A PROPOSAL FOR A SAR INTERFEROMETRIC MODEL OF SOIL MOISTURE

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ABSTRACT

Since long it is known that SAR interferometric observables are influenced by soil moisture variations, however there is a lack of scattering models that link interferometric observables and variations of the dielectric properties. In this work we propose a model based on plane waves and Born approximation, deriving first the vertical wavenumbers in the medium as a function of geometrical and dielectric properties and successively the interferometric coherences. It is observed that soil moisture behaves on the phase in a similar way as tomography does, breaking the phase consistency in triplets of interferograms. This property, along with coherence magnitudes, is exploited in an attempt at moisture inversion on real data.

***Index Terms*—** SAR Interferometry, soil moisture, coherence

1. INTRODUCTION

Several researches have shown that there is a clear influence of soil moisture on SAR interferometric phases and coherences. Early explanations [1] invoked the effect of clay expansion. Hensley has clearly pointed out in [2] that the interferometric effect is not a deformation effect, since in his L-band experiment he observed differences between the HH and the VV interferograms, and the deformations would anyway be too large to be realistic. Similar conclusions were reached in [3]. Other explanations [4] involve the change in penetration depth, however this theory does not have a sound physical background in interferometric terms as it is discussed later.

Rabus has shown [5] thanks to FDTD modeling that small scattering bodies in the soil or moisture gradients can produce phase and coherence variations. However there is still a need for an analytical description, which we attempt here. An analytical description is useful because it helps the physical intuition even though it is usually less flexible compared to numerical modeling.

We try to explain the observations with electrical effects, in particular by modeling the soil as a lossy dielectric in which a plane wave propagates. The scattering is modeled with the Born approximation: the scatterers are small particles that do not disturb the incident field. Most of the incident radiation is dissipated in the material (or it is scattered forward).

The main idea is that a change in soil moisture from one acquisition to another will be reflected in changes in the dielectric properties. These in turn will affect the vertical wavenumber within the soil, hence the phase and coherence effects. The horizontal wavenumber will stay unaffected, because it has to satisfy the boundary conditions.

2. OBLIQUE INCIDENCE ON A LOSSY DIELECTRIC

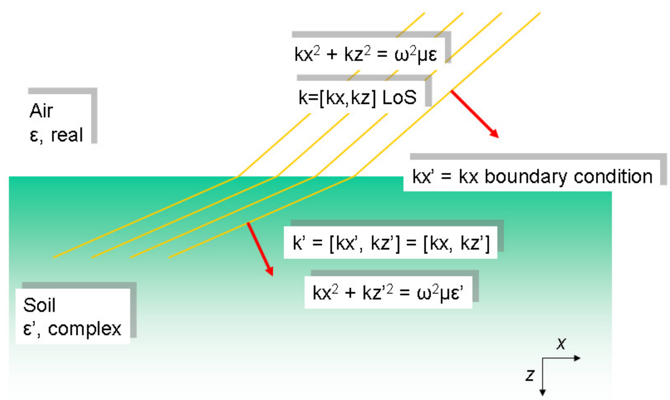

Fig. 1. The geometry of plane wave incidence and refraction on a flat lossy medium.

The 2-D geometry of the problem is sketched in Fig. 1. The xz plane is the incidence plane (the azimuth direction is orthogonal to this plane). For the TE case (HH polarization) here are the expressions for the incident and refracted (with primes) electric fields:

$$E(\mathbf{r}) = \hat{\mathbf{y}} E_0 e^{-jk_z z} e^{-jk_x x} \quad (1)$$

$$E'(\mathbf{r}) = \hat{\mathbf{y}} \tau_{TE} E_0 e^{-jk'_z z} e^{-jk'_x x} \quad (2)$$

The symbol $\hat{\mathbf{y}}$ indicates the versor in the y direction. The complex amplitude of the incident field is E_0. The symbols k_x and k_z represent the wavenumbers in the two directions (with primes in the second medium). Since the horizontal boundary conditions have to be satisfied: $k'_x = k_x$. The transmission coefficient is $\tau_{TE} = 2k_z/(k_z + k'_z)$.

In both media the wave equations hold in the Fourier domain: $k_x^2 + k_z^2 = \omega^2 \epsilon \mu$ and $k_x'^2 + k_z'^2 = \omega^2 \epsilon' \mu$. The ϵ and ϵ' are the two dielectric constants at the radar operating frequency. For the first medium (air) we can assume $\epsilon = \epsilon_0$.

From the incident angle it will be possible to derive $k_x = (2\pi/\lambda) \sin \theta_{inc}$. Having fixed the incidence geometry, k_z' is a only function of ϵ':

$$k_z'(\epsilon') = \sqrt{\omega^2 \epsilon' \mu - k_x^2}. \tag{3}$$

Since the medium is lossy, ϵ' will be complex, and k_z' too. The above equation has two solutions because of the ambiguity of the square root, and we chose the "physical" one, i.e. the one with a negative imaginary part. This corresponds to a wave that attenuates going downward, so that $|E'(x, y, z)| \to 0$ when $z \to \infty$. The constant amplitude and constant phase planes will not be parallel.

3. INTERFEROGRAMS AND SOIL MOISTURE

For each moisture value there will be a different ϵ' and consequently a different k_z'. We model the dependence of the (complex) dielectric constant on moisture according to [6].

The expected value of the interferogram between two images with different k_z' in the second medium is computed as an integral in the vertical direction (the horizontal direction is irrelevant, being $k_x' = k_x$, assuming of course zero baseline):

$$I(\epsilon_1', \epsilon_2') = \int_0^\infty e^{-jk_{z1}' z} (e^{-jk_{z2}' z})^* \, dz \tag{4}$$

$$= \frac{j}{{k_{z2}'}^* - k_{z1}'} \tag{5}$$

This is valid assuming randomly positioned scatterers with equal radar cross-section. Each one of them will "interfere" only with itself, with the complex weighting given by the local phasor. One should really use the two-way wavenumbers, but the effect is not visible in the coherence, so we will ignore it:

$$\gamma = \frac{I(\epsilon_1', \epsilon_2')}{\sqrt{I(\epsilon_1', \epsilon_1') I(\epsilon_2', \epsilon_2')}} \tag{6}$$

$$= \frac{2j \sqrt{\text{Im}(k_{z2}') \text{Im}(k_{z1}')}}{{k_{z2}'}^* - k_{z1}'} \tag{7}$$

This expression gives both interferometric phases and coherences (see Fig. 2-3 for some examples). For the phases there is an additional contribution due to the complex transmission coefficients at the boundary. It is a small contribution and it is the only aspect that distinguishes the HH and VV interferograms for this model. It does not affect the coherence moduli.

From the coherence expression (6) it follows that a pure change in the penetration depth does not change the interferometric phase. This is because a change in the penetration depth is linked to a change in the imaginary part of k_z, while

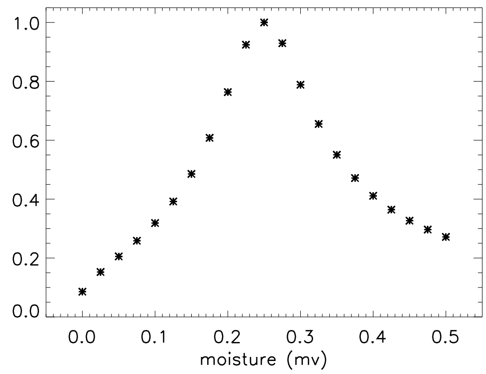

Fig. 2. The modulus of the coherence (6) as a function of soil moisture for a soil 51% sand and 13% clay acquired in L-band from and incidence of 45 deg (ϵ modeled following [6]). The reference is the image with coherence 1 (moisture=25%).

a change in the vertical wavenumber is linked to a change in the real part of k_z. If the real part of k_z stays the same, so will the phase of the coherence. One can think that the change in penetration depth between two acquisitions has the effect of adding new scatterers to the drier of the two. However the new deeper scatterers in the drier image are not correlated with the ones visible in the wetter image, so that finally they do not contribute to the interferometric phase but only to the coherence loss. The phase effect, according to this model, is essentially due to the common scatterers which are taken with different phases due to propagation effects. Penetration plays a role only in weighting the scatterers (hence the phases) at different depths.

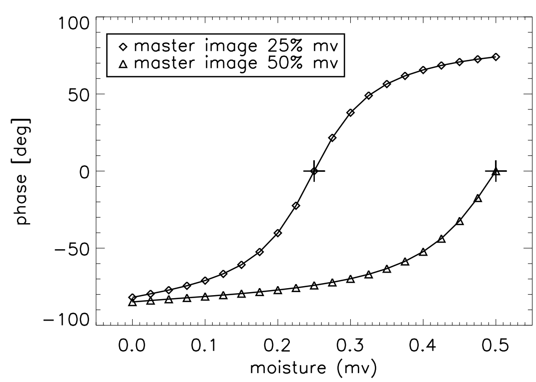

Fig. 3. The interferometric phases as a function of soil moisture for a setting as in Fig. 2. Depending on the choice of the master image (marked with a cross), the total phase excursion is about 150 deg or 80 deg.

The interferometric phases have a slightly surprising behavior which is clear looking at Fig. 3: depending on the images taken as a reference, the total phase excursion looks larger or smaller. This is an indication that we are not seeing a single object, but more than one, similarly to what happens in tomography. Another way to see it, is to say that, even after compensating for a free-space propagation term, the covariance matrix of the acquisitions is not real.

4. PHASE TRIPLETS AND INVERSION

In order to use entirely the phase information it is necessary to start with a good calibrated phase. Here we attempt to circumvent this problem by using coherence magnitudes and phase triplets. Phase triplets are phases of the three possible interferograms that can be made with three images. In the easiest case, one would expect that these phases match in such a way that having two of them allows to systematically predict the third, apart from decorrelation effects. For example, if $\varphi_{m,s}$ is the multilooked phase between master m and slave s, with three images one would expect the triple difference

$$\epsilon_{1,2,3} = \varphi_{1,2} + \varphi_{2,3} - \varphi_{1,3} \tag{8}$$

to be small (modulo 2π).

However our soil-moisture model predicts systematic "mismatches" and we invert the problem by finding the soil moisture values that better predict those mismatches in the phase triplets. Similar results were obtained exploiting exclusively the phase triplets and using in addition the coherence magnitude. Coherence-only inversions suffer from an ambiguity problem, since both increasing and decreasing soil moisture produce a coherence loss.

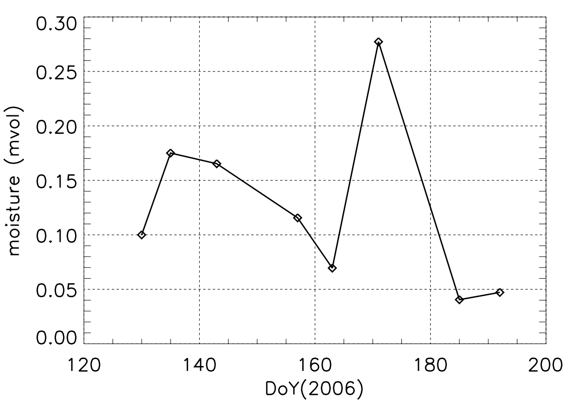

Fig. 4. Moisture from model inversion on a supposedly bare field (E-SAR AgriSAR campaing). The first value is forced at 0.1. The averaging window is 50×200. The inversion algorithm is based on phase triplets and coherences.

We report some results obtained with the ESA AgriSAR campaign of 2006. The dataset comprises, among others, 12 SAR images acquired by the E-SAR L-band system of DLR

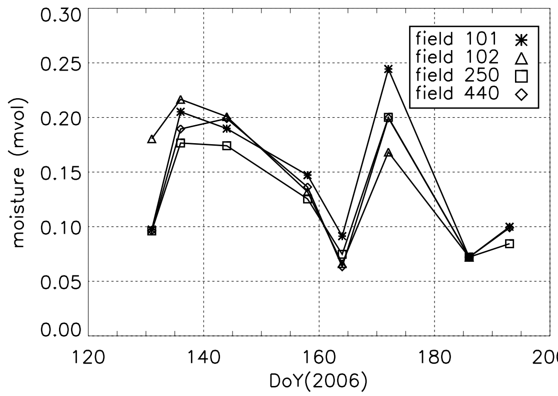

Fig. 5. *In situ* measurements of moisture in the top 5cm of soil in fields nearby field 222, on which the inversion was attempted. (Data provided by the European Space Agency, collected by the University of Kiel)

and ground measurements of moisture. The testsite is near the village of Demmin in northern Germany. For the inversion we picked a corn field for its delayed growth (field 222 in [7]). The first two and the last two images seem not to fit with the model, so they were discarded for the inversion. For the first two it is clear that they are totally uncorrelated with rest, probably due to plowing. In the last two the influence of vegetation might be too large. The results for the remaining 8 images (Fig. 4) are to be compared with ground measurements, reported in Fig. 5 (see also [7, 8]). The match between the inverted moisture and *in situ* data is quite good. Interferometry seems to be particularly sensitive to small moisture variations. The starting level of volumetric soil moisture was arbitrarily set to 10% since it looks likely that this inversion technique is unable to yield absolute moisture levels.

5. CONCLUSIONS AND FUTURE INVESTIGATIONS

According to these preliminary results, a model based on plane waves is able relate moisture variations to interferometric observables. Inversion of moisture variations from interferometric phases could be feasible from a series of frequent observations, even though absolute figures might have to be obtained in a different way. Further investigations are needed to assess the validity of the proposed approach, also examining different frequency bands.

If the *non-conservativeness* of triplets of interferograms is confirmed, the optimal estimators derived for SAR interferometry with stacks (e.g. [9]) will have to be revised for some scenarios, taking into account non-real coherency matrices.

In order to explain differences between polarizations, more complex scattering models can be considered. For example one could add a surface scattering component with polarization-dependent intensity. Differences between polarizations could also be caused by an anisotropic medium, in which the propagation depends on the polarization and direction of the incident field.

6. REFERENCES

[1] M. Nolan, D. R. Fatland, and L. Hinzman, "DInsar measurements of soil moisture," *IEEE Trans. Geosci. Remote Sensing*, vol. 41, pp. 2802–2013, Dec 2003.

[2] S. Hensley, T. Michel, J. Van Zyl, R. Muellerschoen, B. Chapman, S. Oveisgharan, Z. S. Haddad, T. Jackson, and I. Mladenova, "Effect of soil moisture on polarimetric-interferometric repeat pass observations by UAVSAR during 2010 Canadian Soil Moisture campaign," *Geoscience and Remote Sensing Symposium (IGARSS), IEEE International*, pp. 1063 –1066, Jul 2011.

[3] K. Morrison, J.C. Bennett, M. Nolan, and R. Menon, "Laboratory measurement of the dinsar response to spatiotemporal variations in soil moisture," *Geoscience and Remote Sensing, IEEE Transactions on*, vol. 49, no. 10, pp. 3815 –3823, Oct 2011.

[4] M. Nolan and D. R. Fatland, "Penetration depth as a DInSAR observable and proxy for soil moisture," *IEEE Trans. Geosci. Remote Sensing*, vol. 41, pp. 532–537, Mar 2003.

[5] B. Rabus, H. Wehn, and M. Nolan, "The importance of soil moisture and soil structure for InSAR phase and backscatter, as determined by FDTD modeling," *IEEE Trans. Geosci. Remote Sensing*, vol. 48, pp. 2421–2429, May 2010.

[6] M.T. Hallikainen, F.T. Ulaby, M.C. Dobson, M.A. El-Rayes, and Lil-Kun Wu, "Microwave dielectric behavior of wet soil - Part 1: Empirical models and experimental observations," *Geoscience and Remote Sensing, IEEE Transactions on*, vol. GE-23, no. 1, pp. 25 –34, Jan 1985.

[7] DLR (German Aerospace Center), "AGRISAR 2006 Final Report," Tech. Rep., European Space Agency, Jan 2008, [available online at `http://earth.esa.int/`].

[8] I. Hajnsek and P. Prats, "Soil moisture estimation in time with D-InSAR," *Geoscience and Remote Sensing Symposium (IGARSS), IEEE International*, vol. III, pp. 546–549, Jul 2008.

[9] A. Monti Guarnieri and S. Tebaldini, "On the exploitation of target statistics for SAR interferometry applications," *IEEE Trans. Geosci. Remote Sensing*, vol. 46, pp. 3436–3443, Nov 2008.