ATMOSPHERIC SENSING BY ADVANCED SPACE GEODETIC TECHNIQUES: ARE THERE POSSIBLE SYNERGIES WITH THE PROPOSED FORUM MISSION?

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1° Workshop on the Far-infrared Outgoing Radiation Understanding and Monitoring (FORUM) mission

23 - 25 October 2018. Florence, Italy

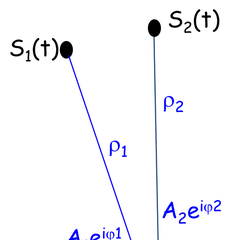
1. Introduction

Synthetic Aperture Radar (SAR) and Global Navigation Satellite System (GNSS) are two space geodetic techniques using the propagation delay of microwaves to study the physical properties of atmosphere.
Synthetic Aperture Radar images, processed by the SAR interferometry (inSAR) technique, complemented by dense GNSS data, may provide Precipitable Water Vapor (PWV) maps with very high spatial resolution. Recently, it has been shown that the assimilation of PWV maps obtained by processing Sentinel-1 images in A Numerical Weather Prediction (NWP) model has a positive impact on the performance of severe weather forecasts.
This opened new perspectives a InSAR data as a new source of water vapor data for weather forecasting, since their sampling frequency could reach the sub-daily scale by merging different SAR platforms, or when future geosynchronous radar missions will become operational.
Furthermore, attempts to merge SAR interferometry and GNSS tomography to improve the 3D reconstruction of water vapor in troposphere provided another examples of positive synergy between these two microwave techniques partially overcoming a their drawback of not be able to provide a vertical quantification of the water vapor content along the troposphere height.
In this work the basics of SAR and GNSS meteorology are presented by emphasizing the contribution that data acquired by the FORUM mission could have on these techniques.

2. SAR meteorology

Methodology: A couple of interferometric SAR images provides a phase map, which after the modelling and correction of phase contribution due to terrain morphology and displacements provides a map of Prectipitable Water Vapor having the spatail resolution of SAR images, i.e. a few tens of meters.

$$\Delta\varphi = \varphi_2 - \varphi_1 = \frac{4\pi}{\lambda}\cdot(\rho_2 - \rho_1)$$



InSAR phase contributions

$$\Delta\varphi = \varphi_{topo} + \varphi_{disp} + \varphi_{atm} + \varphi_{noise}$$

$$SWD = \frac{\lambda}{4\pi}\cdot\Delta\varphi \quad \Rightarrow \quad PWV = \Pi\cdot SWD\cdot M(\vartheta) \cong \Pi\cdot SWD\cdot\cos\vartheta$$

$$\Pi = 10^{-6}\cdot\rho_{H_2O}\cdot R_v\cdot\left[\frac{k_3}{T_m} + k'_2\right]$$

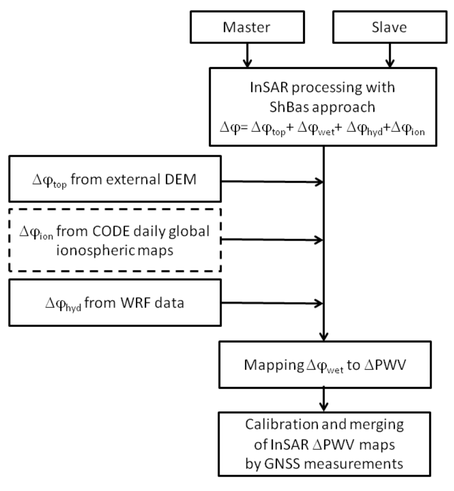
$$k'_2 = 22.96\ \mathrm{K\cdot mbar^{-1}}$$

$$k_3 = 3.747\cdot10^5\ \mathrm{K^2\cdot mbar^{-1}}$$

A set of GNSS stations within the area covered by SAR images are needed to calibrate and merge the PWV maps obtained by different and partially overlapping SAR images.

Phase delays due ionospheric and hydrostatic contributions are modeled and removed from InSAR phase images.

Figure 1 display two examples of InSAR PWV maps over the Iberian Peninsula used to study an extreme weather event in Adra (2015).



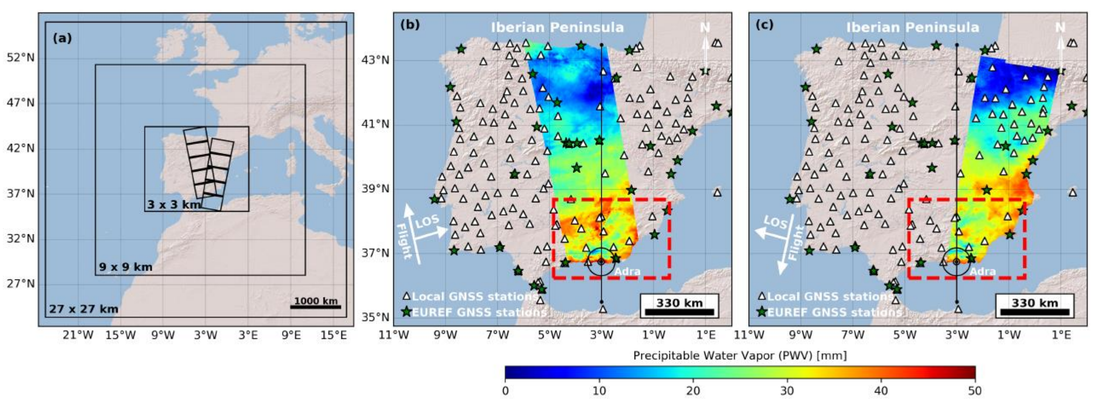
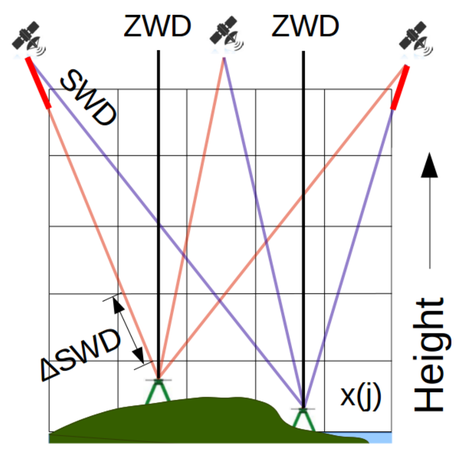


Figure 1: Model domains and InSAR PWV map locations: (a) WRF model domains (27, 9 and 3 km horizontal grid spacing) with the location of SAR images; (b) ascending image at 1810 UTC, 6 September 2015; (c) descending image at 0610 UTC, 7 September. The red rectangle shows the footprint of the analyzed area. Adra is in the center of the back circle and the black line along the 3W shows the cross-section location used in experiments.

Can the FORUM mission provide a spatially denser set of PWV measurements to be used in the calibration / merging of InSAR images?

If yes, which would be the spatial density of FORUM measurements and the temporal sampling?

2. GNSS Tomography

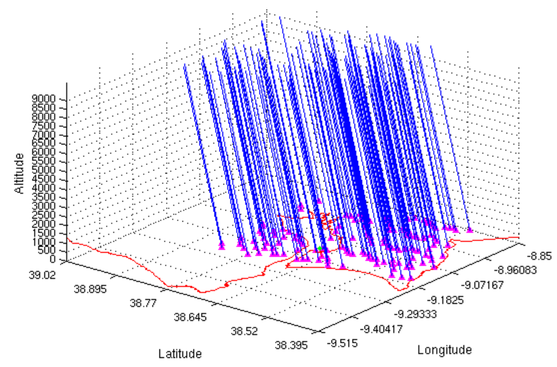


Methodology: The local troposphere is discretized by dividing the space into voxels x(j), forming a 3-D grid. Reconstruction of slant path wet delay (SWD) observations from the ZWD measurements results in several ray paths in the satellite line of view. The relation between the ray traced GNSS signals through the grid and the distance traveled inside each voxel (ΔSWD), provides the wet refractivity index in all voxels.

$$Y = A \bullet X$$

Y: number of GNSS SWD observations, X: unknown voxel wet refractivity, A: linear operator relating SWD values with the distances travelled inside each voxel

To include InSAR data in the GNSS tomography, the processing scheme has to be modified to account for the InSAR temporal baseline, where water vapor changes occurred between master and slave image acquisition times.



Can the FORUM mission provide more measurements of SWD for the 3D reconstruction of refractivty?

Can the output of GNSS tomography help the processing of FORUM data?

3. Example of application

The assimilation of (2D) InSAR PWV maps by WRF leads to 3D changes in the water vapor and other variables (temperature and wind), obeying the constraints imposed by the 3D-Var scheme.

Figure 3 compares the initial state of an experiment with PWV assimilation, A-GNSS and A-INSAR, in a South-North (SN) vertical cross-section, against the CTRL simulation, in each set. An increase in spesific humidity, and in temperature, at low levels is observed in all experiments.

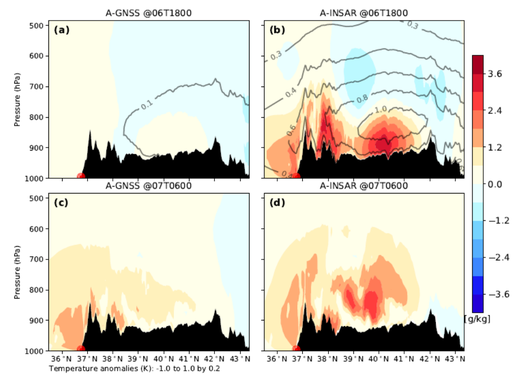


Figure 2: Increments of the water vapor mixing ratio (in g/kg, color shading) and potential temperature (in K, isotherms) at the data assimilation time along the 3W cross-section, in experiments: (a) A-GNSS at 6/1800 UTC, (b) A-INSAR at 6/1800 UTC, (c) A-GNSS at 7/0600 UTC, (d) A-INSAR at 7/0600 UTC. The red point shows the location of Adra.

Figure 3 shows the horizontal circulation in the same model level shown in Figure 2, represented by instantaneous streamlines at that time, superimposed on the distribution of CAPE, at the same time. This helps to understand the impact of those important changes in the initial low level tropospheric fields.

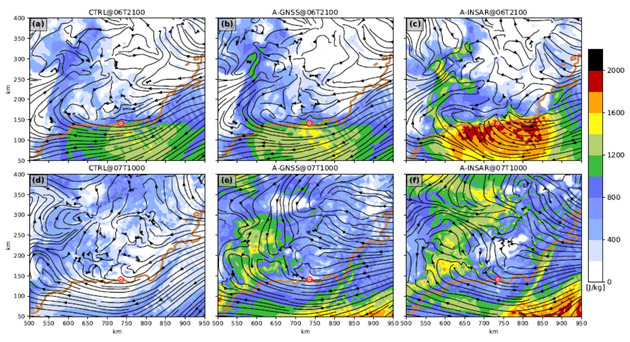


Figure 3: Convective available potential energy (CAPE, in J/kg, color shading), and streamlines of the low level ow (at the 4th model level, around 470 m of height), before the onset of each storm: (a,d) CTRL, (b,e) A-GNSS, (c,f) A-INSAR. The red point shows the location of Adra.

The vertical structure of the developing storm is shown in Figure 4, representing meridional cross-sections at a longitude 3W, in the A-INSAR simulations. Its streamlines are representative of the flow across Adra, and they do show the establishment of deep convection starting at the hour (2100 and 1000 UTC, respectively) very close to the coast, and leading to large concentration of precipitating water (largely graupel) extending to about 10 km in height.

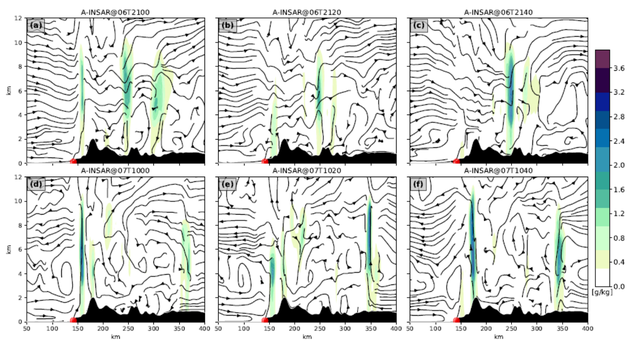


Figure 4: Vertical proles of the sum of snow, graupel and rain mixing ratios (in g/kg, color shading), and streamlines of the vertical levels ow. Top row, (a-c) A-INSAR at 6/2100, 6/2120 and 6/2140 UTC. Bottom row, (d-f) A-INSAR at 7/1000, 7/1020 and 7/1040 UTC. The red point shows the location of Adra.

References:

[1] Benevides, P., Catalão, J., Nico, G. and Miranda, P. (2018). 4D wet refractivity estimation in the atmosphere using GNSS tomography initialized by radiosonde and AIRS measurements: results from a 1-week intensive campagin, GPS Solutions, 22(4), 91.
[2] Mateus P., Miranda, P., Nico, R., Catalão, J., Pinto, P., Tomé, R. (2018). Assimilating InSAR maps of water vapor to improve heavy rainfall forecasts: a case study with 2 successive storms, Journal of Geophysical Research: Atmosphere, DOI:10.1002/2017JD027472