ATMOSPHERIC WATER VAPOR EFFECTS ON SPACEBORNE INTERFEROMETRIC SAR IMAGING: COMPARISON WITH GROUND-BASED MEASUREMENTS AND METEOROLOGICAL MODEL SIMULATIONS AT DIFFERENT SCALES

N. Pierdicca[1], F. Rocca[2], B. Rommen[3], P. Basili[4], S. Bonafoni[4], D. Cimini[5], P. Ciotti[5], F. Consalvi[6], R. Ferretti[5], W. Foster[7] F.S. Marzano[1], V. Mattioli[4], A. Mazzoni[8], M. Montopoli[5], R. Notarpietro[9], S. Padmanabhan[7], D. Perissin[2], E. Pichelli[5], S. Reising[7], S. Sahoo[7], and G. Venuti[10]

[1.] Dept. Electronic Engineering, Sapienza University of Rome, Italy. Email: nazzareno.pierdicca@uniroma1.it
[2.] Dept. of Electronic and Information of Polytechnic of Milan, Milan, Italy.
[3.] ESA-ESTEC, Noordwijk, Netherlands..
[4.] Dept. of Electronic Engineering and Information, University of Perugia, Perugia, Italy
[5.] CETEMPS, University of L'Aquila, L'Aquila, Italy
[6.] Fondazione U. Bordoni, Roma, Italy
[7.] Colorado State University, Colorado, USA.
[8.] Dept. Idraulics, Transport and Roads, Sapienza University of Rome, Roma, Italy
[9.] Dept. of Electronics, Politechnic of Turin, Italy
[10.] Dept. of Idraulic, Ambiental, Road Infrastructures, Sensing Engineering, Polytechnic of Milan, Milan, Italy.

ABSTRACT

Spaceborne Interferometric Synthetic Aperture Radar (InSAR) is a well established technique useful in many land applications, such as monitoring tectonic movements and landslides or extracting digital elevation models. One of its major limitations is the atmospheric variability, and in particular the high water vapor spatial and temporal variability, which introduces an unknown delay in the signal propagation. On the other hand, these effects might be exploited, so as InSAR could become a tool for high-resolution water vapor mapping. This paper describes the approach and some preliminary results achieved in the framework of an ESA funded project devoted to the mitigation of the water vapor effects in InSAR applications. Although very preliminary, the acquired experimental data and their comparison give a first idea of what can be done to gather valuable information on water vapor, which play a fundamental role in weather prediction and radio propagation studies.

Index Terms — SAR interferometry, water vapor, atmospheric corrections.

INTRODUCTION

InSAR is based on the measurement of the difference in phase of the signal backscattered by each land surface element observed from different points and/or at different times [1]. The atmosphere, particularly due to the high spatial and temporal variability of water vapor, introduces an unknown delay in the signal propagation. This effect might be also exploited, so as InSAR could become a tool for high-resolution water vapor mapping. The ingestion of the latter into weather prediction models is a challenging task, but also very promising, since water vapor state change is responsible for cloud and precipitation and its interaction with radiation is a crucial factor in climate variation [2].

The InSAR corrections for water vapor can be approached at two different geographic scales, namely regional and local. In the case of the regional scale, no sudden ground motions are to be expected, so that the InSAR surveys, that are in general multi pass, will be mostly dedicated to the analysis of progressive tectonic motions, or to the improvement of a Digital Terrain Model (DTM). In both cases, the atmospheric artifacts, in general of the same order of magnitude of the motions to be measured, or at times even much greater, can be abated using the multi pass technique and time averaging [1]. At any time, a running average of the interferograms (i.e., the image formed by the phase difference between two radar acquisitions) will be available. Neglecting the effects of baseline changes, the interferograms are expected to be all very similar to each other, with the main changes induced by the atmospheric signal, to be estimated and then subtracted. After 20–50 passes, the variance of the atmospheric signal is sizably reduced by the same factor. In other words, as the changes to be measured are more than an order of magnitude inferior to the atmospheric disturbance, the latter will be very well estimated just by comparison with the running interferogram stack. In this case, InSAR Atmospheric Phase Screens (APS) (i.e., time difference of excess path between interferometric acquisitions), mainly related to water vapor anomalies along the line of sight, could be exploited by meteorologists, as a new source of high resolution information on water vapor distribution. Conversely, when a long sequence of interferograms does not exists, or sudden movements have been occurred on large areas, as in the case of an earthquake, the water vapor variability still remain a problem for InSAR processing and any information on its distribution could be useful to try to correct, or at least to mitigate such effect.

This work is related to the ESA project METAWAVE (Mitigation of Electromagnetic Transmission errors induced by Atmospheric Water Vapor Effects), where the above mentioned problematic is deeply investigated by a large team composed of SAR experts, meteorologists, atmospheric remote sensing experts. In the frame of such project the local circulation in the urban area of Rome has been studied using a high-resolution Mesoscale Model (MM5), InSAR maps of APS, a network of microwave radiometers, and Global Positioning System (GPS) estimates of Zenith Wet Delay (ZWD) also related to integrated water vapor (IWV). A parallel experiment has been conducted near Como (Northern Italy), where the reference information to be compared to InSAR APS were provided by a fairly dense network of GPS receivers enabling tropospheric water vapor tomography. The project is presently undergoing and some preliminary results of the multiplatform experiment will be summarized in the paper, together with the general philosophy that has inspired the research project.

I. THE ENVISAGED APPROACH

A. Numerical Weather Prediction models

The first source of water vapor information potentially useful for InSAR data correction are the Numerical Weather Prediction (NWP) systems. The increased computational power of computer machines allows for a commensurate increase of the resolution of these models, which may become able to reproduce the physical phenomena involved in water vapor formation and evolution. The fully compressible non-hydrostatic models allows for reaching resolution in the order of 1 km or even better. In this project, it is foreseen to use the PSU/NCAR mesoscale model (known as MM5) that is a limited-area, non-hydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale atmospheric circulation.

Two open issues are worth to be investigated: the optimization of modeled high resolution water vapor fields to correct InSAR interferograms, and the assimilation of InSAR water vapor into the model. For what concerns the first problem, generally the water vapor produced by a high resolution NWP is a good approximation of the real distribution and can be used to correct the radar interferogram as was done in [3] using the UK Met Office Unified Model. A limiting factor for high resolution NWP is the poor resolution of the initial condition. In this respect, atmospheric Data Assimilation (DA) aims at incorporating observations into NWP models with maximum accuracy and efficiency, and filling in the data gaps using physical, dynamical, and/or statistical information. The envisaged approach foresees the assimilation of any observable (except InSAR APS maps) using the 3DVAR technique, as done in [4]. The observations to be considered for this scope may include ground based networks, such as GPS receiver Zenith Total Delay (ZTD) estimates, or ground based microwave radiometers, as well as spaceborne remote sensors, such as microwave or infrared radiometers.

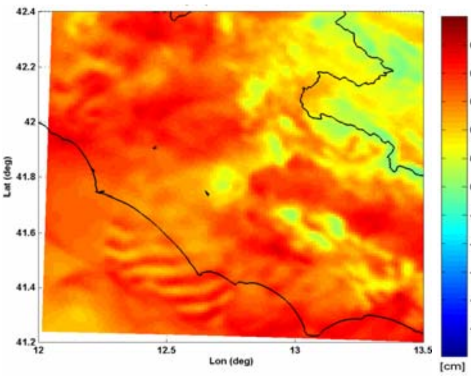

Fig. 1 Sample of MM5 integrated water vapor differences in the area of Rome (Italy) (February 3 and March 5, 1994 at 10:00 UTC) derived from ECMWF first guess. No assimilation of real observations was done.

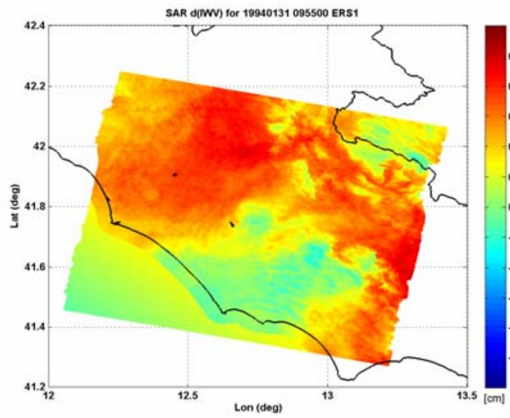

Fig. 2 APS from InSAR related to the acquisition of ERS-SAR on February 3, 1994 with respect to a master acquisition on March 5, 1994 at 9:55 UTC.

Fig.s 1 and 2 compare the difference in integrated water vapor at two different days (February 3 and March 5, 1994) predicted by MM5 (without any assimilation) with the APS map derived by InSAR acquisitions at the same days. The comparison between the two differential maps looks satisfactory, even if a more detailed analysis is required to discriminate between map features correlated to the topography of the area, and those concerning the atmospheric turbulent structures related to the specific meteorological conditions. Note that the former is predicted and corrected during InSAR processing if a consistent number of interferograms is made available. Nonetheless, getting independent information on path delay vertical gradient would represent a valuable contribution to diminish the number of required SAR images to be stacked. Additionally, gathering information on the turbulent component represents an extraordinary contribution to InSAR applications, but also a real challenging task.

B. Ground based networks

Another potential source of water vapor information is a network of GPS receivers, providing the ZTD from which the Zenith Wet Delay (ZWD), and thus the water vapor columnar content, can be derived by proper models. Those estimates, if available from a network with a sfficient spatial density, can enable to infer the slant path delay along the SAR line of sight using geostatistical techniques, thus allowing to correct the InSAR interferograms in correspondence of specific targets to be monitored (e.g., landslides) as done in [6]. A sample of what can be expected from this approach is presented in Fig. 3, where the kriging interpolation from the network is compared with the real data collected by a GPS receiver used as test. If the slant path delays are derived in each GPS station one can also attempt to perform a tomographic processing to reconstruct a 3-dimensional water vapor field at high resolution.

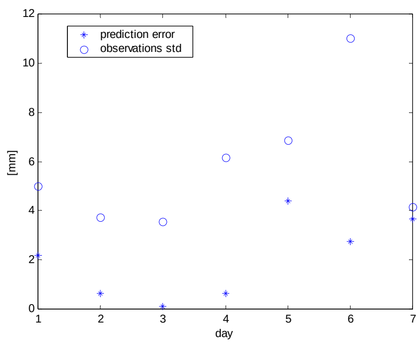

Fig. 3. Test of kriging performances comparing standard deviation of the error when estimating ZWD in a station, assumed as test, using data from the other stations in the network.. The prior standard deviation of the test station is drastically reduced. Of course, requirements about the characteristics of the network, such as spatial sampling and data processing are going to be specified with reference to the InSAR application requirements.

Similar tomographic techniques can also be used to retrieve 2-dimensional or 3-dimensional water vapor densities from two or three microwave radiometers sampling in elevation and azimuth the downward sky brightness temperature at different frequency channels within the water vapor absorption channel centered at 22.238 GHz. To give a preliminary example, Fig. 4 shows a 2-dimensional map derived by a couple of radiometers, developed and operated by Colorado State University (CSU), deployed in two different sites, during the experiment organized in Rome at the and of 2008 [8], as described in sec. III.

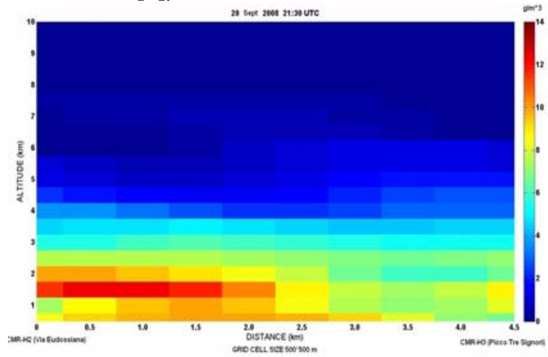

Fig. 4. Sample of a 2-dimensional map of water vapour density derived from two scanning compact multichannel microwave radiometers deployed in Rome during the experiment. The radiometers have been developed and operated by Colorado State University.

C. Earth Observation data

The project is going to consider Earth Observation data to be integrated with ground network observations. Optical infrared and microwave sensors shall be considered. Beside their accuracy in WV, their ground resolution is another factor, to be compared with the resolution of the InSAR APS, which is in the order of tens of meters. The optical sensors have a resolution in the order of some hundreds of meters, whereas the microwave radiometer resolution is several kilometers, but they are able to operate both day and night and also in cloudy conditions (with some degradation of the accuracy).

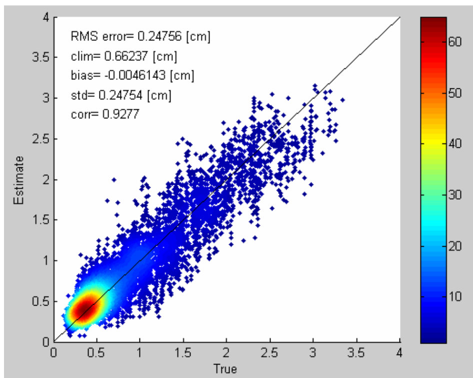

Fig. 5. Comparison of AMSR-E based retrievals of IPWV over the experimental site of Como and ECMWF data (considered as the true). The estimated accuracy is encouraging, but more reliable tests will be based on the comparison with ground based experimental data.

In spite of these advantages, microwave radiometers suffers from the high emissivity of land background with respect to the sea surface when attempting to retrieve WV. The exploitation of several radiometric channels, both multifrequency and multipolarization, is required to achieve acceptable results over land. A neural network approach has been tested and its performances when applied to AMSR-E data and compared to ECMWF IPWV are presented in Fig. 5. Although the results are relatively good, they are not adequate to correct the troposphere errors in InSAR.

D. Statistical data integration techniques

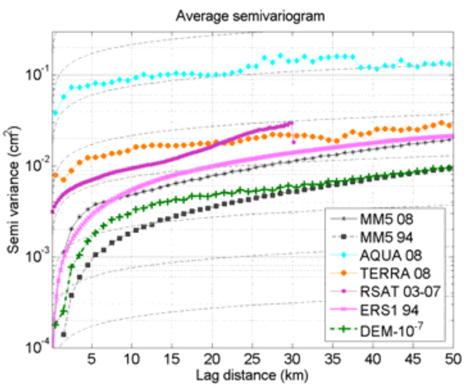

Fig. 6. Semivariograms of the IPWV field computed from different sources of data.

Beside data assimilation within NWP models, the integration of data from different source, taking into account their different spatial-temporal scale and reliability, can be performed by geostatistical and downscaling techniques (see for instance [7]). Without going into details, both techniques require the knowledge of the spatial characteristics of the field to be estimated at the best possible resolution. This information can be represented in terms of bidimensional spectral density or semivariogram. As a by-product of the activity performed up to know, the plenty of data we have collected have enabled the study of the spatial structure of the water vapor. Fig. 6 compares the semivariograms derived from different data sets with different spatial resolutions after removing the average dependence on the topography. In the same figure the spatial structure of the Digital Elevation Model (DEM) is shown as well for comparison.

II. **THE EXPERIMENTAL ACTIVITY**

Two experiments have been carried out to assess the data set and methodologies summarized before. One experiment in Rome was attempting to assess the different data integration techniques (NWP model assimilation and statistical downscaling algorithms) to produce accurate regional scale water vapor maps to be used for InSAR correction, but also to assess the feasibility to assimilate InSAR APS within NWP models. A fairly wide spread of data have been acquired in the area of Rome, beside radar images collected by ASAR ENVISAT. Namely, different EO data (MERIS, MODIS, AMSR-E), GPS data and of course MM5 predictions. Note that in this case the GPS is intended as a source of opportunity, and the network was not designed specifically for the experiment. In addition radiosoundings have been launched and ground based microwave radiometers have been operated. Besides a dual channel radiometer (by Radiometrics), three portable compact radiometers developed and operated by Colorado State University [8] have been deployed for assessing tomographic products (see sample in Fig. 4).

The experiment in Como (Northern Italy) was mainly focused on the extraction of path delay information from a GPS receiver network at a spatial resolution suitable for correcting InSAR interferograms. The objective of the experiment imposed the deployment of a number of GPS receivers to fulfil the requirement in terms of spatial sampling for geostatistical and tomographic reconstruction of the path delay.

III. **CONCLUSIONS**

Although at a preliminary stage, the paper gives an overview of what has been done and what is planned to do for mitigating the tropospheric artifacts in SAR interferometry. The study has also a wider objective that is mapping the water vapor at high resolution and possibly improving NWP accuracy by integrating InSAR products. The paper shows as the experimental activity and the collected data look quite valuable to further progress toward this highly challenging objective.

ACKNOWLEDGMENT

The project is funded by the European Space Agency under contract N. ESTEC-21207/07/NL/HE. We would like to thank University of Tor Vergata and the Condominio via Picco Tre Signori 35 for hosting some instruments during the campaign.

REFERENCES

[1] Rocca, F., “Modeling Interferogram Stacks”, IEEE Trans. Geosci. Rem. Sens, 2007, in Vol. 45, Issue 10, pp. 3289–3299, October 2007.

[2] Peixoto J.P., A.H. Oort, Physics of climate, American Institute of Physics, 1993

[3] Wadge G., Zhu M., Holley R. “Forward atmpspheric modelling to correct for water vapour delays to InSAR ground deformation measurements over mountains”, JCMM

[4] Faccani C., D. Cimini, R. Ferretti, F.S. Marzano, and A.C. Taramasso, “3DVAR assimilation of SSM/I data over the sea for the IOP2 MAP case”, *Adv. in Geosci*., vol. 2, p. 229-235, 2005.

[5] Liu, Z. and Rabier, F., 2002: The interaction between model resolution, observation resolution and observation density in data assimilation: A one-dimensional study. *Q.J.R. Meteorol. Soc.*, 128, 1367–1386.

[6] Onn, F., H. Zebker, “Correction for interferometric synthetic aperture radar atmospheric phase artifacts using time series of zenith wet delay observations from a GPS network”, *JGR*, Vol. 111, B09102, 2006.

[7] Basili, P.; Bonafoni, S.; Mattioli, V.; Ciotti, P.; Pierdicca, N., “Mapping the atmospheric water vapor by integrating microwave radiometer and GPS measurements”, *IEEE Trans. on Geosci. Rem. Sens*., Vol. 42, Issue 8, pp. 1657–1665, Aug. 2004

[8] Iturbide-Sanchez, F., S.C. Reising, S. Padmanabhan, “A Miniaturized Spectrometer Radiometer Based on MMIC Technology for Tropospheric Water Vapor Profiling”, *IEEE Trans. on Geosci. Rem. Sens*., Vol. 45, Issue 7, Part 2, pp. 2181–2194, July 2007.