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Study of high SAR backscattering caused by an increase of soil moisture over a sparsely vegetated area: implications for characteristics of backscattering

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Abstract. We used interferometric methods on a pair of repeat-pass ERS-1 synthetic aperture radar (SAR) images to study soil moisture changes over sparsely vegetated targets. The intensity of the SAR image acquired at one time was higher than that of an image acquired at an earlier time. We used a correlation image computed from the SAR image pair to study the cause of the observed changes in SAR intensity. Because a reduction of correlation over areas with intensity changes was not observed, we interpreted the intensity changes as not being caused by changes in roughness/structure, but by a change in soil moisture owing to rainfall. An increase in soil moisture ranging from 5% to 20% is the most likely explanation for the increase of intensity. These analyses imply that both intensity and phase information should be used in SAR change detection applications.

1. Background

Soil moisture is an important environmental parameter that plays a key role in the hydrological cycle, affecting applications in meteorology, climatology, ecology and agriculture. Studies indicate that soil moisture plays a signifciant role in near-surface atmospheric variability and is an important component of water and energy transfer between the surface and the atmosphere (Shukla and Mintz 1982, Delworth and Manabe 1989). For ecosystem and agricultural studies, soil moisture is an important factor in modelling ecosystem dynamics and crop yields (Choudhury *et al.* 1995). Many studies have explored the use of passive microwave systems to infer soil moisture from airborne and spaceborne instruments (Wei 1995, Njoku and Entekhabi 1996). However, these instruments are severely limited by their coarse spatial resolution, usually of the order of tens of kilometres per resolution cell. Synthetic aperture radar (SAR), having high spatial resolution, all-weather acquisition capabilities, and high sensitivity to soil moisture, provides an opportunity to overcome the limitations of the other methods if certain limitations on its use can be addressed.

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Increases in soil moisture result in an increase in radar backscatter approaching 11 dB (Dobson and Ulaby 1986). This is because a change in soil moisture changes the dielectric constant, a primary factor controlling radar backscatter. In theory, the change in soil moisture can be inferred from changes in radar backscatter. Although much progress has been made in the use of SAR to measure soil moisture (Dobson and Ulaby 1986, Oh *et al.* 1992, Engman 1995), many difficulties remain owing to the effects of soil and terrain characteristics other than moisture—primarily surface roughness and local terrain slope (Engman 1995, Islam and Engman 1996). In most natural settings, the effect of roughness is generally equal to or greater than the effect of soil moisture on radar backscatter. Therefore, to derive changes in soil moisture from single-band, multi-temporal SAR data, one must deal with the effects of surface roughness and local slope on the radar signal.

Repeat-pass SAR images acquired with almost identical viewing geometry can be used for interferometric data analysis. The interferometric phase is a measure of change in distance from SAR sensor positions to the ground target, and can be used to map surface topography or change of topography (see, for example, Massonnet and Feigl (1998) and Lu *et al.* (2000)). The interferometric coherence or correlation coefficient (see §2.1) is a measure of the variance of the difference of phase values in the two SAR images. The correlation coefficient of repeat-pass SAR images is primarily controlled by changes in the backscattering phase, and mainly depends on parameters related to land surface (Wegnuller and Werner 1997, Lu and Freymuller 1998).

This paper discusses how we studied a feature in southeastern New Mexico that had an anomalously high SAR reflectance, possibly caused by an increase in soil moisture resulting from a recent rainstorm. We used multi-temporal repeat-pass SAR images in an attempt to explain these SAR returns by exploring both intensity and phase information in the radar signal. To determine whether the high return was caused by changes in surface roughness (owing to changes in surface texture) or by the change in moisture content, we studied interferometric coherence using the repeat-pass image pair. After determining that the change was most likely caused by soil moisture rather than surface roughness, we used a geometric optical SAR backscattering model to quantify the amount of soil moisture increase required to cause the observed change in backscatter coefficient. Finally, an interferometric coherence map was compared to a Landsat 5 Thematic Mapper (TM) image to show that the putative moisture signature occurred mostly in an area devoid of vegetation, consistent with the high coherence maintained between the two dates used in the repeat-pass image pair.

2. Methods

2.1. *Correlation coefficient or interferometric coherence*

Radar backscattering represents the amount of energy reflected back to the sensor from each resolution element of the imaging surface and is the coherent sum of backscattered energy from individual scatterers. A radar backscatter has a size of the order of a radar wavelength, and therefore the radar backscattering at a pixel level (the size of several metres to tens of metres) consists of contributions from hundreds of thousands of individual scatterers generally considered to be independent. The backscattering of a pixel in SAR imagery can be simplified as a complex value of $|\sigma^0|e^{-j\varphi}$, where $|\sigma^0|$ and φ represent amplitude and phase of the backscattering respectively.

The phase φ, at each point in a radar image, is the sum of scattering phase φ_s, a statistical variable, and the propagation phase φ_p, a deterministic variable. The propagation phase φ_p is equal to $-(4\pi/\lambda)r$, where r is the apparent range distance from the antenna to the imaged point. The apparent range distance is the sum of the absolute distance from the antenna to the target and a range delay caused primarily by water vapour in the atmosphere. The backscattering phase, on the other hand, is primarily controlled by the macrostructure and texture of the surface.

For simplicity, let us consider SAR backscattering over sparsely vegetated or bare soil to minimize volume scattering as a random influence on φ_s. Both phase and intensity can be altered by surface roughness and dielectric constants, which are primarily controlled by soil moisture content. Surface roughness represents the macrostructure of the scatterers. Changes of surface roughness would modify the relative positions of the scatterers within each pixel and therefore affect both the intensity and the phase information of the backscattering signal. In this scenario, both the statistical backscattering phase and the deterministic propagation phase will change owing to changes in roughness. On the other hand, a change in soil moisture content may only alter the intensity of the backscattering and the propagation phase (owing to the possible swelling of soil) and have no effect on the backscattering phase. Therefore, if we can measure quantitatively the changes of the scattering phase, we can determine whether the change in radar backscattering is caused by surface roughness or water content.

Because both amplitude and phase information can be retrieved from SAR imagery, we propose the following equations to quantify the degree of changes of backscattering phase and amplitude between two repeat-pass SAR images.

$$\rho=\left|\sum_{i=1}^{n} \mathrm{e}^{-j(\varphi_{1si}-\varphi_{2si})}\right|=\left|\sum_{i=1}^{n} \mathrm{e}^{-j(\varphi_{1i}-\varphi_{2i})}\times \mathrm{e}^{-j(\varphi_{2pi}-\varphi_{1pi})}\right| \tag{1}$$

$$k=\frac{\sum_{i=1}^{n}|\sigma_{1i}^{0}|}{\sum_{i=1}^{n}|\sigma_{2i}^{0}|} \tag{2}$$

where φ_{1i} and φ_{2i} are the phases at pixel i from two SAR images, and $|\sigma_{1i}^0|$ and $|\sigma_{2i}^0|$ are the amplitudes of backscattering at pixel i. The correlation coefficient or interferometric coherence is ρ. The change of backscattering coefficient is k. We can calculate $(\varphi_{2pi}-\varphi_{1pi})$ by using a digital elevation model (DEM), image geometry and satellite restitute vectors (see, for example, Massonnet and Feigl (1998) and Lu *et al.* (2000)). The role of this term is to remove the effects of propagation phase on the calculated correlation value, and therefore the correlation coefficient reflects the change of the backscattering phase. The numebr of pixels (or window size) is n and is used to estimate ρ. It is normally taken to be 20 (two pixels across-track direction and ten pixels along-track direction) for ERS-1 images used in this study.

The correlation is a measure of the variance of the backscattering phase difference of two SAR observations. The correlation value depends on the changes of the scattering characteristics of the ground surface between the two SAR acquisitions (Zebker and Villasenor 1992, Lu and Freymuller 1998). The correlation coefficient ranges from 1, or no change on SAR backscattering , to 0, a complete change of SAR returned signal. The correlation coefficient over a densely vegetated land surface is generally lower than that over a sparsely vegetated surface, which in turn maintains a lower correlation coefficient than that of bare soil. For bare or sparsely vegetated soil, the coherence will be highest when the scattering characteristics of the illuminated soil remain unchanged; lower correlation values could be caused by changes in the relative positions of the scatterers or changes in soil properties. Therefore, a correlation image derived from equation (1) can be used to delineate the regions where surface roughness or soil properties are changes.

If we can prove that the change in SAR backscattering is not caused by a change in roughness, but rather by a change in soil moisture content, we propose the following technique to retrieve the change of soil moisture content.

2.2. *Estimation of change of soil moisture*

For sparsely vegetated regions, the backscattering coefficient σ^0 can be expressed as

$$|\sigma^0| = f(\varepsilon, \theta)\, g(\theta, s, l) \tag{3}$$

where f is a function that accounts for the dependence of backscattering on the relative dielectric constant of the surface ε and incidence angle of radar θ; g is a function of surface roughness parameters, i.e. surface rms s and surface correlation length l (Ulaby *et al*. 1986).

On the basis of the geometric optics model for rough surfaces (Ulaby *et al*. 1986), equation (2) can be further expressed as

$$|\sigma^0| = \Gamma(0)\, h(\theta)\, g(\theta, s, l) \tag{4}$$

where $h(\theta)$ is a function dependent on the incidence angle only, and $\Gamma(0)$ is the Fresnel reflectivity evaluated at normal incidence angle, which is only a function of the relative dielectric constant. The dependence of $\Gamma(0)$ on soil volumetric moisture Mv is linear, and can be expressed as (Ulaby *et al*. 1986):

$$\Gamma(0) = 0.0579 + 1.0263\, Mv \tag{5}$$

For repeat-pass radar observations, if there is evidence that surface roughness remains unchanged, the ratio of backscattering becomes

$$|\sigma_1^0| / |\sigma_2^0| = \Gamma(0)_1 / \Gamma(0)_2 \tag{6}$$

where $|\sigma_1^0|$ and $|\sigma_2^0|$ are the amplitudes of the backscattering coefficient in two SAR images acquired at two different dates. Therefore, on the basis of equations (5) and (6), if the ratio of the backscattering of two radar images is known and if the soil moisture content of the first observation is assumed, the change of soil moisture in the second observation can be derived.

3. Analysis

3.1. *ERS-1 data and study site*

The four images in this study were collected by the European Space Agency (ESA) ERS-1 sensor. The ERS-1 SAR is a C-band radar with wavelength $\lambda = 5.66$ cm. The images were acquired during descending passes in which the satellite travels approximately from north to south and looks to the west with 23° from vertical. Repeat-pass images were acquired at about 17 h 34 m 18 s GMT or 10 h 34 m 18 s mountain local time on 15 October 1992, 18 January 1993, 31 May 1995 and 27 December 1995. The two images acquired in January 1993 and May 1995 have identical acquisition geometry, ideal for interferometric analysis.

The intensity images from three of the repeat-pass acquisitions, acquired in 1992, 1993 and December 1995, look very similar; the 1993 image is shown in figure 1(*a*). The terrain is quite flat over most of the image area. Mescalar Ridge, running approximately south–north along the centre of the image, is delineated by the strong radar returns. Agricultural features in the eastern part of the image are visible. The city of Lovington exhibits high-intensity returns, typical of the double-bounce effect caused by buildings. To the east of Mescalar Ridge, land covers consist of rough soil, gravel and very sparse shrubs. Relatively denser vegetation, mainly desert shrubs, lie to the west, north, and south of the Mescalar Ridge.

Figure 1(*b*) shows the SAR intensity observed on 31 May 1995, showing features east of Mescalar Ridge that have anomalously high-intensity returns compared to the other three images. There are three such features over the whole image—two roughly parallel from the northeast to the southwest and the third feature runs east–west at the most southern edge of the image. The track of the parallel features suggests the path of a rainfall event typical for this geographic region and time of year.

3.2. *Identifying the cause of high backscattered return*

So, are the high-intensity returns on the 31 May 1995 image caused by changes in surface roughness or soil moisture? To investigate this feature, we computed the correlation between two complex images acquired on 18 January 1993 and 31 May 1995. The two images were acquired with identical viewing geometries—the antenna look angles were the same and the spatial distance between the two satellite passes is less than 10 m. We first estimated the range and azimuth offsets between the two and resampled one image to align it with the other. The propagation phase difference ($\varphi_{p1}-\varphi_{p2}$) was calculated using the 30 m DEM from the U.S. Geological Survey (USGS), imaging geometry, and satellite position and velocity vectors. The correlation image was then constructed using equation (1).

Figure 2 shows the correlation coefficient image derived on the basis of the above procedure. The correlation coefficient value is represented by colours overlaid on the amplitude image. The correlation coefficient ranges from the highest value of

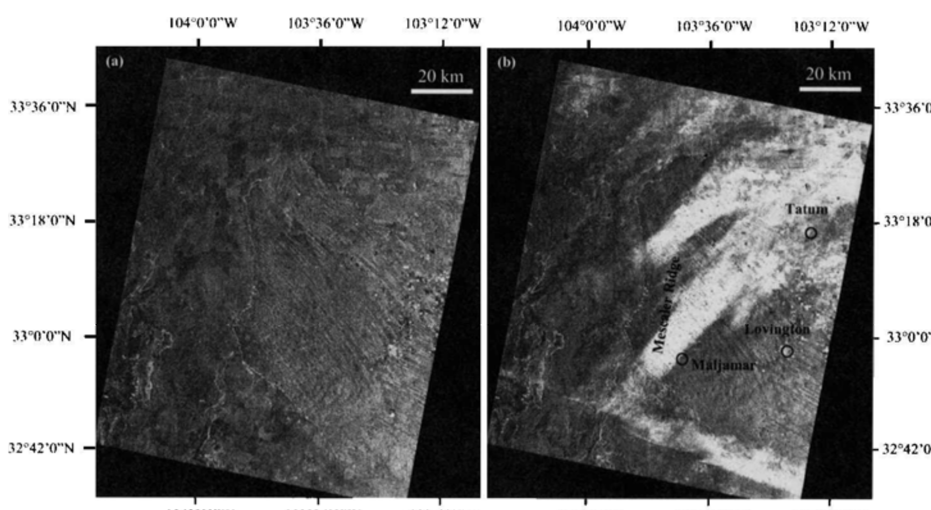

Figure 1. Repeat-pass SAR intensity image of (*a*) January 1993 and (*b*) May 1995.

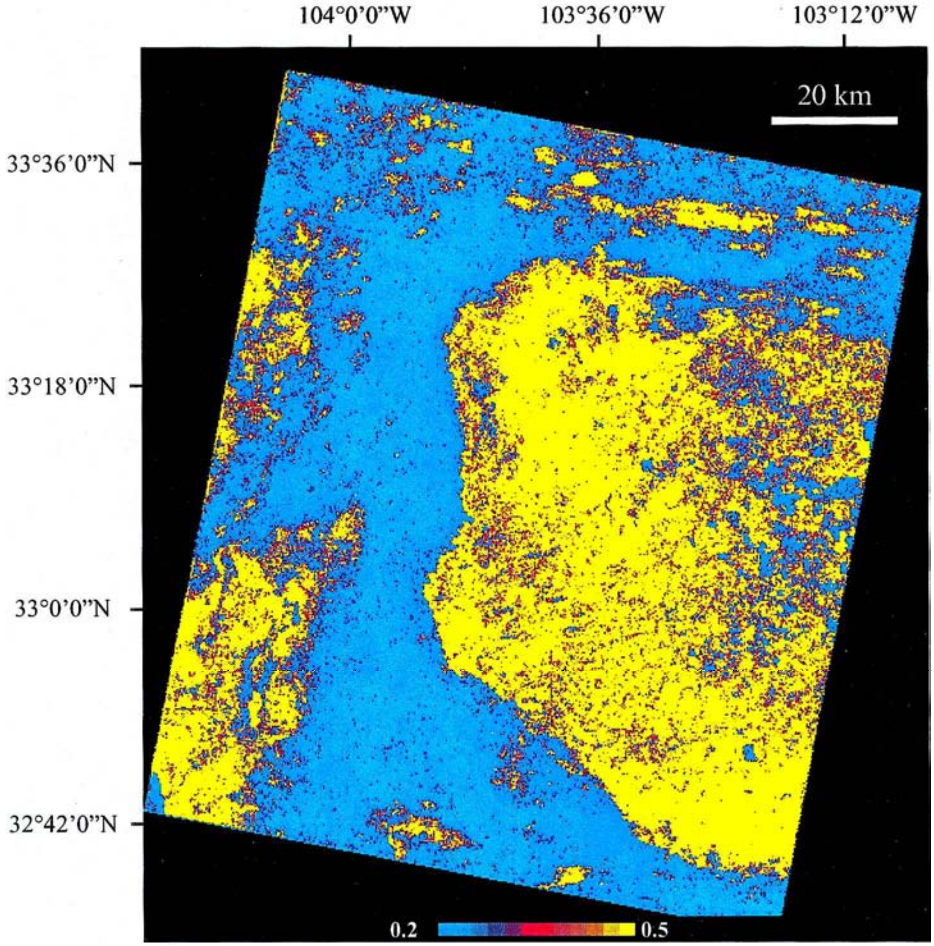

Figure 2. Correlation image derived from January 1993 and May 1995 images. The correlation coefficient ranges from the highest value of ~0.5 (yellow) to ~0.2 (blue).

about 0.5 (yellow) to about 0.2 (blue). Over the aforementioned high-return features, one cannot see abnormal patterns in the correlation coefficient. If the high returns in figure 1(*b*) were caused by changes in surface roughness, the surface backscattering phase would be changed, which would reduce the correlation coefficient. The fact that the higher correlation coefficient is maintained over the high-return features suggests that the high-intensity returns shown in figure 1(*b*) were not caused by changes in surface roughness between image acquisitions. We therefore interpret the intensity changes in figure 1(*b*) as changes in soil moisture.

3.3. *Estimating change of soil moisture*

To quantify the change of radar backscattering during the two acquisitions, we calculated the change of soil moisture on 31 May 1995, by assuming 0.0% of soil moisture content on 18 January 1993 (that is, we cannot compute the actual moisture content for a given date, but we can compute the difference). The changes in the volumetric soil moisture are shown in figure 3. Changes in soil moisture up to 25%

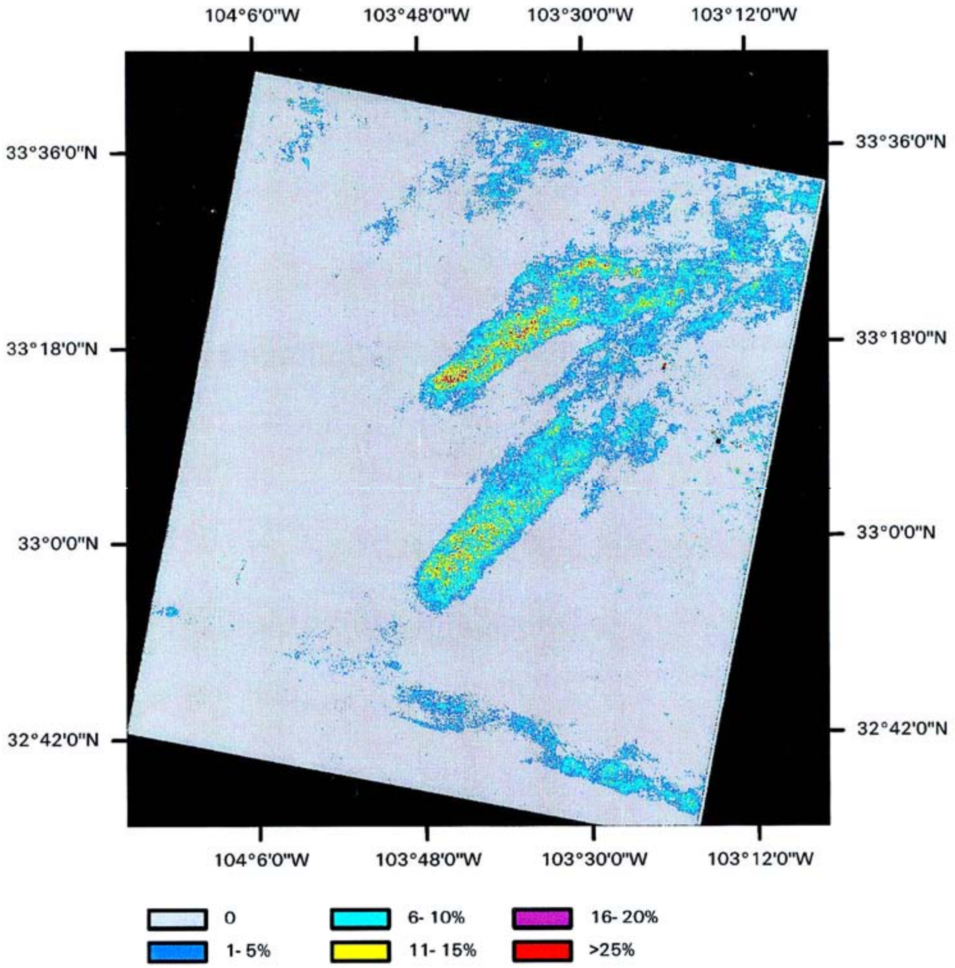

Figure 3. Change (in percentage) of volumetric soil moisture.

were observed. The majority of the soil moisture ranged from 6% to 10%. The highest changes of apparent soil moisture were concentrated primarily along the centre part of the high-intensity regions, running roughly parallel to the northeast to the southwest over the centre of the study site. Smaller changes in soil moisture were observed elsewhere: the two patches located at the northwest of the region had less than 15%, and the east–west feature in the southern part of the image had less than 10% change.

3.4. *Correlation of coherence map with TM image*

To understand the reason for the loss of coherence, we obtained a Landsat 5 TM image acquired on 21 September 1993. The TM scene is co-registered to the SAR images. We calculated the normalized difference vegetation index (NDVI) using band 4 and band 3, in order to identify the vegetation cover type, a major source of decorrelation in interferometric analysis. The resulting NDVI image is shown in figure 4. The dark pixels represent bare soil and very sparsely vegetated regions,

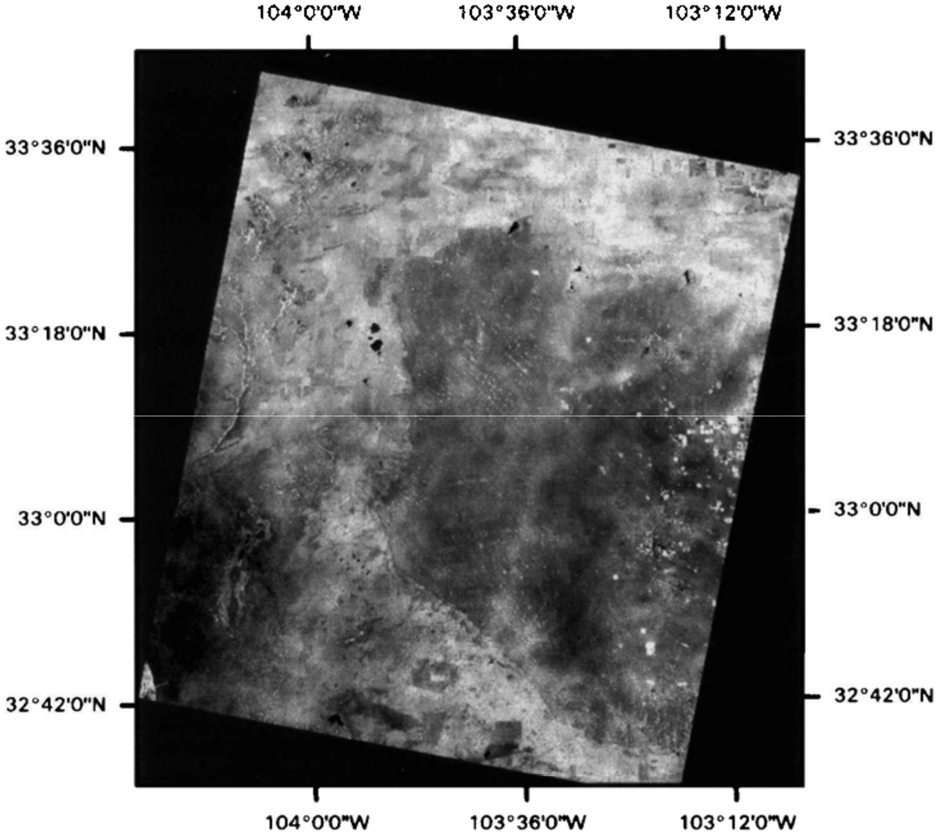

Figure 4. NDVI derived from bands 4 and 3 of Landsat TM data acquired on 21 September 1993.

whereas bright pixels correspond to relatively dense vegetation consisting mainly of desert shrubs. Regions of low correlation coefficient in figure 2 correspond closely to vegetation coverage in figure 4. It makes sense that vegetated regions have lower coherence values, owing to volume scattering effects. Because scatterers in vegetated cover move frequently, the backscattering phase changes rapidly in time, reducing correlation. Mescalar Ridge seems to act as a delineator between both sparsely vegetated land cover and relatively denser vegetation. To the north, west and south of the Mescalar Ridge, vegetation density is relatively high and the correlation coefficient is reduced. As a matter of fact, the correlation coefficient (figure 2) does a better job of delineating the Mescalar Ridge than the SAR intensity image (figures 1(*a*) and 1(*b*)).

Vegetation cover might affect the estimation of soil moisture. To the north of Lovington, interferometric coherence over agricultural land is much lower and therefore the estimated changes in soil moisture might be biased. This is because the backscattering intensity over the agricultural land might be induced by both increases in soil moisture and changes in surface roughness.

4. Discussion

Our observations of changes in soil moisture were supported by weather records at two National Weather Service stations: Tatum and Maljamar (see figure 1(*b*)).

The climatological gauge stations at Tatum and Maljamar recorded about 0.33 inches (8.25 mm) and 0.3 inches (7.5 mm) rainfall respectively within the 24 h before the image was acquired. The ground surface temperature ranged from 55°F (12.8°C) to 80°F (26.7°C); thus, soil moisture was in its liquid phase, eliminating effects associated with solid phase moisture.

Regions with lower values in the correlation image (figure 2) correspond well with areas of relatively dense vegetation. Similar phenomena were studied by Rosen *et al.* (1996). They found that areas with lower correlation coefficient, derived from Spaceborne Imaging Radar-C (SIR-C) images, agreed well with heavily vegetated regions derived from Advanced Very High Resolution Radiometer (AVHRR) imagery.

Is it reasonable to assume that changes in moisture content do not affect coherence significantly? On the basis of information retrieved from the State Soil Geographic Data Base (Natural Resources Conservation Service 1994), the soil type associated with the high-coherence regions in the image is loamy sand to loam in nature, signifying high sand content. For dry sandy soil, which C-band radar penetrates to some depth, the signal that penetrates for the most part does not scatter back. Therefore, the backscatter comes from the air–surface interface. If the surface is moist, there is less penetration, more backscatter, but a very similar arrangement of scatterers. If there was some regionally variable amount of water on the surface that prevented penetration, then the return was brighter. Because the surface did not change much, the correlation did not change compared with surrounding regions.

Our analysis has significant implications for the use of SAR data in change detection techniques (Singh 1989). With SAR, both intensity and phase information can be used in change detection analysis. The ratio of SAR intensity images measures changes in SAR backscattering magnitude. However, this ratio does not indicate whether the change is caused by changes in the relative positions of scatterers (structural changes) or changes in the material (dielectric) properties of the surface. Correlation image analysis used phase information to eliminate this ambiguity. In some situations, SAR intensity may not change from time to time (e.g. a forest under windy conditions), but the phase is most likely to be changed due to a change of leaf positions. In other situations, such as the example cited in this paper, intensity of SAR backscattering is dramatically changed while the phase correlation remains the same. Therefore, changes of intensity and phase information provide the means for discriminating changes in the surface material properties from structural changes in the feature under observation. Thus, using both phase and intensity information enhances the capability to characterize changes in surface conditions over time.

For bare soil or sparsely vegetated surfaces, changes in correlation coefficient indicate mostly changes in surface roughness. A lower correlation coefficient implies a larger change of surface. Because the correlation coefficient is a statistical estimation of difference of backscattering phases in two SAR images, it is not a simple task to quantify the degree of change based on correlation coefficient only. Therefore, if the correlation coefficient is to be used as a change detection technique, quantitative analysis is needed to address the accuracy of change detection and the coherence value.

Care should be taken when using the SAR correlation coefficient to infer surface properties from repeat-pass observations. It has been shown that, for a given land cover type, the correlation coefficient tends to degrade with time (Zebker and Villasenor 1992, Lu and Freymuller 1998). Our studies have shown that correlation over a land surface similar to the one in this study exceeds 0.9 if the images are 1 day apart, is about 0.8 after 35 days, and drops to about 0.6 over a 1-year time span. Correlation over a sparsely vegetated surface, in general, tends to decay over time even more. Therefore, SAR images used to estimate changes in soil moisture should be acquired over short time intervals.

The high-intensity feature approximately running west–east on the southern edge of the image (figures 1(*b*) and 3), is perplexing: part of it has lower coherence and higher backscattering, and part of it has higher coherence and higher backscattering. The relatively denser vegetation here corresponds to desert shrubs, but mainly bare soil and shrubs. The vegetation density, combined with the long temporal separation in SAR image acquisitions (over two years), lowers our confidence in the estimation of changes in soil moisture.

To use repeat-pass SAR imagery to estimate changes in soil moisture, it is advisable to use short-window temporal images to avoid any likely changes in surface structure. It is also preferable for the viewing geometry of the two satellite passes to be as close as possible. If the studied surface structure were to change, the estimation of change in soil moisture on the basis of backscattering intensity would be biased. However, the correlation coefficient can identify regions of such changes. Therefore, we make the following recommendations. Firstly, use short temporal repeat-pass pairs to estimate changes in soil moisture. Secondly, the spatial separation of the two satellite passes should be as small as possible to avoid changes in backscattering intensity due to changes in viewing geometry. Thirdly, always construct a correlation coefficient map first to ensure that surface structure remains unchanged. Finally, longer wavelength SAR (such as 24 cm L-band JERS-1) repeat-pass images are better suited for estimating changes in soil moisture due to their deeper penetration nature.

The purpose of this paper was to explore the use of repeat-pass SAR interferometry to isolate the influence of soil moisture on the SAR signal from surface roughness. The surface moisture model used here is empirical and is acknowledged to be simplistic; soil moisture model development was not the intent of this paper. Significant improvements should be realized through the use of more robust models. The inversion of physical models, such as the Integral Equation method has been demonstrated by Oh *et al.* (1992) and refined by Oevelen and Hoekman (1999). Dawson *et al.* (1997) outlined the use of a robust statistical model coupled with neural networks to design a soil moisture estimator that can operate based either on extensive ground truth or theoretical surface scattering models. It is assumed that the results presented here would benefit from the use of more sophisticated soil moisture models.

5. Conclusions

We used interferometric methods on a pair of repeat-pass ERS-1 SAR images to study soil moisture changes over sparsely vegetated targets. The intensity of the SAR image acquired at one time was higher than that of the image acquired at an earlier time, indicating a change in soil moisture caused by rainfall events. We used a correlation image computed from the SAR image pair to eliminate change of surface roughness/structure as an explanation for the intensity change. We proposed that a change of roughness/structure should result in a change of the relative positions of scatterers, thus reducing the correlation between the two SAR images. Such a reduction was not observed, indicating that the intensity change was likely caused by a change in surface dielectric properties, interpreted as a change in soil moisture. An increase in soil moisture ranging from 5% to 20% is the most likely explanation for the increase of intensity. These analyses imply that both intensity and phase information should be used in SAR change detection applications.

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