Remote Sensing of Environment 170 (2015) 40–47

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Statistical comparison of InSAR tropospheric correction techniques

D.P.S. Bekaert [a,b,*], R.J. Walters [a], T.J. Wright [a], A.J. Hooper [a], D.J. Parker [b]

[a] COMET, School of Earth and Environment, University of Leeds, United Kingdom
[b] ICAS, School of Earth and Environment, University of Leeds, United Kingdom

ARTICLE INFO

Article history:
Received 13 May 2015
Received in revised form 25 August 2015
Accepted 31 August 2015
Available online 12 September 2015

Keywords:
Atmosphere
Tropospheric noise
Corrections
Phase-based
Spectrometers
Weather models
InSAR
State-of-the-art
TRAIN

ABSTRACT

Correcting for tropospheric delays is one of the largest challenges facing the interferometric synthetic aperture radar (InSAR) community. Spatial and temporal variations in temperature, pressure, and relative humidity create tropospheric signals in InSAR data, masking smaller surface displacements due to tectonic or volcanic deformation. Correction methods using weather model data, GNSS and/or spectrometer data have been applied in the past, but are often limited by the spatial and temporal resolution of the auxiliary data. Alternatively a correction can be estimated from the interferometric phase by assuming a linear or a power-law relationship between the phase and topography. Typically the challenge lies in separating deformation from tropospheric phase signals. In this study we performed a statistical comparison of the state-of-the-art tropospheric corrections estimated from the MERIS and MODIS spectrometers, a low and high spatial-resolution weather model (ERA-I and WRF), and both the conventional linear and new power-law empirical methods. Our test-regions include Southern Mexico, Italy, and El Hierro. We find spectrometers give the largest reduction in tropospheric signal, but are limited to cloud-free and daylight acquisitions. We find a ~10–20% RMSE increase with increasing cloud cover consistent across methods. None of the other tropospheric correction methods consistently reduced tropospheric signals over different regions and times. We have released a new software package called TRAIN (Toolbox for Reducing Atmospheric InSAR Noise), which includes all these state-of-the-art correction methods. We recommend future developments should aim towards combining the different correction methods in an optimal manner.

1. Introduction

Interferometric Synthetic Aperture Radar (InSAR) is a geodetic tool that is well suited to the observation of crustal deformation processes. However, the use of InSAR to measure small magnitude and long wavelength deformation signals, such as interseismic slip (e.g. Fournier, Pritchard, & Finnegan, 2011; Hooper et al., 2013; Béjar-Pizarro et al., 2013; Walters, Elliott, Li, & Parsons, 2013), subduction zone slow slip events (e.g. Cavalié et al., 2013; Bekaert, Hooper, & Wright, 2015a), and creep (e.g. Jolivet et al., 2012) is severely limited by atmospheric contamination of the InSAR data. Separating deformation from atmospheric signals, introduced by the variation of atmospheric properties in space and time, remains one of the major challenges for InSAR (Hooper et al., 2013).

Atmospheric delays are typically split into ionospheric and tropospheric terms. Ionospheric effects are caused by variations in free electrons along the travel path, resulting in a phase advance of the radar signal that becomes more significant for larger wavelengths, such as for P and L-band SAR (e.g. Gray, Mattar, & Sofko, 2000). Tropospheric effects are caused by variations in pressure, temperature, and relative humidity in the lower part of the troposphere (<5 km), which cause signals in interferograms of up to 15–20 cm in magnitude, and can often be much larger than the tectonic signals of interest (e.g. Hooper et al., 2013; Bekaert et al., 2015a). In this study, we focus on the testing and comparison of correction methods for tropospheric noise. Contamination from ionospheric noise in our test-data is minimized as we use C and X-band SAR data only.

The 2-way tropospheric phase delay, ϕ_{tropo}, at a specific height $h = h_1$, corresponds to the integration of the hydrostatic and wet component of the refractivity, N, between h_1 and the top of the troposphere, h_{top}, along the radar line-of-sight as:

$$\begin{aligned} N &= \left(k_1 \frac{P}{T}\right)_{\text{hydr}} + \left(k_2' \frac{e}{T} + k_3 \frac{e}{T^2}\right)_{\text{wet}} = N_{\text{hydr}} + N_{\text{wet}} \\ \phi_{\text{tropo}} &= \frac{-4\pi}{\lambda} \frac{10^{-6}}{\cos\theta} \int_{h_1}^{h_{\text{top}}} (N_{\text{hydr}} + N_{\text{wet}}) \mathrm{d}h \end{aligned} \quad (1)$$

where P indicates total atmospheric pressure, T the temperature, e the partial pressure of water vapor, θ the incidence angle, λ the radar wavelength, and $-4\pi/\lambda$ a conversion factor to convert from pseudo-range increase to phase delay (Hanssen, 2001). The coefficients k_1, $k_2{}'$ and k_3 are empirical constants which we take as $k_1 = 77.6$ K hPa^{-1}, $k_2{}' = 23.3$ K hPa^{-1} and $k_3 = 3.75 \cdot 10^5$ K^2 hPa^{-1} (Smith & Weintraub, 1953). For InSAR, the interferometric tropospheric phase delay $\Delta\phi_{\text{tropo}}$

* Corresponding author at: COMET, School of Earth and Environment, University of Leeds, United Kingdom.

http://dx.doi.org/10.1016/j.rse.2015.08.035

(from now on referred to as tropospheric phase delay) is the difference between tropospheric delay at the master and slave acquisition times $\Delta\phi_{\text{tropo}} = \phi_{\text{tropo}}^{\text{slv}} - \phi_{\text{tropo}}^{\text{mst}}$, and thus depends on the change in refractivity, rather than the total refractivity.

Tropospheric corrections can be calculated using auxiliary information from weather models (e.g. Wadge et al., 2002; Liu, Hanssen, & Mika, 2009; Doin, Lasserre, Peltzer, Cavalié, & Doubre, 2009; Jolivet, Grandin, Lasserre, Doin, & Peltzer, 2011; Walters, Parsons, & Wright, 2014; Jolivet et al., 2014), GPS measurements (e.g. Williams, Bock, & Fang, 1998; Onn & Zebker, 2006; Li, Fielding, Cross, & Muller, 2006a; Löfgren et al., 2010), multi-spectral observations (e.g. from the Medium Resolution Imaging Spectrometer (MERIS) onboard the Envisat satellite; or the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra and Aqua satellites) (Li et al., 2006b; Li, Fielding, Cross, & Preusker, 2009; Li, Fielding, & Cross, 2009), or GPS in combinations with spectrometer data (e.g. Li, Muller, Cross, & Fielding, 2005; Puysseégur, Michel, & Avouac, 2007). The estimated corrections are often limited by the spatial and temporal resolution, and the precision of the auxiliary data. GPS stations are often absent or sparsely distributed in many areas around the world. Spectrometers can only provide useful corrections under cloud-free and daylight conditions. Weather models and spectrometer observations that are not acquired simultaneously with SAR data need to be interpolated in time, which can also introduce uncertainties. This is not required for MERIS in combination with Envisat ASAR sensor, as both were operated simultaneously onboard Envisat.

Tropospheric corrections can also be calculated empirically directly from the interferogram. Tropospheric delays $\Delta\phi_{\text{tropo}}$ for an individual interferogram can be estimated by assuming a linear relation, $\Delta\phi_{\text{tropo}} = K_{\Delta\phi}h + \Delta\phi_0$, between topography h and the interferometric phase $\Delta\phi$ in a non-deforming region (Wicks et al., 2002) or in a spatial band insensitive to deformation (Lin, Simons, Hetland, Muse, & DiCaprio, 2010), where $K_\Delta\phi$ is the gradient to be estimated, and $\Delta\phi_0$ is a constant that can be neglected as it merely represents a constant shift applied to the whole interferogram. Elliott, Biggs, Parsons, & Wright (2008) used a modification of this method and removed a preliminary estimate of the deformation displacements prior to estimating $K_\Delta\phi$. Such phase-based methods have been effective in the reduction of tropospheric signals, but are limited as they assume no spatial variability of the tropospheric properties is present. Some authors have attempted to overcome this limitation by applying a piece-wise slope correction over multiple windows (e.g. Béjar-Pizarro et al., 2013). However, this method is technically flawed, as a laterally-varying tropospheric signal requires a common reference between windows, and estimation of the constant $\Delta\phi_0$ within windows is not possible as other phase contributions bias the estimate. Alternatively, Bekaert, Hooper, & Wright (2015b) developed a power-law model, which unlike the linear approach can account for a spatially-varying tropospheric signal in the presence of deformation.

In this study, we perform a statistical analysis of several different tropospheric correction methods that can be used to correct an individual interferogram. This includes corrections estimated from (*i*) MERIS at ~1.2 km spatial-resolution, (*ii*) MODIS at 1 km resolution, (*iii*) the archived European Center for Medium-Range Weather Forecasts (ECMWF) ERA-I weather model at 80 km resolution (Dee et al., 2011), (*iv*) a locally run Weather Research and Forecasting Model (WRF) (Michalakes et al., 2004) nested to a 7 km resolution, and the phase-based empirical (*v*) linear and (*vi*) power-law corrections. All these methods are included in TRAIN, our open-source Toolbox for Reducing Atmospheric InSAR Noise.

2. Tropospheric correction methods for InSAR

Tropospheric signals consist of a short-scale (few km) component, introduced by turbulent as well as coherent dynamics in the troposphere, a longer-scale (10 s of km) component, introduced by lateral variation of pressure, temperature and humidity, and a topography-correlated component due to changes of pressure, temperature, and relative humidity with height (e.g. Hanssen, 2001). Different correction techniques have different sensitivities for these three components of the tropospheric delay. For example, weather models often have timing issues, which render them unable to correctly resolve the turbulent variation of water vapor (e.g. Liu et al., 2009). While the statistical properties of the turbulent component can be representative for the region, the location can be wrong, leading to an adverse effect when removing the estimated tropospheric signal. Unlike water vapor, temperature and pressure are smooth in space, leading to a better-resolved longer wavelength hydrostatic component. Spectrometer measurements only produce an estimate for the wet component of the delay. While a direct comparison is possible between the spectrometer correction and the wet delay as estimated from weather models, the phase-based methods cannot produce separate wet and hydrostatic components of the delay. As the linear and the power-law methods only estimate a topography-correlated component of the delay, they explicitly cannot account for the turbulent and coherent short-scale component.

In the following section we provide more information on the estimation procedure of the different correction methods.

2.1. Tropospheric delays from weather models

The output (pressure, temperature, and relative humidity) from local or global weather models can be used with Eq. (1) to compute both hydrostatic and wet tropospheric delay (Doin et al., 2009; Jolivet et al., 2011). In this study we used the freely available archived ERA-I global model, and also run our own local high spatial-resolution model using the Weather Research and Forecasting (WRF) model (Michalakes et al., 2004).

ERA-I outputs data at a spatial resolution of ~80 km, at a 6 h interval, and on 37 pressure levels (Dee et al., 2011). We performed a lateral and vertical spline interpolation of pressure, temperature, and relative humidity, after which we computed the refractivity and the integration from the surface upwards. To match the SAR acquisition time, we performed a linear interpolation in time.

We modified the WRF set-up to produce outputs at the same 37 pressure levels as ERA-I. We set the boundary of the parent WRF domain using the National Center for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) data (Saha et al., 2010) and NCEP's Global Forecast System analysis (GFS) (Unidata et al., 2003). As GFS did not exist prior to 1 November 2006, we used the CFSR data instead for those dates. The impact of changing between CFSR and GFS on the estimated delays is small. We estimate negligible differences in slant total delay between the two methods; the average RMS difference is <1 mm across 15 interferograms for which CFSR and GFS corrections were both available.

2.2. Tropospheric delays from spectrometer observations

Both MERIS and MODIS provide products of Precipitable Water Vapor (PWV), the vertically integrated water vapor content of the atmosphere. The MERIS estimate for PWV is computed by comparing the radiance ratio between two closely-spaced infrared frequency bands, of which only one is sensitive to water vapor (ESA, 2011). A similar approach is used for MODIS but with five near-infrared bands instead (Gao & Kaufman, 2003). PWV is defined as the equivalent column height of liquid water when integrating all water vapor e from the surface h to the top of the atmosphere (Bevis et al., 1992):

$$\text{PWV} = \frac{1}{\rho_w R_v} \int_h^\infty \frac{e}{T} \mathrm{d}h, \tag{2}$$

where ρ_w is the density of water, R_v the specific gas constant of water vapor, and T temperature. The MERIS PWV accuracy has been estimated