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Can spaceborne SAR interferometry be used to study the temporal evolution of PWV?

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ABSTRACT

In this work we investigate the use of Synthetic Aperture Radar (SAR) interferometry (InSAR) to generate maps of temporal variations of the Precipitable Water Vapor (PWV) spatial distribution with a horizontal resolution as fine as $10 \div 20$ m depending on the radar wavelength, and over a swath typically 100 km wide. We present the result of a time series of PWV maps obtained by processing a set of interferometric SAR images acquired by the ENVISAT-ASAR mission over the Lisbon region from November 2008 to November 2009. Maps are calibrated by means of GPS measurements of the PWV over the same area and covering the time interval between the first and last SAR acquisition. Current interferometric spaceborne missions, which can also be used to generate PWV maps, relies on SAR sensors working at different frequency bands: L (ALOS-PALSAR), C (ENVISAT-ASAR, RADARSAT) and X (TerraSAR-X, Cosmo-Sky-Med) and with a repetition cycle ranging from 11 (TerraSAR-X and Cosmo-Sky-Med) to 46 days (ALOS-PALSAR). The precision of these maps can be smaller than 1 mm depending on the radar wavelength and the spatial filtering. We also demonstrate that the merging of PWV maps obtained by processing time series of interferometric SAR images acquired from different tracks of the same satellite and/or different spaceborne missions gives information about the temporal evolution of the PWV spatial distribution with a sampling period of a few days, much shorter than the revisiting times of each SAR sensor. The availability of such PWV maps could increase the quality of quantitative precipitation forecasting and open interesting perspectives for nowcasting applications.

1. Introduction

Water vapor is the most variable of the major constituents of the atmosphere, playing an important role in many atmospheric processes over a wide range of temporal and spatial scales. It is basically concentrated in the troposphere, the atmosphere layer where the most important phenomena related to weather occur. This layer is destabilized by radiative heating and vertical wind shear near the surface. Radiative heating leads to convection while vertical wind shear is related to baroclinic instability which leads to storms and to the formation of fronts. The spatial distribution of water vapor plays a critical role in the vertical stability of the atmosphere, the distribution of clouds and rainfall and in the structure and evolution of atmospheric storm systems (Bevis et al., 1992). The concept of Precipitable Water Vapor (PWV) is generally used to study the atmospheric water vapor. The PWV is the total quantity of water vapor overlying a point on the earth's surface expressed as the height of an equivalent column of liquid water. Limitations in the analysis of water vapor are the major source of error in short-term (0–24 h) forecasts of precipitation. Improved monitoring of atmospheric water vapor can lead to more accurate forecasts of precipitation and severe weather conditions and to a better understanding of climate and climate change.

Different techniques are used to measure the vertical and horizontal distributions of water vapor: radiosonde (Elliot

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and Gaffen, 1991), ground-based, upward-looking, and spaceborne, downward-looking, WV radiometers (Resch, 1994; McMurdie et al., 1997), Very Long Baseline Interferometry (VLBI) (Tralli et al., 1992), Global Positioning System (GPS) (Bevis et al., 1992) and, recently, Synthetic Aperture Radar (SAR) interferometry (Hanssen et al., 1999). Many techniques currently used on a routine basis are limited in the spatial resolution they provide, such as radiosondes, VLBI and GPS measurements. Moreover, radiometric water vapor observations from contemporary meteorological satellites usually originate from atmospheric layers above 3 km, due to the strong absorption by water vapor (Weldon and Holmes, 1991). This often restricts quantitative interpretation to upper tropospheric moisture distribution (Schmets et al., 1995).

In the repeat-pass SAR interferometry (InSAR), two nearly identical microwave images are acquired from nearly the same position in space at two different epochs. Differences in the phase information in both images are caused by the differences in the imaging geometry (different path lengths) and in the spatial distribution of propagation delay during the first and second acquisition. An interferogram, i.e. a coherent phase image, is formed when the phase signal due to geometric path length differences is eliminated by using a digital terrain model. As the interferometric pairs used for atmospheric studies are acquired with a short time interval, the coherent interferometric phase can be assumed due to only the atmospheric propagation delay and not related to surface deformations as has been recently demonstrated by comparing real SAR interferograms to the corresponding synthetic fringe patterns obtained using a numerical weather forecasting model (Nico et al., in press). However, generally, the geodetic and atmospheric components in a SAR interferogram are not easily disentangable (Catalão et al., in press). What is known is that the atmospheric and geodetic signals in SAR interferograms have different spatial and temporal scales and power spectrums. The signal from a microwave source on a satellite, scattered by the earth surface, will have been refracted by the terrestrial atmosphere. The corresponding delay introduced by the atmosphere depends on the refractive index along the actual path traveled by the signal. The delay of radar signal is caused by an integration over the refractive index of the propagation medium, along the line of sight. Horizontal and vertical heterogeneities in refractive index are influenced by the spatial distribution of water vapor, pressure, temperature, liquid water, and electron content. Yet, over distances less than about 50 km, the main signal in the interferogram is due to water vapor, albeit temperature and liquid water can add some additional mm's of delay (Hanssen et al., 1999). Using surface temperature observations, the integrated water vapor signal can be converted to Precipitable Water Vapor (PWV), its liquid equivalent, when assuming a fixed vertical temperature profile (Bevis et al., 1992). The phase delay measured by SAR interferometry, when terrain deformation can be neglected, is nearly proportional to the quantity of water vapor integrated along the signal path. An estimation of the zenith delay (the wet delay in the vertical direction) can be transformed with very little additional uncertainty into an estimate of PWV. The aim of this paper is to demonstrate the concept of SAR meteorology, i.e. the applicability of the SAR interferometry technique to derive PWV estimates of immediate meteorological utility. In the past, the availability of the tandem ERS-1/2 interferometric SAR data allowed to get PWV maps with a temporal baseline of 1 day but not on a routine basis (Hanssen et al., 1999). In those maps it was possible to recognize the signature of a precipitating cumulonimbus cloud, the effects of a cold front and the phenomenon of horizontal convective rolls. From each track of an interferometric SAR sensor, a time series of ΔPWV maps is obtained containing information about the temporal evolution of PWV. The main difficulty of this operation is the fact that the integration of PWV temporal changes is not direct and requires the calibration of each ΔPWV map. In this work we apply a methodology to merge all the ΔPWV maps composing the time series based on GPS measurements of PWV in a few points in the study area. The availability of GPS measurements allows also disentangle geodetic and atmospheric signals in SAR interferograms and correct for possible errors in SAR processing due to the lack of precise satellite orbits. The merging of all the time series of calibrated ΔPWV maps obtained by different tracks of a spaceborne SAR missions or by the different interferometric missions currently operating, relying on SAR sensors working at different frequency bands: L (ALOS-PALSAR), C (ENVISAT-ASAR, RADARSAT) and X (TerraSAR, Cosmo-Sky-Med) and with a repetition cycle ranging from 11 (TerraSAR-X) to 46 days (ALOS-PALSAR), can give information about the temporal evolution of the PWV with a sampling period shorter than the revisiting time of each one of SAR sensors, opening new perspectives in SAR meteorology.

The paper has the following structure. A motivation about the need for time series of high spatial resolution maps of PWV is given in Section 2. Section 3 is devoted to the physics of microwave phase delay and on the relationship between the interferometric phase and the PWV. The SAR interferometry technique and the methodology used to derive the times series of PWV maps is shortly described in Section 4. Results are presented in terms of time series of PWV maps and discussed in Section 5. Finally, a few conclusions are drawn in Section 6.

2. Why is it important to derive a time series of 2d maps of PWV?

In this section we describe two atmospheric phenomena whose study could benefit from the availability of ΔPWV maps derived by SAR interferometry.

2.1. Convection and precipitation

In phenomena such as cumulus convection and dynamics near atmospheric fronts, fluxes of moisture are driven by wind patterns giving rise to convective clouds and precipitations (Parsons, 1992). These moisture variations cause an increase in phase delay. What can be observed in SAR interferograms over land are bands with increased phase delay located in correspondence of atmospheric fronts and indicating possible rain (Hanssen et al., 2000).

2.2. Boundary layer rolls

The atmospheric boundary layer rolls are related to the phenomena of Rayleigh-Bénard and dynamic instability