Atmospheric water-vapour effects on spaceborne Interferometric SAR imaging: data synergy and comparison with ground-based measurements and meteorological model simulations at urban scale

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***Abstract*— Spaceborne Interferometric Synthetic Aperture Radar (InSAR) is a well established technique useful in many land applications, such as tectonic movements, landslide monitoring and digital elevation model extraction. One of its major limitations is the atmospheric effect, and in particular the high water vapour 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 vapour 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 vapour 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 vapour, which play a fundamental role in weather prediction and radio propagation studies.**

I. 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 water vapour spatial and temporal variability, 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 vapour retrieval. The ingestion of the latter into weather prediction models is very promising, since water vapour is one of the most significant constituents of the atmosphere, and its state change is responsible for cloud and precipitation and its interaction with radiation is a crucial factor in climate variation. Yet water vapour remains one of the most poorly characterized meteorological parameters. Improving knowledge of the water vapour field is needed for a variety of atmospheric applications and for studying the propagation of microwaves as well [2].

The InSAR corrections for water vapour 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 artefacts, 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, as it is to be expected with the narrow orbital tubes of the future platforms like Sentinel-1, 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 related to water vapour anomalies) could be exploited by meteorologists, as a new source of high resolution information on water vapour distribution. Conversely, when a long sequence of interferograms does not exists, or sudden movements have been occurred on large areas, such in the case of an earthquake, the water vapour 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 paper is related to the ESA project METAWAVE (Mitigation of Electromagnetic Transmission errors induced by Atmospheric WAter Vapour Effects), where the above mentioned problematic is deeply investigated by a large team composed of SAR experts, meteorologists and atmospheric remote sensing experts. In the frame of such project the local circulation in the urban area of Rome is studied using a high-resolution Mesoscale Model (MM5), InSAR maps of excess path length variation between different radar acquisitions (which are strictly related to variation in water vapour content along radar line of sight), a network of microwave radiometers, and Global Positioning System (GPS) estimates of integrated precipitable water vapour (IPWV). 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 vapour tomography. The project is presently undergoing and the preliminary results of the multiplatform experiment are summarized in the paper, together with the general philosophy that has inspired the design of the research project.

II. THE ENVISAGED APPROACH

A. *Atmospheric effects in InSAR*

The project is focused on the ENVISAT ASAR radar which operates at C band (5.3 GHz). The atmospheric effects we are referring to are those associated to the variation in signal propagation speed through the atmosphere, which are important when one is interested in the phase difference between pairs of SAR image acquisitions. The attenuation affecting the measurements of the radar backscattering coefficient, once the complex signal is squared detected, are generally neglected, even they may have some effects in few atmospheric conditions. The phase errors are associated to the real part of the atmospheric refractivity which in clear sky condition depends on the slant profile of the atmospheric physical quantity, such as pressure, temperature and humidity. In cloudy conditions, liquid water and hydrometeors in the troposphere are also responsible of phase changes, as well as the ionospheric layers in the stratosphere. Table I shows in a schematic way the minimal, maximum and typical values of the excess path associated to the different contributions coming from different atmospheric constituents.

TABLE I

CONTRIBUTIONS OF DIFFERENT ATMOSPHERIC COSTITUENTS TO THE PATH DELAY AT C BAND (ASAR ABOARD ENVISAT)

	Min Delay	**Max delay**	**Typical**
Ionosphere	2 cm	80 cm (few meters worst case)	< 1 m
Water vapour	<1 cm	>40 cm	
Hydrostatic atmosphere	<1.7 m	>2.3 m	2.1 m
Cloud	<0.01 mm (Stratiform cloud)	Several mm (cumulunimbus)	< 1mm
Rain	<0.3 mm (Drizzle)	Several cm	6 mm (2 mm/km x 3 km rain scale height) (steady rain around 20 mm/h) 72 mm (12 mm/km x 6 km) (Heavy rain around 200 mm/h)

The contribution from water vapour to the errors in radar interferograms is the most relevant, also if we take into account its high spatial (both horizontal and vertical) and temporal variability. Clouds give small contributions, except in case of heavy precipitations. The dry atmosphere has a high contribution, which however remains quite homogeneous within a typical SAR frame.

B. *Numerical Weather Prediction models*

The first sources of water vapour 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 vapour 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, nonhydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale atmospheric circulation.

There are two open issues: optimization of modelled high resolution water vapour to correct InSAR interferograms and, eventually, the assimilation of InSAR water vapour into the model. For what concerns the first problem, generally the water vapour 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 numerical weather prediction models with maximum accuracy and efficiency and fills 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. We will follow the approach used in [4]. The observations to be considered for this scope may include ground based networks, such as GPS receiver slant-path delay or Zenith Total Delay (ZTD) estimates, or ground based microwave radiometers, as well as spaceborne remote sensors, such as microwave or infrared radiometers. The next Fig.s 1 and 2 compare the difference in integrated water vapour 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 what is the signal into the maps which is correlated to the topography of the area, and what is the information content concerning the atmospheric turbulent structures of the specific meteorological conditions. Note that, whereas the former can be predicted quite well, as usually done in InSAR processing, gathering information on the turbulent component would represent the real challenge of the project.

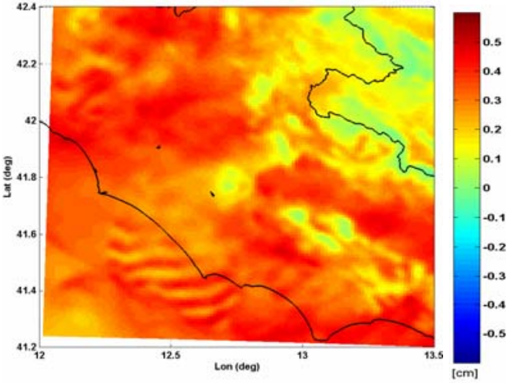

Fig. 1 Sample of MM5 integrated water vapour differences in the area of Rome (Italy) (February 3 and March 5, 1994 at 10:00 UTC) derived from ECMWF first guess. No assimilation of real observations was done.

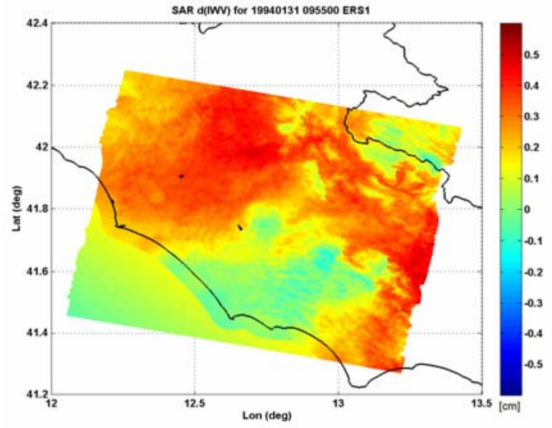

Fig. 2 APS from InSAR related to the acquisition of ERS-SAR on February 3, 1994 with respect to a master acquisition on March 5, 1994 at 9:55 UTC.

For what concerns the assimilation of InSAR data, to our knowledge no applications have been done yet. However, the intermittence nature of the data (overpass every 35 days considering the ENVISAT spaceborne platform) and the fact that the water vapour information brought by multipass InSAR is the difference between the two dates, make the task of operational assimilation of these data quite challenging.

The most important characteristic of InSAR is the high spatial resolution, which may be very important for improving the high resolution weather forecast. Therefore, we have to be sure to retain this characteristic, and the presence of eventually local structures which are generally missed by the conventional observation network. The 3DVAR will allows for assimilating the InSAR water vapour, but it will not allow for retaining the local (ageostrophyc, convergence structure etc..) structures, because of the geostrophyc adjustment performed, at least in the present configuration of MM5, by the algorithm to compute the model variables. Another limiting factor for using 3DVAR is the lack in InSAR products of a comparable vertical resolution to balance the high horizontal resolution. This is a requirement for successfully assimilating any variable, as stated in [5]. Finally, the last limiting factor is the lack of any information on the observation error matrix for InSAR that may completely mess up the positive benefit of the InSAR data assimilation. A robust alternative to the variational assimilation would be the Nudging technique and/or the Objective Analysis (OA) technique because of the possibility of assimilating the water vapour data retaining the local structures.

C. *Ground based networks*

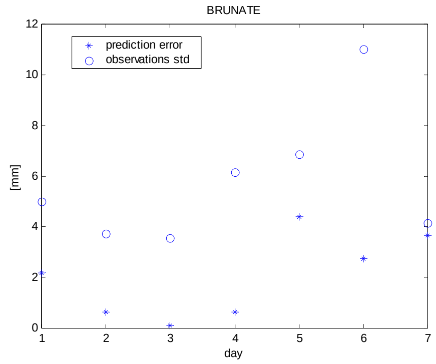

Fig. 3. Test of kriging performances comparing standard deviation of the error when estimating ZWD in a station assumed as test using data from the other stations in the network.. The prior standard deviation of the test station is drastically reduced. Of course, requirements about the characteristics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

Another potential source of water vapour information is a network of GPS receivers, providing the ZTD from which the Zenith Wet Delay (ZWD), and thus the water vapour columnar content, can be derived by proper models. Those estimates, if available from a network with a sufficient 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 vapour field at high resolution.

Similar tomographic techniques can also be used to retrieve 2-dimensional or 3-dimensional water vapour densities from two or three microwave radiometers sampling in elevation and azimuth the downward sky brightness temperature at different frequency channels within the water vapour absorption channel centred at 22.238 GHz. To give a preliminary example, Fig. 4 shows a 2-dimensioanl 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.

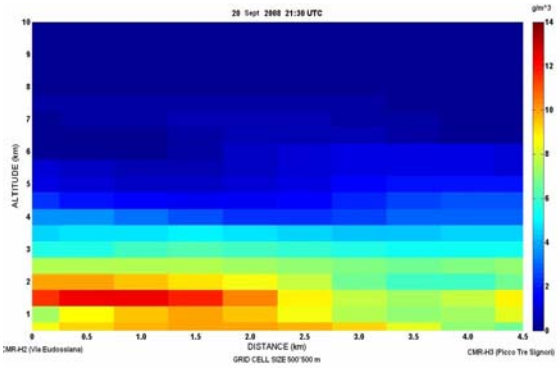

Fig. 4. Sample of a 2-dimensional map of water vapour density derived from two scanning compact multichannel microwave radiometers deployed in Rome during the experiment. The radiometers have been developed and operated by Colorado State University.

D. Earth Observation data

TABLE II
NOMINAL ACCURACY OF IPWV AND ZWD RETREIVAL FROM DIFFERENT REMOTE SENSING SENSORS.

SENSOR	Literature (nominal)		*ΔIPWV [mm]*		*ΔZWD [mm]*	
	Rms error Over ocean	Rms error Over land	Over ocean	Over land	Over ocean	Over land
MERIS	20 % Over glint: 10%	10 %	1-8 Over glint 0.5–4	0.5–4	6-48. Over glint 3-24	3-24
MODIS	20 % Over glint 10%	10 %	1-8 Over glint 0.5–4	0.5–4	6-48. Over glint 3-24	3-24
SSM/I	7%	0.4 - 0.5 g/cm^2	0.35–2.8	4-5	2.1-16.8 mm	24-30
AMSR-E	0.2 g/cm^2	0.6 g/cm^2	2	6	12	36

The project is going to consider Earth Observation as a possible source to be integrated with ground network data. Optical infrared and microwave radiometers will be assessed. The expected accuracy, according to the literature, is summarised in Table II. The ground geometrical resolution is another factor, to be compared with the resolution of the InSAR interferogram, 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 kilometres, but they are able to operate both day and night and also in cloudy conditions (with some degradation of the accuracy).

Retrieval of water vapour over land from spaceborne microwave radiometers suffers from the high emissivity of the land background with respect to the sea surface. Their improvement is objective of the project and some preliminary comparison between retrievals from AMSR-E and ECMWF IPWV are presented in Fig. 5.

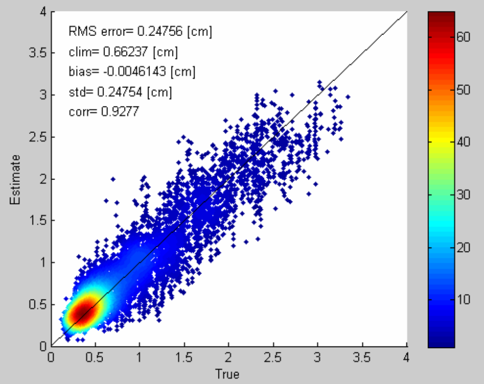

Fig. 5. Comparison of AMSR-E based retrievals of IPWV over the experimental site of Como and ECMWF data (considered as true data). The estimated accuracy is encouraging, but more reliable testS will be based on the comparison with ground based experimental data.

E. Statistical data integration techniques

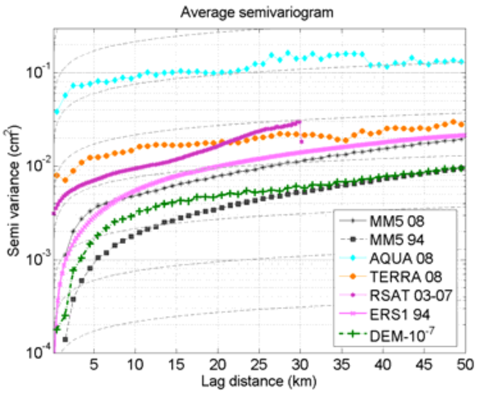

Fig. 6. Semivariograms of the IPWV field computed from different sources of data.

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 vapour. 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.

III. THE EXPERIMENTAL ACTIVITY

Two experiments have been carried out to assess the data and methods summarised 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 vapour maps to be used for InSAR correction, but also to assess the feasibility to assimilate InSAR APS within NWP models. 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.

A. *Experiment in Rome*

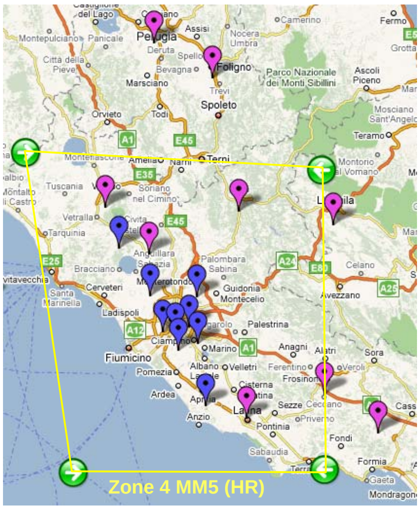

Fig. 7. Frame of the inner MM5 domain for high resolution products and location of the operational GPS network. The four microwave radiometers and the RAOB launching site are not shown for seek of clarity.

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 (see Table II), GPS data and of course MM5 predictions. Fig. 7 shows the domain of high resolution MM5 products together with the location of the GPS network operationally available in the area. 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 radiosounding 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).

B. *Experiment in Como*

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. The locations of the inner part of the network and the already existing operational network of Regione Lombardia are depicted in Fig. 8.

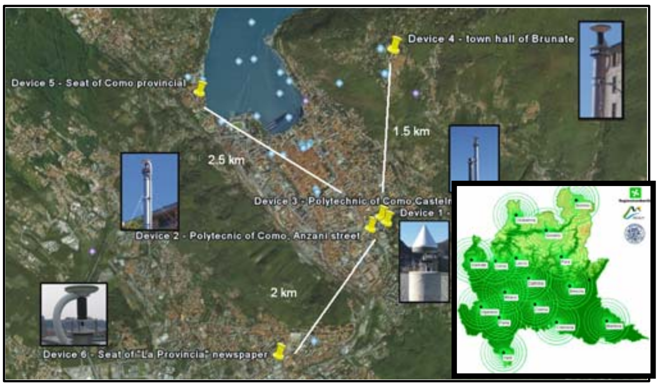

Fig. 8. Location of the GPS receiver network specifically deployed for the project in Northern Italy. Thee network will be combined with the fairly dense operational network of Regione Lombardia (see small inset).

IV. CONCLUSIONS

Although at a very preliminary stage, the paper gives an overview of what has been done and what is planned to do for mitigating the tropospheric artefacts in SAR interferometry. The study has also a wider objective, that is mapping the water vapour 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.

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