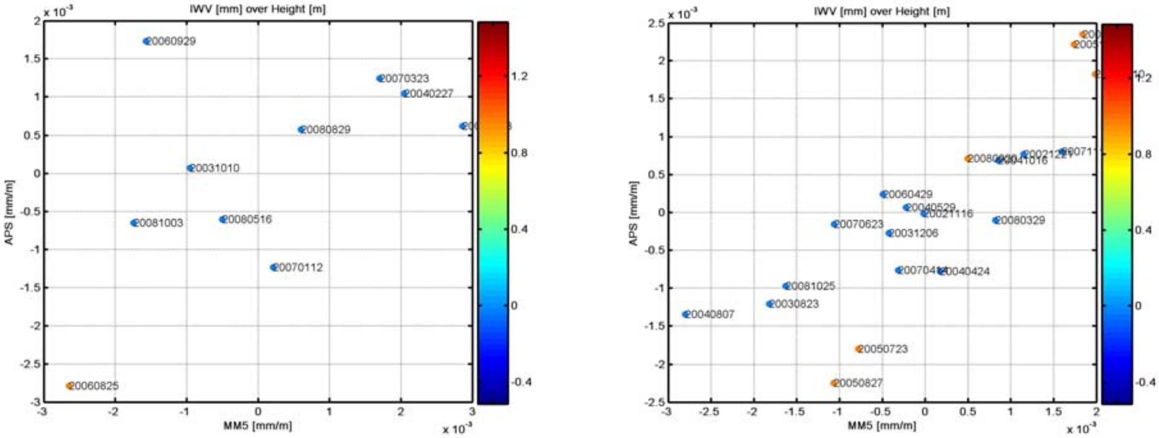

Figure 3. Scatter plot between InSAR (ordinate) and MM5 (abscissa) δk_i in [mm/m]. Left desce, right asce Envisat orbits over Rome.

CONCLUSIONS

In this work an experimental analysis to compare the Atmospheric Phase Screen retrieved with InSAR data with MM5 IWV maps has been provided. About 40 data takes have been processed over Rome in three SAR datasets: during the 3-days phase of ERS1 in 1994, and in two different orbits of Envisat in the last 7 years. The results show a better matching in recent years, in particular for ascending passes taken at evening time. Nevertheless, whenever the turbulent part of the water vapor exceeds the stratification one, MM5 is not able to reduce the InSAR atmospheric disturbances. As an overall conclusion, in 30% of cases MM5 can be successfully used to mitigate the electromagnetic delay induced by the water vapor concentration.

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