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Assessment of soil moisture effects on L-band radar interferometry

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ABSTRACT

Differential SAR interferometry, a popular technique for measuring displacements of the Earth's surface, is potentially influenced by changes in soil moisture. Different mechanisms for this impact have been proposed, but its magnitude, sign and even presence remain poorly understood. In this study the dependence of the phase, the coherence magnitude as well as the phase triplets on soil moisture was inferred empirically with regression techniques: this was done for two airborne data sets at L-band. The phase dependence was significant (at a significance level of 0.05) for more than 70% of the fields at HH polarization, its sign corresponding to an increase in optical path upon wetting, and the magnitude of the associated deformation commonly exceeding 2 cm for a change in soil moisture of 20%. This trend was similar in both campaigns, whereas the prevalence of soil moisture-related decorrelation differs. These results are only consistent with a dielectric origin of the soil moisture effects, and not with soil swelling or the penetration depth hypothesis. Changes in vegetation impact the phase depending on the crop and polarization, with the vegetation influence at VV being more pronounced for the agricultural crops present in the study area.

1. Introduction

Radar interferometry is an established technique for the observation of a broad range of phenomena. These include volcanology (Massonnet, Briole, & Arnaud, 1995), tectonics (Massonnet et al., 1993), permafrost studies (Liu, Zhang, & Wahr, 2010), or the analysis of groundwater-related subsidence (Galloway & Hoffmann, 2007). It works by coherently combining two radar images. When these images are acquired at different times, the technique is sensitive to displacements on the scale of the radar wavelength, i.e. typically 1–10 cm (Gabriel, Goldstein, & Zebker, 1989; Rosen et al., 2000). These two images can also be taken from different positions, in which case height information can be derived from the data (Bamler & Hartl, 1998).

When there is a time gap between the two acquisitions, not only can there be deformations, but also the vegetation and soil moisture can change. If this is the case, such soil moisture m_v changes can lead to systematic errors in the estimated deformations. However, the prevalence and magnitude of these influences are not well understood. A possible influence of variations in soil moisture on the interferometric signal was initially postulated by Gabriel et al. (1989) due to an observed correspondence of the phase ϕ and thus the estimated deformations with hydrological units such as agricultural fields. However, dedicated observational studies have been scarce and limited to a handful of laboratory experiments (Morrison, Bennett, Nolan, & Menon, 2011; Nesti et al., 1998; Rudant et al., 1996; Yin, Hong, Li, & Lin, 2014), as well as a few air- or satellite-borne campaigns (Barrett, Whelan, & Dwyer, 2012; Barrett, Whelan, & Dwyer, 2013; Hajnsek & Prats, 2008; Hensley et al., 2011; Nolan, 2003a). Simultaneously, different mechanisms and models that could describe some of these effects have been proposed, alongside electromagnetic simulations based on Maxwell's equations (Rabus, Wehn, & Nolan, 2010). These explanations attribute the change in ϕ to deformations (Gabriel et al., 1989), changes in the optical path due to soil moisture variations Δm_v (De Zan, Parizzi, Prats-Iraola, & Lopez-Dekker, 2014; Rudant et al., 1996), or differences in the penetration depth of electromagnetic waves (Nolan, 2003b).

Despite these analyses, there is no consensus on the magnitude, sign and even presence of these effects (Morrison et al., 2011; Rabus et al., 2010; Rudant et al., 1996). This is partly due to the lack of suitable data. The speckle patterns tend to decorrelate over time, which implies that the phase cannot be estimated reliably (Barrett et al., 2013; Zebker & Villasenor, 1992). The lack of temporal stability of many areas (especially those covered by vegetation) has led to the development of algorithms that estimate deformations using only stable, point-like scatterers (Ferretti et al., 2011). When the data over the less stable areas are to be analysed with respect to the influence of soil moisture on the phase, a small time gap and preferably bare soil are required. In addition, the radar signals are also influenced by other parameters such as the elevation (for non-zero spatial baselines), deformations,

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and vegetation properties. Furthermore, there are sizeable differences between the different studies with regards to the wavelength, incidence angle, soil type, vegetation cover, etc., and these render comparisons and model assessments difficult (Barrett et al., 2013). The proposed explanations have not yet been assessed with extended data sets or compared with each other.

In view of these open questions, we want to study these soil moisture effects in two L-band airborne campaigns. The low frequency, short revisit times, small spatial baselines, and (in one campaign) absence of vegetation cover are expected to reduce the impact of these additional influences such as the topography and vegetation-related processes. The soil moisture effects, by contrast, are expected to be more dominant and thus detectable. In particular, this allows us to address the question of the sign, magnitude and statistical significance of these effects. We do so by using regression techniques whereby we describe the interferometric observables as a function of the change in soil moisture Δm_v. Furthermore, we want to assess the plausibility of the different conjectured mechanisms that could describe these effects. This assessment is made by comparing their predictions with the empirically found impact of soil moisture on the interferometric data. As the applicability and relevance of these explanations are not well understood, we focus on the differences between these explanations rather than particular models and parameterizations. This analysis is conducted for different polarizations, as the sensitivity to soil moisture is not necessarily identical. In most previous studies (both observational and models), the polarimetric aspect was not addressed explicitly, often due to lack of suitable data or because the proposed physical explanations did not involve any polarimetric differences (De Zan et al., 2014; Nolan, 2003a).

The interferometric observables along with the notation and sign conventions of this paper are introduced in Section 2. Subsequently, the study sites and data sets are outlined, followed by an overview of the SAR processing and the statistical methods. The results of these analyses are presented in Section 6; in Section 7 they are scrutinized and compared to the predictions of the different hypotheses.

2. Radar interferometry

In a polarimetric framework (Cloude, 2009), from which the standard single channel scenario arises as a special case, each single look complex (SLC) pixel is described by a scattering vector $\mathbf{q}$; in the lexicographic basis (reciprocal backscatter situation), $\mathbf{q} = \left[S_{HH}, \sqrt{2}S_{HV}, S_{VV}\right]$. From two SLC images $\mathbf{q}_1$ and $\mathbf{q}_2$ – they usually differ in their acquisition time and/or position – one derives the scalar quantity called complex coherence (Cloude & Papathanassiou, 1998)

$$\gamma_{12}(\omega) = \frac{\omega^\dagger \left\langle \mathbf{q}_1 \mathbf{q}_2^\dagger \right\rangle \omega}{\sqrt{\omega^\dagger \left\langle \mathbf{q}_1 \mathbf{q}_1^\dagger \right\rangle \omega \, \omega^\dagger \left\langle \mathbf{q}_2 \mathbf{q}_2^\dagger \right\rangle \omega}} \tag{1}$$

where ω is a polarimetric measurement functional (e.g. $[1, 0, 0]^T$ for HH). The $\langle \cdot \rangle$ denotes an ensemble average, which can be estimated by spatial multilooking (Bamler & Hartl, 1998; Gabriel et al., 1989). This averaging applies if the target is treated as a distributed one, i.e. as realization of a random process. The coherence can be factored as $\gamma = |\gamma| exp(i\phi)$. From this factorization, the three observables (phase ϕ, coherence magnitude $|\gamma|$, and phase triplets Ξ) used in this study can be derived.

The phase ϕ (the $exp(i\omega t)$ convention is employed throughout) is sensitive to the geometry and displacements. After flat earth phase removal, spectral filtering, and neglecting noise and propagation effects in e.g. the atmosphere, ϕ of a point target can be approximated as $\phi = \kappa_z z + 2k_0 d$, where the first part determines the impact of the elevation above a reference surface z, and the second one to displacements d along the RADAR look direction. The first coefficient of proportionality is given by $\kappa_z \equiv \left(\frac{\partial \phi}{\partial z}\right)_R \propto k_0 B_\perp R^{-1}$, where $B_\perp$ is the antenna offset perpendicular to the look direction, R the distance to the target, and k_0 the wavenumber in free space. The sensitivity to displacements is given by twice the wavenumber in free space.

The coherence magnitude $|\gamma|$ can be interpreted as a measure of the correlation of the speckle patterns in $\mathbf{q}_1$ and $\mathbf{q}_2$ (Rosen et al., 2000). A value less than one can e.g. be caused by volume scattering for $B_\perp \neq 0$, or by changes in the arrangement and physical properties of the target for non-simultaneous acquisitions, as well as noise (Tsang, Kong, & Ding, 2000).

The phase triplets (De Zan et al., 2014; Ferretti et al., 2011) are a combination of the phases of the three interferograms formed from three SLC images $\Xi_{123} = \phi_{12} + \phi_{23} - \phi_{13}$: they are only different from zero if $|\gamma_{ij}| \neq 1$. In astronomy they are usually referred to as closure phases (Monnier, 2007) and have proven useful due to their insensitivity to a phase offset (e.g. due to the atmosphere) in any of the acquisitions.

3. Hypotheses

The four hypotheses about the origins of the soil moisture effects that have been framed in the literature will each be briefly presented. The focus will be less on the implementation of these mechanisms in particular parameterized models, but rather on the physical basis and the predictions that can be formulated based on them. The sign of the dependence of the interferometric observables on soil moisture changes Δm_v for each of the mechanisms is summarized in Table 1. These explanations, although distinct, are not necessarily mutually exclusive.

3.1. Null hypothesis (Null)

The null hypothesis states that there is no relationship between the moisture content and the interferometric observables, including the phase ϕ; this is schematically depicted in Fig. 1a. This hypothesis is implicitly assumed in virtually all interferometric studies (Ferretti et al., 2011), where soil moisture effects are either not considered, minimized by excluding soil, or deemed negligible.

3.2. Deformation (Defo)

ϕ variations whose patterns match those of hydrological units such as field boundaries have previously been interpreted as deformations (Gabriel et al., 1989; Nolan, 2003a). Certain types of soils (e.g. montmorrillonite clay) are known to swell upon wetting (Mitchell, 1991; Norrish, 1954), and such deformations have indeed been studied (and compared with in-situ measurements) with differential interferometry (te Brake, Hanssen, van der Ploeg, & de Rooij, 2013). The influence of an expanding soil on the phase of the coherence is illustrated in Fig. 1b. The impact on the magnitude of the coherence depends intricately on the detailed mechanism: a piston-like shift would in general not lead to decorrelation, whereas non-uniform deformations easily could. The generality of these effects is, however, doubtful, as these swelling and shrinking behaviours are restricted to certain types of soil (Mitchell, 1991). Furthermore, the sensitivity of ϕ to these effects diminishes with decreasing radar frequency. For example, at L-band

Table 1
Model predictions for the sign of the sensitivity of an observable on m_v: + positive, − negative, 0 no influence, and ? not explicable. The volume hypothesis is used for the Diel mechanism.

	Null	Defo	Pene	Diel
$\frac{\phi}{\Delta m_v}$	0	−	−	+
$\frac{\lvert\gamma\rvert}{\lvert\Delta m_v\rvert}$	0	0?	?	−
$\Xi(m_{v0:2})$	0	0	?	$\neq 0$