Empirical Model for Backscattering at Millimeter-Wave Frequency by Bare Soil Sub-Surface With Varied Moisture Content

Alon Eliran, Naftaly Goldshleger, Asher Yahalom, Eyal Ben-Dor, and Menachem Agassi

Abstract—This paper presents results of the angular variation of millimeter-wave-radiation backscattering-coefficient for various levels of soil moisture content. The research sets the basis for a method, which enables assessment of the soil-moisture content in the upper part of the shallow root zone. Further development of the method should provide a micro-profile measurement of soil moisture up to the root zone depth. The method is based on the emerging technology of millimeter waves, providing improved spatial resolution of the sub-surface concurrent with surface mapping. Development and use of the method described herein will make it easier to analyze and understand processes governing the soil-water interface, such as soil crusting, infiltration, runoff and soil erosion.

Index Terms—Soil, Moisture, Scattering, Millimeter wave radar.

I. THEORETICAL BACKGROUND

CURRENT methods for assessing soil moisture are limited in either penetration depth or spatial resolution [4]. Attempts to extend the capabilities have been made during the recent decades. Dobson and Ulaby [2] measured the backscattering of microwaves in the frequency range 1-8 GHz for various soil textures, soil moisture-contents and surface-roughness levels. They came to the following conclusions: 1) Soil moisture-content in the top few centimeters can be assessed with high accuracy by an air or space-borne radar; 2) The logarithm of the backscattered signal level is proportional to the soil moisture-content, and thus, to the permittivity; 3) The backscatter angular variation slope decreases with an increase in surface roughness; 4) If soil moisture is expressed in terms of the field capacity (the amount of soil moisture held in soil after excess water has drained away), the backscatter is a function of the moisture content and surface roughness, independent of soil texture; 5) Moisture content of the top-1-cm layer is highly correlated to that of deeper layers, and consequently, it is difficult to determine which depth is represented by the measurement. Ulaby et al. [15] detected at L band a coherent backscattering component at low incidence angles and a non-coherent component at higher angles. Tagawa et al. [12] obtained similar results at Ka band and added a linear regression analysis, which enables the calculation of moisture content based on the measured backscattering coefficient for a few incidence angles (for each angle separately). Nashashibi et al. [7,8] extended the results to two bands within the millimeter-wave range (Ka and W bands) and examined various moisture-content and roughness levels. Their studies clearly indicated the presence of significant volume scattering. One of their conclusions was that for a given surface roughness, the slope of the backscatter angular variation was proportional to moisture content, however, they did not present a quantitative prediction of moisture content based on the backscatter angular variation. Their study concerned one soil type only. The current study brings results of millimetre-wave backscattering for a few of Israel’s soils with the moisture content varied and the surface roughness for each soil left unchanged. The next stage of the research will add the roughness dependence and the curves. Eliran et al. [4,5,6,16]. They found and modeled the relationships between both, the specular reflection and the diffuse backscattering of laser radiation in the range 9-11 µm, and moisture content in the top 200 µm of laboratory soil samples. On this basis, we hypothesize that MIR can be of value for studying soil crust behavior which is our goal in the next research stages. This should lead to a multisensor approach covering the subsurface soil layers.

Surface scattering depends strongly on surface shape and roughness and consequently, on the radiation incidence angle, as well as on the dielectric constant of the soil [5,9,16]. Volume scattering is based on the principle of multiple scattering. Therefore, it is less dependent on surface shape and roughness [15]. Thus it is hypothesized that the backscattering from moist soil should have a stronger dependence on the incidence angle than dry soil. On this basis, moisture moist soil should have a stronger dependence on the content can be mapped by millimeter-wave measurement, as preliminarily shown by Eliran et al. [4]. While the spatial resolution of GPR is sufficient for the deeper layers of the root zone, higher resolution is required for the very top soil layers (0-2 cm), in which structural changes occur on the particle scale, such as swelling, dispersion, compaction and crusting, processes which govern water infiltration, especially in arid and semi-arid regions [10]. Millimeter and sub-millimeter (THz) waves offer resolution on the order of millimeters [13] and penetration depths on the order of millimeters to centimeters, depending on moisture content, thus providing the optimal trade-off between the two parameters. A particularly advantageous frequency is 94 GHz [4].
II. METHODOLOGY

An experiment was performed to measure the moisture content of several soil samples. Nine metal boxes (30 x 50 x 10 cm) were used to pack loess (calcic haploxeralf), gromosol (typic chromoxerets) and terra rossa (lithic rustic xerochrept) soils (three boxes for each soil type), whose mechanical composition is detailed in table I [1],[11]. Their bottom was covered with a 1-cm layer of gravel, covered by geotextile, and then they were filled with a 9 cm soil layer of 0-2 mm particle size. The soil surfaces were smoothed with a straight edge, and their rms height was measured by a lidar. First, the boxes were sub-irrigated to saturation and placed on an inclined surface until the drainage of excess water. The soils were measured for backscattering of millimeter waves at 94 GHz, as explained below, immediately after excess-water drainage and a few more times along the drying process, which was done in an oven at 60°C. Six points were measured in each box, with four repetitions at each point, in order to generate a statistical data base. Following each stage of oven drying, gravimetric moisture content was measured.

<table>
<thead>
<tr>
<th>TABLE I: MECHANICAL COMPOSITION OF THE SAMPLED SOILS.</th>
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<tr>
<td>Sand, %</td>
</tr>
<tr>
<td>Loess</td>
</tr>
<tr>
<td>Gromosol</td>
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<tr>
<td>Terra Rossa</td>
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Later, the backscattering of millimeter waves from the soils was measured as follows: a source of 94 GHz frequency, 3.2 mm wavelength, 1 mW power, was used. A horn antenna, placed 100 mm above the soil surface, transmitted the radiation in the direction of the soil. The same antenna was used to receive the backscattered radiation and its power was measured by diode detector. The angle of incidence was changed over a series of values within the range 0 to 30°, where 0° was defined as the vertical direction (nadir). The measurements were performed with both vertical (v) and horizontal (h) transmit/receive polarizations, however, as reported by Ulaby et al. [14], the vertical polarization did not add any significant information, and consequently, only the results for horizontal polarization are presented. A reference measurement was performed prior to each group of measurements. The following procedure was used for calibration: reflectance at nadir from a metal plate, 100 mm below the bottom of the antenna, was measured; whenever deviations from the known value were found, the set-up was re-adjusted. See Fig. 1 for a description of the measurement system.

Fig. 1. Measurement system (dashed line: as antenna is tilted, sample is moved accordingly).

Fig. 2. The soil boxes and the millimeter-wave measurement setup.

III. RESULTS AND DISCUSSION

Preliminary results for this research were presented at the 2011 COMCAS IEEE International Conference on Microwaves, Communications, Antennas and Electronics Systems [3]. The current paper presents results of comprehensive experiments.
Backscattering coefficient $\sigma^o$ as a function of incidence angle $\theta$ was analyzed for different levels of moisture content. The results are presented in Fig. 3. For horizontal polarization, deviations of the backscattering coefficient from the rough-surface diffuse reflectance $\sigma^d(0)\cos^o(\theta)$ were detected. The power $x$ ranges between 2 for medium to high roughness to 4 for slight roughness \([7],[15]\). For angles above 20° and moisture-content levels below 0.15 g/cm\(^3\) and lower, the backscattering coefficient was higher than expected for rough-surface scattering. Surface roughness was measured by lidar for all three boxes. For the loess soil, the rms surface height was 1 mm, with a standard deviation of 0.3 mm. For the 3.2-mm wavelength used, this surface is seen as slightly rough. For the gromosol and terra rossa soils, the rms surface height was 2.7 mm and the standard deviation was 0.3 mm, which is regarded as medium rough. The soil surfaces are seen in Fig. 4.

![Fig. 4. Soil surfaces of the samples: (a) Loess, slight roughness; (b) Gromosol, medium roughness; (c) Terra rossa, medium roughness.](image)

The low/high-angle behavior was parametrized as the difference, in dB, between the levels of the backscattering coefficient at the incidence angles of 0° and 7° or 20° and 30°, respectively, as defined in (1):

$$\Delta \sigma^o_h = \sigma_{\theta=7^\circ} - \sigma_{\theta=0^\circ}; \Delta \sigma^o_i = \sigma_{\theta=20^\circ} - \sigma_{\theta=30^\circ}. \quad (1)$$

For angles below 7° and moisture-content levels above 0.15 g/cm\(^3\), a coherent-scattering component was present, characterized by a steep descending slope. For the high moisture-content levels, above 0.15 g/cm\(^3\), the slopes had negligible dependence on moisture. For lower levels of moisture content, $\Delta \sigma^o_h$ decreased significantly with moisture content. A summary of the parameters’ values measured is given in table II. Terra rossa was omitted due to insufficient coverage of low-medium moisture levels.

**TABLE II**

<table>
<thead>
<tr>
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<th>Loess</th>
<th>Gromosol</th>
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<tr>
<td>Moisture content((g/cm^3))</td>
<td>$\Delta \sigma^o_h$((dB))</td>
<td>$\Delta \sigma^o_i$((dB))</td>
</tr>
<tr>
<td>0.31</td>
<td>1.2</td>
<td>2.0</td>
</tr>
<tr>
<td>0.23</td>
<td>1.2</td>
<td>1.9</td>
</tr>
<tr>
<td>0.14</td>
<td>0.4</td>
<td>1.1</td>
</tr>
<tr>
<td>0.10</td>
<td>0.2</td>
<td>0.9</td>
</tr>
<tr>
<td>0.03</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>0.05</td>
<td>0.07</td>
</tr>
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<td></td>
<td>0.03</td>
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The absolute level is a combination of specular reflection which may be high for high moisture content (at low angles, of course) and volume scattering, which is higher for dry soil. For high angles, volume scattering may be dominant, so, again, dry soil may have a higher scattering level. Accordingly, the decrease in $\Delta \sigma^o_i$ and $\Delta \sigma^o_h$ is attributed to volume scattering, which becomes more significant as moisture content decreases and penetration depth increases \([7],[8]\). Volume scattering has a weak dependence on surface shape and roughness, and therefore, for low moisture content, a smaller variation of the backscattering coefficient with incidence angle is obtained, since it is surface shape and roughness which are mostly responsible for angular variation.

High correlation was obtained by a multi-variate linear regression between the parameters $\Delta \sigma^o_i$ and $\Delta \sigma^o_h$, and moisture content for moisture content of 0.15 g/cm\(^3\) and lower. The results are presented in Fig. 5.

Based on the linear regression, a linear approximation for the predicted moisture content of the form

$$mc_{predicted} = a \Delta \sigma^o_h + b \Delta \sigma^o_i + c \quad (2)$$

was obtained for each soil, where $mc$ is the moisture content in g/cm\(^3\), a and b are the regression coefficients, and the parameters $\Delta \sigma^o_h$ and $\Delta \sigma^o_i$ defined above are taken for a given measured value of the moisture content. a and b \([g/(cm^3\cdot dB)]\) obtained for loess and gromosol soil types are listed in **TABLE III**. Data were insufficient to perform the same analysis for Terra rossa.
The maximum error for the predicted moisture content is 0.015 g/cm$^3$.

For values of moisture content higher than 0.15 g/cm$^3$, backscattering coefficient was found to be a linear function of moisture content, as previously reported for lower-frequency bands [2],[12],[15]. Here, the parameter used is the average level of the backscattering coefficient at 0° and 7°, defined as

$$\sigma_{avj}^o = (\sigma_0^o + \sigma_7^o) / 2$$

(3)

The results of the linear regression analysis for the gromosol soil are presented in Fig. 6 (correlation plot) and (4) (regression coefficients). Data from the other soil types was insufficient to perform the same type of analysis.

$$mc_{predicted} = 0.065\sigma_{avj}^o + 1.047$$

(4)

### IV. CONCLUSIONS

The angular variation of millimeter-wave radiation backscattered from soil has been shown to be correlated with soil moisture content for several soils typical to Israel. This is an elaboration of results included in previous works. It forms a basis for predicting the moisture content based on backscattering measurement. The empirical formulæ used for the prediction, as given in (2) and (4) and Table III, are specific to each soil type. On this basis, the method can be further developed to provide a micro-profile of the top-soil moisture-content.

The experiment described herein lays the foundation for the development of a method for soil moisture assessment offering a spatial resolution that is on the order of a millimeter for the near-surface layers. Combining this method with currently employed methods would enable multi-sensor remote-sensing of soil moisture content along the vertical profile at root zone depths (up to 30 cm). In the horizontal dimension, the addition of the millimeter-wave technique to existing ones should provide fine details within a small region of interest. Further research is needed in order to model the effect of physical soil crust and surface roughness on the backscattering patterns and to obtain a vertical profile of the moisture content.

### ACKNOWLEDGEMENT

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### REFERENCES


