Theoretical Study of Global Sensitivity Analysis of L-Band Radar Bistatic Scattering for Soil Moisture Retrieval

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Abstract—This letter explores the optimal bistatic radar configurations for bare soil moisture retrieval at L-band using a global sensitivity analysis method, the extended Fourier amplitude sensitivity test (EFAST) algorithm. Complete sets of bistatic scattering, covering a wide range of geometric parameters and ground surface conditions, are simulated by the well-established advanced integral equation model. The sensitivity of radar bistatic signals to soil moisture and surface roughness, and the interactions among the parameters are quantified using the EFAST algorithm. The results show that in bistatic scattering, VV polarization has notably higher sensitivity to soil moisture than HH polarization, particularly at large incident angles. For VV polarization, as incident angle increases, the sensitivity zone of soil moisture expands and shifts toward the forward direction, specifically at small azimuth scattering angles and large scattering angles, thereby becoming promising configurations for soil moisture retrieval. For HH polarization, in contrast, the sensitive area gradually moves to the backward direction as incident angle increases, and an intermediate incident angle (e.g., $40^\circ$) is recommended for retrieving soil moisture by considering both sensitivity strength and parameter interaction effects.

Index Terms—Bistatic scattering, EFAST, radar response, sensitivity analysis, soil moisture, surface roughness.

I. INTRODUCTION

Soil moisture is well recognized as a pivotal parameter to link the water, energy, and carbon cycle [1]. The importance of estimating soil moisture in a bistatic mode has attracted considerable attention in recent years, as bistatic measurements open new opportunities to decouple the effects of soil moisture and surface roughness which is a very tricky issue in soil moisture estimation using traditional radar backscatter. Global navigation satellite signal reflectometry (GNSS-R) is an emerging bistatic radar technique that provides the only satellite bistatic radar observations for soil moisture detection up to now. The potential and effectiveness of GNSS-R in soil moisture estimation have been extensively investigated in recent years (see a comprehensive review in [2]). However, these efforts mostly focus on the specular region due to received power considerations, and the optimal bistatic radar configurations, especially geometries that are outside of the plane of incidence for soil moisture estimation, are still rarely explored.

Aside from GNSS-R (see [3]–[7]), only very limited theoretical studies (see [8], [9]) have investigated the benefit of bistatic measurements for inferring soil moisture under various geometric configurations. In these studies, the advanced integral equation model (AIEM) [10] is adopted to simulate bistatic scattering coefficients, and a local sensitivity analysis (LSA) is employed to investigate the sensitivity of simulated scattering signals to the surface parameters. The potential optimal bistatic radar configurations are then determined based on the results of LSA. However, LSA can analyze only one parameter in a model at a time by fixing the other parameters as a constant value and cannot quantify the effects of interactions among the parameters [11], [12]. It is commonly known that many parameters (e.g., soil moisture and surface roughness) usually vary simultaneously in the natural world. In addition, it may be questionable to apply LSA in a nonlinear and nonmonotonic model, such as the AIEM scattering model. Compared with LSA, the global sensitivity analysis (GSA) can quantify the sensitivity when all the parameters simultaneously vary within their defined ranges. Moreover, it considers the interaction effects of the parameters on the model outputs and can be applied to nonlinear and nonmonotonic models effectively [11]. This offers us an opportunity and motivation to fully explore the optimal bistatic scattering geometry for soil moisture retrieval by using the GSA method.

In this letter, we investigate, for the first time, the possible optimal radar bistatic configurations for bare soil moisture retrieval based on a GSA method, i.e., the extended Fourier amplitude sensitivity test (EFAST) algorithm [11], [12]. The EFAST method combines the high efficiency of FAST and the capacity for total effect computation of SOBOL, and it is recognized as one of the most elegant methods for SA. Though the EFAST algorithm has been used for model simplification and calibration, it has not been applied to identify the sensor configuration. The AIEM model is adopted to simulate complete sets of bistatic scattering coefficients, covering a wide range of surface roughness and dielectric parameters. We focus on L-band (i.e., $f = 1.26$ GHz) since it is considered the optimal band for topsoil moisture monitoring due to its...
capability of being nearly unaffected by atmospheric conditions and penetrating vegetation with low to moderate coverage [13]. The results are analyzed and interpreted in detail, and the recommendations of the possible optimal bistatic radar configurations for soil moisture retrieval are also provided.

II. MODEL AND METHOD

A. AIEM Model

The simulation of bistatic scattering coefficients from bare soil surface is accomplished by the single scattering AIEM model as it is capable of predicting the scattering behavior of rough surfaces for any possible scattering direction. The AIEM is an improved and updated IEM model, which is currently one of the most widely used analytical models that seamlessly bridges the gap between the small perturbation method and Kirchhoff approximation models. The validity of single scattering AIEM in simulating the bistatic scattering coefficient has been evaluated and examined in many studies (see [14], [15]). The results showed that the single scattering AIEM model can well reproduce the bistatic scattering coefficient over a wide range of geometric parameters and ground surface conditions. In our study, we consider the total scattering. The coherent scattering can be derived from Ulaby et al. [16]. Detailed descriptions of the AIEM can refer to [10], [14], and [15].

Fig. 1 illustrates the geometry of bistatic scattering. As an incident plane wave impinges onto a rough dielectric surface, the upwardly scattered wave may propagate in all directions of the upper half-space. In a traditional monostatic radar system, the transmitter and receiver are located at the same position, i.e., $\theta_i = \theta_t$ and $\phi_s = 180^\circ + \phi_t$. For a bistatic radar system, the transmitter and receiver are spatially separated. Note that the incident plane is $\phi_s = 0^\circ$ or $180^\circ$ and the specular regions are $\theta_s = \theta_i$ and $\phi_s = 0^\circ$.

B. EFAST Method

In this letter, a GSA method, namely, the EFAST algorithm is used to quantify the sensitivity of radar bistatic scattering coefficients to soil moisture and surface roughness, and the interactions between the parameters at various bistatic configurations. The EFAST belongs to the variance-based SA method, and it combines the advantages of both the high sampling efficiency of the FAST algorithm and the inclusion of parameter interaction effects from the Sobol’s method.

In the EFAST, two sensitivity indices (SIs), namely, the main sensitivity index (MSI) and the total sensitivity index (TSI), and parameter interaction effects (TSI–MSI) are computed by analyzing the variance of the input parameters on the output as

$$\text{MSI}_i = \frac{\text{Var}_i(Y)}{\text{Var}(Y)}$$

$$\text{TSI}_i = 1 - \frac{\text{Var}(-i)(Y)}{\text{Var}(Y)}$$

$$\sum_{j=1, j \neq i}^n S_{i,j} = \text{TSI}_i - \text{MSI}_i$$

where $Y$ represents the model output, $\text{Var}_i(Y)$ is the estimated conditional variance of the $i$th factor, $\text{Var}(-i)(Y)$ is the estimated conditional variance except for the $i$th factor, and $\text{Var}(Y)$ is the variance of output $Y$. MSI$_i$ is the main (or first order) sensitivity index of the $i$th factor, which represents the main contributions of each input parameter to the variance of the model output, and TSI$_i$ is the total (including higher order effects) sensitivity index of the $i$th factor, which considers the interactions among parameters. If MSI$_i$ differs from TSI$_i$, interactions between parameters exist. Both MSI$_i$ and TSI$_i$ range between 0 and 1; higher MSI$_i$ and TSI$_i$ values suggest more significant effects of the $i$th factor on the output. In (3), $S_{i,j}$ represents the parameter interaction effects. For a detailed description and mathematical derivations of EFAST, readers are referred to [11] and [12].

III. RESULTS AND DISCUSSION

Previous studies found that the parameter sample size $N_s$ affects the convergence of the SIs and the computational cost [17], [18]. Thus, to ensure a stable and reliable SA result with a relatively high computational efficiency, we conduct simulation runs to examine the influence of $N_s$ on the SIs in the AIEM scattering model. We found that $N_s = 4100$ is sufficient to make the results convergent. Thus, this value is adopted in our experiments. In addition to the sample size, the range and distribution of every input parameter should be determined for performing the EFAST algorithm. In [17] and [18], the parameter distribution had little impact on the SA results, and a uniform distribution was commonly assumed for the input factors; therefore, a uniform distribution is used in this letter for all the input parameters.

Three dominant parameters, including soil moisture, root-mean-square height (RMSH), and correlation length (CL), are selected since they play the most significant roles in radar signals [9]. Their distributions and ranges in the AIEM are listed in Table I. We set a wide range for these parameters

<table>
<thead>
<tr>
<th>Parameter (unit)</th>
<th>Definition</th>
<th>Distribution</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM (m$^3$ m$^{-3}$)</td>
<td>Surface soil moisture</td>
<td>uniform</td>
<td>0.01–0.5</td>
</tr>
<tr>
<td>RMSH (cm)</td>
<td>Root mean square height</td>
<td>uniform</td>
<td>0.1–3</td>
</tr>
<tr>
<td>CL (cm)</td>
<td>Correlation length</td>
<td>uniform</td>
<td>2.5–35</td>
</tr>
</tbody>
</table>

TABLE I

INPUT PARAMETERS AND THEIR DISTRIBUTIONS AND RANGES IN THE AIEM SCATTERING MODEL.
in the model to ensure a comprehensive understanding of their impacts on the model outputs. We conduct SA tests with $0^\circ \leq \theta_i \leq 60^\circ$ and $0^\circ \leq \phi_s \leq 180^\circ$ for three typical incident angles: 20°, 40°, and 60° on the whole upper half-space. (The results for 30° and 50° are very similar to those for 20°, 40°, and 60°; thus, they are not presented in the study.) The exponential correlation function is found to be capable of characterizing natural land surface at L-band [14], [19], and thus is adopted in our study. We compute the SIs (TSI and MSI) and their difference (parameter interaction effects) for soil moisture, RMSH, and CL regarding to HH- and VV-polarized bistatic scattering coefficient, respectively. The distributions of MSI and TSI on the whole upper half-space are very similar, and thus we only present the results of MSI. In our study, the SA is carried out based on the decibel values.

A. Sensitivity of VV-Polarized Bistatic Scattering to Surface Parameters

Fig. 2 presents the distributions of MSI of soil moisture, RMSH, and CL at VV-polarization on the whole upper half-space as a function of scattering angle $\theta_s$ and azimuth angle $\phi_s$ for different incident angles $\theta_i$, i.e., 20°, 40°, and 60° from top to bottom for an exponential correlated surface. As the incident angle increases, it is found that the sensitive zone of soil moisture is closer to the forward direction at small azimuth scattering angles and large scattering angles (i.e., farther away from the orthogonal plane). In such case, the scattering signals are measurable and insensitive to RMSH and CL, thereby constituting promising bistatic configurations for soil moisture estimation. In addition, the sensitivity of RMSH always decreases near the specular region (i.e., $\theta_i = \theta_s$) and is independent of incidence angles, and yet the sensitivity of CL in these regions always increases. No obvious increase in the MSI of soil moisture near the specular region is observed. This indicates that the specular region or quasi-specular region may be not very suitable for soil moisture estimation due to the influence of CL. In previous SA studies, CL is often, for the sake of simplicity, assumed to be constant (or to have very limited values). This assumption may produce biased SA results. Consequently, it is vital to apply a GSA method in nonmonotonic and nonlinear models, such as those for soil moisture estimation from bistatic scattering.

B. Sensitivity of HH-Polarized Bistatic Scattering to Surface Parameters

We then investigate the sensitivity pattern of soil moisture, RMSH, and CL on the whole upper half-space for HH-polarized scattering coefficients, shown in Fig. 3. The sensitivity distribution of soil moisture at HH polarization is generally different from that at VV polarization. The highest MSI values of soil moisture are very close to the orthogonal plane ($\phi_s = 90^\circ$), which is in line with the SA results at VV polarization. As the incident angle increases, the sensitive zone of soil moisture gradually shifts toward the backward direction. This is opposite to the results that were obtained for VV polarization (the highest MSI of soil moisture is located in the forward direction),
particularly at large incident angles. Unlike at VV polarization, the increase of incident angle does not lead to a monotonic increase in the sensitivity of soil moisture at HH polarization. The sensitive zone of soil moisture increases at small to intermediate incident angles (from 20° to 40°), and then decreases at large incident angles (e.g., 60°). Accordingly, an intermediate incident angle (e.g., 40°) is recommended for soil moisture retrieval from HH-polarized bistatic scattering.

However, the MSI values of soil moisture at HH polarization are generally small compared with those at VV polarization on the whole upper half-space. Therefore, bistatic VV polarization is preferable to HH polarization for soil moisture estimation, in particular at large incident angles. Although the bistatic sensitivity distributions of RMSH and CL at HH and VV polarizations are somewhat different, similar phenomena can be observed. The sensitivity of RMSH is reduced near the specular region, where the sensitivity of CL is generally enhanced, regardless of the incident angles.

C. Parameter Interaction Effects for VV Polarization

As stated before, a unique advantage of EFAST compared with LSA is that it can compute the interaction effects (expressed by TSI minus MSI) among the input parameters. In this section, we examine the interactions between soil moisture/RMSH/CL and other parameters for VV polarization as a function of scattering angle $\theta_s$ and azimuth angle $\phi_s$, with incident angles ranging from 20° to 60°, shown in Fig. 4. For all the three parameters, the interaction effects are generally small and close to zero for most parts of the whole upper half-space. The maximum interaction effects of soil moisture are very close to the orthogonal plane at small incident angles and then shift toward the forward direction as the incident angle increases. This phenomenon is similar to the sensitivity trend of soil moisture, displayed in Fig. 2. Moreover, the interaction effects of all the three parameters increase slightly as the incident angle increases.

It is very difficult to identify and quantify the sources of the interactions. The interactions represent the confounding effects of multiple parameters on the model outputs [11]. However, it is not generally possible to determine which parameters are involved, and to what extent, in the interactions. Therefore, from the perspective of the retrieval algorithm, we expect a configuration at which the MSI of the target parameter (e.g., soil moisture) is as large as possible (e.g., close to 1), while the interactions of the target parameter with other parameters are as small as possible (e.g., close to 0). In conjunction with Figs. 2 and 4, most of the sensitive zones and maximum interaction zones of soil moisture are overlapped at small incident angle (e.g., 20°). Therefore, aside from the detectability issue of echo signals at these configurations, the interactions among the parameters should be decoupled before reliable soil moisture retrieval can be attempted. Furthermore, though the confounding effects of soil moisture with surface roughness slightly increase as the incident angles increase, these “perturbing zones” are much smaller than the sensitive zones of soil moisture. This phenomenon becomes more conspicuous at large incident angle (e.g., 60°). Based on these findings, we propose configurations of bistatic measurements at large incident angles, large scattering angles, and small scattering azimuth angles for soil moisture retrieval at VV polarization. In these configurations, the high sensitivity of radar signals to soil moisture is preserved, while the confounding effects from surface roughness are greatly avoided, and thus have great potential for soil moisture estimation.

D. Parameter Interaction Effects for HH Polarization

Fig. 5 illustrates the interaction effects of soil moisture, RMSH, and CL with other parameters for HH polarization. In general, the difference between TSI and MSI for all the three parameters is very small at L-band. In addition, the distributions of interactions of soil moisture and RMSH are very similar, and the interaction effects of these two parameters are generally higher than those of CL, which is coincident...
with the results of VV polarization. In conjunction with Figs. 3 and 5, the high sensitive zone of soil moisture almost overlaps with the strong interaction regions of soil moisture at small incident angle (e.g., 20°). Both regions are very close to the orthogonal plane. Consequently, they are not appropriate for soil moisture retrieval. The interaction effects of soil moisture with other parameters are comparable to the MSI of for soil moisture retrieval. The interaction effects of soil moisture at a large incident angle (e.g., 60°), suggesting that it difficult to decouple the effects of soil moisture and surface roughness. At an intermediate incident angle (e.g., 40°), the interaction zones are generally smaller than the sensitive zones of soil moisture. Thus, an intermediate incident angle seems to be the optimal choice for soil moisture retrieval at HH polarization.

IV. CONCLUSION

This letter explores the optimal radar bistatic configurations for bare soil moisture retrieval at L-band using a GSA technique. The theoretical AIEM model is adopted to simulate bistatic scattering coefficients under various geometrical parameters and surface conditions. The EFAST algorithm is used to quantify the sensitivity of radar response to soil moisture and surface roughness, and the interactions between the parameters. It is the first time to use a GSA method to identify the bistatic scattering geometry that provides the best soil moisture estimates. We believe that our work provides a new way to identify the possible radar bistatic configurations for investigating geophysical parameters (not only for soil moisture but also for vegetation biomass, wind speed, and snow depth).

The results show the SIs (TSI, MSI, and their difference) of soil moisture and surface roughness vary significantly for different bistatic configurations. In bistatic scattering, VV polarization is generally more sensitive to soil moisture than HH polarization, and the sensitivity becomes more remarkable as the incident angle increases. Both VV- and HH-polarized bistatic scattering show the highest sensitivity to soil moisture near the orthogonal plane at small incident angle (e.g., 20°), but with very low returned signals and undesirable interaction effects. For VV polarization, the sensitive zone of soil moisture increases significantly as the incident angle increases. Moreover, these sensitive zone shifts toward the forward direction with small azimuth scattering angles and large scattering angles (i.e., farther away from the cross plane), particularly at large incident angles (e.g., 60°). The scattering signals are measurable and preserve rich information on soil moisture at these geometries, making them favorable configurations for soil moisture retrieval. For HH polarization, as the incident angle increases, the high-sensitivity zone of soil moisture gradually becomes closer to the backward direction with large azimuth scattering angles and large scattering angles. However, an intermediate incident angle (e.g., 40°) is recommended for retrieving soil moisture when using HH-polarized bistatic scattering because low sensitivity is exhibited at small (e.g., 20°) and large incident angles (e.g., 60°) and in the presence of interaction effects.

Due to the complexity of a bistatic radar system, future efforts should focus on examining the technical feasibility of the identified configurations by considering specific receiver sensitivity, dynamic range, antenna footprint tracking, and synchronization, among others. To this end, efforts to validate the proposed optimal bistatic radar configurations by conducting indoor and field experiments as well as using real satellite bistatic measurements (e.g., Cyclone Global Navigation Satellite System) will continue in the future.

REFERENCES