Atmospheric delay for electromagnetic signals associated with space / time variations of the refractive index in the lower atmosphere:
Applications in spatial geodesy.

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Abstract. The feasibility quantifying atmospheric delay of electromagnetic signals using a mesoscale numerical model (WRF model) is explored. The experiment investigates a new alternative to reduce uncertainty sources in data exploitation for spatial geodesy applications. Our experiment was compared with GPS estimations of stations located in the South-America. The GPS estimations are consistent with values of our proposed methodology. This opens the possibility of using a mesoscale numerical model applied to spatial geodesy. However, these results, despite being promising, need further analysis and research, opening the opportunity to numerical modeling of atmospheric delays using mesoscale models.

1. Introduction

The techniques based on remote sensing have been a data source for volcanic deformation studies during the last years [1, 2]. However, remote measurements like GPS or synthetic aperture radar (SAR) have an intrinsic uncertainty in their measurements. Cheng et al. [3] showed that there are sources of uncertainty in GPS and SAR signals related to the atmospheric component. This is consistent with the basic fundamentals of electromagnetic theory, which depends on the material in which the electromagnetic signal travels [4]. A study case corresponds to the space geodesy data. For space geodesy, one of the most difficult issues corresponds to the atmospheric effect due to the water vapor presence. Previous studies have shown that spatial and temporal changes of 20% in relative atmospheric humidity could lead to 10-14 cm errors in measurements of volcanic deformation [5]. Remy et al. [6] have found that the incorrect elimination of atmospheric uncertainty can lead to misinterpretation in the sign InSAR coming to associate the atmospheric influence to the signs of volcanic deformation. Therefore, the atmosphere is a limiting factor for geodetic applications, such as radar altimeters, SAR and GPS.

To solve the atmospheric delay problem, global products such as the Vienna functions [7] or models derived from global climate models [5] exists. However, these products are too coarse respect to the spatial resolution and are far of the minimum requirements for correcting
geodetic data for local studies. This work offers a new alternative of atmospheric correction using numerical models of mesoscale in development. For this, mesoscale weather simulations (Weather Research and Forecasting) were implemented to a theoretical model of atmospheric delays that allowed estimating the values locally. In this way, this work addresses the atmospheric delays with the goal of quantifying their effect reducing the uncertainty associated. We perform atmospheric delay maps for 8 GPS stations located in active volcanoes of the Southern Andes. We choose Villarrica (VnV) and Nevados de Chillín (VNC) volcanoes due to the presence of differential GPS stations to validate our work.

2. Study zone
The Villarrica volcano is located in the south of Chile (39.42 S - 71.93 W). Many cities such as Villarrica, Pucón, Coñaripe, and Lican-Ray are emplaced around the volcano. Moreover, the Villarrica volcano is classified as a high-risk volcano due to historical eruptive processes. The crater has a height of 2847 m.a.s.l. with a basal diameter of 12.5 km covering an area of 490 km². The main structure is covered by a glacier of approximately 30 km². Moreover, the crater has a diameter of 200 m that shows a constant emission of gases. Currently, 5 GPS stations are emplaced near the crater: Llafenco (LLFN), Tralco (TRAL), Vn. Villarrica II (VNV2), Lomo (LOMO) and Vetado (VTDO) (see Map 1 in Annexes), which monitor the volcano, constantly delivering position data.

Moreover, Nevados de Chillán complex (NCC) is located close to Villarrica Volcano (36 51.2’S, 71 23.8’ W). NCC volcano is classified as a high-risk volcano due to their proximity to villages and geological characteristics. The volcano height reaches the 3216 m.a.s.l with a basal diameter of 13.8 km. The last major eruption was registered in 1973. The volcano has 5 GPS stations named Chintuco, Fresco (FRSC), Portezuelo (PTZL), Shangrila (SHLA) and Ñuble (NUBL), which are constantly delivering position data for analysis.

3. Methodology
We perform an atmospheric delay mapping in order to understand spatio-temporal changes. We use an integration of the air refraction index as a function of the surface (elevation) and the vertical according to the proposal of [8].

\[
\delta = 10^{-6} \frac{1}{\cos(\theta)} \int_{z_o}^{z_{ref}} \frac{k_1 R_d}{g_m} (P(z) - P(z_{ref})) + \left( K_2 - \frac{R_d}{R_v} K_1 \right) \frac{e}{T} + K_3 \frac{e^2}{T^2} \]  

(1)

Where \( z_{ref} \) was chosen as the height above the troposphere (typically 15,000 m). The value was considered due to this zone does not have larger variations in the time. The first term in equation 1 corresponds to the dry air component of the delay path (hydrostatic term), while the second term is related to the humidity of the air (wet term). We forced the equation 1 through a mesoscale climate model called the Weather and Research Forecast (WRF) [9]. The WRF model allows obtaining atmospheric variables from a dynamic downsampling process [9] based on data from the NCEP reanalysis system [10].

This model provides values of various meteorological parameters with a spatial resolution of 3 km covering the study area from 2012 to the present time scale. Vertical stratification is described in 52 pressure levels, densely spaced at low altitude (25 hPa interval), with the highest level of about 50 km (1 hPa). The total delay maps were combined by stacking to produce time series. These results were compared with GPS measures of the chilean volcanic monitoring network of national agencies (OVDAS-Sernageomin).

4. Results
The results were obtained in a defined temporal baseline according to available GPS data. In VnV, WRF data is in a time series from January 2012 to December 2015, the same for VNC.
Figure 1. Correlation map between atmospheric delay (in meters) and topography for Villarrica Volcano.

Our results show that VnV experiments episodes of atmospheric delay ranging between 0.7 cm and 2.1 cm. These are similar to GPS stations that show temporal variations between 1.5 cm up to 2.7 cm. Moreover, VNC shows temporal variations between 2.5 cm and 2.7 cm for the delay calculated using our atmospheric delay proposed scheme. These values are consistent
Figure 2. Relative atmospheric delay for the Nevados de Chillán volcano. Temporal baseline for four days (01 to 04 January 2015).

again with GPS measurements (temporal variations of 2 cm up to 2.5 cm). Additionally, a seasonal variability was observed in the values of atmospheric delays in the two zones, which correlates with the local dynamics of the low atmosphere.

5. Discussion and Summary
We propose that the present methodology is able to quantify atmospheric delay. We observe the feasibility to implement an atmospheric delays model at a local-scale as possible in the study zone. Our results show the ability of atmospheric models to estimate atmospheric delays on continental areas. These estimations were demonstrated using a GPS data comparison.

Our product will allow correct geodetic data of satellite measurements like radar altimeters or SAR. The methodology will reduce the uncertainty, improving atmospheric delay estimations associated with potential rates of deformation. For example, our study can be used for volcanic deformation estimations associated with magma intrusion activity. Therefore, new estimations with these corrections will allow taking adequate decisions in volcanic risk assessments. However, the current results are preliminary yet. Moreover, from the literature, we think that the estimation could be less accurate on the coastal zones due to the parameterizations during
Figure 3. Relative atmospheric delay for the Villarrica volcano. Temporal baseline for four days (01 to 04 January 2012).

the implementation of the WRF model. Likewise, there may be strong temporal fluctuations in areas with complex topography as shown in Figures 1 and 2. This work corresponds to a preliminary approach within the group of geophysics and remote sensing of the Universidad de la Frontera and Catholic University of Temuco in close collaboration with the OVDAS volcanological observatory.

References

[1] Ebmeier, S. K., Biggs, J., Mather, T. A., Elliott, J. R., Wadge, G., & Amelung, F. (2012). Measuring large topographic change with InSAR: Lava thicknesses, extrusion rate and subsidence rate at Santiaguito volcano, Guatemala. Earth and Planetary Science Letters, 335336, 216225. https://doi.org/10.1016/j.epsl.2012.04.027

[2] Jay, J., Costa, F., Pritchard, M., Lara, L., Singer, B., & Herrin, J. (2014). Locating magma reservoirs using InSAR and petrology before and during the 2011-2012 Cordón Caulle silicic eruption. Earth and Planetary Science Letters, 395(September 2016), 254266. https://doi.org/10.1016/j.epsl.2014.03.046

[3] Shilai Cheng, Daniele Perissin, Hui Lin, Fulong Chen, Atmospheric delay analysis from GPS meteorology and InSAR APS, Journal of Atmospheric and Solar-Terrestrial Physics, Volume 86, September 2012, Pages 71-82, ISSN 1364-6826, https://doi.org/10.1016/j.jastp.2012.06.005.
[4] John David Jackson, 2010. Classical electrodynamics. 3rd edition, illustrated. Wiley Editors, 1975. ISBN 047143132X, 9780471431329. 848 pages.

[5] Jolivet, R., Grandin, R., Lasserre, C., Doin, M.-P., & Peltzer, G. (2011). Systematic InSAR tropospheric phase delay corrections from global meteorological reanalysis data. Geophysical Research Letters, 38(17), n/a. https://doi.org/10.1029/2011GL048757

[6] Remy, D., Chen, Y., Froger, J. L., Bonvalot, S., Cordoba, L., & Fustos, J. (2015). Revised interpretation of recent InSAR signals observed at Llaima volcano (Chile). Geophysical Research Letters, 42(10), 3870-3879. https://doi.org/10.1002/2015GL063872

[7] Boehr, J., and H. Schuh (2004), Vienna mapping functions in VLBI analyses, Geophys. Res. Lett., 31, L01603, doi:10.1029/2003GL018984.

[8] Berrada Baby, H., P. Gol, and J. Lavergnat (1988). A model for the tropospheric excess path length of radio waves from surface meteorological measurements, Radio Sci., 23, 1023-1038.

[9] Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, W. Wang and J. G. Powers, 2005. A Description of the Advanced Research WRF Version 2

[10] National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce, 2000. NCEP FNL Operational Global Tropospheric Analyses, continuing from July 1999, http://rda.ucar.edu/datasets/ds083.2, Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory, Boulder, Colo.