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# Soil moisture change detection model for slightly rough surface based on interferometric phase

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**Abstract.** We propose a model for soil moisture change detection using phase information of synthetic aperture radar data. It is expected to be applied for drought monitoring over grasslands in north China. This model is developed from the coherent scattering model, which was originally studied for random oriented volume over ground scattering. Compared to the conventional water content estimation methods employing amplitude information, the methods based on phase information have advantages over change detection. In particular, the phases caused by topography can be removed by the use of external digital elevation model data with high accuracy. Simulations are presented to show the phase sensitivity on soil moisture variations, as well as soil moisture changes that can be feasibly inverted under different conditions of system phase accuracy and incidence angle. Then the inversion scheme is given on the basis of the proposed model. Finally, a relevant experiment in the anechoic chamber was implemented, in which good agreement is achieved between the model computations and the measurements. The results are discussed considering the practical limitations of potential applications. © *The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: [10.1117/1.JRS.9.095981](https://doi.org/10.1117/1.JRS.9.095981)]

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## 1 Introduction

Soil moisture is a key parameter in hydrology, climate, and ecology models, and it plays an important role in drought monitoring and yield estimations of crops. Synthetic aperture radar (SAR) data have been successfully employed in soil moisture estimations for years because of the high spatial resolution as compared to the passive microwave remote sensing approach. Scattering modeling is an effective way to relate soil parameters to those microwave sensor parameters, and they are generally divided into physical and empirical ones. The main approach is to establish an empirical relationship between polarimetric backscattering coefficients and surface parameters.<sup>1-3</sup> However, most of the research done has focused on the utilization of the amplitude information of SAR data or multipolarization SAR data, for which the estimation results are not stable due to the influences of roughness and topography. On the other side, the phase information contained in microwave data has not been fully utilized and the direct relationship with the physical meaning between data phase and soil moisture has not been revealed.

Detection of soil moisture change from interferometric SAR (InSAR) data is a recently developed technique. Compared to the conventional water content estimation methods employing the amplitude information of SAR data, this kind of approach is advantageous over change detection. When we measure the soil moisture change in a relatively short time, the roughness could be considered to be stable and, thus can be naturally separated from the moisture influence.

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Because the phase information is employed, a high phase accuracy is usually achieved with low requirements for amplitude calibration. For most natural surfaces in real environments, there always exist topographies of different levels. It is much easier to remove the topography effects when the phase-based method is used rather than the amplitude-based approach. In this case, the phase item(s) caused by topography could be eliminated by means of external digital elevation model data with a high accuracy. For the past few decades, the InSAR technique for soil moisture estimation has not been fully investigated, we believe, because of the long revisit time of previous spaceborne SAR satellites. With the recently launched Sentinel1A, ALOS PALSAR2, RCM, etc. in the future, this technique is soon expected to be widely utilized in high-resolution soil moisture monitoring.

In review, the literature of these phase-based methods for estimating soil moisture change can be divided into two major groups. One is the study of an experimental phenomenon, and the other is the research on scattering models. Gabriel et al. probably first found the link between the interferometric phase and the water in soil in 1989.<sup>4</sup> However, the proposed explanation was based on the shrinking/swelling of clay soils. In 1998, Nesti et al. implemented an experiment in an anechoic chamber in the frequency band of 2 to 12 GHz, which revealed that the phase shift can be interpreted as the effect of the change of the dielectric properties of the surface soil.<sup>5</sup> After that, Nolan et al., Hajnsek and Prats, S. Hensley et al., Morrison et al., Barrett et al., and Zwieback et al. investigated this technique further with the use of spaceborne, airborne, and ground-based SAR data, respectively.<sup>6-11</sup> The scattering modeling on the relation between the interferometric phase and the dielectric constant of soil is very promising in its ability to analyze the influence and sensitivity of the system parameters on the soil moisture inversion. However, only a few studies concerning the scattering modeling of interferometric phase information for soil moisture applications could be found until recently. Oh et al. first developed the semiempirical relationship of the differential Mueller matrix for microwave backscattering from a bare surface.<sup>12</sup> No soil moisture estimation method based on scattering models was developed from an interferometric phase until De Zan et al. in 2014.<sup>13</sup> They proposed a model based on plane waves and the Born approximation, in which it is assumed that the backscatter is generated by a volume model under a flat surface. Then soil moisture values are obtained by minimizing the differences of coherence and phase triplets between the model predictions and L-band airborne SAR observations. The relation between the interferometric phase and soil moisture change is examined through comparison between the predicted and observed mismatches of the phase triplets. In this paper, we will insert the small perturbation method for a slightly rough surface assumption into the coherent scattering model and then present the phase relation of soil moisture values and system parameters, which can be directly utilized for soil moisture change detection. It can also be used for the occasions where the variations of coherence are small.

First, the coherent scattering model is introduced in Sec. 2. Then simulations are presented to show the range sensitivity on soil moisture variations and the range of soil moisture changes that can be inverted under different conditions of system phase accuracy and incidence angle in Sec. 3. After that, in Sec. 4, the whole inversion scheme for soil moisture change is proposed. Finally, the experiments are carried out in an anechoic chamber and the comparisons of phase difference as well as soil moisture values between the model and measurements are presented in Sec. 5. Phase stability is discussed with coherence and the number of looks.

## 2 Coherent Scattering Model

### 2.1 Randomly Oriented Volume + Direct Ground

The coherent scattering model first developed by Treuhaft and Siqueira in 2000 is for the purpose of research on vertical structures of vegetated land surfaces from interferometric and polarimetric radar.<sup>14</sup> According to the physical models proposed in this paper, the cross-correlation due to a randomly oriented volume over a backscattering ground surface is given in Eq. (23) of Ref. 14.

$$\langle \hat{p}_1 \cdot \vec{E}_{\hat{i}_1}(\vec{R}_1) \hat{p}_2 \cdot \vec{E}_{\hat{i}_2}^*(\vec{R}_2) \rangle = A^4 e^{i\phi_0(z_0)} \exp \left[ -\frac{2\sigma_x h_v}{\cos \theta_0} \int_0^{2\pi} W_\eta^2 d\eta \int_{-\infty}^{\infty} W_r^2 r_0 e^{i\alpha_r r} dr, \right. \\ \left. \left[ \rho_0 \langle (\hat{p}_1 \cdot F_b \cdot \hat{i}_1) (\hat{p}_2 \cdot F_b^* \cdot \hat{i}_2) \rangle \int_0^{h_v} e^{i\alpha_z z'} \exp \left[ \frac{2\sigma_x z'}{\cos \theta_0} \right] dz' \right. \right. \\ \left. \left. + 4k_0^4 \cos^4 \theta_0 W_P(-2k_0 \sin \theta_0, 0) \langle \alpha_{\hat{p}_1, \hat{i}_1} \alpha_{\hat{p}_2, \hat{i}_2}^* \rangle \right] \right]. \quad (1)$$

The left side of Eq. (1) represents the most general cross-correlation, applicable to both interferometry and polarimetry, where  $\hat{p}_1$  is the received polarization at end 1 of the baseline, located at  $\vec{R}_1$ , and  $\vec{E}_{\hat{i}_1}(\vec{R}_1)$  is the vector signal received at  $\vec{R}_1$ , due to a wave transmitted at polarization  $\hat{i}_1$ .  $\hat{p}_2$  is the received polarization at end 2 of the baseline, while  $\hat{i}_2$  is the transmitted polarization, which induces the return received at end 2 of the baseline. The ensemble average brackets  $\langle \rangle$  in Eq. (1) indicate the average over all statistical properties of the terrain, which affect the signals. In practice, multilook averaging is assumed to be equivalent to the ensemble averaging.

The right side of Eq. (1) is composed of two items. The first item of the sum on the right side refers to the volume scattering, while the latter one corresponds to the direct ground scattering, which is our concern.

### 2.2 Direct Ground

When we consider slightly rough direct-surface scattering, we have the volume height  $h_v = 0$  and only the latter item is reserved; then Eq. (1) can be simplified as<sup>15</sup>

$$\langle \hat{p}_1 \cdot \vec{E}_{\hat{i}_1}(\vec{R}_1) \hat{p}_2 \cdot \vec{E}_{\hat{i}_2}^*(\vec{R}_2) \rangle = A^4 e^{i\phi_0(z_0)} \int_0^{2\pi} W_\eta^2 d\eta \int_{-\infty}^{\infty} W_r^2 r_0 e^{i\alpha_r r} dr \cdot 4k_0^4 \cos^4 \theta_0 W_P(-2k_0 \sin \theta_0, 0) \langle \alpha_{\hat{p}_1, \hat{i}_1} \alpha_{\hat{p}_2, \hat{i}_2}^* \rangle, \quad (2)$$

where

$$\alpha_{HH} = \frac{\epsilon_r - 1}{[\cos \theta_0 + (\epsilon_r - \sin^2 \theta_0)^{1/2}]^2}, \quad (3)$$

$$\alpha_{VV} = \frac{(\epsilon_r - 1)[\epsilon_r \sin^2 \theta_0 + (\epsilon_r - \sin^2 \theta_0)]}{[\epsilon_r \cos \theta_0 + (\epsilon_r - \sin^2 \theta_0)^{1/2}]^2}, \quad (4)$$

$$\alpha_{HV} = \alpha_{VH} = 0. \quad (5)$$

In Eq. (2),  $A$  is a factor related to the range from the antenna to the scatterer, and  $\phi_0(z_0)$  is the topographic phase determined by the ground surface position  $z_0$ .  $W_r$  and  $W_\eta$  are the range and azimuth resolution functions. The third line describes the slight surface scattering, which is consistent with the small perturbation method shown by Ulaby et al., where  $W_P$  is the power spectrum of roughness, and  $k_0$  and  $\theta_0$  are the wave number and incident angle, respectively.  $\langle \alpha_{\hat{p}_1, \hat{i}_1} \alpha_{\hat{p}_2, \hat{i}_2}^* \rangle$  contains the complex dielectric constant  $\epsilon_r$  and the incident angle parameters as indicated in Eqs. (3) and (4).

The normalized interferometric cross-correlation from Eq. (2) for a direct ground scenario is then given by

$$\frac{\langle \hat{p} \cdot \vec{E}_{\hat{i}_1}(\vec{R}_1) \hat{p} \cdot \vec{E}_{\hat{i}_2}^*(\vec{R}_2) \rangle}{\sqrt{\langle |\hat{p} \cdot \vec{E}_{\hat{i}_1}(\vec{R}_1)|^2 \rangle} \sqrt{\langle |\hat{p} \cdot \vec{E}_{\hat{i}_2}(\vec{R}_2)|^2 \rangle}} = A_r e^{i\phi_0(z_0)} \frac{\langle \alpha_{\hat{i}_1} \alpha_{\hat{i}_2}^* \rangle}{\sqrt{\langle |\alpha_{\hat{i}_1}|^2 \rangle} \sqrt{\langle |\alpha_{\hat{i}_2}|^2 \rangle}}. \quad (6)$$

In Eq. (6),  $\alpha_{\hat{i}_1}$  and  $\alpha_{\hat{i}_2}$  represent the corresponding parameters determined by the soil water dielectric constant of two observation times  $\hat{i}_1$  and  $\hat{i}_2$ . This has different forms for HH and VV polarizations. As to the relations between the dielectric constant of soil  $\epsilon_r$  and the volumetric

water content  $M_v$ , the widely applied dielectric model can be found in Ref. 16. The imaginary part of the complex dielectric constant is assumed to be 10% of the real part.<sup>17</sup>

It can be easily found that the phase of normalized interferometric cross-correlation is only related to the complex dielectric constant  $\epsilon_r$  of two observations, the incidence angle  $\theta_0$  and the initial phase induced by topography  $e^{i\phi_0(z_0)}$ . We can see from Eq. (6) that only when  $\alpha_{i_1} \neq \alpha_{i_2}$ , i.e., the soil moisture changes between two observations, does the interferometric cross-correlation yield an additional phase item. Thus, it is possible to invert the changes of the soil water content from the phase information. Note that we consider the soil roughness is invariant here because of its relative stability compared to the moisture. In this way, we separate the two major factors influencing the surface backscattering. This is the difficulty in traditional surface parameter retrieval with amplitude information, as the effects caused by those two-dimensional parameters are always complicated when coupled with each other.

Equation (6) reveals the basic relationship among the interferometric phase, sensor parameters, and surface parameters. Moreover, the increase or decrease trends of soil water content can be identified from the sign of the phase difference. This is very important for monitoring soil moisture changes. Still we should note that with the use of this model, soil moisture change estimations depend on the soil water content at the first time moment  $\hat{t}_1$ , which means a certain amount of interferometric phase difference does not always represent the same amount of soil moisture change.

Until now, the modeling methods that make use of interferometric phase to estimate soil moisture change have not taken the vegetation contribution above the ground into account but have only considered the bare surface or very sparse vegetated surface. The few studies that have focused on the InSAR phase over agricultural fields were concerned with phenomenon analysis rather than a scattering modeling. The reason for this, we believe, is that the interferometric phase characteristics of a bare surface have not been fully understood so far. Additionally, polarimetric information is necessary if the vegetation effects are involved, which means a greater amount of data than single or dual polarizations.

### 3 Simulations

Based on the established relationship between the changes of soil moisture and the varieties of interferometric cross-correlation phase, the sensitivity analysis can be performed in order to understand how many degrees of phase change the model predicts as the soil moisture content varies. In addition, it is also necessary to assess the influence of phase accuracy. In another word, the phases caused by a soil moisture change smaller than the system's measurement ability cannot be feasibly inverted. In this section, these two aspects of analysis are discussed.

Referring to the sensitivity of the proposed model, Fig. 1 shows the phase change with the soil moisture variation under an initial soil moisture value of 5% for 30 deg incidence and VV

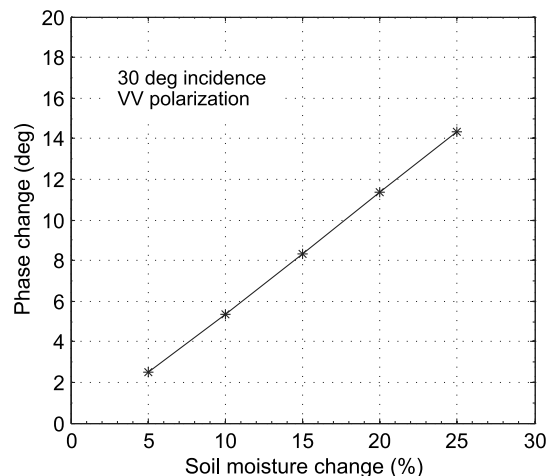
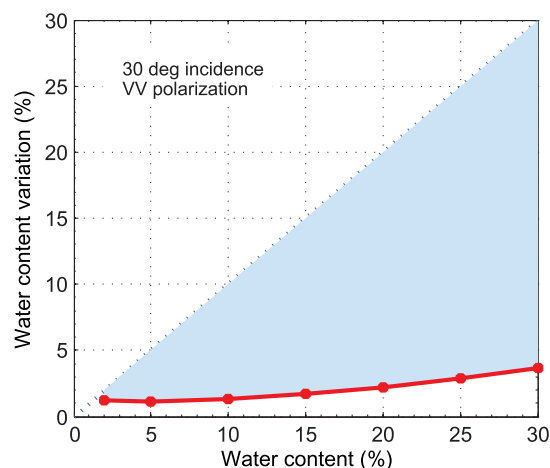


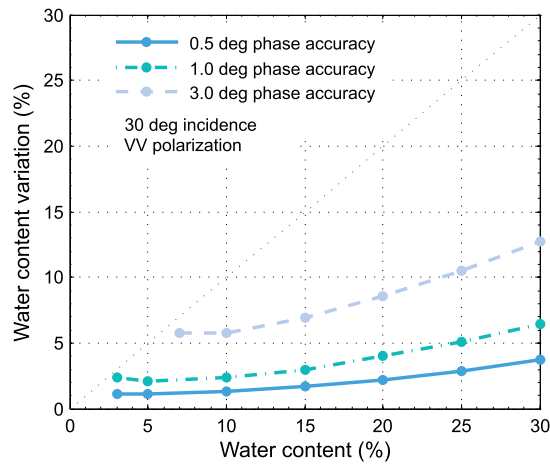
Fig. 1 Phase sensitivity on soil moisture.

polarization. The phase displays a consistent change as the soil moisture increases. Twenty-five percent of soil moisture variation causes 14 deg of phase change. Although larger phase variations are observed in Refs. 13 and 18, our results are in good agreement with the explanations for homogeneous soil bulk given in Ref. 19 by means of a finite difference time domain simulator. They found out that combinations of vertical moisture gradients and small air-filled voids can produce larger phase changes than homogeneous soil. Usually, the inhomogeneities within soil are caused by nonuniform vertical moisture distribution, air voids, small pebbles, etc. In much of the relevant literature, a common assumption made implicitly by empirical and explicitly by most theoretical backscatter models at the C-band (6 cm wavelength) is that the soil moisture can be approximated as uniform with depth and that soil inhomogeneities much smaller than the wavelength can be neglected.<sup>19</sup> Further, considering the potential application of grassland drought monitoring in north China, we focus on homogeneous soil for the model study as well as the laboratory experiment in this paper. The reason for this is that, not like the agricultural areas studied in Refs. 13 and 18, the huge area of grasslands in north China have more homogeneous soils. This is due to infrequent plow and irrigation activities on the grasslands in this area; hence, the vertical moist difference as well as the air void effects are much less than those of agricultural fields.

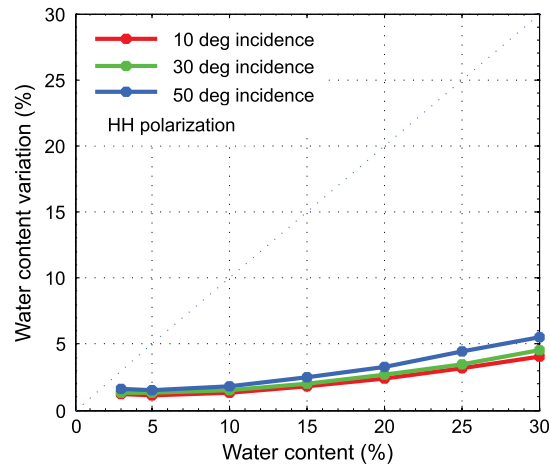
As to the influence of phase accuracy, the range of the soil moisture changes that can be reflected by the phase differences under certain conditions of phase accuracy is shown in Fig. 2. Here, the  $x$  axis refers to the initial water content before changes, while the  $y$  axis represents the amount of water content change. A 0.5 deg phase accuracy is considered. The red line depicts the boundary of the 0.5 deg phase difference. Hence, the blue area above the line shows the soil moisture change amount that causes a phase difference  $>0.5$  deg. Usually, soil moisture of 1 to 30% is the value of most natural soil surfaces and also the range of our interest. For instance, with a 30 deg incident angle and VV polarization, soil moisture changes from 3.7 up to 30% can be observed with an initial moisture of 30%. The higher the phase accuracy, the larger the range of soil moisture changes that are observed. Figure 3 shows the influences of phase accuracy on the feasible inverted ranges of soil moisture change. This figure presents the same results as Fig. 2. In fact, for the experiment implemented in the laboratory in Sec. 5, the phase accuracy can reach a level of 0.1 deg. Under this condition, the curved line in Fig. 3 falls to lower than 1% for any initial soil moisture. This means the variations of 1% water content can be obtained through the computation of the interferometric cross-correlation phase. We have to agree that the ground-based system can achieve much higher phase accuracy than airborne/spaceborne ones. However, for drought monitoring applications, it is not necessary to invert each 1% water content variation. Even the *in situ* time domain reflectometry (TDR) measurements have errors of up to this level. Here, we simulated the case of 3 deg phase accuracy and included it in Fig. 3. For example, with the initial soil moisture of 15%, those changes  $>7\%$  could still be inverted by the use of the proposed model. Besides, theoretical scattering models



**Fig. 2** Feasible inverted range of the soil moisture changes by the variation of interferometric phase.



**Fig. 3** Influences of system phase accuracy on the feasible inverted range of the soil moisture changes.



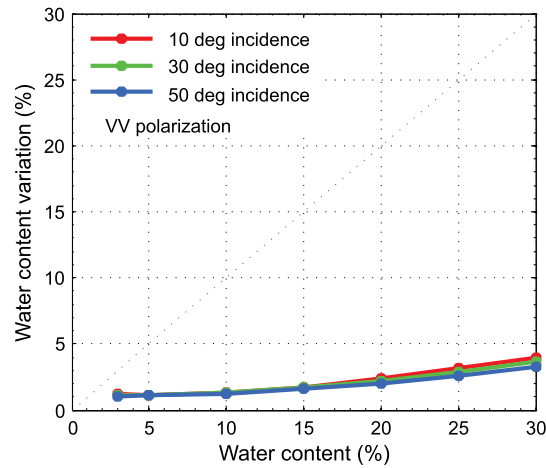
**Fig. 4** Influences of incidence angle on the feasible inverted range of the soil moisture changes for HH polarization.

usually have to be adjusted by empirical parameters when applied to specific data. It is thought that the basic relationship is proposed with the understanding of a scattering mechanism, which needs to be improved according to certain data.

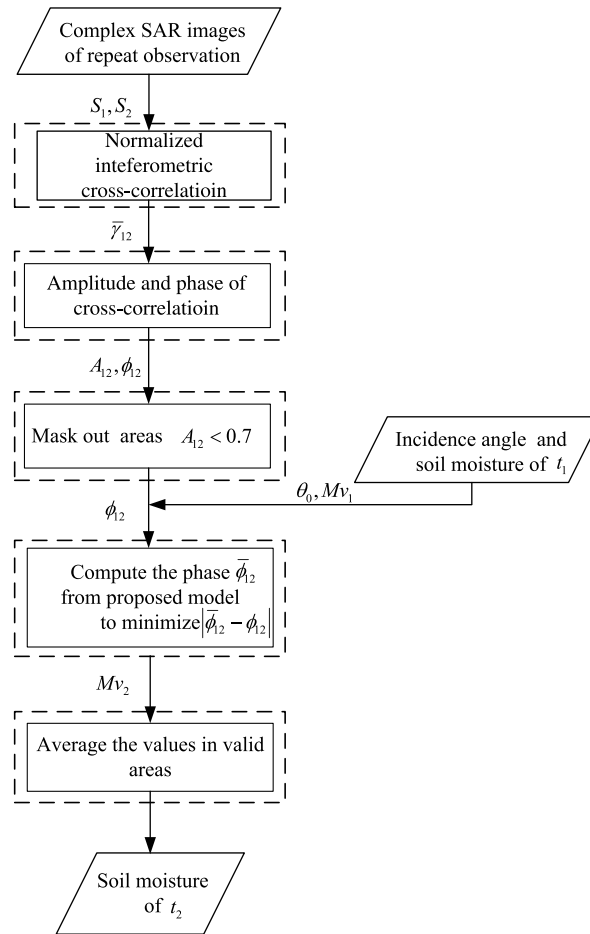
Furthermore, the influences of incidence angle and polarization are analyzed in Figs. 4 and 5, which have the same meaning as Fig. 2. It is clear that VV polarization has a larger capability to estimate soil water changes according to the proposed coherent scattering model. The feasible inverted range does not change as much as for HH polarization with different incident angles. Therefore, VV polarization is selected for further analysis and experiments.

#### 4 Inversion Scheme

On the basis of the proposed scattering model, an inversion scheme is developed for the application of soil moisture change detection, given in Fig. 6. It should be noticed that this scheme can be applied to two arbitrary complex SAR images,  $S_1(x, y)$  and  $S_2(x, y)$ , from repeat observations as long as coherence exists between them. First, the normalized interferometric cross-correlation  $\gamma_{12}(x, y)$  is computed for each pixel. Then the amplitude  $A_{12}(x, y)$  and  $\phi_{12}(x, y)$  are obtained, respectively. After masking out pixels with amplitude  $A_{12}(x, y)$  smaller than a certain value, for each pixel in the valid area, the soil moisture value of  $t_2$  is calculated according to the proposed coherent scattering model, incidence angle, and the soil moisture value of  $t_1$ .



**Fig. 5** Influences of incidence angle on the feasible inverted range of the soil moisture changes for VV polarization.

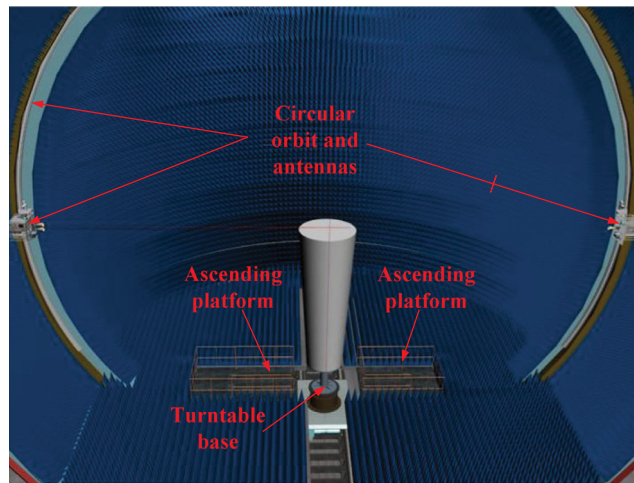


**Fig. 6** Inversion scheme based on the proposed model.

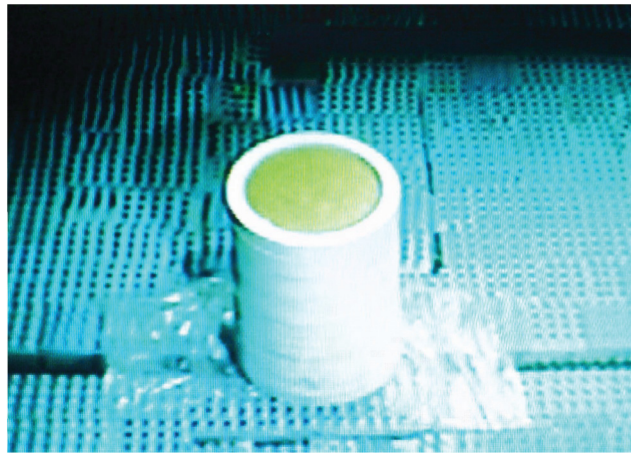
## 5 Experiments and Discussions

The experiment was designed and implemented in the anechoic chamber of Science and Technology in the Electromagnetic Scattering Laboratory in China. The chamber provides a highly controlled radar measurement environment; the structure is shown in Fig. 7. Figure 8 shows the picture of the soil sample in its measurement position, within a cylinder container





**Fig. 7** Structure of the anechoic chamber.



**Fig. 8** Soil sample in its measurement position.

of 1-m inside diameter above the turntable base. This container is made of polystyrene foam. Its dielectric constant is very small, close to 1; hence, its influence on scattering can be neglected. Inside, the depth of the soil sample is 13 cm, with a slight roughness on the surface.

Radar measurement was carried out in step frequency mode from 2 to 3 GHz at a 15 MHz interval, with a distance of 8.722 m between the antenna and the center of the soil surface. In order to increase the signal-to-noise ratio of the scattered wave by soil, the measurement was taken for each azimuth angle with an interval of 0.1 deg for the whole range of 360 deg. In our designed experiment, the incidence angle is set to be 30 deg.

To assess the phase stability of the measurement system before the soil sample measurement, a metal ball of 50 cm diameter was measured two times at a time interval of 30 min. Following that, the soils with different water content were observed four times. Among these measurements, water was added into the soil sample gradually, so the soil moisture increased accordingly. There were 20 min between each watering activity and the microwave measurement in order to assure the stable state of the water in the soil. TDR 300 was used for the ground truth measurement of the soil volumetric water content each time after microwave measurement. Here, five sample values from different positions in the container were recorded and averaged for further study.

The data processing flowchart is given in Fig. 9. The radar data are first processed for circular SAR imaging. In the metal ball experiment, the phase difference between two images is no larger than 0.1 deg. This means that the system stability is quite high. Then the soil measurement data are processed, and the circular imaging results are shown in Fig. 10. We can see the changes of backscattering due to soil moisture variations. To simplify the statement, the four times of radar

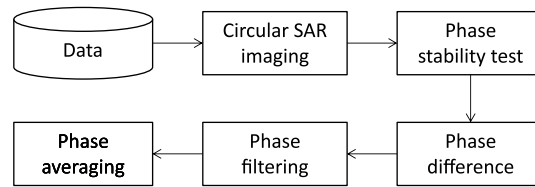


Fig. 9 Data processing flowchart.

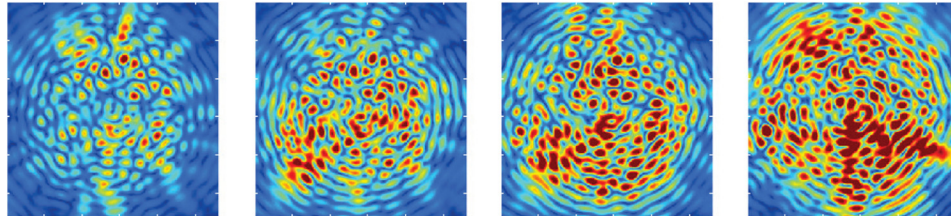


Fig. 10 Circular imaging results of soil sample (the soil moisture increases from left to right).

observations are marked as 0, 1, 2, 3. Thus, the phase differences between each image 1, 2, 3 and the first image 0 are calculated and filtered. A mask is employed to remove the pixels corresponding to the side areas with no soil sample and the pixels with low coherence, or a small amplitude. Because the size of the soil sample is limited, and from the viewpoint of application, the whole sample can be considered as one point of effective observation; the phases in the whole valid area are averaged to obtain the final phase value.

At the same time, the phase changes modeled in Eq. (6) are computed by the use of ground truth measured soil moisture values and the incident angle parameter. Comparison results are shown in Table 1 when the coherence threshold is 0.7 and number of looks equals to 9. It is obvious that the proposed model achieved good agreement with the microwave measurements for the phase differences induced by soil moisture changes. According to the inversion scheme proposed in Sec. 4, the soil moisture values are inverted from the interferometric phase and the initial soil moisture value of 5.9%. Then the results are compared with the *in situ* measurements, as given in Table 2.

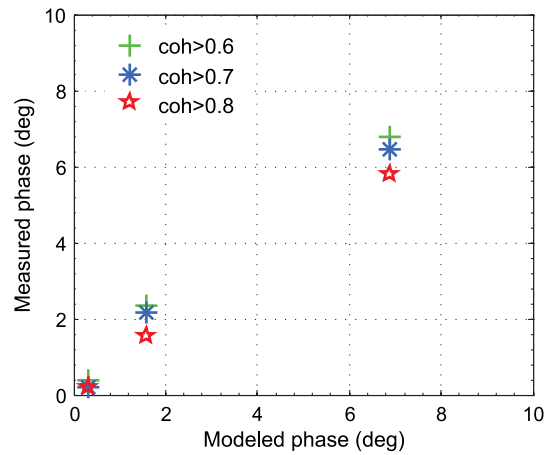
Figures 11 and 12 show the measured phase dependency on coherence and the number of looks in regard to its stability. In Fig. 11, when the number of looks equals to 9, the measured phases obtained from pixels with coherence >0.8 are relatively smaller than those with

Table 1 Comparison of the phase differences between the model and measurements (degrees).

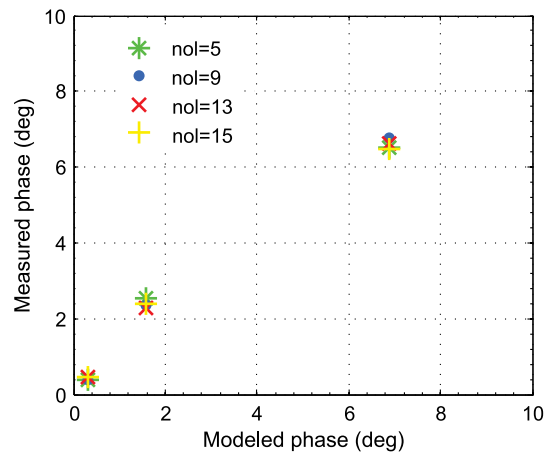
	0 to 1	0 to 2	0 to 3
Modeled phase	0.32	1.59	6.88
Measured phase	0.21	2.17	6.44
(Measured std deviation)	(0.16)	(0.24)	(0.26)

Table 2 Comparison of the soil moisture values between inversion and *in situ* measurements (percentages).

	$t_1$	$t_2$	$t_3$
Measured soil water content	6.6	9.3	19.1
Inverted soil water content	6.4	10.4	18.3
(Inverted std deviation)	(0.42)	(0.54)	(0.50)



**Fig. 11** Phase dependency on coherence (number of looks is 9).



**Fig. 12** Phase dependency on number of looks (coherence threshold is 0.6).

coherence  $>0.6$ . This is because the larger moisture changes, which induce a larger phase difference oppositely, which will result in lower coherence. In other words, the moisture change is a type of decorrelation source, this the threshold of coherence should not be set high. Otherwise, the pixels with large phase differences are filtered out and then phase values tend to be smaller. In our laboratory experiment, this threshold is better when it is no larger than 0.7. Figure 12 presents the measured phase dependency on the number of looks when the coherence threshold is set to be 0.6. There is no clear trend that can be observed when the number of looks varies, and all the phase values are very close to the modeled one. However, in the case of a high coherence threshold, it is found that the deviations between the modeled and measured phase are much larger. Therefore, the coherence threshold should be selected carefully in the process of interferometric phase computations. The standard deviations of phase differences are obtained among all the phase results under coherence thresholds of 0.7/0.6/0.5 when the number of looks equals 5/9/13/15, respectively. The values are added in the brackets of Table 1. Accordingly, Table 2 includes the deviation values of inversion as well.

In the above experiment with the S-band, the proposed model based on a slight roughness surface assumption could explain the observed phases, although much larger phase variations are obtained in the studies of Refs. 13 and 18. In Ref. 13, the authors assumed the only-volume model plus a flat surface, while the authors of Ref. 18 examined two airborne data sets and then concluded the volume effects are the main contributors to the interferometric phase. We found that the experiments in these two papers are all implemented on agricultural fields, which is different from our potential application object—the grasslands of north China. There are

almost no plow and irrigation activities in this area; hence, the inhomogeneities such as vertical moisture difference as well as the air void effects are much less than those in agricultural fields. In addition, the penetration depth of the S-band or even the L-band is quite limited. It is usually <5 cm except for very dry soil. The concerned soil moisture values are also those in the upper surface with a depth of several centimeters in practical applications. According to Ref. 19, moisture variations in uniform homogeneous soil result in much smaller interferometric phase than those in inhomogeneous soil with vertical moisture gradients and small air-filled voids. Therefore, we believe the surface scattering is the major factor that should be considered in our potential application and focus on it in this study. However, it is definitely our future work to consider both surface and underground volume contributions with more inhomogeneous soil within this topic of interferometric phase study for soil moisture change detection.

The grassland area in Inner Mongolia of north China covers more than 80 million hectares and it almost extends from the northwest to then northeast of China. Because of overstocking and drought hazards, severe degeneration has taken place in large areas of grasslands in recent decades, and the vegetation covered land is increasingly becoming bare or sparsely vegetated soil surface. Under such circumstances, our proposed method is proper for use, especially when a lower-frequency microwave is transmitted, which could penetrate sparse vegetation and receive backscattering from the soil surface. Another characteristic of the grassland in Inner Mongolia is that its roughness is relatively small and stable. This means that the method of using time series InSAR phase is applicable. Additionally, when the microwave of a longer wavelength is used, the normal scale roughness of grassland becomes relatively small so that the assumption of a small perturbation method can be satisfied. However, there exist some practical limitations of the proposed method in real applications. The terrain displacement or atmospheric delays should be taken into account when the airborne/spaceborne platform is considered. Since the time span of concerned soil moisture change is from a couple of days to tens of days, the slow displacements of the terrain surface usually on the level of several centimeters per year could be reasonably neglected. As to the phase distortion results from atmospheric effects, it is generally considered that using scenes acquired under anticyclonic conditions and/or at night can help reduce atmospheric effects rather than daytime acquisitions, due to the relative inactivity of vegetation and a more stable atmosphere at night. Meantime, the variation in phases caused by atmospheric heterogeneities is typically of the order of several kilometers. According to this phenomenon, the use of a persistent scatter technique in neighboring areas where scatterers are not affected by soil moisture such as rock or buildings, could show the atmosphere influence on interferometric phase as a good reference. Since the atmospheric phase is random compared to soil moisture change, we can also use multitemporal data up to tens of scenes to eliminate it from the interferometric observations. Soil moisture change is consistent with the local precipitation. Another limitation is vegetation. This is due to the fact that the vegetation effects cannot be neglected in areas with dense grass. In this case, a new model has to be studied, probably by use of the polarimetric InSAR phase information.

## 6 Conclusion

A coherent scattering model is proposed for soil moisture change detection using InSAR phase in this paper. It reveals the basic relationship between interferometric phases with system parameters and surface parameters, and is a promising tool for the sensitivity analysis of system parameters in the InSAR phase-based soil moisture change estimation. Simulations on the developed model show us the phase sensitivity on soil moisture variation as well as the influences of system phase accuracy, polarization, and incidence angle on the invertible ranges of soil moisture change. VV polarization is employed because of its larger ranges than HH polarization. Experiments designed especially for the model in an anechoic chamber are implemented and achieve good agreement between the coherent model and the real data measured in anechoic chamber. Phase stability with different coherence thresholds and numbers of looks is analyzed, and the results show that the coherence threshold should not be set high. We believe this interferometric phase-based soil moisture change detection model is promising for drought monitoring on grasslands. More experiments should be implemented for different observation parameters and soil parameters in the future.

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