Penetration Depth as a DInSAR Observable and Proxy for Soil Moisture

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***Abstract*—We use prior theory and experimental results to construct a quantitative relationship between soil moisture and the penetration depth of synthetic aperture radar (SAR) microwaves at L-, C-, and X-bands. This relationship is nonlinear and indicates that a change of 5% volumetric water content (VWC) can cause between 1 and 50 mm of change in C-band penetration depth depending on initial VWC. Because these depths are within the range of differential interferogram SAR (DInSAR) measurement capability, penetration depth may be a viable proxy for measuring soil moisture. DInSAR is unlikely to detect a measurable change in penetration depth above 30% VWC, though certain clay rich soils may continue to cause surface deformation above that level. The possibility of using clay swelling as a proxy for soil moisture was found to be less feasible than penetration depth. Soil moisture may also be a significant, and previously unrecognized, source of noise in the measurement of subtle deformation signals or the creation of digital elevation models using repeat-pass DInSAR.**

***Index Terms*—Agriculture, attenuation, remote sensing, synthetic aperture radar, terrain mapping, water.**

I. Background

THE POSSIBILITY for using differential interferometric synthetic aperture radar (DInSAR) to measure spatial variations in soil moisture was likely first recognized by Gabriel *et al.* [1] in the late 1980s. These researchers used the L-Band Seasat to produce the first published differential interferograms (DIGs), using farmland in California as their study area. Their results (Fig. 1) show spatial variations in phase over an eight-day period that correspond exactly to the boundaries of farm fields. In such flat areas, these variations in phase cannot be accounted for by atmospheric phase delays or topographic noise. Gabriel *et al.* confirmed that the source for these variations in phase was indeed related to surface variations in soil moisture by reviewing irrigation records from 52 of the farms within the scene and finding that in nearly every case a decrease in phase was related to an increase in soil moisture.

Gabriel *et al.* [1] hypothesized that an increase in soil moisture caused the soil surface to rise, due to swelling of clays in the soil. While this soil behavior is fairly well described in the literature [2]–[4], not all clays swell, and Gabriel *et al.* [1] did not validate their hypothesis with clay mineralogy surveys indicating that the soils were expansive. Unfortunately surface elevation measurements were also not conducted, likely due to satellite data being acquired before the DInSAR study began. Several DInSAR studies using European Remote Sensing (ERS) or Radarsat data have also noted phase variations related to farm fields, and have likewise attributed it to clay swelling without further validation [5]–[7], though the soil moisture signal in these studies was treated incidentally to studies of surface subsidence due to earthquakes or well pumping. Therefore, while a soil moisture phase signal has been conclusively demonstrated, the causal mechanism remains an open question.

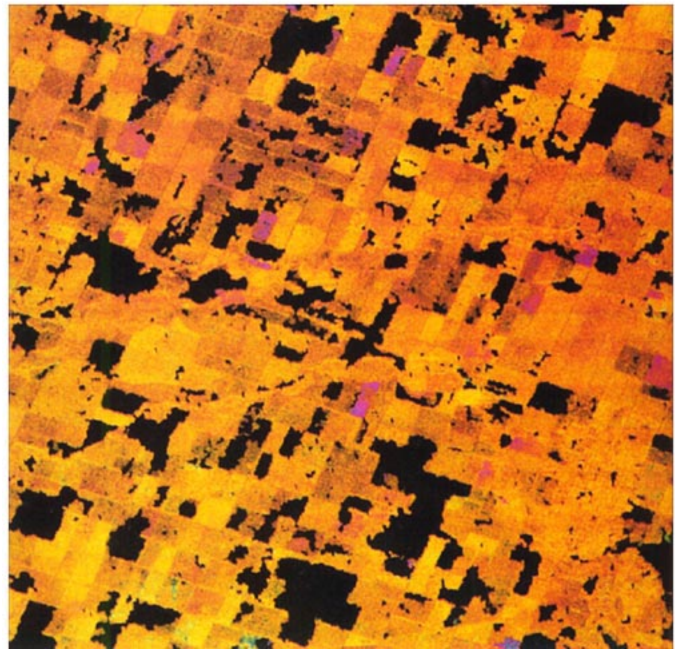

Fig. 1. First published differential interferogram (reproduced with permission from Gabriel *et al.* [1]). Using L-band Seasat data, Gabriel *et al.* created the first published differential interferogram (DIG), covering farm fields in California. Their results and subsequent field validation clearly indicated that a phase signal related to soil moisture exists and is detectable. Colors from blue to red to green indicate decreases to increases in path length (2–3 cm total) respectively; yellow indicates little to no change; and black indicates decorrelation.

It is remarkable that despite the considerable demand for a synthetic aperture radar (SAR) technique to measure soil moisture and the initial outstanding success of DInSAR to provide such measurements, that there has not since been a single published DInSAR study, to our knowledge, dedicated to the detection of spatial variations in soil moisture [8], especially considering that no viable alternative has been demonstrated using the satellites in operation to date [9]. In this paper, we provide the theoretical background to support the case that soil moisture affects penetration depth even in soils with no clay content and with a magnitude large enough to act as either signal or noise, depending on analysis. In two related papers, we demonstrate penetration

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depth as signal using DInSAR examples and field validation [10] and show that the vertical accuracy of digital elevation model (DEM) used to create the synthetic interferogram is the key to successfully making such subtle measurements [11].

II. Relationship Between Soil Moisture and Penetration Depth

While it has been well documented that clay swelling can change surface elevation as a function of soil moisture, in this section we present prior theory and lab measurements that indicate that microwave penetration depth should also vary with soil moisture in a quantifiable way, regardless of clay content. Here we define soil moisture as the volumetric water content (VWC, expressed as fraction or percent), which is more directly applicable to SAR studies than gravimetric water content [12] and discuss changes in phase more conveniently in units of path length, as the two are linearly related via the wavelength.

That the dielectric property of soils (namely the permittivity) controls the penetration depth of microwaves has been well established [13]–[17]. Here we follow [14] and define penetration depth as "the distance in the medium over which the intensity of propagating radiation decreases (owing to attenuation) by the exponential factor e^{-1} (i.e., by about 63%)." However, because of the large contrast between the permittivities of dry soil and water, and because the amount of water in the soil is variable, soil moisture largely controls the permittivity of the soil and thus penetration depth as well. Several studies have developed empirical relationships between soil moisture and permittivity [12], [16], [18], [19]. Here we select the 5-GHz equations from [12, Table 1] as an example

$$\begin{aligned} e' =& 2.46 + (13.07 + 0.14S - 0.44C)w \\ &+ (132.11 + 0.38S + C)w^2 \\ &+ (-103.86 - 1.16S - 0.49C)w^3 \end{aligned} \quad (1)$$

$$\begin{aligned} e'' =& 0.12 + (4.7 + 0.00646S - 0.002356C)w \\ &+ (30.65 - 0.61S + 1.12C)w^2 \\ &+ (-34.29 + 1.36S - 1.15C)w^3 \end{aligned} \quad (2)$$

where e' and e'' are the real and imaginary components of the permittivity; S and C are the sand and clay fraction of soil by weight; and w is volumetric water content in cubic meters per cubic meter. Note that these equations are valid only up to a VWC of 50%.

A convenient expression for penetration depth as a function of permittivity (using the small angle approximation) is [20]

$$\delta_p = \frac{\lambda\sqrt{e'}}{2\pi e''} \quad (3)$$

where δ_p is penetration depth, and λ is wavelength, both in millimeters. This equation assumes uniform properties with depth.

The case of layered media having transmission losses is more complicated [21], [22]. Here we reproduce (13) from [22] (modified as suggested by [21]) for the nonuniform case

$$P_n = P_o \prod_{1,n} T_{i-1,i} e^{-2k_i''(z_i - z_{i-1})} \quad (4)$$

where P_o and P_n are the power of the incident wave initially and at layer n, respectively; T is the transmission coefficient between layer n and $n-1$; and k'' is the imaginary part of the attenuation coefficient in layer n. Equations for T and k are complicated functions of geometry based on Snell's law and the consideration that the complex transmission medium is equivalent to a "real" medium having a "real equivalent" refraction index, with the full derivations given in [22]. These equations are similar to those used in seismic reflection analyses. Penetration depth using (4) is determined by finding the layer n in which P_n/P_o equals e^{-1}.

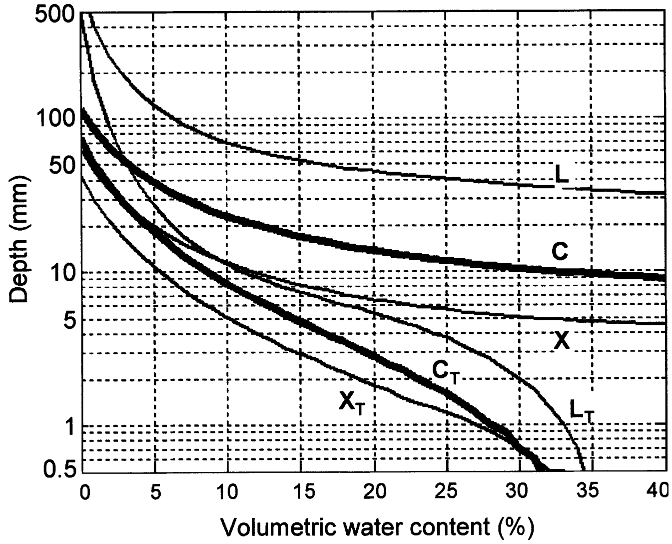

Fig. 2. Penetration depth of SAR microwaves as a function of soil moisture for L-, C-, and X-bands. The subscript T indicates penetration depths when transmission losses at 0.1-mm increments have been assumed; the other curves indicate attenuation losses only. The soil moisture is assumed uniform with depth.

We combined these equations in a computer program to develop a relationship between volumetric water content and penetration depth, for both the uniform and nonuniform moisture profile cases. The soil permittivity portion of the code was validated against figures in [12] and [19], and the two penetration depth portions (uniform and nonuniform soil properties) were validated both against figures in the original paper [22] and against each other for the uniform case. Transmission losses can be specified at either the interfaces where soil moisture changes at depth or at some fixed thickness increment. The latter, therefore, might represent a more conservative approach, assuming that pore space itself is causing transmission loss, but this remains to be verified experimentally. This program (coded in Matlab) is available from the authors upon request.

We used this program to demonstrate that the relationship between soil moisture and penetration depth is nonlinear and varies considerably with SAR wavelength (Fig. 2). As the amount of water in the soil increases from near zero, the imaginary part of the dielectric constant increases dramatically [13], decreasing the penetration depth rapidly. As the soil moisture exceeds about 10%, however, further increases have a reduced affect on penetration depth. Here we chose three common SAR frequencies for illustration purposes (L-, C-, and X-bands at 1.4, 5, and 10 GHz, respectively), quantitatively showing, for example, that L-band has significantly deeper penetration all else being equal. When transmission losses are present, as would typically be the case, penetration depth is decreased further. Actual transmission losses cannot be calculated without

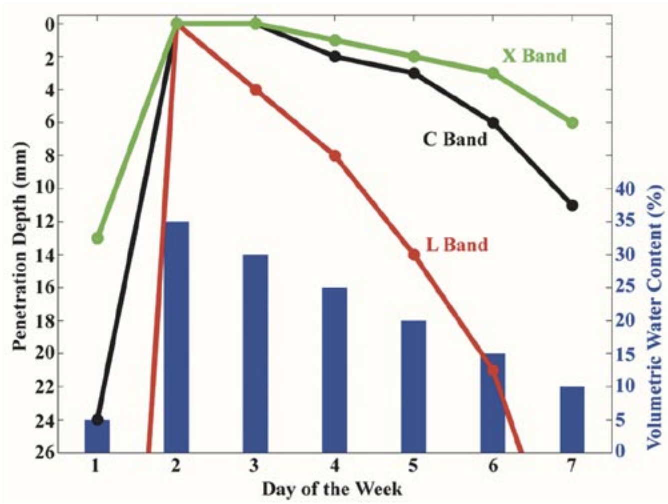

Fig. 3. Change in penetration with time using modeled rain and evaporation. Lines indicate penetration depth for three frequencies and bars indicate soil moisture. A rainfall on Day 2 abruptly decreases penetration depth to near zero, while the subsequent drying yields a gradual increase. Soil properties and moisture are assumed uniform with depth.

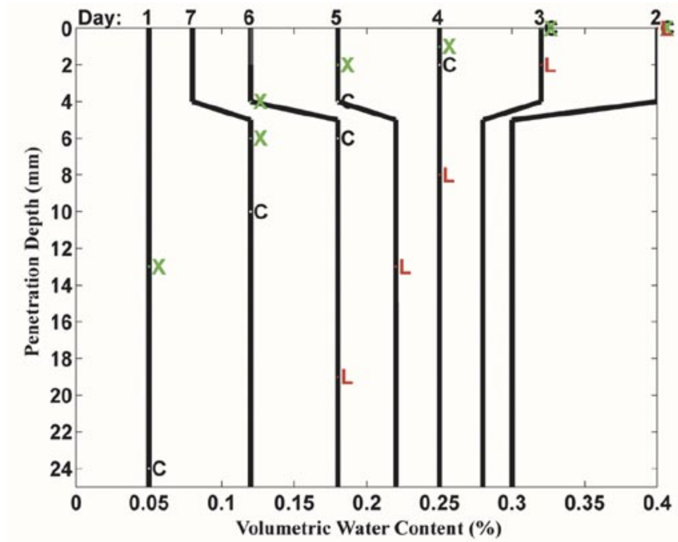

Fig. 4. Penetration depth as function of time assuming nonuniform soil moisture levels. Black lines correspond to the soil moisture profile on the day indicated at top of graph. Labels on these moisture profiles (e.g., "C") indicate the modeled penetration depth for either L-, C-, or X-bands on that day; "L" is not shown when it exceeds 25 mm and on Day 2 all three bands are at zero penetration depth. Soil moisture here varies with depth but has the same average values (over the upper 2 cm) as in Fig. 3 with a rainfall on Day 2. Penetration depth is more sensitive to the upper soil moisture values than the lower.

knowledge of the soil structure and scatterer positions; we used scatterers on 0.1-mm layers and note that the layer thickness in the range of 0.01–1 mm has relatively minor influence on the curves in Fig. 2. We chose 0.1 mm, as it is the maximum possible DInSAR instrument resolution for ERS-2 and Radarsat-1 [11], and chose the crossing point of 0.5 mm somewhat arbitrarily as the shallowest penetration depth of interest. This figure is based on a soil with 51% sand and 13% clay (following [12]); the affect of soil type on permittivity is relatively minor for the purposes of our paper and is not considered further here. Thus, actual penetration depths will likely lie between the two curves shown for each frequency in Fig. 2 for spatially uniform soils with vertically uniform soil moisture, and soil moistures over about 30% VWC may not produce a measurable change in penetration depth when transmission losses are encountered (though clay swelling effects may still produce a measurable surface deformation signal). Note also that when transmission losses are encountered, the differences between frequencies become reduced.

To demonstrate how penetration depth would vary in practice if measured daily, we calculated penetration depth for a hypothetical one-week time-series of soil moisture variation with a rain event on Day 2. The results are shown in Fig. 3. The rainfall causes penetration depth to drop abruptly to zero for all wavelengths on the day of the event. Unlike the rainfall event, the subsequent drying signal decreases gradually by only several millimeters per day. Similar to soil drying due to evaporation, a redistribution of soil moisture due to a gradual flow of water downhill through the soil pore space would also likely have a gradual effect on penetration.

The previous analysis described the case of soil moisture that is constant with depth, but this case is rarely observed in the field. Soil moisture typically varies with depth, and this variation has a noticeable effect on penetration depth. Fig. 4 repeats the simulation of Fig. 3, this time using a nonuniform soil moisture distribution that has the same average values (over upper 2 cm) as in Fig. 3. In this case, we have a used a two-layer model for presentation clarity, but any number of layers could be prescribed. As might be expected, penetration depth is most sensitive to the soil moisture of the uppermost layers. If the upper layer is drier than the average, penetration depth will increase, and if wetter it will decrease, compared to the uniform case. Because most soil moisture profiles vary with depth, this sensitivity to near-surface conditions needs to be taken into account, probably through modeling, should penetration depth changes be used for soil moisture measurement; note that this constraint is also imposed on backscatter studies.

III. Penetration Depth as Signal

Several field studies have demonstrated that penetration depth varies with soil moisture, though none indicated the potential of penetration depth as an observable and useful signal. Farr *et al.* [23] installed receivers in the Nevada desert during the Shuttle Imaging Radar B mission to measure attenuation within desert soils. They found that measured attenuations as a function of soil moisture closely matched theoretical curves, similar to those presented here, with L-band penetration depths up to 85 cm in very dry soil. Farr *et al.* point out that the index of refraction changes with permittivity, an effect not accounted for in Figs. 2–5 of our paper. Using a ground-based radiometer-scatterometer in the field, Wegmuller [24] measured diurnal cycles freeze-thaw that corresponded with the predicted effects of changing liquid content on permittivity. For example, at 4.6 GHz, measured changes in backscatter were observed to correspond to calculated penetration depths of 0.7 cm at 38% VWC to 3.8 cm at 5% VWC. These studies verify that radar penetration depth varies as a function of soil moisture. The accuracy and resolution of these proxy measurements remains to be determined, however, and the fact that these results vary slightly from ours may also be evidence that new relationships between soil moisture and permittivity need to be measured in the lab using local soils (that perhaps have higher ionic content than used in [12]) or that *in situ* measurements of the relationship between penetration depth and soil moisture may be required. Such empirical relationships would also simplify the DIG inversion process.

Converting DInSAR signals to soil moisture values is not necessarily straightforward. Because of the nonlinear relationship between soil moisture and penetration depth, a measurement of a change in penetration depth from a single DIG cannot be converted directly to a change in soil moisture unless one of the soil moisture values is known *a priori* or if some linearizing assumptions can be made. For example, a measured displacement of 5 mm could ambiguously mean a change in soil moisture from 1% to 2% or from 10% to 17% (Fig. 2). However, if the initial soil moisture value is known, and assuming that a phase change is fully attributable to a change in penetration, the initial value can be converted to a penetration depth using the equations presented previously and subtracted from the DInSAR measurement to arrive at the penetration depth on the second date. This penetration depth can then be inverted numerically assuming uniform conditions with depth; the nonuniform solution is not unique, and assumptions must therefore be made regarding the moisture profile before solving for it. For C-band in soils with typical VWC $> 10\%$, the uniform soil moisture assumption may be reasonable as penetration depths would remain less than 10 mm. Use of the longer wavelength L-band might necessitate the use of the nonuniform solution because of deeper penetration, and thus likely some hydrological modeling to assist with estimating profiles, such as has been done with passive [25] and active [26] microwave backscatter.

In a companion paper [10], we describe a time-series of eight DIGs over a ten-month period in a rural area of Colorado. We made the uniform soil moisture assumption and converted our time domain reflectometry data (a measure of permittivity) directly with DInSAR displacements and found nonrandom correlations with some probes at 97%, though most were much lower, and reasonable doubt exists regarding the validity of these correlations because 1) clay swelling may be affecting both measurements and 2) the subpixel natural variability of the field measurements was high enough such that good correlations were possible with some probes but not others. However, the spatial patterns of phase change in these DIGs show clear visual correlations with hydrological features such as stream channels, drainages, and watershed boundaries, in a manner that suggests a soil moisture source. Similar to Fig. 1, farm fields in these DIGs showed phase change, and clay fractions measured in these soils was only several percent. The key processing constraint that allows for this signal to be observed is the vertical accuracy of the DEM used to reduce topographic noise [11]. We found that a DEM with a 2-m vertical accuracy was sufficient to reduce topographic noise such that signals on the order of 1 mm could be observed. There is also some evidence to suggest that it is the slope accuracy of the DEM that is most important, since success in phase unwrapping is largely controlled by the spatial gradient in phase. The DEM we used had an instrument noise level of about 30 cm, in which case 0.5-mm signal resolution should be possible, as was observed [10].

These DIGs and the associated field data also demonstrate that rainfall does not permanently alter the scattering centers to the point where coherence is lost, though there is some evidence that minor alterations or hystereses can persist, perhaps through raindrop detachment of surface soils [27]. Although not clear at this stage of our research, it may be that soil moisture's main effect is not changing the location of soil scattering centers but simply acting as a refractive delay, similar to atmospheric distortions [28].

IV. Clay Swelling as Signal

This paper has concentrated on the relationship between soil moisture and penetration depth because it has largely gone unrecognized previously, but it is also likely that DInSAR measurement of some clay rich soils will detect a soil moisture signal related to the swelling of clay rich soils. However, swelling occurs only under certain conditions and is likely neither as endemic a signal as penetration depth nor as easy to use as a proxy for soil moisture.

Clay swelling is a chemical reaction modeled by atomic-scale force balances and is a complicated function of clay mineralogy, surface charge density of the particles, the concentration of counter-ions in the pore-water, the valence of the counter-ions, and the pH of the soil-water mixture [3], [4], [29]. The classical approach, DLVO theory [4], [29], is based on the opposing forces of van der Waals (attraction) and electrical double-layer (repulsion). The double-layer results from the colloid surface attracting counter-ions of opposite charge and repulsing co-ions of the same charge, both of which can migrate through the pore-water. As these double-layers overlap in soils, repulsive forces increase. If either the concentration or valency of the counter-ions is reduced, repulsion also increases. For our interests, concentration is likely to vary temporally more than valency; thus a soil moisture signal should exist. Modeling these layers beyond the simplest of analytical cases has largely failed [29]. Van der Waals forces, though typically considered small, largely balance these repulsive forces because the force is additive between adjacent particles and decay less rapid when very large numbers of atom pairs are involved, as is the case of clays. DLVO modeling has met with some success in limited cases [4], but largely the problem is simply too complex to model with sufficient accuracy [29]. What is clear is that some clays (namely, montmorillonite) are far more predisposed to swelling than other, as are some ions (e.g., sodium).

Several diagnostics are available to assess the likelihood that a soil can swell appreciably [30]. These include determining the clay mineralogy and fraction, as well as ion type and concentration. The U.S. Department of Agriculture (USDA) uses the exchangeable sodium percentage (ESP) as a simple metric, and suggests that montmorillonitic soils with ESP values greater than 15% are most susceptible. These ESP values are associated with a saturated paste pH of 8.2 for sodic soils.

The likelihood is low that clay swelling can be used as a quantitative proxy for soil moisture, at least not without substantial additional research, and not just due to the difficulties with modeling. Because clay content varies spatially and vertically in many soils, predicting the effects is difficult and likely must be derived at each field site. Lab measurements of the phenomena have largely been restricted to engineering studies; thus, relationships have been most concerned with the pressures generated by swelling as relates to the unloading of soils due to excavation or the loading of soils due to building construction. Unfortunately, these measurements of confined swelling pressures as a function of moisture cannot be converted to surface elevation changes. Even GPS measurement is exacerbated by the fact that the soil layers responsible for the swelling may be substantially deeper than the typical C-band microwave penetration depth (i.e., >20 mm), and without extreme caution, the anchoring system used for the antenna itself may well change soil conditions beneath the antenna enough to invalidate the millimeter-scale measurements. For DInSAR purposes, the phase shifts that would likely result from the cracking and subsequent sealing of clay rich soils are likely larger and easier to measure than the swelling phenomena itself. We also found that soils maps from the USDA Soil Conservation Service at our research site in [10] were not concerned with spatial variations in the upper few centimeters of soil, which may be thin windblown deposits; thus, their use over large heterogeneous regions must be qualified by additional field work.

Enough data exists, however, to develop an order-of-magnitude DInSAR relationship. Expansive soils have been known to swell by 30% of volume [31], and for a typical clay-rich soil we can reasonably assume that a maximum surface elevation change of 30 mm might occur for a soil moisture change in the range of 10% to 40% [2], such that 1 mm of path length change would indicate a 1% change in volumetric soil moisture. Even cases of extreme surface motion (up to 0.15 m has been measured [2]) do not change the general conclusion that a change in soil moisture will cause a change in penetration depth on the same order as a change in surface elevation—i.e., on the order of a millimeter per 1%, above 10% VWC. Further, the penetration depth effect should operate in all soil types, not just those rich in clay, and this effect is likely larger than swelling in dry soils or when using L-band.

Several possibilities exist for distinguishing the two effects (penetration depth and clay swelling). Perhaps the most straightforward would be the direct measurement of surface elevation using differential GPS (if a suitable anchoring system were used) and penetration depth using methods similar to [23] or [24]. Use of the multiple frequencies should yield the same phase change if due to surface elevation change but different phase change if due to penetration depth (Fig. 3). Coherence maps may also differ based on mechanism, as coherence might be better preserved if due to the simple uplift of scattering centers in clay swelling. However, if the swelling occurred within the penetration depth, the scatterers would actually be stretched apart, not simply translated upward, and this would likely decrease temporal coherence.

The analysis and examples presented here demonstrate that, irrespective of clay content and its reaction to a change in soil moisture, a decrease in soil moisture will cause a well-behaved increase in penetration depth of a magnitude that is measurable with DInSAR. As particular clay-rich soils dry, they will contract, lower the surface, and also increase the path length. Therefore, decreasing soil moisture has the same qualitative effect on clay action and penetration depth—in both cases microwave path length would increase. With further research on signal source mechanisms (penetration depth or clay swelling), a method to remotely determine clay content of soils may also be possible.

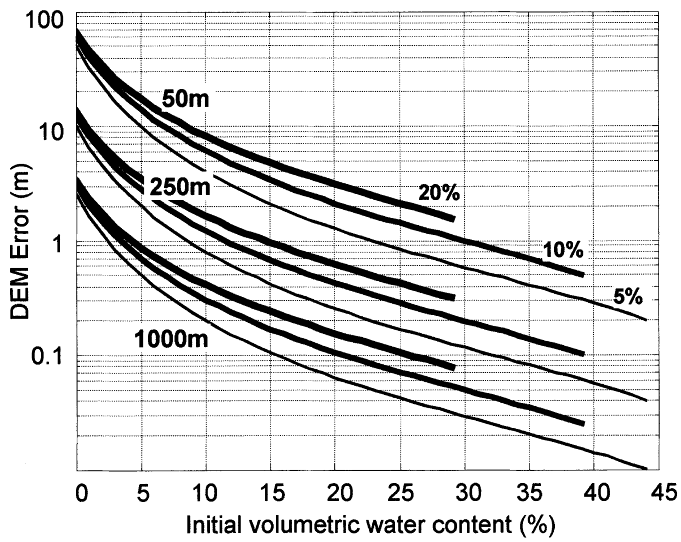

Fig. 5. DEM error as a function of temporal change in soil moisture. Thick medium and thin lines represent the error in elevation that a change of 20%, 10%, and 5% volumetric water content, respectively, would cause for each of three perpendicular baseline because the empirical relations describing permittivity are valid only up to 50% VWC.

V. Soil Moisture as Noise

Soil moisture largely remains unrecognized as a source of error in both subtle measurements of deformation and the creation of DEMs. While soil moisture variations have long been associated as a source of temporal decorrelation similar to vegetation growth, it has rarely, if ever, been considered a source of quantitative error in DInSAR in manner similar to atmospheric phase delays [8], [32]. Fig. 2, however, shows that we can expect changes in path length of up to 60 mm using C-band, an error that rivals atmospheric phase delays [28]. For example, recent DInSAR work showing subtle deformation of the Yellowstone caldera [33] left unexplained variations between DInSAR and field surveying that could neither be accounted for by "standard" DInSAR errors (such as atmospheric phase delays) nor surveying error. The magnitude of this discrepancy varied along hillslopes associated with the caldera (ranging from 0–15 mm) and was present in some comparisons but not others. Temporal and spatial variations in soil moisture of less than 10% VWC could explain the full range of discrepancy, and might be expected along hillslopes. In another example, Hannsen *et al.* [28] measured atmospheric phase delays as signal. By using the two-pass method and limiting measurements to one-day repeat data, they declared that "the observed signal can be interpreted uniquely as the superposition of the atmospheric delay signal during the two acquisitions." Accounting for the changes in soil moisture that likely occurred during some of their measurements would probably not alter their general conclusions, but this paper is a recent example typical of the literature of a failure to recognize soil moisture as a potential source of error, whether due to the penetration depth or clay swelling mechanisms.

Similarly, the only source of quantitative error (i.e., phase delays that do not cause significant loss of coherence) that is typically considered in the construction of DEMs from repeat-pass InSAR is atmospheric (or ionospheric) phase delays [8], [32]. Fig. 5 uses (1)–(3) to demonstrate the effects that temporal variations in soil moisture might have on such DEMs. Here, C-band

DEM error is plotted as a function of initial soil moisture, with the curves representing changes of 5%, 10%, and 20% VWC for perpendicular baselines of 50, 250, and 1000 m. For example, given a 250-m baseline and an initial soil moisture of 5%, a change of 5% (i.e., final value 10% VWC) would lead to 2 m of error, and 10% and 20% changes would lead to 3 and 3.5 m, respectively. The error is increased at lower baselines, as expected. Because spatial variations in soil moisture are likely smoothly varying, the errors they would cause will be difficult to distinguish from natural terrain because they would appear as smooth hillslopes. Because soil moisture phase is zero mean over long time intervals, averaging several repeat-pass DEMs together may reduce this noise, as it does for atmospheric phase delays.

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