Tropospheric Correction Techniques in repeat-pass SAR Interferometry

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[Abstract] For the first time, the application of a spaceborne near infrared (IR) water vapour product from the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) for reducing water vapour effects of ERS-2 measurements are presented. The MODIS near IR water vapour product has been available since the end of February 2000 with a spatial resolution of 1km (at nadir) and a moderate accuracy of 5-10%. Coincident data with ERS-2 used in this study were located over Mt. Etna and Southern California. The results showed that the MODIS near IR water vapour product could be useful in reducing atmospheric effects in ERS-2 SAR interferometric data. Taking these results into account and the fact that, the MEdium Resolution Imaging Spectrometer (MERIS) has a higher accuracy and is on board the same platform, ENVISAT, as the Advanced Synthetic Aperture Radar (ASAR), future prospects look optimistic. The major limitation for either MODIS or MERIS is the reliance on cloud-free water vapour retrievals with the percentage of cloud free observations as low as 25%. In this paper, also for the first time, 3D GPS water vapour (or wet refractivity) models were applied to correct ERS-2 SAR interferometric data. Firstly, the WAter Vapour Extraction Software (WAVEs), developed at UCL, was used to construct a 3D water vapour (or wet refractivity) model with an appropriate resolution making full use of the spatial structure of zenith wet delays; then the difference in LOS (Line-of-Sight) path delays were calculated and applied to correct InSAR measurements. The results showed that the volumetric fields derived using the 3D GPS water vapour model can reduce water vapour effects significantly. It also showed that such 3D models are sensitive to the distribution of GPS receivers. Presently, a new way to fuse MODIS or MERIS with ground-based GPS networks within the WAVEs package is under investigation at UCL.

1. Introduction

Tropospheric delay (especially that part due to water vapour) in radio signal propagation is known to be one of the major limitations of repeat-pass Interferometric Synthetic Aperture Radar (InSAR) [1, 2, 3, 4]. A 20% spatial or temporal change in relative humidity is estimated to cause between 80 and 290 m of topographic error for baselines between 400 and 100 m, and the corresponding error is of the order of 10 to 14 cm in the case of deformation estimates [4]. So far, several methods have been proposed to reduce the tropospheric effects on interferograms; temporal stacking, calibration and the use of permanent scatterers are the three most common methods. Temporal stacking reduces the spatially uncorrelated variance by averaging N independent interferograms in time with a factor of N. Reference [5] demonstrated an analytical method to determine the length of observation time necessary to measure a given deformation rate using the temporal stacking method. In [6], permanent scatterers and stacking were combined to reduce tropospheric effects and other short wavelength noise to recover a fault slip signal. Calibration utilises independent sources such as GPS and microwave radiometer (MWR) measurements to reduce tropospheric effects [3]. It has been suggested that numerical modelling could also be applied to the calibration [7, 8].

In this paper, two distinct correction methods are discussed and tested: the use of contemporaneous Near Infrared (IR) water vapour measurements from MODIS and the application of a 3D water vapour model derived from a dense network of contemporaneous GPS measurements.

2. MERIS, MODIS and 3D GPS water vapour model (WAVEs)

The MEdium Resolution Imaging Spectrometer (MERIS) is a key payload on ESA's ENVISAT, an advanced polar-orbiting Earth observation satellite launched on 1 March 2002. MERIS allows for the global retrieval of total columnar atmospheric water vapour of the Earth every 3 days, with two water vapour channels in the near infrared. MERIS near infrared water vapour products are available at two spatial resolutions. In full resolution (FR) mode each pixel has a nominal resolution of 300m with an instantaneous field of view (IFOV) of 0.019°, with a nadir spatial sampling of 260 m across track by 290 m along track. In reduced resolution (RR), the nominal resolution is 1.2km where each pixel

Proc. of FRINGE 2003 Workshop, Frascati, Italy,
1 – 5 December 2003 (ESA SP-550, June 2004) 61_li

is approximately 1.04 km across track by 1.2 km along track at nadir. The unprecedented high spatial resolution makes MERIS very attractive to the meteorological community. Furthermore, the Advanced Synthetic Aperture Radar (ASAR) is on board the same platform as MERIS and these two datasets can be acquired simultaneously during the daytime, which provides for the possibility of reducing water vapour effects on ASAR measurements. MERIS has therefore gained a lot of attention in the remote sensing community. Comparisons with radiosonde, GPS and MWR showed small standard deviations and small biases under moderate conditions [9; Z. Li et al., manuscript in preparation, 2004]. Unfortunately, no ASAR interferometric data has been made available to date to test this approach.

The NASA Moderate Resolution Imaging Spectroradiometer (MODIS) instrument is a key instrument on the Terra and Aqua satellites, launched on 18 December 1999 and 4 May 2002, respectively. NASA provides a near IR water vapour product with a spatial resolution of 1 km x 1 km (at nadir). The Terra platform flies in a near-polar sun-synchronous orbit while ERS-2 is in a sun-synchronous polar orbit, and both have a descending mode across the equator at 10:30 am local time. This means that contemporaneous measurements of Terra MODIS and ERS-2 are feasible. Since near IR observations are sensitive to the presence of clouds, cloud-free observations are preferred although it should be noted that an above-cloud water vapour product is also available. Currently, MODIS near IR water vapour values can only be collected under clear sky conditions and hence only these measurements can be applied to correct InSAR measurements. In this study, the cloud mask product used to cloud screen the data had to indicate at least 95% confidence clear [10]. MODIS near IR water vapour collection 4 (first stage validated) product was used. The percentage of cloud free conditions is approximately 25% (Z. Li et al., manuscript in preparation, 2004), which is a major limitation to applying either MODIS or MERIS near IR water vapour products for this purpose. However, in theory, a Numerical Weather Prediction Model (utilising water vapour above cloud product) could be used to densify the grid.

The emerging ground-based Global Positioning System (GPS) networks present an appealing opportunity for estimating water vapour and calibrating InSAR measurements. GPS water vapour has been well characterised and validated, with an accuracy of 1-2mm [10, 11]. The spatial resolutions of local/regional GPS networks are usually from a few kilometres to tens of kilometres, which is relatively sparse compared with the spatial resolution of SAR images. So spatial interpolation is required to predict the values of unknown points [3]. Tomographic techniques aim to recover a 3D or 4D field from integrated measurements along ray paths. The most important advantage of tomographic techniques, over the common interpolation techniques, is that physical characteristics can be fully taken into account. Several studies have demonstrated that tomographic techniques are feasible to recover 3D or 4D water vapour (or wet refractivity) from GPS data [12, 13]. At UCL, the WAter Vapour Extraction Software (WAVEs) has been developed to construct 3D/4D water vapour models using GPS data with tomographic techniques. In WAVEs, the average profile of refractivity and the spatial structures of zenith wet delays (ZWD) are considered as well as topography. In this study, GPS data were analysed using the GIPSY-OASIS II software package with the same processing strategy as described in [10]. The estimated variables such as zenith wet delay, the delay gradient parameters and their standard deviations were imported into WAVEs as observation measurements.

3. Case study one: MODIS correction model over Mt. Etna

Two descending ERS-2 SAR images were available with 35 days separation on 28 June 2000 and 2 August 2000 at 9:41 UTC over Mt. Etna. Coincident MODIS data were also acquired: one at 9:40 UTC and the other at 10:10 UTC.

The ERS-2 SAR images were processed with the PulSAR software using ESA PRC orbit products. Topographic effects were removed from each interferogram using a 30m CNR DEM with a height uncertainty of about 5m. The altitude of ambiguity was 41m, and the accuracy of the CNR DEM could cause a phase error of 0.1 of a fringe. Therefore, artefacts due to the DEM are likely to be negligible.

An Interferogram was produced using 3 looks in range and 12 looks in azimuth resulting in a pixel spacing of approximately 60m. In order to minimize the uncertainty of phase unwrapping, low coherence areas were masked with a threshold of 20%.

Since the MODIS near IR water vapour product has an irregular spatial resolution of 1km (at nadir), a bi-linear interpolation method was applied to co-register MODIS data to the SAR grid in the WGS-84 system. Water vapour was converted into path delays in the line of sight (LOS) to the ERS-2 satellite using surface temperatures and mapping

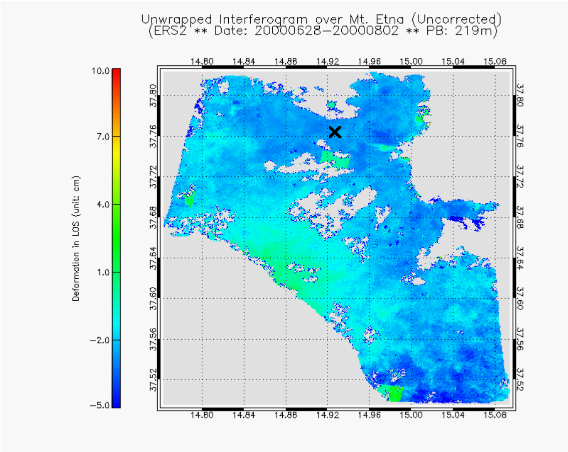

Fig. 1a. After MODIS Correction

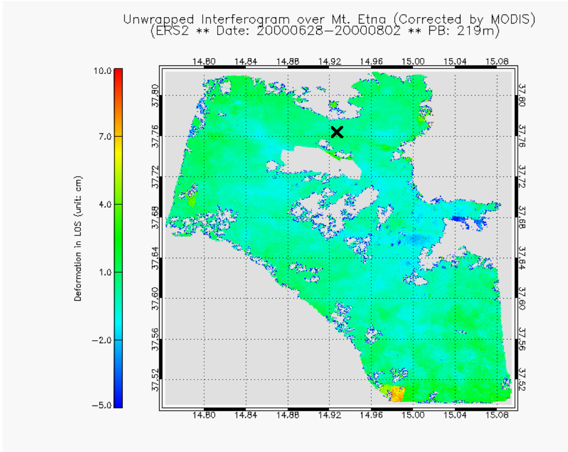

Fig. 1b. After MODIS Correction

functions [10]. The differences of LOS path delays (single way) varied from –6.8cm to 4.6cm with –2.5cm.

Fig. 1a shows an unwrapped image without MODIS correction, and Fig. 1b after MODIS correction. The black cross represents a reference pixel, whose value was assigned using the difference of MODIS path delays in the LOS. There are more pixels with null values in the centre of Fig 1b because no MODIS data were available due to cloudy conditions.

During this period, no significant deformation was expected [8], so the values closer to zero in Fig. 1b imply the MODIS correction was effective.

4. Case study two: 3D GPS correction model (WAVEs) over Mt. Etna

Fig. 2 shows the location of the 14 GPS receivers deployed over Mt. Etna by the Universities of Reading, Nottingham and Newcastle for two 10-day periods in 2000 [14]. The WAVEs package was used to construct 3D GPS water vapour models for 6 September 2000 and 11 October 2000 at 9:41 UTC, respectively, coincident with two descending passes of ERS-2. The output grids were 2km x 2km x 1km, and a bi-linear interpolation method was applied to interpolate GPS path delays to the SAR grid in WGS-84 system. Contrary to the MODIS correction model, no surface temperature is required to convert water vapour into path delays here, and the additional uncertainty associated with the conversion is avoided.

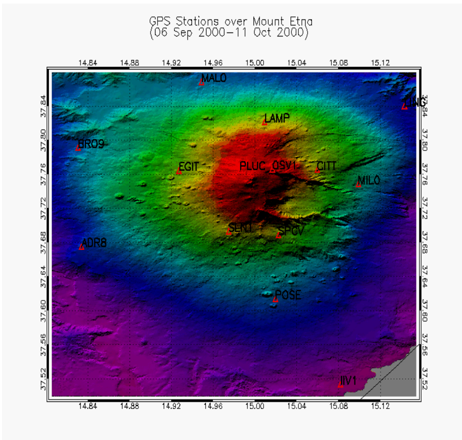

Fig. 2. GPS Sites over Mt. Etna

The same processing strategy as shown in Case One was applied to process the ERS-2 SAR images (Fig. 3a). The perpendicular baseline (PB) was 304m, and the CNR DEM should introduce a phase error of 0.2 fringes. According to [8], no significant deformation was expected during this period. In Fig. 3a, the InSAR delay measurements were shifted to the difference of WAVEs at station EGIT (black cross, where there was high coherence). Fig 3b shows that the WAVEs correction model reduced water vapour effects significantly in the vicinity of the crater. At the lower right corner, the residuals are still large. The most likely explanation is that only one GPS receiver was available there. This suggests that the spatial distribution of GPS sites will play a key role in the construction of 3D water vapour models using this technique.

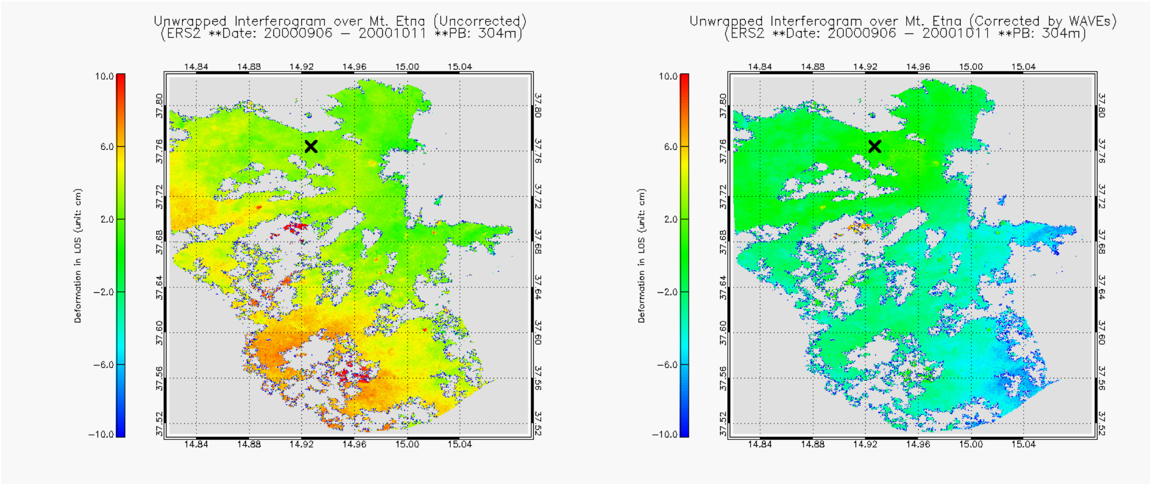

Fig. 3a. Before WAVEs Correction **Fig. 3b. After WAVEs Correction**

5. Case study three: both correction models over SCIGN

Coincident GPS, MODIS and ERS-2 data were studied in Southern California. The time difference between MODIS and ERS-2 passes were 20 minutes and 40 minutes on 29 July 2000 and 18 August 2001, respectively.

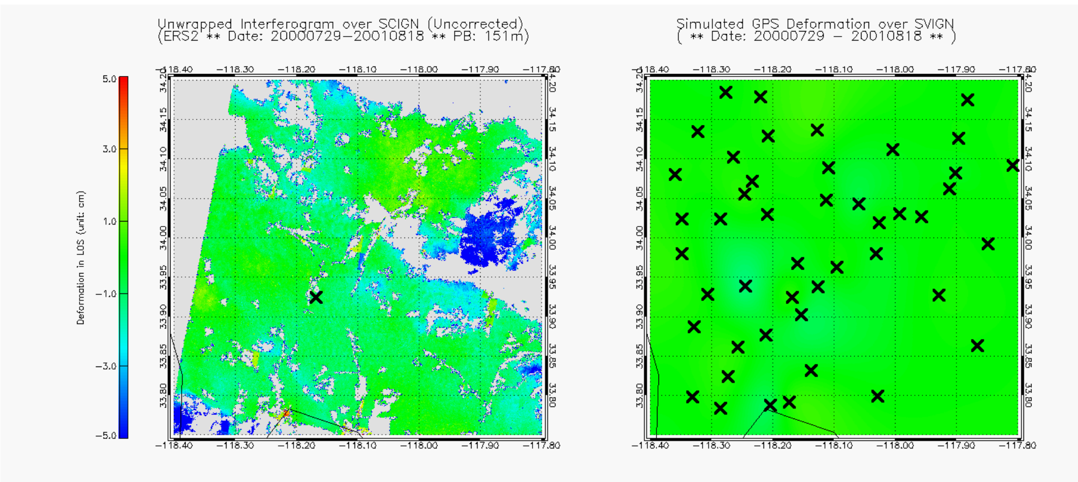

Fig. 4a. Before Correction **Fig. 4b. Deformation detected by GPS**

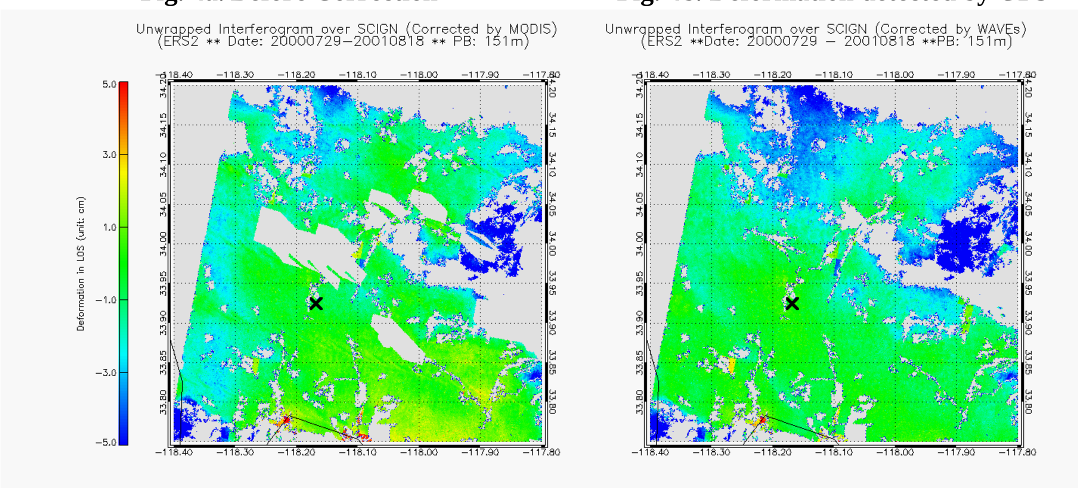

Fig. 4c. After MODIS Correction **Fig. 4d. After WAVEs correction**

A 1 arc-sec SRTM DEM, with a relative vertical height accuracy of better than 10m, was used to remove topographic contributions which might result in a phase error of 0.2 fringes with a PB of 151m (Fig 4a). Fig 4b shows the deformation interpolated using GPS data during the 385-day period, where the black crosses represent GPS stations available on both days. During this period, the deformation detected by GPS ranged from –1.1cm to 0.5cm with an average of 0.02cm in this area. The GPS-detected deformation (Fig 4b) was applied to Fig 4a to remove deformation contributions, and little land surface change took place in most of the area of interest (not shown here).

In Fig 4a, the HOLP GPS site was chosen as a reference, and the value was assigned as the delay difference detected by GPS. The residuals decreased significantly both for MODIS (Fig 4c) and WAVEs (Fig 4d) correction models in the top of the area of interest, while they increased much more in the lower right corner of Fig 4c than they do in Fig 4d.

6. Conclusions

For the first time, MODIS near IR water vapour product was applied to reduce tropospheric effects in ERS-2 SAR images. The results indicate that MODIS near IR water vapour product could be useful in reducing water vapour effects. There are several possible types of error sources for this approach: 1) Uncertainties inherited from MODIS itself such as the uncertainty in the surface spectral reflectance, sensor calibration, haze, undetected clouds and etc. Typical errors in the derived water vapour values are estimated to be 5-10%[15]. 2) Uncertainties in the conversion from water vapour to path delays using surface temperatures. Since surface temperature cannot be acquired at each pixel of interest, some assumptions need to be made. 3) Ray paths of MODIS are different from ERS-2 either in space or in time. Fortunately, MERIS near IR water vapour product is expected to have a higher accuracy than MODIS and finer spatial resolution. Moreover, MERIS shares the same altitude and ray paths with ASAR. The major limitation for its application is the low percentage of cloud free conditions.

Applications of the 3D GPS water vapour models produced by the WAVEs package were presented. Results show that GPS data can reduce water vapour effects significantly with a constraint due to the distribution of GPS sites. The most attractive features for this purpose are high accuracy and continuousness. The shortcomings are: 1). The path delays detected by GPS are the average along the paths of GPS satellites in views during the observation period; 2). WAVEs is sensitive to the distribution of GPS sites, which needs further research and is out of the scope of this study.

Taking into account the unprecedented spatial resolution of MERIS near IR water vapour product and the high accuracy of GPS water vapour product, it is appealing to combine them to construct a 3D water vapour model. A new approach to fuse MODIS/MERIS data into the WAVEs package is currently under development at UCL.

Acknowledgements. This research is supported by Overseas Research Students Awards (ORS) and UCL Graduate School Research Scholarships at University College London. This work is also linked to the NERC Earth Observation Centre of Excellence: Centre for the Observation and Modelling of Earthquakes and Tectonics (COMET). We thank Prof. Geoff Wadge and Dr. Peter Webely (ESSC, Reading) for providing us with the GPS data over Mt. Etna. We would also like to express our appreciation to Andy Smith for valuable discussions. The ERS data were supplied under ESA ENVISAT data grant AO ID=853 (HAZARDMAP), and the GPS data over SCIGN were obtained from Scripps Orbit and Permanent Array Centre (SOPAC, http://sopac.ucsd.edu/).

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