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Vegetation and soil moisture inversion from SAR closure phases: First experiments and results

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ABSTRACT

The inversion of soil moisture from Synthetic Aperture Radar (SAR) closure phases is intrinsically plagued by ambiguities that affect the moisture order. This work shows a characterization of the ambiguities and a way to solve for them with the help of interferometric coherence. This allows to properly constrain the inversion and to retrieve the moisture signal. A data set of ALOS-2/PALSAR-2 L-band images is used as an example of successful inversion at the scene level, with sub-kilometer resolution. The results are validated with soil moisture products based on ASCAT and show a high degree of correlation. The raw moisture derived by the algorithm could be immediately used to correct SAR interferometric phases; however, for applications that need absolute moisture levels, a calibration step is likely necessary. Unexpectedly, a good performance was observed over forested areas, which suggests a sensitivity of closure phases to tree moisture; at the same time, over pastures and agricultural fields the closure phase signal was found relatively weak. Additional research is needed to evaluate the applicability of the same measurements principle to shorter wavelengths and exploitation of potential synergies with backscatter and polarimetric information.

1. Introduction

Soil moisture is a key variable in modeling the water cycle, energy and carbon fluxes and therefore relevant for many disciplines including hydrology, meteorology, and climatology (Ochsner et al., 2013; Wagner et al., 2012). Whereas moisture probes give precise point measurements, the high spatial variability of the moisture signal limits the usefulness of single probes or even sensor networks for characterizing a given area (Peng et al., 2017; Crow et al., 2012). Remote sensing techniques are useful in sensing the moisture field over large areas, with their limitations: coarse spatial resolution (e.g. > 10 km), sparse temporal sampling (e.g. a few days), sensitivity only to the first centimeters of soil (i.e. no root zone moisture) (Mohanty et al., 2017). Currently, the most successful wide-area retrieval concepts belong to the field of microwave remote sensing, active and passive (Peng and Loew, 2017; Das and Paul, 2015; Kornelsen and Coulibaly, 2013).

Both active and passive techniques often require compensation of unwanted influences related to the vegetation cycle and surface roughness (Brocca et al., 2011; Wagner et al., 1999). Products derived from synthetic aperture radar backscatter cannot fully exploit the high resolution of SAR images: extensive spatial averaging is typically needed in order to counter the instability of surface roughness (Thoma et al., 2008).

This paper presents a novel moisture measurement concept based on SAR closure phases. This concept has the potential to offer moisture products with fine spatial resolution (e.g. 500 m or better), which is one unmet need identified in Peng and Loew (2017), the other being high temporal resolution. Considering the three interferograms $I_{l,m}$,$I_{m,n}$,$I_{n,l}$ generated with three images l,m,n and averaged spatially, the closure phase is simply the phase of the cyclic product of the interferograms:

$$\Phi_{l,m,n} = \arg(I_{l,m} I_{m,n} I_{n,l}). \tag{1}$$

Closure phases are interferometric observables whose potential in SAR has not been entirely explored yet (De Zan et al., 2015). It has been known for a few years that interferometric and closure phases carry information on soil moisture (Morrison et al., 2011; De Zan et al., 2014; Zwieback et al., 2015), however the retrieval of moisture levels from closure phases has not shown any progress (Zwieback et al., 2017). On the other hand, there would be obvious advantages in using closure phases instead of interferometric phases for moisture inversion: closure phases are immune to all simple propagative effects like target displacement, delays in atmospheric propagation, topographic effects, i.e. the usual contributors to the interferometric phase.

The approach proposed in this contribution could complement existing methods (radiometric or scatterometric) for soil moisture retrieval. However, with this work we do not claim to introduce an

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operational, efficient, and validated technique for soil moisture retrieval. We report first experiments with L-band data, which we selected considering the coherence advantage and the fact that closure phases are larger in L-band compared to higher frequencies. Our first results are promising; however, the only L-band spaceborne SAR sensor today is PALSAR-2 onboard ALOS-2, and for any operational soil moisture applications its spatial and temporal sampling is likely insufficient. However, more satellite L-band SAR's are being launched, and we should prepare today for future opportunities.

The physical modeling and understanding is also not complete: in the data set we examined, for example, the scale of the closure phase signal is rather small over the (relatively small) areas of pasture and rice fields. Surprisingly, we were able to perform consistent inversions over large forested areas, where the closure signal is very strong. All this shows the need for further understanding before an operational algorithm can be designed and the potential of closure phases can be fully harnessed.

Apart from the potential for soil moisture retrieval, the successful inversion of a moisture model will allow correcting the interferometric phases, both for single interferograms and for multi-image interferometric processing. These corrections are especially relevant for the lower frequency SAR's, since the effect of moisture variations roughly scales with the wavelength (Zwieback et al., 2017).

In this publication we specifically address the presence of an ambiguity in the moisture model for closure phases: the same set of observed closure phases can be explained almost equally well by different sets of moisture levels. The ambiguity arises because the closure phases can only partially constrain the ordering of the acquisitions according to moisture levels. This is illustrated in Section 2. Once this ambiguity is tackled explicitly and correctly solved, the way is open for reliable moisture inversion (Section 3). Section 4 presents inversion results and a comparison with several available products. Successful inversion of moisture levels allows compensating moisture-induced contributions to interferometric phases (Section 5) thus improving traditional repeat-pass InSAR products like deformation monitoring of the Earth's crust.

2. Ambiguities in closure phases models

2.1. Interferometric models for moisture

We want to model the interferograms as a function of the moisture values in the two interfering acquisitions, indexed by l and m. Our starting point is Eq. (11) in De Zan et al. (2014), which derives the expected value of the interferogram as a function of the two wavenumbers (k_l and k_m) and the scattering profile in the soil $f(z)$. We report it here for convenience:

$$I_{l,m} = \int_0^\infty f(z)\exp(-j2k_l z)(\exp(-j2k_m z))^* \quad dz. \tag{2}$$

The star indicates the complex conjugation operation.

The wavenumbers k_n depend on the dielectric constant, which is a function of the moisture levels (θ_n, in the following) and soil type (Hallikainen et al., 1985; Bircher et al., 2016). A good approximation is to take the formula for normal incidence (Morrison and Bennett, 2015; De Zan et al., 2014)

$$k = \sqrt{\omega^2 \mu \epsilon}, \tag{3}$$

where ω is the angular frequency, μ and $\epsilon = \epsilon(\theta)$ are respectively the dielectric permeability and permittivity.

Assuming an exponential scattering profile $f(z) = \exp(-2\alpha)$,$\alpha > 0$, the expected value of the interferogram is:

$$I_{l,m} = \frac{1/2}{j(k_l - k_m^*) + \alpha}. \tag{4}$$

If $\alpha = 0$, the model is trivially the one of Eq. (12) in De Zan et al. (2014),

$$I_{l,m} = \frac{1/2}{j(k_l - k_m^*)}, \tag{5}$$

and the scattering intensity at different depths is governed solely by the dielectric constant itself, or more precisely, by the imaginary part of the wavenumbers. Note that the interferogram in Eq. (5) is not normalized: normalization is straightforward and is necessary if one needs to compute interferometric coherences. The coherence decays approximately with moisture difference, as one can see in De Zan et al. (2014). The corresponding closure phase $\Phi_{l,m,n}$ is simply the phase of the cyclic triple product

$$\Phi_{l,m,n} = \arg\left(\frac{1/2}{j(k_l - k_m^*)}\frac{1/2}{j(k_m - k_n^*)}\frac{1/2}{j(k_n - k_l^*)}\right). \tag{6}$$

It is useful to consider another specialization of Eq. (4), by discarding the imaginary part of the wavenumbers and setting necessarily $\alpha \neq 0$:

$$I_{l,m} = \frac{1/2}{j(k_l - k_m) + \alpha}. \tag{7}$$

This case describes also the SAR tomographic setting (see Dall, 2007, Eq. (9)), in which it is common to assume that the variations of the viewing angle do not affect the scattering profile. This model is useful to derive an approximation to the closure phase (De Zan et al., 2015)

$$\begin{aligned}\Phi_{l,m,n} &= \arg(I_{l,m}I_{m,n}I_{n,l}) \\ &\approx -\alpha^{-3}(k_l - k_m)(k_m - k_n)(k_n - k_l).\end{aligned} \tag{8}$$

By further approximating $k_l - k_m \propto \theta_l - \theta_m$, i.e. the soil moisture difference, one can obtain a direct link between closure phases and moisture variations:

$$\Phi_{l,m,n} \approx -\alpha^{-3}(\theta_l - \theta_m)(\theta_m - \theta_n)(\theta_n - \theta_l) \tag{9}$$

where the proportionality parameter α will have to be properly adjusted.

2.2. Ambiguities in sorting the acquisitions according to the moisture level

Ambiguities in closure phase models block the way to the successful inversion of the parameters of interest, in this particular case the moisture level, as Zwieback et al. (2017) has clearly identified. In this section we will try to shed light on the character of the ambiguities. We are going to base our discussion on the signs of the closure phases, as we observed that ambiguities arise in the inversion when two or more moisture histories yield a set of closure phases which have the same signs. We start by considering the simplified model for closure phases given by Eq. (9). This model is not totally equivalent to the one of Eq. (6), however the signs of the closure phases are identical, as one can easily verify. The two models are therefore considered equivalent for our purpose, and the conclusions will be valid for both.

It is immediate to verify that cyclical permutations of the moisture ordering of three acquisitions will not change the sign of $\Phi_{l,m,n}$ (Zwieback et al., 2017). The same extends to any number of acquisitions and any closure phase that can be generated with those acquisitions. Thus it follows that the signs of the closure phases can be exploited to sort the acquisitions according to the moisture level, up to a special kind of ambiguity: The signs of the closure phases are invariant to cyclic permutations of the moisture order. Fig. 1 illustrates an example of the ambiguous ordering of six acquisitions. This ambiguity means that there are many indistinguishable sorting possibilities: for instance, both orders (5,2,1,4,3,6) and (1,4,3,6,5,2) of increasing moisture are acceptable by looking just at the signs of the corresponding closure phases. Of course the different permutations correspond to totally different moisture trajectories in time as shown in Fig. 2.

The central problem is therefore recovering the right order among those allowed by the closure phase signs. This is equivalent to finding