# Measuring Surface Roughness Height to Parameterize Radar Backscatter Models for Retrieval of Surface Soil Moisture

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***Abstract*—Surface roughness is a crucial input for radar backscatter models. Roughness measurements of root mean-squared height ($h_{\mathrm{rms}}$) of the same surface can vary depending on the measuring instrument and how the data are processed. This letter addresses the error in $h_{\mathrm{rms}}$ associated with instrument bias and instrument deployment issues such as number and length of measurement transects. It was found that at least 20 transect measurements, 3 m in length, for study sites ranging from 3.5 to 1225 $\mathrm{m}^2$ in size were necessary to get a consistent $h_{\mathrm{rms}}$ measurement. Also, roughness heights of longer transect lengths were highly dependent on the method of detrending the transects. Finally, soil moisture was predicted by inverting the integral equation model using roughness heights taking into account instrument bias, number of measurements, and the detrending method. For common configurations of the Radarsat sensor and reasonable $h_{\mathrm{rms}}$ values, error associated with measurement of $h_{\mathrm{rms}}$ generally exceeded $\pm 20\%$ of soil-moisture prediction.**

***Index Terms*—Integral equation model (IEM), laser radar, modeling, pinmeter, radar imaging, rough surfaces, roughness measurement, soil moisture measurement.**

## I. Introduction

A GREAT deal of progress has been made in the use of images from satellite sensors for mapping surface soil moisture, where surface soil moisture ($m_v$) is the average moisture (cubic centimeter per cubic centimeter) in the top few centimeters of soil over a heterogeneous volume [1]. Active microwave sensors such as synthetic aperture radar (SAR) currently represent the best approach for obtaining spatially distributed surface soil moisture at spatial resolutions of 10–100 m [2]. The magnitude of the SAR backscatter coefficient for bare soil ($\sigma^o$) is related to surface roughness and $m_v$ through the contrast of the dielectric constants of dry bare soil (∼3.5) and water (∼80). Radar backscatter models exist for bare-soil conditions. These radar scattering models generally predict $\sigma^o$ as a function of the sensor configuration and surface conditions and can, thus, be inverted to predict $m_v$. A widely used radar scattering model is the integral equation model (IEM), which characterizes microwave scattering on a theoretical basis to address a wide range of roughness for bare-soil surfaces, which can be inverted to predict soil moisture [3].

TABLE I
THREE RADAR CONFIGURATIONS USED IN THIS LETTER AND THE ASSOCIATED EQUATION FOR CALCULATING $L_c$

| Band | Polarization | Incidence angle | $L_c$ |
|---|---|---|---|
| | | | |
| C | VV | 23° | $e^{1.41*h_{RMS}^{-0.95}}$ |
| C | HH | 39° | $e^{0.91*h_{RMS}^{-0.94}}$ |
| C | HH | 47° | $e^{0.78*h_{RMS}^{-1.23}}$ |

Thus, for robust $m_v$ retrieval from SAR images, it is imperative that surface roughness be measured in a repeatable manner with known bias taken into account. The two most common characterizations of surface roughness are correlation length ($L_c$) and root mean-squared height ($h_{\mathrm{rms}}$)

$$h_{\mathrm{rms}} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(z_i - \bar{z})^2} \tag{1}$$

where $n$ is the number of measurements of the height, $z_i$ is a single measurement, and $\bar{z}$ is the mean of measurements.

Recent studies have offered empirical [4], semiempirical [5], and theoretical [6] approaches that derive $L_c$ directly from a measurement of $h_{\mathrm{rms}}$. Thus, for parameterization of radar scattering models like IEM, it may be possible to characterize surface roughness with only a measurement of $h_{\mathrm{rms}}$. Consequently, this letter focused exclusively on measurement of $h_{\mathrm{rms}}$ with *in situ* instrumentation. $L_c$ values were derived from $h_{\mathrm{rms}}$ using equations developed by Baghdadi *et al.* [4] (Table I). Baghdadi *et al.* developed equations based on ground data to calculate $L_c$ from $h_{\mathrm{rms}}$ for any one radar configuration essentially treating $L_c$ as a calibration parameter based on radar configuration, $h_{\mathrm{rms}}$ and field data, rather than an inherent physical property of the ground surface.

Although much research has focused on measuring roughness height of natural surfaces [7], [8], comparison of measurement techniques and accuracy assessment have not been thoroughly investigated. In this letter, we assessed the issues associated with deployment of the pinmeter and laser scanner and the postprocessing necessary to obtain repeatable measurements of $h_{\mathrm{rms}}$ with known bias over natural surfaces. Specifically, this letter addressed the issues of: 1) bias of the

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TABLE II
CHARACTERISTICS OF THE STUDY AREAS AND SUMMARY OF METHODS

| *Study area* | *Location* | *Area* | *Topography* | *Land Use* | *Number of sites* | *Size of sites* | *Measurement instrument* | *Maximum Number of 1-meter length transect measurements per site* | *Maximum transect length (m)* |
|---|---|---|---|---|---|---|---|---|---|
| Arizona USA | Gravel pit in Walnut Gulch Experimental Watershed | 900 $m^2$ | Rolling | Abandoned gravel pit | 7-12 | 3.5 -18.5 $m^2$ | laser scanner/ pinmeter | 400 laser scanner 7-20 pinmeter | 10 |
| Georgia USA | Little River Experimental Watershed | 334 $km^2$ | Flat | Row crop/forest | 16 | 1225 $m^2$ | pinmeter | 20 | 5 |
| Oklahoma USA | Little Washita Experimental Watershed | 603 $km^2$ | Rolling | Range/Wheat | 18 | 1225 $m^2$ | pinmeter | 20 | 5 |
| Andalucia Spain | Torvizcon Watershed | 100 $km^2$ | Steep | Cultivated Almonds / Vineyards | 12 | 400$m^2$ | pinmeter | 5 | 5 |

measurement instrument; 2) instrument-induced differences in measurements of $h_{\rm rms}$; 3) number of measurements needed to represent surface $h_{\rm rms}$; and 4) effect of transect length and detrending on the processing of $h_{\rm rms}$ measurements. Sensitivity of predicted soil moisture to different methods of measuring $h_{\rm rms}$ was determined using the IEM. This letter focused on the application to natural surfaces, such as the bare soils and sparsely vegetated sites that are most suitable for IEM application. Results are applicable to common radar configurations of the Radarsat sensor (Table I) and reasonable roughness lengths (near 1 cm) for agricultural resources.

## II. INSTRUMENTATION, STUDY AREAS, AND METHODS

The pinmeter used in this letter is a relatively inexpensive and a simple device that holds 101 metal pins loosely on an aluminum plate spaced 1 cm apart for a total transect length of 1 m. The pinmeter is set on the surface to be measured, and the pins slide through the metal plate. The top of the pins create a profile of the surface that is photographed with a digital camera. The ground-based laser scanner used in this letter was the Intelligent Laser Ranging and Imaging System–Three-Dimensional (ILRIS–3D) manufactured by Optech with a vertical accuracy of 0.3 cm, which is confirmed in this letter.

Data were acquired from four different study areas for analysis (Table II). In addition, an office floor was used to assess the bias of the instruments. An abandoned gravel pit in the USDA ARS Walnut Gulch Experimental Watershed in Southeastern Arizona was a completely nonvegetated study area used to compare the two instruments on a natural surface. For the analysis of sample number and the effect of detrending, deploying only the pinmeter instrument, we used two additional data sets from other ARS experimental watersheds and one data set from the Torvizcon watershed in Andalucia, Spain. The ARS study areas were the Little Washita Watershed in Oklahoma and the Little River Watershed in Georgia. All three watersheds in Georgia, Oklahoma, and Andalucia are characterized by production agriculture (including orchards) and pasture lands. Unlike the ARS watersheds, the Torvizcon watershed has extremely rugged topography with slopes on the order of 25%.

Throughout this letter we use the terms study area, site, and transect, as defined here. Within each study area, measurements of roughness were made at numerous sites. For example, in the Arizona study area, there were up to 12 sites that were characterized for roughness, where multiple transects were measured at each site. The transect is the linear distance along the ground that is measured with the pinmeter. One measurement with the pinmeter corresponds to a 1-m transect, since the pinmeter is 1 m long. Transects longer than 1 m were measured with the pinmeter by making consecutive 1-m transects by aligning the location of the first pin of the second pinmeter measurement with the last pin of the first pinmeter measurement and, then, releveling the pinmeter. Consequently, in some analyses, one 10-m transect was also considered as ten 1-m transects. When analysis was done on 1-m transects at a site, the 1-m transects were extracted randomly from the entire data set of that site. Transects from the laser-scanner data were extracted with a computer program.

The four issues in this letter were investigated with data acquired from four study areas at multiple field sites using the same general sampling design. The unvegetated relatively flat surface of the Arizona gravel pit (approximately 100 $m^2$) was measured with the laser scanner. We divided this area into seven sections and took 7–20 pinmeter measurements of each section. At the Georgia and Oklahoma study areas, 16 sites of 1225 $m^2$ area were measured with the pinmeter along four 5-m transects at each site. At each of the 12 sites (400 $m^2$ each) in the Andalucia study area, pinmeter measurements were made along one 5-m transect. The pinmeter measurements at all study areas were oriented parallel to the view angle of the satellite. General methods are summarized in Table II and more detail specific to each analysis is given in the sections with results.

## III. INTEGRAL EQUATION MODEL

The IEM is one of the most widely used radar backscatter models for retrieving surface soil moisture from sparsely vegetated soils [9], [10]. IEM is a mathematical representation of the scattering behavior when radar-transmitted microwave energy hits ground targets and is scattered back to a receiving antenna. The backscatter as quantified by the model is a function of radar-specific parameters such as frequency of transmitted-microwave energy, polarization, and incidence angle. The backscatter is also a function of target-specific factors such as the roughness of the ground surface and moisture contents of the material. The sensitivity of IEM to roughness parameters is well-documented [11]. Soil moisture can be predicted with the IEM by developing lookup tables.

Three lookup tables were generated for three different radar configurations available for the Radarsat SAR sensor (Table I). The exponential autocorrelation function was used when the lookup tables were generated. Throughout this letter, the configurations are referred to as VV_23 (C-band, VV polarization, and 23° incident angle), HH_39 (C-band, HH polarization, and 39° incident angle), and HH_47 (C-band, HH polarization, and 47° incident angle). These configurations were taken from [4], where equations were developed to derive $L_c$ from $h_{\rm rms}$ based on the IEM output and field data (Table I).

## IV. Results

### A. Bias of $h_{\rm rms}$ Measurement Using the Pinmeter and Laser Scanner

The two instruments used for this letter (the laser scanner and the pinmeter) were compared in a controlled environment over a surface with a known roughness to determine measurement bias. At the scale (centimeter to subcentimeter) typically used in the field, a smooth artificial surface has an effective $h_{\rm rms}$ of 0. The smooth surface selected for this analysis was a 2.5-m$^2$ section of an office floor. With the pinmeter, 32 randomly oriented measurements of the floor were made and detrended. The laser scanner was set on a tripod at $\sim$1.5 m above the floor in order to scan it. The laser scanner data set was grided to 1-cm resolution to match the resolution of the pinmeter. The original resolution was 3 mm. From these data, 30 1-m transects were extracted for comparison to the pinmeter data and $h_{\rm rms}$ was calculated for each data set. Each data set was then detrended, and the roughness statistics were again determined.

The average $h_{\rm rms}$ of a smooth detrended surface was 0.15 cm for the pinmeter and 0.35 cm for the laser scanner. Assuming that the floor has an $h_{\rm rms}$ of zero, this is a measure of the positive bias of these two instruments. The bias will have a very significant effect on $h_{\rm rms}$ measurements at low $h_{\rm rms}$ values, which are quite common on natural surfaces. Many natural surfaces, including all but one in this letter, had an $h_{\rm rms}$ of 1 cm or less. For the pinmeter, this bias is most likely due to the camera resolution (one pixel is approximately equal to 0.06 cm) and the fact that the pins are somewhat flexible and, therefore, not absolutely straight. The laser scanner has a precision of 0.3 cm that would translate into a 0.3 cm $h_{\rm rms}$ bias.

### B. Measuring the Roughness of a Natural Surface With a Pinmeter and Laser Scanner

The unvegetated relatively flat surface of the Arizona gravel pit was used for comparison of $h_{\rm rms}$ measurements of a natural surface. For the seven measurement sites, the pinmeter measurements were averaged and detrended for comparison to the laser scanner data. Transects of the laser-scanner data were extracted in the same manner from the same sites in the laser image and, subsequently, averaged and detrended. This resulted in seven sites ranging in size from 3.5 to 18.5 m$^2$ with corresponding pinmeter and laser-scanner measurements.

Comparing $h_{\rm rms}$ measurements with the two instruments at the Arizona gravel-pit study area after adjusting for instrument bias resulted in a fairly good linear relationship with an $R^2$ of 0.60 and a very close one-to-one relationship with a slope of 1.1 and an intercept of $-0.07$ (Fig. 1). This data set consisted of only seven different roughness measurements, and the number of pinmeter measurements for each study site ranged from 6 to 20, with only one site having 20 measurements. To better compare measurements of the pinmeter with the laser scanner, further studies are needed, where more pinmeter measurements are taken in an area with a wider range of roughness values. This issue is discussed further in the section on the minimum number of measurements needed to obtain a representative sample.

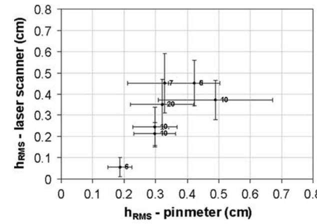


Fig. 1. Pinmeter measurements of root mean-squared height ($h_{\rm rms}$) compared to laser-scanner measurements of the Arizona gravel-pit study area. Error bars are one standard deviation. Numbers indicate number of measurements averaged.

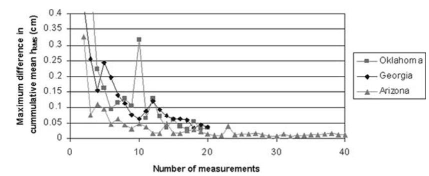


Fig. 2. Maximum difference in the cumulative mean of $h_{\rm rms}$ from measurements of 1-m transects for three study areas: Georgia (total of 16 sites), Oklahoma (total of 16 sites), and Arizona (total of 12 sites). The size of the Oklahoma and Georgia sites was 1225 m$^2$. The size of the Arizona study sites was from 6.2 to 17.6 m$^2$.

### C. Number of Transects Required to Obtain a Representative $h_{\rm rms}$ Value

To determine the number of transects required to obtain a representative $h_{\rm rms}$, we analyzed the data sets from the Arizona study area with the laser scanner and the data sets from the Georgia and Oklahoma study areas with the pinmeter. The following section indicates that transect length should be 3–5 m, but for this analysis, due to lack of number of field measurements at this length, these measurements were treated as 1-m transects for a total of 20 transect measurements for each site within the study area. Theoretically, the results would be similar with 20 5-m transects, but the actual $h_{\rm rms}$ values would be different.

At the Arizona gravel-pit study area, we extracted 40 1-m transects from the laser-scanner data for each site. With these three data sets (two from the pinmeter and one from the laser scanner), we attempted to determine the number of 1-m transect measurements needed to determine a repeatable estimate of surface roughness. First, a cumulative mean for all the sites of the $h_{\rm rms}$ for the 40 1-m transects at the Arizona gravel-pit study area from the laser-scanner data was calculated. Then, the maximum difference of the cumulative mean for the sites was determined. The same was done for 20 transects measured with the pinmeter for each site at the Georgia and Oklahoma study areas.

For the Arizona gravel-pit study area, the difference in the cumulative mean of the $h_{\rm rms}$ dropped to 0.05 cm at 15 measurements regardless of the size of the site, where site sizes ranged from 3.5 to 18.5 m$^2$. This indicated that the number of transects needed to obtain a representative measurement was not related to the size of the site. The same procedure was applied to the Georgia and Oklahoma data, where the size of the all sites was 1225 m$^2$ with the maximum difference in the cumulative mean dropping to 0.05 cm at 20 measurements (Fig. 2). These results are similar to [8] where modeled data were used with a known $h_{\rm rms}$ and correlation length.

TABLE III
ROOT MEAN-SQUARE HEIGHT DETRENDED BY THE LENGTH OF THE TRANSECT AND BY 1-m SEGMENTS FOR FOUR STUDY AREAS

| | Arizona gravel pit | | Georgia watershed | | Oklahoma watershed | | Andalucia watershed | |
|---|---|---|---|---|---|---|---|---|
| Length of transect | Detrended length of transect, $h_{RMS}$ (cm) | Detrended 1 meter segments, $h_{RMS}$ (cm) | Detrended length of transect, $h_{RMS}$ (cm) | Detrended 1 meter segments, $h_{RMS}$ (cm) | Detrended length of transect, $h_{RMS}$ (cm) | Detrended 1 meter segments, $h_{RMS}$ (cm) | Detrended length of transect, $h_{RMS}$ (cm) | Detrended 1 meter segments, $h_{RMS}$ (cm) |
| 1 | 0.4 | 0.4 | 0.6 | 0.5 | 0.6 | 0.6 | 1.8 | 1.8 |
| 2 | 0.5 | 0.4 | 0.7 | 0.6 | 0.9 | 0.7 | 2.5 | 2.0 |
| 3 | 0.6 | 0.4 | 0.8 | 0.6 | 1.1 | 0.8 | 2.7 | 2.1 |
| 4 | 1.0 | 0.4 | 0.9 | 0.6 | 1.2 | 0.8 | 3.3 | 2.2 |
| 5 | 1.3 | 0.5 | 1.1 | 0.6 | 1.3 | 0.8 | 4.0 | 2.2 |
| 6 | 1.7 | 0.5 | | | | | | |
| 7 | 2.2 | 0.5 | | | | | | |
| 8 | 2.8 | 0.5 | | | | | | |
| 9 | 3.2 | 0.5 | | | | | | |
| 10 | 3.3 | 0.4 | | | | | | |

TABLE IV
ERROR IN SOIL-MOISTURE PREDICTION FROM THE IEM BASED IN RELATION TO $h_{\mathrm{rms}}$ MEASUREMENT TECHNIQUES

| | | Configuration | | |
|---|---|---|---|---|
| | | VV_23 | HH_47 | HH_39 |
| Bias Effects | Andalucia | -13% | 1% | 0% |
| | Georgia | -4% | -25% | -37% |
| | Oklahoma | 17% | -5% | -17% |
| | Gravel Pit | -32% | -61% | -76% |
| Measurement Number Effects (10 transects vs. 20) | Georgia | +/-3% | +/- 9% | +/-13% |
| | Oklahoma | +/-12% | +/-19% | +/-24% |
| | Gravel Pit | +/-9% | +/-13% | +/-16% |
| Detrending Effects | Georgia | 25% | -32% | -57% |
| | Oklahoma | 67% | 15% | -20% |
| | Gravel Pit | 3% | -57% | -82% |

### *D. Effect of Transect Length and Detrending on $h_{\mathrm{rms}}$ Measurements*

We analyzed 40 transects ranging from 1 to 10 m from the laser-scanner data at the Arizona gravel-pit study area to investigate the effects of detrending on $h_{\mathrm{rms}}$ measurements. We also analyzed the pinmeter data sets from the watershed study areas in Oklahoma, Georgia, and Andalucia, where 5-m transects were taken in 1-m increments at each site. In Georgia and Oklahoma and in Andalucia, 16 and 12 sites were characterized, respectively. The $h_{\mathrm{rms}}$ was calculated for 1-m transect lengths, 2-m lengths, and 3-m lengths and incrementing by 1 m up to the full length of each transect. Each set of transect lengths was detrended in two ways: 1) at 1-m lengths regardless of the length of the transect and 2) over the entire length of the transect. The $h_{\mathrm{rms}}$ was calculated for each detrended transect length, and the results for each study area were averaged to a single value for comparison. Detrending of measurement transects was performed by fitting each transect with a straight line using least squared regression techniques and, then, removing the slope of the line from the transect.

Very different $h_{\mathrm{rms}}$ values resulted for the same study area depending on the method of detrending the transects (Table III). Transects that were detrended by their full length exhibited increased $h_{\mathrm{rms}}$ values with increased transect length. Whereas, roughness measurements that were calculated with transects detrended in 1-m increments showed relatively stable $h_{\mathrm{rms}}$ values. The results here indicate that detrending should be done on lengths of 1 m on transect lengths of at least 3 m to obtain a consistent characterization of $h_{\mathrm{rms}}$. Even after detrending transects at 1-m increments, the Oklahoma study area exhibited a significant variation in $h_{\mathrm{rms}}$ at transect lengths less than 3 m (Table III). To assure that an $h_{\mathrm{rms}}$ determined using a 1-m detrended transect is stable, transect length of at least 3 m should be used for the determination of $h_{\mathrm{rms}}$. We chose 5 m in the following IEM analysis, because the Andulucia data stabilized at 5 m, although, the difference between 5 and 3 m was slight. These results are confirmed by [12], although in this letter, the method of detrending was not described.

### *E. Sensitivity of IEM Output to $h_{\mathrm{rms}}$*

An example of the sensitivity of IEM simulations to the variation in $h_{\mathrm{rms}}$ was determined using the IEM to generate radar backscatter values for the three radar configurations with the different $h_{\mathrm{rms}}$ values. Surface soil moisture was set at $0.15\ \mathrm{cm}^3/\mathrm{cm}^3$ (converted to an equivalent dielectric constant according to Hallikainen *et al.* [13]) for all three configurations.

The "best" $h_{\mathrm{rms}}$ values for each study area were considered to be the measurements of 5-m transects (10-m transects for the Arizona gravel-pit study area) detrended at 1-m increments and adjusted for instrument bias. The "best" number of transects was the total number of transects measured, which was 20 for the Georgia and Oklahoma study areas and 40 for the Arizona gravel-pit study area. This may appear inconsistent, however, the relative results would be the same; only the absolute $h_{\mathrm{rms}}$ would be different. For the $h_{\mathrm{rms}}$ values for these conditions, the IEM was used to produce a set of backscatter values that could be used as the baseline for all other comparisons at the Arizona, Georgia, Oklahoma, and Andalucia study areas. Then, $h_{\mathrm{rms}}$ values were varied according to the findings of this letter to determine the effect of $h_{\mathrm{rms}}$ measurements on IEM lookup-table outputs. The results are reported in the more commonly understood units of volumetric soil moisture (derived from the inverted IEM through the lookup table) to facilitate interpretation of results. Prediction error is reported as a percentage of the $0.15\ \mathrm{cm}^3/\mathrm{cm}^3$ volumetric soil moisture used in this simulation.

Instrument bias had a negative effect on the prediction of soil moisture (Table IV) with the exception of VV_23 for Oklahoma and HH_47 and HH_39 for Andalucia. Comparisons of measurements with and without adjustment for instrument bias for the Andalucia data (where the overall $h_{\mathrm{rms}}$ was 2.25 cm) had little effect on soil-moisture prediction for two of the radar configurations ( $+1\%$ for HH_47 and 0% for HH_39), whereas for the Georgia data set (overall $h_{\mathrm{rms}} = 0.61$ cm) soil moisture was under predicted from 5% to 37%. The Arizona gravel-pit study area had the lowest $h_{\mathrm{rms}}$, and soil moisture for this area was under predicted from 32% to 76%. For HH_47 and HH_39 configurations, the error in soil moisture was related to the magnitude of the $h_{\mathrm{rms}}$. Whereas for the VV_23 configuration, there was no relationship to the magnitude of $h_{\mathrm{rms}}$.

As expected, fewer transects per site resulted in greater errors in prediction of soil moisture in relation to the mean of 20 transects (Table IV). If the difference between the average $h_{\mathrm{rms}}$ of ten transects versus 20 transects was treated as an overestimation of roughness, then soil moisture was under predicted by 3%–24%. Conversely, if the difference was treated as an underestimation of surface roughness then soil moisture was over predicted by 3%–24%. In general, lower incidence angle configuration had lower error. Fewer than ten measurements resulted in even greater error in over prediction of soil moisture and under prediction of soil moisture.

The effect of 5-m length detrending on soil-moisture prediction varied tremendously depending on the study areas and radar configuration (Table IV and Fig. 3). For example, soil moisture was over predicted by more than 60% at the Oklahoma study area at the VV_23 configuration. At the Arizona study area, soil moisture was over predicted by only 3% at the same

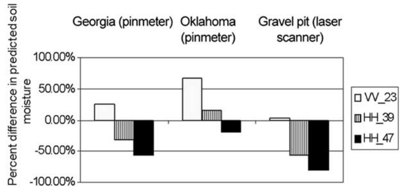


Fig. 3. Percent difference in predicted soil moisture from inverted IEM detrended at 5-m segments rather than 1-m segments for different radar configurations. The difference is the mean difference of all sites for one study area. The Andalucia study area was omitted because the $h_{\rm rms}$ (4.2 cm) at 5-m detrended segments was not valid for the IEM.

configuration but under predicted by 82% at the HH_47 configuration. Conceptually, a higher $h_{\rm rms}$ should result in a higher $\sigma^o$, so the resulting predicted soil moisture would be expected to be lower because the inversion of the IEM "assigns" more of the $\sigma^o$ signal to the roughness component of the signal that really exists. This was not always the case due to the complex relationship that exists between $h_{\rm rms}$, $L_c$, and backscatter in the IEM. For example, some of the greatest differences in soil-moisture prediction occurred in the VV_23 configuration. This was a relatively low incident angle, where the radar backscatter was theoretically less sensitive to roughness.

In summary, the degree of error in soil-moisture measurements varied tremendously in this analysis, from $< 1\%$ to 82%. Roughness effects on radar backscatter are very complex depending on the configuration of the sensor, and the relationship between $h_{\rm rms}$ and correlation length, whether the correlation length is derived from $h_{\rm rms}$ as it was in this letter or whether it is measured in the field. In addition, we used only one soil-moisture value (0.15) in this analysis. Different soil-moisture values would result in different errors.

## V. Conclusion

This letter offers insight into the errors associated with deployment of pinmeters and laser scanners for the measurement of $h_{\rm rms}$ and the postprocessing necessary to obtain repeatable measurements of $h_{\rm rms}$ with known bias over natural surfaces. The conclusions are valid for the radar configurations tested with the IEM (Table I) and reasonable $h_{\rm rms}$ values (Table IV).

1) The pinmeter and laser scanner used to acquire $h_{\rm rms}$ measurements exhibited a positive bias when measuring a smooth floor, 0.15 and 0.35 cm, respectively. For low $h_{\rm rms}$ measurements, this can have a significant influence and should be taken into account. On a natural unvegetated surface, the pinmeter and laser scanner made similar $h_{\rm rms}$ measurements after the different bias values were taken into account.
2) Due to the heterogeneity of natural surfaces, at least 20 3-m transects should be acquired to obtain a representative $h_{\rm rms}$ measurement of a study site.
3) Measurements of $h_{\rm rms}$ longer than 1 m are dependent on the method used to detrend transects. Detrending by 1-m segments results in an $h_{\rm rms}$ value that is independent of transect length for transect lengths greater than 3 m.
4) When the IEM is inverted, different methods of measuring $h_{\rm rms}$ can result in very different predictions of soil-moisture values. For example, detrending a 5-m transect by its full length resulted in an under prediction of soil moisture by more than 80% at the Arizona study area with an HH_47 radar configuration when compared to an $h_{\rm rms}$ calculated after detrending the transect in 1-m segments.

When using field measurements of roughness height to predict soil moisture by inverting radar backscatter models, it is extremely important to understand the accuracy of these measurements which, in many cases, may be the limiting factor in the accuracy of soil-moisture predictions. The different roughness statistics acquired from transect measurements detrended by their full length and transects detrended in segments are an indication of multiscale characteristics of this measurement. Both Davidson *et al.* [14] and Le Toan *et al.* [15] have reported similar conclusions. The effect of this multiscale characteristic on satellite-based radar backscatter is an area of research that requires further attention.

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