MERGING INSAR AND GNSS METEOROLOGY: HOW CAN WE MINE INSAR AND GNSS DATABASES TO EXTRACT AND VISUALIZE INFORMATION ON ATMOSPHERE PROCESSES?

Giovanni Nico (1), Amaia Gil (2), Marco Quartulli (2), Pedro Mateus (3) and Joao Catalao (3)

(1) CNR IAC, Bari, Italy

(2) Vicomtech-IK4, San Sebastian / Donostia, Spain

(3) University of Lisbon, Lisbon, Portugal

ABSTRACT

The use of Numerical Weather Models (NWMs) provides forecasts of meteorological events based on hypothesis on surface cover, boundary layer and other mechanisms of atmosphere processes. In many cases, the selection of appropriate parameters and the tuning of models at the basis of NWMs is made by non-advanced users in *a hoc* manner.
The availability of huge databases of InSAR and GNSS measurements of PWV provides those users a unique possibility to falsify the hypothesis at the basis of their choice of parameters. In this work we introduce features, based on statistical analysis and graph theory, that can help to compare InSAR and GNSS measurements to NWM simulations. From the point of view of the user, the meaning of comparison is to quickly catch the informative potential of InSAR and GNSS data if assimilated in a NWM.

Index Terms— Meteorology, Sentinel-1, visualization, databases, Numerical Weather Model (NWM), Synthetic Aperture Radar (SAR), SAR Interferometry, Global Navigation Satellite System (GNSS).

1. INTRODUCTION

Synthetic Aperture Radar (SAR) Interferometry has recently demonstrated its capability to provide useful information about water vapor in atmosphere opening a field of application called SAR meteorology which complement GNSS meteorology [1]-[3]. The knowledge of acquisition geometries, of both SAR interferometry (InSAR) and GNSS data, as well as of the corresponding processing parameters (e.g. the Vienna mapping function for GNSS data) can help to visualize the InSAR and GNSS measurement processes, compute the synthetic data corresponding to the different hypothesis on the description of the atmosphere physical processes and compare with the real measurements [4]-[6].
The launch of both satellites A and B of Sentinel-1 SAR mission of the European Space Agency opened new perspectives in the mapping of Precipitable Water Vapor (PWV) with an unprecedented spatial resolution up to 25 m and a temporal update of 6 days over the same region [7]. It has been demonstrated that this information can describe meteorological phenomena, such convective processes, with spatial details not captured by dense networks of GNSS sensors. Figure 1 shows an example of availability of GNSS and Sentinel-1 data over the Iberian Peninsula. The temporal sampling of PWV maps provided by Sentinel-1 over a given region can be further reduced if images acquired from different orbits are used as reported in Figure 2.
However, the use of Sentinel-1 data is not so straightforward, and different phase contributions related to both geodetic and atmosphere phenomena must be disentagled,. For instance, it should be assumed that terrain displacements contribute with a negligible phase and therefore interferograms are processed using the smallest temporal baseline of six days. Furthermore, SAR interferometry can directly measure only the temporal change of phase propagation delay in atmosphere at the master and slave acquisition times. This delay mainly depends on the turbulence in troposphere (as the laminar component of phase delay in atmosphere is pretty stable in time) and it is canceled out in the interferometric processing. Furthermore, a tiny phase delay due to propagation in ionosphere is also present in Sentinel-1 interferograms also due to it large spatial coverage. In this respect, it can be stated that Sentinel-1 maps of PWV are somehow complementary to GNSS information. In fact, GNSS measurements refer average measurements of propagation delay, both in time (each GNSS estimate refers to a time interval of about half an hour) and space (measurement refers to the average values within the observation cone set during the processing.
The development of tools to visualize information about atmosphere (both troposphere and ionosphere) delay is essential to:

- identify the presence of laminar and turbulence regime in the water vapor spatial distribution
- study the role of terrain morphology and land cover properties on physical processes occurring in the boundary layer

- effectively use the high information content of Sentinel-1 data.

A set of metrics is used to study the temporal correlation of GNSS measurements taken at different locations together with its interaction with

- local topography and land use
- to predict PWV measurements both in space (e.g. at places where no GNSS receivers are available) and in time (near-future time acquisitions).

The relationship between GNSS and InSAR measurement of PWV is studied based on the GNSS and SAR observation geometries and acquisition time intervals. To compute synthetic GNSS and InSAR PWV measurements, NWM numerical simulations are used. The aim of this experiment is to understand how anisotropies in the atmosphere refractivity are mapped in the GNSS processing and how InSAR measurements can help to partially recover those anisotropies. The same metrics developed to study the correlation of GNSS are applied to Sentinel-1 PWV maps, synthetic GNSS PWV profiles and InSAR maps of PWV (or wet delay). In particular, the use of this metrics on synthetic data could be used to identify features and their relationship with the 3D distribution of atmosphere refractivity estimated by NWM output

2. EXAMPLE OF VISUALIZATION OF METEOROLOGICAL INFORMATION

The output of NWMs are basic physical variables, like P, T, relative humidity and so on. These variables are used to compute more advanced magnitudes (e.g. wind distribution, convective available potential energy, etc.) related to the study of the atmosphere. However, these variables can also be used to estimate the 3D distribution of atmosphere refractivity. Figure 3 shows an example of PWV map computed from NWM output using basic physical laws. This map is based on hypothesis at the basis of NWM runs and on numerical solutions of fluid dynamics equations under specific boundary conditions. The comparison of these synthetic PWV maps with the PWV information available in InSAR and GNSS archived data is a way to take benefit from the high spatial resolution data of Sentinel-1 and the real-time GNSS measurements of PWV.

Besides this approach, users in meteorology can benefit from the assimilation of InSAR and GNSS measurements in a NWM [8]. In this case, different scenarios can be studied for atmosphere events and useful thermodynamic quantities. Variables such as the Convective Available Potential Energy (CAPE) and the Convective Inhibition Index (CIN) that are relevant to convective processes in atmosphere as the basis of many extreme weather events can be computed. Figure 4 shows an example of CAPE and CIN maps computed from NWM data over the Iberian Peninsula.

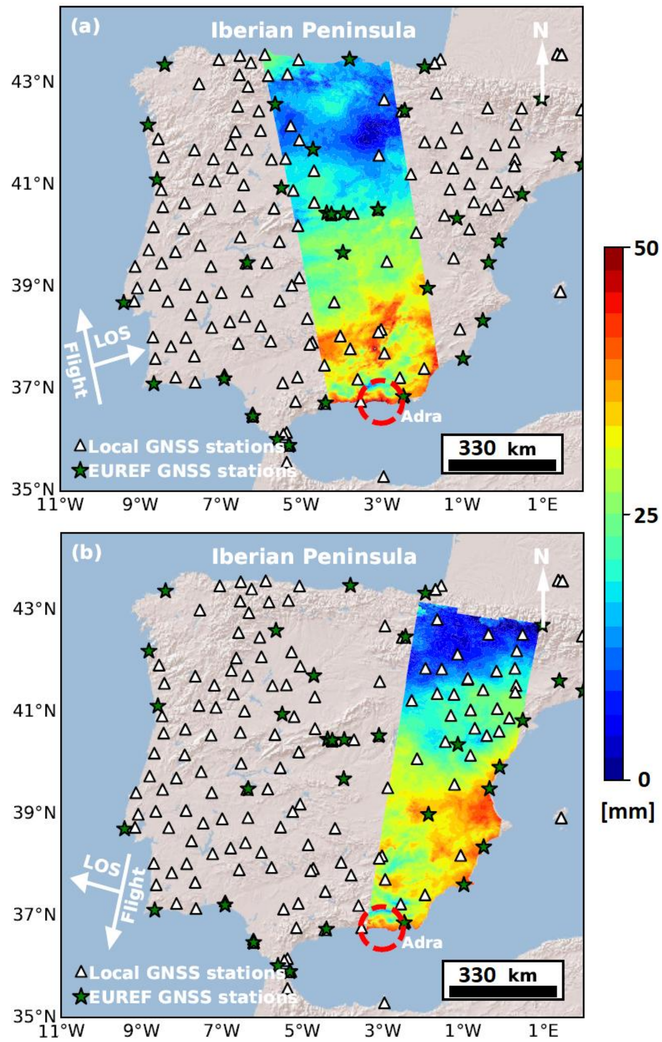

Figure 1: Example of GNSS and Sentinel-1 data acquired over the Iberian Peninsula which are used for the measurement of atmosphere PWV.

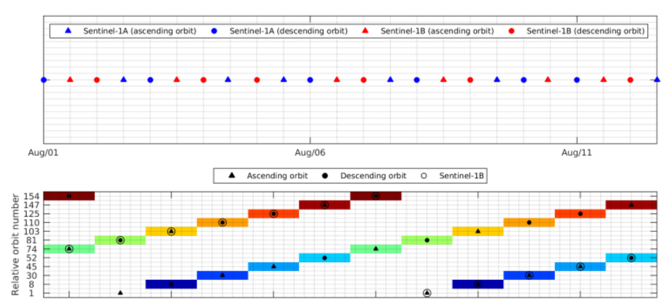

Figure 2: Example of acquisition plane of Sentinel-1 images over the same region. Data are acquired along different orbits, both ascending and descending.

3. STATISTICAL PROCESSING FOR VISUALIZATION

A first step when visualizing the PWV information contained in GNSS and InSAR databases is the comparison between the different data sources and the analysis of the spatial and temporal correlations of PWV data. In order to allow users to follow the evolution of this structure in time we have developed a tool that relies on graph theory to describe the geo-spatial structure of the set of correlation measures among PWV measurements. This approach can be applied directly to GNSS data, where each GNSS station provides a graph node. Figure **5** displays the temporal correlation between GNSS measurement of PWV within a temporal window of 24h. The temporal correlation among GNSS stations can be related to the underlying terrain morphology and land use, as well as the time evolution due to atmospheric phenomena. Figure 6 shows how this temporal correlation is changing in time. The same tool has been applied to study the spatial structure of correlations in Sentinel-1 interferograms and the synthetic PWV maps computed from the NWM output. In this case, a mask has been applied to identify pixels on Sentinel-1 and NWM maps filling the atmosphere portions around each GNSS stations to make a comparison between the different possible data sources.

Visualizations help to evaluate the relationships between different stations and the stability of this relationship in time. This is valuable from both the scientific point of view and for identifying predictive variables to be exploited in modeling efforts. In the case of large databases of direct and indirect measures, visualization options can be particularly relevant in a preliminary exploration phase: the limited availability of methods for the early characterization of extended volumes of data can effectively be complemented by integrating the human visual system in the analysis loop. Specialized techniques [9]-[11] are needed to manage and visually represent extended coverages of remote sensing data in near real-time together with the results of e.g. machine learning regression models allowing a level of interaction that enables visual exploratory statistics on extended datasets.

This work is currently being carried out towards the integration of the described PWV analysis tools with existing frameworks composing web-based mapping interfaces and scalable machine learning engines. The objective of this work is to create a user-oriented tool for the supervised training of classification systems capable of

- detecting extreme situations in the obtained water vapor maps and regression systems
- predicting and smartly interpolating on a global scale the measured values based on ground coverage, geographical and external descriptors
- progressively reducing the deviation of regression results from measured outcomes.

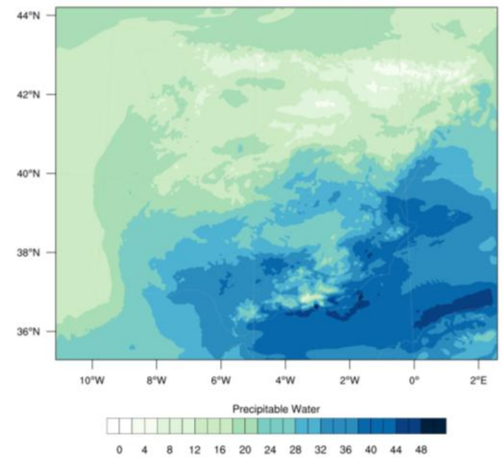

Figure 3: Example of real-time visualization of PWV computed from WRF output

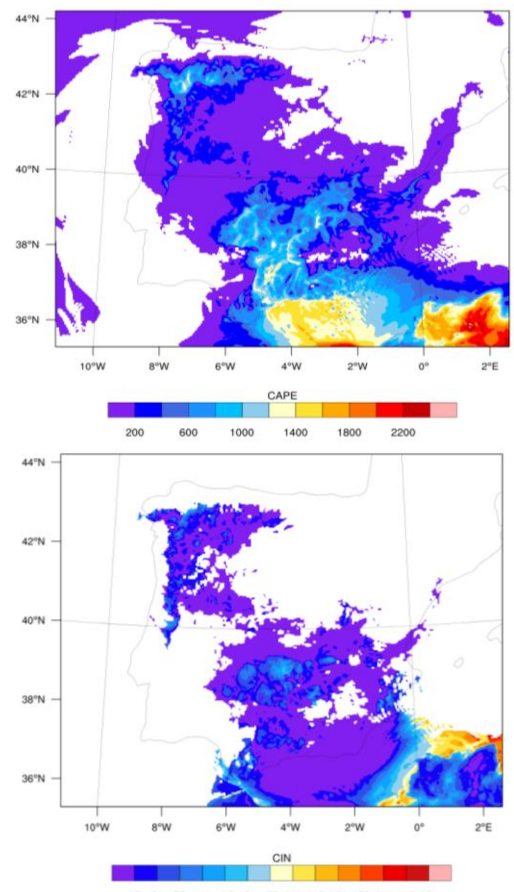

Figure 4: Example of real-time visualization of CAPE (top) and CIN (bottom) information over the Iberian Peninsula.

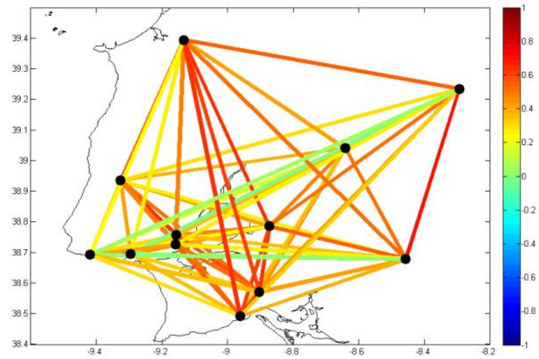

Figure 5: Temporal evolution of correlation between GNSS stations over the western part of the Iberian Peninsula.

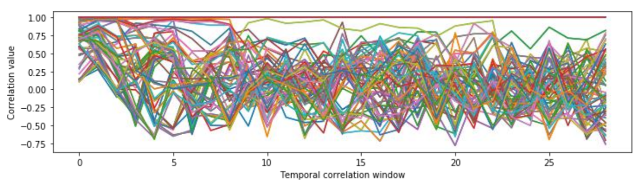

Figure 6: Time series of correlation among GNSS stations over the western part of the Iberian Peninsula.

4. CONCLUSIONS

We have introduced a methodological framework for the exploration of Numerical Weather Models (NWMs) that provides forecasts of meteorological events based on hypothesis on surface cover, boundary layer and other mechanisms of atmosphere processes. The availability of huge databases of InSAR and GNSS measurements of PWV provides non-expert users a unique possibility to falsify the hypothesis at the basis of their choice of parameters. In this work we introduce features, based on statistical analysis and graph theory, that can help to compare InSAR and GNSS measurements to NWM simulations.

5. REFERENCES

[1] R. Hanssen, Radar Interferometry: Data Interpretation and Error Analysis, Remote Sensing and Digital Image Processing, vol. 2, 1 ed., Springer, Netherlands, 2011.

[2] Y. Kinoshita, M. Shimada, M. Furuya, InSAR observation and numerical modeling of the water vapor signal during a heavy rain: A case study of the 2008 Seino event, central Japan, Geophysical Research Letters, 40(17), 4740–4744, doi:10.1002/grl.50891, 2013.

[4] P. Mateus, G. Nico, J. Catalão Can spaceborne SAR interferometry be used to study the temporal evolution of PWV?, Atmospheric Research, 119, 70–80, doi:http://dx.doi.org/10.1016/j.atmosres.2011.10.002, 2013.

[4] P. Mateus, G. Nico, R. Tomé, J. Catalão, P. M. A. Miranda, Experimental Study on the Atmospheric Delay Based on GPS, SAR Interferometry, and Numerical Weather Model Data, IEEE Transactions on Geoscience and Remote Sensing, 51(1), 6–11, doi:10.1109/TGRS.2012.2200901, 2013.

[5] P. Mateus, G. Nico, J. Catalão, Uncertainty Assessment of the Estimated Atmospheric Delay Obtained by a Numerical Weather Model (NMW), IEEE Transactions on Geoscience and Remote Sensing, 53(12), 6710-6717, doi: 10.1109/TGRS.2015.2446758, 2015.

[6] P. Mateus, G. Nico, J. Catalão, Maps of PWV Temporal Changes by SAR Interferometry: A Study on the Properties of Atmosphere's Temperature Profiles, IEEE Geoscience and Remote Sensing Letters, 11(12), 2065-2069, doi: 10.1109/LGRS.2014.2318993, 2014.

[7] P. Mateus, J. Catalão, and G. Nico, Sentinel-1 Interferometric SAR Mapping of Precipitable Water Vapor Over a Country-Spanning Area, IEEE Transactions on Geoscience and Remote Sensing, 55(5), 2993–2999, doi:10.1109/TGRS.2017.2658342, 2017.

[8] P. Mateus, R. Tomé, G. Nico, J. Catalão, Three-Dimensional Variational Assimilation of InSAR PWV Using the WRFDA Model, IEEE Transactions on Geoscience and Remote Sensing, 54(12), 7323–7330, doi:10.1109/TGRS.2016.2599219, 2016.

[9] P. Mateus, G. Nico, J. Catalão, Using TerraSAR-X SAR interferometric data to derive maps of the atmospheric phase delay, IEEE International Geoscience and Remote Sensing Symposium, Munich, 3819-3822, 2012

[10] M. Quartulli, I. Olaizola A review of EO image information mining, ISPRS Journal of Photogrammetry and Remote Sensing, 75, 11-28, 2013

[11] J. Lozano, M. Quartulli, I. Tamayo, M. Laka, I. Olaizola, Visual analytics for built-up area understandign from metric resolution Earth Observation data, ISPRS International archives of Photogrammetry, Remote Sensing and Spatial Information Science, VOl, 1, Issue 2, pages 151-154, 2013

[12] J. Lozano, N. Aginako, M Quartulli, I Olaizola, E. Zulueta, Web based supervised thematic mapping, Selected Topics in Applied Earth observation and Remote Sensing, IEEE , Vol 8, Issue 5, pages 2165-2176 2015