Microwave scattering (1 – 10 GHz) from a vertically heterogeneous grass canopy

Jan G. Hofste, Rogier van der Velde, Paolo Ferrazzoli, Life Senior Member, IEEE, and Zhongbo Su

Abstract—This study concerns the effects of considering vertically heterogeneous canopy structure when modeling microwave scattering from grassland with the Tor Vergata (TVG) model, which uses the matrix doubling method (MDM). The TVG model was extended with the M-volume approach to accommodate height-dependent variation in structure for every scatterer type. Used approach was to reproduce 1 – 10 GHz backscatter for all linear polarization combinations from an alpine meadow measured by a ground-based scatterometer with both the default (1-volume) and the M-volume approach with 3 volumes. Measured in-situ vegetation parameters were used to constrain the model. We found that both models were able to reproduce the angle-dependent backscattering for C- and X-band, measured on two afternoons, and the 31-day average measured radar return power for L-, S-, C-, and X-band within, or close to, the measurement uncertainty. Our analysis proved inconclusive on whether the 1- or 3-volume approach worked better for the considered grassland, but did show that the 3-volume approach allows for more flexibility in reproducing the actual angle-dependent backscattering for multiple frequencies, a flexibility that may prove necessary when more scattering angles are considered. Furthermore, predictions of the bistatic scattering coefficient at higher frequencies (C- and X-band) were significantly different between both models. For X-band with hh polarization differences up to 3 dB were found for the specular direction. We conclude that considering vertical heterogeneity of vegetation canopy structure with MDM leads to significantly different results than with the vertically homogeneous canopy approximations typically used.

Index Terms—Electromagnetics for Remote Sensing, Scattering Models, Vegetation and Land Surface.

I. INTRODUCTION

SINCE the 1970s there have been many efforts to model microwave (back)scattering and -emission from terrestrial vegetation for the purpose of retrieving its properties, and that of the soil beneath, from within signals measured by tower-based radars, aircraft, and satellites. The majority of these studies used either the wave-theory approach in combination with the distorted Born approximation (DBA) [1], [2] [3] or a method involving radiative-transfer (RT) which is intensity-based [4] [5]. In both cases typically a simple representation of the scene was used: one vegetation layer or volume on top of a half-space representing the soil. Within this volume the vegetation structure was represented by a large number of discrete scattering elements whose positions were random, though statistically the volume was homogeneous. These scatterers had properties such as dielectric constant, shape, and orientation that were either identical throughout the volume or according to some statistic distribution. More recent studies tried advancing the approaches and models described above by improving the in-model representation of vegetation morphology. The importance of considering vertical heterogeneity in vegetation canopy structure and constituency was demonstrated in, for example, [6] with the radiative transfer approach. Multiple vegetation volumes (‘layers’ in their terminology) with varying properties were used instead of a homogeneous one in order to account for the height-dependent variation of scattering elements in a pine forest canopy. By doing so their modeled cross-polarization response for L- and C-band matched better with observations. Similarly, in [7] multiple volumes were used to better mimic the forest canopy comprising of different tree-species. With their Multilayer Michigan Microwave Scattering Model (Multi-MIMICS), they showed an improvement over the MIMICS reference model in reproducing measured P-, L-, and C-band backscatter when the forest had several tree-species. With the DBA approach [8] extended the model of [9] to better accommodate vertical heterogeneity and mixed tree-species also by working with multiple volumes. They claim improved model accuracy when simulating L-band backscatter of wooded savanna. Further improvement on representation of vegetation morphology was done in [10], also with the DBA method, for modeling L-band backscatter of cultivated maize. By working with an artificial “typical” agricultural maize canopy, including spatial positions of plant stems and leaves, coherent scattering effects due to the row structure were included. The same approach was used in [11] for Soybeans. With modeling approaches where Maxwell’s equations are solved numerically the degree of control for the shape and position of canopy elements is even greater, for example in [12] where an numerical iterative method is used to calculate the scattering of marsh grass.

Investigations on the effect of considering vertical canopy structure heterogeneity when modeling (back)scatter from grasses seems to be missing. Microwave backscattering of prairie grassland was investigated in [2] and [12]. The former
represented the scene in a simple manner though: a half-space representing soil with one vegetation volume on top thereby omitting effects caused by changes in the canopy over height. Also, they compared their backscatter simulations using the DBA approach only with C-band measurements. The investigation in [12], which does consider canopy structure rigorously was only theoretical for L-band, though they did also consider bistatic scattering. With [10] and [11], where agricultural corn and soybeans were considered respectively, modeling results were compared with measurements, but also only for L-band. Then, the studies [6], [7], and [8], mentioned earlier all investigate scattering of forests/trees up to C-band.

In this paper we want to reproduce measured angle-dependent backscatter, over 1 – 10 GHz, from a dense Alpine grass canopy by applying the improvements in representing vertical heterogeneity of canopy structure with simulation of microwave (back) scattering as used in [6] – [8]. More specifically, we want to apply the multi-volume approach to the matrix doubling method (MDM) [13] [4] for solving the radiative transfer equation. The main question to answer in this paper is whether doing so will lead to a better match with backscatter measurements than a representation of the canopy with just one volume. Additionally, we explore the consequences of considering height-dependent variations in canopy geometry for bistatic scattering.

We chose to work with the Tor Vergata (TVG) microwave scattering model [14] which uses the MDM for solving the RT equations numerically. With MDM multiple scattering effects within a vegetation volume can be accounted for. We expect these to be significant with our considered grass canopy especially for C- and X-band, as there the dielectric contrast is high and the scatterers are large compared to the wavelength, resulting in strong scattering. The DBA approach is not suitable in such cases [6], [12], [15], nor are methods such as MIMICS [16], [5] that solve the RT equations analytically up to the first order [17]. Also, with TVG the simulation time is manageable for the purpose of parameter optimization as used in this study. With methods that solve Maxwell’s equations numerically, such as [12], this is not the case. A disadvantage of RT methods (including also TVG) is that coherent effects cannot be accounted for. However, since our grass canopy may be regarded as an ensemble of randomly located scatterers coherent effects are not expected. A similar approach to MDM that would have also been suitable for this study is the discrete ordinate eigenvalue method (DOEM), [18], [6]. We chose to work with TVG as it was validated by many other studies. Some examples are: [19] (trees), [20] (maize), [21] (wheat) or [22] (maize and wheat). Depending on the vegetation type, in these studies the canopy was divided into a stem-, branch-, and/or leaf volume. However, within one such a volume the scattering elements, or scatterers, had homogeneous properties such as dielectric constant, dimension and angular distribution function. As a consequence, the order of interaction between incident radiation with the scatterers within such a volume (from top to bottom) was not accounted for. By using multiple stacked volumes of scatterers of the same type (leaves for example) as we do here this feature can be controlled. For example, by letting the amount of biomass or leaf inclination angle increase over depth in the canopy.

This paper is organized as follows: first, the TVG model is briefly introduced, after which we explain what modifications are necessary to work with multiple vegetation volumes. Next, we give information on the used scatterometer observations and the in-situ vegetation measurements. Then, we describe the modeling approach, which includes both the new proposed model and the default (1-volume) TVG model as reference, and subsequently its results. In the discussion section we consider some issues that arise from the results, such as the numbers of volumes to use, differences in vv and hh backscatter, and the effects of varying the leaf inclination angles over height in the canopy. Also, we discuss possible implications of the proposed model for the bistatic scattering of vegetation canopies and how this may affect working with both active and passive microwave observations.

II. THE TOR VERGATA MICROWAVE SCATTERING MODEL

A. Tor Vergata model

The Tor Vergata microwave scattering model (TVG model) was developed at Tor Vergata university [14], [19], [22] and uses the Matrix Doubling Method (MDM) [13], [4]. MDM is a means of solving the vector radiative transfer equations within a volume of thickness $d$ [m] numerically. The global idea is that a finite number of elementary geometries (ellipsoids, discs, cylinders, thin resistive layers) with density $N^V$ [m$^{-3}$] are envisioned, at random positions, within the volume that represents a vegetation canopy on top of a dielectric half-space representing the underlying soil, see Fig. 1 (disregard volumes 2 and 3 for now). The elemental geometries have known angular radiation scattering patterns. The volume is divided into $L$ layers, among which the elementary geometries are divided. The elementary geometries’ scattered intensities interact mutually though the interaction of intensity fluxes between the layers they are in. All scattering and transmission of fluxes between and through all of these layers in the volume is described by MDM. Now we describe some features of this process. The thickness of a thin layer is $\Delta d = d/L$ [m]. As explained in for example [4], scattering within one upper (lower) hemisphere of a layer is described by matrices $S$ ($S^*$), that map incident radiation at a discrete set of angular intervals $\theta_i$ and polarization v(h) to scattered radiation with angles $\theta_s$ with polarization v/h(v). Scattering between a layer’s hemispheres, is described by matrices $T$ and $T^*$ that map angles $\theta_i$ to $\theta_t$. Matrix $E$ is the diagonal extinction matrix whose element represent forward propagation (from upper- to lower hemisphere with the $\theta_i = \theta_t$). Elements of $S$, $S^*$, $T$, and $T^*$ follow from $(\sigma(\theta_s, \theta_t, \Delta\phi))$ [m$^2$], and those for $E$ from $(\sigma^e(\theta))$ [m$^2$], respectively the orientation-averaged bistatic scattering- and extinction cross sections of the elementary geometries envisioned within the volume. See [4] and [23] for the derivation of these scattering cross sections and [19], [14] for the translation into matrices. The size of all matrices is determined by the number of angular intervals $N_\theta$ in $\theta$ direction between $0 – \pi/2$:
B. N-vegetation-volumes model

In order to account for a natural canopy’s height-dependent variation of geometrical structure and composition we propose to stack multiple $M$ vegetation volumes as depicted in Figure 1. With this approach, it is possible to assign the elemental scatterers with different densities, dimensions, compositions (dielectric constant $\epsilon_r$) and orientations over height, accommodating a better resemblance of a natural canopy structure. Same as with a single volume, matrices $E, E^*, T,$ and $T^*$ of the other volumes are calculated with the doubling method as described above.

The scatter- transmission- and extinction matrices of the $M$ volumes are combined according to a set of iterative equations:

$$S_M = S_{M-1} + (T_{M-1} + E_{M-1}) S_m D(T_{M-1} + E_{M-1})$$

$$T_M + E_M = (T_m + E_m) D(T_{M-1} + E_{M-1})$$

$$D = (I - S_{M-1} S_m)^{-1}$$

where the capital subscripts $M$ refer to the total number of volumes, i.e. a compound of volumes, and lower case $m$ to the new $m^{th}$ volume that is to be added. One starts with $M = 2$, then goes to $M = 3$ etc. New volumes ($m$) are added below the existing stack ($M - 1$). When all volumes are combined the resulting extinction matrix will be

$$E_M = \prod_{m=1}^{M} \left( I - \text{Diagonal} \left[ \frac{\langle \sigma_m^e(\theta_i) \rangle N_m^V d}{\cos(\theta_i)L} \right] \right)^m L$$

The $M$-volume model’s behavior equals that of the default, 1-volume, TVG model when the scatterer’s dimensions, constituents, orientations, and scatterer density $N_m^V$ for all $M$-volumes are identical and the thickness of every volume $d$ is $1/M$-th of the 1-volume model value.

The number of volumes to use depends on the type of vegetation canopy. The number should be sufficiently high to ensure that parameters such as volumetric biomass, canopy element constituents, dimensions and their inclination angles change over height as in the actual canopy. On the other hand, with increasing $M$, at some point adjacent volumes end up having similar parameters causing the resulting matrices to converge, as mentioned above. Also, more volumes imply a longer computation time. In order to keep the TVG model computation time manageable in this study we chose to work with three volumes to demonstrate the multiple-volumes principle. We considered three volumes to be sufficient for mimicking the bending of grass leaves as was observed with many plants on site, see Figures 1b and 2b. In section VI-A the matter of number of volumes is discussed further.

III. SCATTEROMETER MEASUREMENTS SUMMER 2017 & 2018

A. Measurement site

For this study we consider measurements of microwave backscattering from a 5 m high tower and in-situ vegetation-and soil parameters taken at the Maqu site within the period 12

Matrix size $= 2N_\theta \times 2N_\theta$, where the factor two is due to the mapping between the two polarization directions. The azimuthal-dependence of scattering is incorporated in the TVG model by Fourier decomposition with respect to the azimuth angle. Each harmonic base function has its own matrices $S$ ($S^*$) and $T$ ($T^*$) [13], [4], [14]. The three types of matrices for all layers are combined via MDM to form the total matrices $S, T$ and $E$ for the volume. With an increasing value of $L$ these matrices will converge, at what stage the $E$ entries are in accordance with the actual optical depth of the volume [13]. The soil scattering can be simulated by using the a geometrical optics surface scattering model [24], [14], the integral equation method (IEM) [25], or other soil scattering models. For this study the advanced integral equation method (AIEM) [26] [27] was used. The surface scattering patterns, generated by said models, are converted into a soil scattering matrix that is combined with the $S, T$ and $E$ matrices of the vegetation canopy to realize the total scattering model of the scene [4], [14].
B. Scatterometer setup

We used measured backscatter data over the 31-day period 13 July – 13 August 2018 obtained with the ground-based scatterometer described in [28] and available under [30]. The scatterometer was built using a vector network analyzer and two dual polarization broadband gain horn antennas. Radar return amplitude and -phase were measured over 1 – 10 GHz for all four linear polarization combinations (vv, vh, hv, hh) once per hour with the antennas fixed at angle $\alpha_0 = 55^\circ$, where $\alpha_0$ is the angle between the antenna-boresight line and the ground-surface normal. Because the antenna gain patterns varied over frequency, the effective angle-of-incidence ranges were band- and polarization dependent [28]. Widest ranges were, for L-band (1.5 – 1.75 GHz) $0^\circ \leq \theta \leq 60^\circ$, for S-band (2.5 – 3.0 GHz) $20^\circ \leq \theta \leq 60^\circ$, for C-band (4.5 – 5.0 GHz) $36^\circ \leq \theta \leq 60^\circ$ and for X-band (9 - 9.875 GHz) $47^\circ \leq \theta \leq 59^\circ$.

C. Measuring angle-dependent $\sigma^0$

On two afternoons, first on 25 August 2017 and second on 19 August 2018 the angle-dependent backscatter was measured by placing both antennas on a motorized stage and varying the antenna’s elevation angle $\alpha_0$ and azimuth angle $\phi$ [28]. On 25 August 2017 $\alpha_0$ was varied in 8 steps from $35^\circ, 40^\circ, \ldots, 70^\circ$ and on 19 August 2018 in 3 steps ($35^\circ, 55^\circ, 70^\circ$). The azimuth angle $\phi$ was varied on 25 August 2017 between -20, -15, -10, -5, 0, 10, 15, 20$^\circ$ and on 19 August 2018 between -30, -20, -10, 0, 10, 20, 30$^\circ$. The 19 August 2018 measurements were performed 6 days after the 31-day period described above, while the 25 August 2017 measurement one year before. For the analysis in this paper, we assume the vegetation state at the time of the angle-dependent backscatter measurements to be similar as during the 31-day period. Measurement data of the volumetric soil moisture content $m_v$ [m$^3$m$^{-3}$], soil-, and air temperature (for estimating vegetation temperature $T_{veg}$) was available for all days (see below).

D. In-situ measurements of vegetation and soil

To quantify the vegetation canopy at the Maqu site, fresh- and dry above-ground biomass, $BM_f$ and $BM_d$ respectively [kg m$^{-2}$], average canopy height $h$ [cm] and average plant radius $r$ [cm] was measured on two days close to the start- and end date of the considered 31-day period: 12 July and 17 August 2018. Within ten $1.2 \times 1.2$ m$^2$ sample sites located around the observed area, see Fig. 2a, plant height was measured with a ruler at 30 or more random positions [28]. Per sample site the mode value was identified, $h$ is the average mode value over these ten sites. Then fresh above-ground biomass was harvested within one or two 45 cm diameter circular areas per individual site, see Fig. 2b. A subset of the harvested plant material was photographed on-site along with a reference scale. From these photographs $r$ was retrieved using ImageJ imaging software [31]. Finally, all harvested samples and their subsets were stored in air-tight bags. The fresh- ($BM_f$) and dried ($BM_d$) above-ground biomass of the Maqu site was obtained by weighing all samples pre- and post oven
TABLE I

<table>
<thead>
<tr>
<th></th>
<th>12 July</th>
<th>17 Aug.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh biomass [Kg m(^{-2})]</td>
<td>(BM_f)</td>
<td>1.0 ± 0.3</td>
</tr>
<tr>
<td>Dry biomass [Kg m(^{-2})]</td>
<td>(BM_d)</td>
<td>0.3 ± 0.1</td>
</tr>
<tr>
<td>Plant radius [cm]</td>
<td>(r)</td>
<td>0.032 ± 0.002</td>
</tr>
<tr>
<td>Canopy height [cm]</td>
<td>(h)</td>
<td>20 ± 6</td>
</tr>
</tbody>
</table>

Fig. 3. Measured volumetric soil moisture \(m_v\) [m\(^3\) m\(^{-3}\)] at 2.5 cm depth and precipitation at the Maq site. Horizontal lines mark \(m_v\) values 0.13, 0.18, 0.23 and 0.28 m\(^3\) m\(^{-3}\) and dots indicate corresponding radar return power values at selected times \(P_{RX}(m_v^i)\).

heating for 20 hours at 105 °C. Results are shown in Table I. Measurements on the inclination angle of the grass plants were not performed. The only reference here were field observations by the authors and photographs such as Fig. 2. Volumetric soil moisture \(m_v\) [m\(^3\) m\(^{-3}\)] and -temperature \(T_{soil} [°C]\) was measured with an array of 5TM probes that retrieve \(m_v\) from the measured soil capacitance via the effective dielectric constant and \(T_{soil}\) from a thermistor voltage. The 5TM Probes were buried at depths [2.5, 5.0, 7.5, 10, ...90, 100] cm. Figure 3 shows the measured timeseries of \(m_v\) at 2.5 cm depth, together with measured precipitation. The vegetation temperature \(T_{veg}\) was assumed to be similar as the air temperature measured at 1.5 m height.

IV. FORWARD MODELLING

A. Approach

We will investigate the ability of the TVG model, using both the default- (1-volume) and modified (3-volume) approach, to reproduce the following features from the scatterometer measurements: (1) the angular response of the backscattering coefficient \(\sigma_{pq}^0(\theta)\) [m\(^3\) m\(^{-2}\)] for C- and X-band during the two August experimental days, and (2) the radar return power \(P_{RX}^{pq}\) [dBm] at \(m_v\)-levels 0.13, 0.18, 0.23, and 0.28 cm\(^3\) cm\(^{-3}\) for L-, S-, C-, and X-band. The performance between the 1- and 3-volume approach is compared.

Because for L- and S-band the antenna gain patterns are broad, relating \(P_{RX}^{pq}\) to \(\sigma_{pq}^0\) via the commonly used narrow-beam approximation would lead to errors: for these bands you would effectively measure \(\sigma_{pq}^0\) over a wide range of incidence angles simultaneously. Instead, a deconvolution procedure would have been required to obtain measurement data of \(\sigma_{pq}^0\) over \(\theta\) to compare against the modeled curves [28]. As such a procedure is prone to uncertainties we chose to focus instead on the C- and X-band measurement data as the gain patterns of those bands were deemed narrow enough for a straightforward comparison of measured and modeled \(\sigma_{pq}^0(\theta)\). For the comparison of \(P_{RX}^{pq}\) the measurement data of all bands could be used.

For both the 1- and 3-volume TVG model, we searched for parameter values that produce best overall match for all aforementioned scattering measurements. Additionally, these parameter values should be conform to the measured in-situ fresh biomass, vegetation water content, plant radii and canopy height. Also on-site observations of the vegetation geometry by the authors (see for example Figure 2) were considered in this process. The search approach was that of lookup-table instead of an iterative-search algorithm which poses the risk of finding local- instead of global optima. Table II lists all TVG parameter and their varied ranges, the motivation of which is discussed in Section IV-D. Parameters describing the underlying soil, such as surface roughness (rms surface height \(s [cm]\) and surface correlation length \(\ell_{corr}\)), volumetric soil moisture content \(M_v [cm^3 cm^{-3}]\) and soil temperature \(T_{soil}\) were kept fixed while those concerning the vegetation canopy were varied.

For the 1-volume model all 13824 parameter-value combinations, or parameter sets (parsets), as mentioned in the table II were simulated. Using the same parameters for each of the three volumes with the 3-volume model would result in a too high number of parsets to compute in practice, so instead a sequence of three iterations was performed with smaller parameter ranges as indicated in the table. The first iteration covered a broad search over parameter space involving 82944 parsets. After analysis of its results, explained in Sections IV-B and IV-C, an overall well-performing cylinder dimension was chosen for the 2\(^{nd}\) iteration, exploring in particular the effects of the cylinder inclination angles \(\beta_{m range}^{\theta} (233280 \text{ parsets})\). The third iteration (with 103680 parsets) was again a broader search with good \(\beta_{range}^{\theta} \text{-candidates from the } 2^{nd} \text{ iteration.}

In order to find/identify the best parsets after the simulations, we followed a two-step procedure to find optimal parset(s) for the 1- and 3-volume models. First, parsets were selected based on their performance in terms of reproducing the measured angular response of \(\sigma_{pq}^0\) for C- and X-band for all four polarization combinations, so eight channels (4 × 2) in total. Details on the selection criteria are described in section IV-B. The second selection round, performed on the remaining parsets, involved comparing the simulated- and measured \(P_{RX}^{pq}\) over \(m_v\) for all bands and polarizations, except for the cross-polarization channels of L-band. As mentioned in the introduction, the AIEM model was used to simulate the soil scattering. Our version [32] did not account for multiple surface scattering effects, while these constitute the major component for cross polarization in the backscattering direction [33] [27]. Additionally, also in-soil volume scattering...
was not considered in our used AIEM model, which becomes more important with lower values of \(k\sigma\) (\(k\) is the wavenumber \([\text{m}^{-1}]\)) [8] [34]. For vegetated surfaces with high optical depths these issues are circumvented for high frequency bands, but this is not the case for L-band (and possibly also for S-band). Therefore the L-band cross polarization channels were omitted in the analysis. Details on the criteria for the second selection round are described in section IV-C.

For the remainder of the text we shall use the short-hand notations when addressing individual channels. For example, C-band with \(\text{vh}\) polarization and S-band with \(\text{hh}\) polarization will be written as Cvh and Shh respectively.

\[ \begin{array}{c|c|c|c|c|c|c|c|c|c|}
0 & \sigma & 0 & [\text{dB}] & 0 & \sigma & 0 & [\text{dB}] & 0 & \sigma & 0 & [\text{dB}] \\
10 & 20 & 30 & 40 & 50 & 60 & 70 & 80 & 10 & 20 & 30 & 40 \\
\end{array} \]

\[ \begin{array}{c|c|c|c|c|c|c|c|c|c|}
\text{C-band} & \text{X-band} & \text{vv pol.} & \text{vh pol.} & \text{vv pol.} & \text{vh pol.} & \text{vv pol.} & \text{vh pol.} & \text{vv pol.} & \text{vh pol.} \\
\end{array} \]

B. Comparing simulated \(\sigma^0(\theta)\) with measured \(\sigma^0(\theta_0)\)

Figure 4 shows the measured angular response of the backscattering coefficient \(\sigma^0_{pq}\) for C- and X-band. By finding the corresponding peak values of \(G^2/R^3\) over the ground surface (part of the integrand in Eq. 5, see also [28]) eight (for 25 August 2017) or three (for 19 August 2018) effective incidence angles, denoted \(\theta_0\), were found. The modeled \(\sigma^0_{pq}(\theta)\) was compared to the measurements at these \(\theta_0\) angles. For every measured \(\sigma^0_{pq}(\theta_0)\) frequency-averaging was used to reduce the fading uncertainty. Further uncertainties are due to calibration- and system offsets [28]. For our analysis the measured \(\sigma^0_{pq}(\theta_0)\) values of both days combined were averaged over all \(\phi\)-angles. The individual measurements over \(\phi\) were not used to further reduce the fading uncertainty since their footprints partially overlap.

To compare the simulated \(\sigma^0_{pq}(\theta_0)\) values with the measurements skill scores \(S\) (see for example [35]) were computed for all eight channels. Used \(S\) incorporated weighted correlation coefficient \(R\), weighted root-mean-square-difference RMSD, and the ratio \(\sigma_{rat}\) of the simulated over measured weighted standard deviation (see Appendix A). Used weights were the inverse of the standard variation over \(\phi\) for each \(\theta_0\). All statistic measures were applied on the dB values of \(\sigma^0_{pq}(\theta_0)\). Per parset we calculated the average skill \(S\) and standard deviation \(\sigma_S\) over the eight channels. The best parsets were found by searching for the highest values for \(S - \sigma_S\).

C. Broadband simulation of radar return power

Figure 5 shows the measured radar return power \(P^\text{rxm}_{pq}\) over the whole 31-day period. With the calculated \(\sigma^0_{pq}(\theta)\) from the TVG model the simulated radar return power \(P^\text{rxs}_{pq}\) is obtained via

\[
P^\text{rxs}_{pq} = P^\text{pq} \frac{\langle \sigma^0 \rangle^4}{\sigma^0_{pq}} \int \frac{G^2}{R^3} \sigma^0_{pq}(\theta) dA \quad (5)
\]

where \(P^\text{pq}\) and \(\sigma^0_{pq}\) are the return power from the reference target and reference target radar cross section \([\text{m}^2]\) respectively. Other known parameters are the distance to reference target \(R_0\) and antenna normalized gain patterns \(G\). The first subscript \(p\) refers to the polarization direction of the scattered (for \(\sigma^0\)) or returned (for \(P\)) radiation and the second subscript \(q\) to that of the incident (for \(\sigma^0\)) or transmitted (for \(P\)) radiation.

In the parset selection process the measured \(m_v\) dynamics (Fig. 3) were considered by selecting from the measurements four pairs of \(P^\text{rxm}_{pq}\) and \(m_v\) to which the simulated counterparts \(P^\text{rxs}_{pq}\) of each parset were compared. First, we identified the times at which \(m_v = 0.13, 0.18, 0.23, \) and 0.28 cm\(^3\) cm\(^{-3}\). We omitted times at, or very close to rain events. Then the corresponding \(P^\text{rxm}_{pq}\)-values were averaged into one value \(\langle P^\text{rxm}_{pq}\rangle\) to establish four sets for all 14 channels \((2 \times 3 \times 4)\).

The match between \(P^\text{rxm}_{pq}\) and \(P^\text{rxs}_{pq}\) was quantified by the
measure $f$ [-] (dB), which is defined as
\[
f = \begin{cases} 
    dB(P^{rs}_{hi}/P^{rs}_{lo}), & \text{if } (P^{rs}_{hi}) < P^{rs}_{lo}, \\
    0, & \text{if } (P^{rs}_{lo}) < P^{rs}_{lo} < (P^{rs}_{hi}), \\
    dB(P^{rs}_{lo}/P^{rs}_{lo}), & \text{if } P^{rs}_{lo} < (P^{rs}_{lo}) 
\end{cases}
\]
(6)
where, for readability, we omitted the polarization subscripts. $P^{rs}_{lo}$ and $P^{rs}_{hi}$ indicate the uncertainty in the retrieved return power (68% confidence intervals). For each of the 14 channels four $f$-values were calculated, corresponding to the four $m_i$-levels: $f^i$ with $i = 1, 2, 3, 4$, $(P^{rs}_{hi}) = (P^{rs}_{lo}(m_i^1))$, $(P^{rs}_{hi}) = (P^{rs}_{lo}(m_i^2))$ and $P^{rs}_{lo} = P^{rs}_{lo}(m_i^3)$ with which we then calculate the $RMSD_f$:
\[
RMSD_f = \sqrt{\frac{1}{4} \sum_{i=1}^{4} (f^i)^2}
\]
(7)

D. Vegetation canopy modeling

Given the long, thin and round shape of the grass plants at the Maqu site (Fig. 2) we chose to use dielectric cylinders as our scattering elements. Table II lists all varied parameters and their value ranges, which we explain here. The basic assumption is that the size, number, and orientation of the model cylinders represent an average value of the actual vegetation canopy.

Instead of using the product $N^V d$ in the matrix equations (for example with Eq. (4)) the number of scattering elements per underlying surface area $N^A$ [m$^{-2}$] was used. This quantity was not measured. Based on field observations by the authors values of 0.5 to 5 cm$^{-2}$ were deemed plausible. The values in Table II were chosen to be within this range. Additionally, $N^A$ was constrained indirectly via the measured biomass $BM_f$ as explained below. The range of average cylinder radii $r$ was chosen to cover the measured values of Table I. In the TVG model $\ell$ represents the average length of the plants or plant segments, for both 1- and 3-volume model. This parameter is relevant by how it determines the scattering phase functions of the elemental cylinders (see [36] [37]). The actual plant lengths were not measured, nor were estimates made of typical plant segmentation lengths. However, we do have an estimate for the average canopy height through the mean mode value of the measured plant heights within the sampling sites $h$, (Table I). This average, ranging from 15 to 25 cm, gives us an indication of what is an appropriate range for $\ell$: 1 cm would be too short, 1m too long, hence the values ranging from 5 to 40 cm. Note that in the context of radiative transfer theory the measured average canopy height cannot be explicitly linked
to the physical thickness \(d\) of the vegetation volumes, as this would lead to logical inconsistencies. With the 3-volume model the scaling coefficients \(C_N\), \(C_r\), and \(C_\ell\), all smaller than, or equal to 1 – determine the inter-volume ratio’s of \(N^A\), \(r\), \(\ell\) according to:

\[
\begin{align*}
N^A_1 &= N^A(C_N)^2 \\
N^A_2 &= N^A(C_r) \\
N^A_3 &= N^A
\end{align*}
\]

(8) in the case of \(N^A_{m,m}\). For \(r_m\) and \(\ell_m\) similar equations hold. These relations imply that vegetation biomass, the plant- radii, and (segment) length decrease over height in the canopy. The \(\beta\)-ranges, representing the inclination-angle ranges of the plant (segments) or cylinders (Figure 1b), were varied as to simulate canopies with pronounced vertical-, diagonal-, or horizontally oriented plants (or plant segments), canopies with uniform plant (segment) inclination distributions, i.e. \(\beta^0_m = 0^\circ\) \& \(\Delta\beta_m = 90^\circ\), and variations in between. An investigation on the effect of the \(\beta\)-ranges alone is described in the discussion section VI-C. The fresh biomass \(BM_f\) [Kg m\(^{-2}\)] of the artificial canopies of each parset is calculated with:

\[
BM_f = \frac{\rho_{dm}\rho_w V_{tot}}{VWC(\rho_{dm} - \rho_w) + \rho_w} \tag{11}
\]

where \(V_{tot}\) [m\(^3\) m\(^{-2}\)] is the sum over three vegetation volumes, \(\rho_{w}\) is the water density, 1 g cm\(^{-3}\), and \(\rho_{dm}\) is the dry vegetation matter density for which we use the value 0.3 g cm\(^{-3}\) [38]. The vegetation water content (VWC) is the weight factor of water [-]. We considered only parsets whose \(BM_f\) and \(r\) were close to the measured in-situ values. Parameters influencing the canopy constituency; VWC and \(T_{veg}\) were kept fixed at their measured time-average values. For the soil \(m_v\) was varied in four steps \(m_v = 0.13, 0.18, 0.23, \& 0.28\) cm\(^2\) as mentioned earlier, spanning the range measured at 2.5 cm depth (Fig. 3). Soil temperature \(T_{soil}\) was kept fixed as its influence is small. We used the AIEM surface scattering model in our simulations with an exponential correlation function, \(s = 1\) cm rms surface height and \(\ell_{corr} = 9\) cm correlation length. No surface roughness measurements were performed, we chose the exponential correlation function as this type was found to be most applicable to surfaces with moderate roughness [39], [40]. Used values for \(s\) and \(\ell_{corr}\) were adapted from [41] in which an empirical calibration process was performed for the Maqii site area.

E. TVG model settings

In this study two approximations were used for calculating \(\langle\sigma(\theta_s, \theta_i, \Delta\phi)\rangle\) and \(\langle\sigma^r(\theta_i)\rangle\) of the elemental cylinders. The Infinite Length (IL) approximation [37], [23] assumes the cylinder’s internal fields to be equal to that of an equivalent cylinder with infinite length, thereby neglecting the fringing fields at the cylinder’s edges. Based on the measurements and analysis in [37] we assumed the IL model is applicable for \(kr \leq 0.3\) (\(k\) is the wavenumber in free space [cm\(^{-1}\)]) and \(\ell/r \geq 5\). The Rayleigh-Gans (R-G) approximation is more far-reaching in that the cylinder’s internal fields assumed to be uniform everywhere, making it applicable for \(kr|\sqrt{\tau}| < < 1\) and \(\ell >> r\) [36], [42]. In general, R-G is faster than IL. For calculating the relative dielectric constant \(\epsilon_r\) [-] of vegetation material and soil we used the models of Mätzler [43] and Dobson [44] respectively. Given the range of cylinder dimensions as stated in Table II, and \(\epsilon_r\)-range of 21 - 61 for L-band, to 16 - 91 for X-band (VWC = 0.60 Kgm\(^{-1}\)) the R-G model was used for L-band and the IL for other bands.

For the TVG simulations to converge we used the settings as summarized in Table III. We found that convergence of \(\langle\sigma(\theta_s, \theta_i, \Delta\phi)\rangle\) and \(\langle\sigma^r(\theta_i)\rangle\) of the elemental cylinders is especially sensitive to the \(\theta_i\) and less to the \(\phi\) resolution. While for the soil scattering it turns out the \(\phi\) resolution is critical. When the soil surface is smooth with low \(k_s\) and high \(kl\) values, the number of Fourier terms must be sufficiently high for convergence. The resolution over the \(\beta\)-range was found to be sufficient at 3° and 8° for \(\alpha\). Finally, we note here that we used \(L = 2048\) layers within the vegetation volumes.

V. Results

For the 1-volume model a threshold of \(\bar{s} - \sigma_S \geq 0.36\) and \(RMSD_f \leq 1.5\) dB for co- and \(RMSD_f \leq 2.0\) dB for cross polarization was applied to the 13,824 parsets’ simulation results, resulting in 13 parsets whose statistics in terms of \(S\) (and thus \(R\), \(RMSD\), and \(\sigma_{rat}\)) and \(RMSD_f\)-value were similar. Next, by looking at the individual \(S\)- and \(RMSD_f\)-values the overall best 1-volume parset was identified, see Table IV. It’s parameter values are listed in Table V. For the 3-volume model, with the third (final) iteration, used thresholds \(\bar{s} - \sigma_S \geq 0.29\) and \(RMSD_f \leq 1.5\) dB for co- and \(RMSD_f \leq 2.0\) dB for cross polarization resulted in 8 similarly good parsets. The total number of 3-volume model parsets evaluated was 419,904. The statistics of the best overall parset out of these eight are also listed in Table IV. Table V shows its parameter values. In Figure 6 the simulated \(\sigma_{pq}(\theta)\) of the best 1- and 3-volume model parsets are shown together with the measurements. In Figure 7 the \(P_{pq}^{\sigma \sigma}\) of said best parsets are plotted with the measured values.

First, we note here that, regardless of whether the 1- or 3-volume approach was used, the TVG model managed to reproduce the measured backscatter, \(P_{pq}^{\sigma \sigma}\) for L- to X-band and \(\sigma_{pq}(\theta)\) for C- and X-band, with satisfactory accuracy. Concerning the simulation of \(P_{pq}^{\sigma \sigma}\) both with the optimal 1- and 3-volume parsets the \(RMSD_f\) for all co-polarization channels were within 1 dB. In other words, the co-polarized simulated backscatter-values for all channels were outside the 68% confidence intervals, averaged over the four \(m_v\)-values, no more than 1 dB. For the cross-polarization the match for C-band was good. For Xvh both model’s simulations had \(RMSD_f\)-values near 2 dB, while for Xhv this was somewhat better (1 and 1.3 dB for the 1- and 3-volume model respectively). For S-band (\(RMSD_f\) close to 1.5 - 2 dB), soil scattering is dominant. The underestimation of cross-pol \(P_{pq}^{\sigma \sigma}\) here (see Fig. 7) is probably because multiple-surface- and soil-volume scattering effects were not considered in the used AIEM model. Considering the \(RMSD_f\)-values of all 14 channels, the overall performance for simulating \(P_{pq}^{\sigma \sigma}\)
was similar with 1- and 3-volume model. Note also that the simulated sensitivity to $m_v$ is almost identical for both found optimal parssets. We found this to be the case with all parssets considered.

Concerning the simulation of $\sigma_{pq}^0(\theta)$ (Figure 6 and Table IV), with both modeling approaches the angular response of $\sigma^0$ for C-band was matched nicely. The performance, in terms of $R$, $RMSD$, and $\sigma_{rat}$ were similar with both models for all the polarizations. The match with measured X-band $\sigma_{pq}^0(\theta)$ for both models was not as good. With the 1-volume approach all possible parssets were calculated, with the 3-volume approach this was not the case. So, there remains the possibility that more suitable parssets than the one found exist. Measurement data beyond the available $30 – 70^\circ$ range could have helped in identifying such better suitable canopy configurations. Then, the fairly good match for C-band, despite these hypothetical differences in shape over $\theta$ – 90° is almost identical for both found optimal parssets. We found this to be the case with all parssets considered.
difference in net interaction between the two polarizations is smaller. When the same random $\beta$-range configuration is applied to the 3-volume model, see Section VI-C, there is little difference in shape with the 1-volume case: these are the pink dash-dot-dot curves in the figure. We continue our discussion of the found optimal parsets. For X-band with co-polarizations the statistics were better with the 1-volume model. The correlations were similar and the values of $\sigma_{r_{\text{vol}}}^0$ were actually a bit better for the 3-volume model, however, the offsets ($R\text{MSD}$) with the 3-volume model were 0.6 dB (for vv) and 1 dB (for hh) higher compared to the 1-volume model. For cross polarization on the other hand, the 3-volume model performed a bit better.

An important feature, that speaks for the 3-volume approach is the higher flexibility in modeling the $\sigma_{\text{pq}}^0(\theta)$ response. This is illustrated for example by the Xvv-case. When we examine the shape of $\sigma_{\text{pq}}^0(\theta)$ for both models (Fig. 6) and disregard the offset, we observe that the curve for the 1-volume model runs centered through the measurements and thereby fits nicely with $R = 0.94$. For the 3-volume model however (also $R = 0.94$) the measured trend is matched better, although there clearly is a shift of the simulated curve too far to the left. In a more general sense, given the same ranges for parameters $N^A, r, \ell, \beta^0_m, \Delta \beta_m$ more variations, and thus $\sigma_{\text{pq}}^0(\theta)$ responses, can be generated with the 3-, than with the 1-volume model. Of course the scaling coefficients $C_N, C_\ell, C_\beta$ don’t apply to the latter. The model parameters of the optimal 1- and 3-volume parsets (Table V) both lead to a fresh-biomass values $BM_f$ within the $1.3 \pm 0.9 \text{ Kg m}^{-2}$. The found optimal average cylinder radii are both also close to the in-situ 0.035 ± 0.006 cm. With the optimal 3-volume model parset the height dependent biomass density is in accordance with on-site observations by the authors that vegetation biomass decreases over height in the canopy. Also, the decreasing average cylinder radius over height corresponds to on-site observations. The found decrease of cylinder segment length $\ell$ is less trivial. The angular configuration imposed by the found 3-volume model approach seems to better represent the vegetation canopy structure as observed on site than the 1-volume model. The $0 - 90^\circ$ $\beta$-range for the 1-volume model is interpreted as a uniform distribution of plant(segment) inclination angles. In itself this is a fair assumption. The three different $\beta_m$-ranges in the 3-volume case on the other hand represent a close-to-horizontal orientation of plant segments in the top canopy to a gradually vertical-to-uniform distribution at the bottom. This configuration is an agreement with the idea that the longest grass plants eventually start bending over, while the shorter ones tend to remain more vertical. It is interesting to note that with the 3-volume TVG model this closer-to-reality vegetation morphology can be derived from the scattermeter measurements.

VI. DISCUSSION

A. Number of volumes

As mentioned in Section II-B the choice for using three volumes used in our analysis was based on practical reasons (computation time). Additional research is needed to derive guidelines for the number of volumes to use in a vegetation canopy. For example, for the Maqu grass canopy a next step would be to try four or five volumes in order to better accommodate strong leaf curvatures in the top of the canopy.

The difficulty in determining such guidelines is illustrated also by the absence of these in the similar studies mentioned in the introduction. For modeling pine forest [6] used 20 layers without further explanation. In [7] they state that “the number of layers depend on what best represents actual canopy composition”. In an example they mention ten layers. Finally,
in [8], a guideline that the number of layers should be twice the number of different tree species is stated, but without clear reasoning. They show an example of six layers.

**B. Differences in vv- and hh backscatter**

From the measurements (Fig. 5) we observe that with all bands, averaged over time, $P^{\text{hh}}_{^\text{rxm}} > P^{\text{vv}}_{^\text{rxm}}$, especially with L-band, where this difference is about 5 dB. Other studies using backscatter measurements of grasses report similar findings, albeit without such large differences for L-band. In [45] the results of numerous studies on the backscattering of grasses are summarized into empirical curves of $\sigma_0^0(\theta)$ for commonly used radar bands. When we consider the $\theta$-ranges that contribute to the $P^{\text{pq}}_{\text{pq}}$ signal per band (see [28]), the empirical curves state that $\sigma_0^\text{hh} - \sigma_0^\text{vv}$ ranges from 0 to 1 dB over $\theta = 0 - 60^\circ$ respectively for L-band, 0 to 2 dB over $\theta = 20 - 60^\circ$ for S-band, and 4 to 2 dB over $\theta = 47 - 59^\circ$ with X-band. For C-band, however, this was -2 to 0 dB over $\theta = 35 - 60^\circ$. Unfortunately, it proved difficult to retrieve in-situ information on the measured grass canopies (species, biomass, height etc.) of these studies. Another study, [46], considered C-band hh-polarization synthetic aperture radar (SAR) satellite data over Sahel grassland in the validation of their microwave scattering model, which predicts $\sigma_0^\text{hh} > \sigma_0^\text{vv}$ by 1 dB at $\theta = 50^\circ$. For greater angles this difference will be a bit higher. Little- to no difference between Prairie Tallgrass $\sigma_0^\text{hh}(\theta)$ and $-\sigma_0^\text{vv}(\theta)$ for C-band was inferred from measurements and simulations described in [2]. Studies considering wheat crop, which stems are thicker and longer than those of grass, do show larger differences between hh- and vv-polarization for L-band. With [47] $\sigma_0^\text{hh} - \sigma_0^\text{vv} = 6$dB was measured for L-band at $\theta = 40^\circ$. Stated values were measured at the fully-emerged-leaf stage at which the average stalk had a 0.29 cm radius and 29 cm length. A difference of $\sigma_0^\text{hh} - \sigma_0^\text{vv} = 5$dB for L-band was reported in [48] prior to heading stage.

The TVG model, both with the 1- and 3-volume approach, was capable of reproducing the measured differences between hh- and vv-polarization for all bands except with L-band (see Fig. 7). To explain this discrepancy, we decomposed the total backscatter in parts [4] [20]: $\sigma^\text{tot}_\text{pq} = \sigma^\text{veg}_\text{pq} + E^2\sigma^\text{soil}_\text{pq} + \sigma^\text{int}_\text{pq}$ where $\sigma^\text{veg}_\text{pq}$ is the total vegetation volume backscatter (1 or 3-volumes), $E$ is the extinction coefficient (or one-way canopy transmission), $\sigma^\text{soil}_\text{pq}$ the soil only backscatter coefficient, i.e. AIEM-model output, and $\sigma^\text{int}_\text{pq}$ is the interaction term representing scattering between the soil and vegetation volume, (polarization indices are omitted here.) Figure 8 shows $\sigma^\text{veg}_\text{pq}$, $\sigma^\text{soil}_\text{pq}$, $E^2\sigma^\text{soil}_\text{pq}$, and $E$ of L- and X-band for the found optimal 1- and 3-volume parsets. For L-band, we see that for both polarizations $E^2\sigma^\text{soil}_\text{pq}$ forms the main part of the backscatter, as $\sigma^\text{veg}_\text{pq}$ is as least 7 dB lower for both vv than hh for $\theta \leq 50^\circ$. The interaction term (not shown for clarity of the figure) is about 5 dB or more below $\sigma^\text{veg}_\text{pq}$ so even less important for the total. In order to achieve $\sigma^\text{hh}_\text{pq} > \sigma^\text{vv}_\text{pq}$ the $E$ for vertically polarized radiation, for example at $\theta = 50^\circ$, would have to be at least 3 dB lower than that for horizontally polarized radiation, currently this difference is 1.6 dB.

Such attenuation could be realized with thicker vertically-oriented cylinders, as the measurements in [47], [48] show. In case of our grassland, we could consider the possibility that thicker cylinders were present at the canopy bottom, as (ticker) main stems from which numerous filiform leaves emerge. This
Fig. 7. Measured and simulated radar return powers $P_{rx}^m$ over soil moisture content $m_v$. Symbols represent average measured $\langle P_{rxm}^m \rangle$ at $m_v = 0.13, 0.18, 0.23,$ and $0.28 \text{ cm}^3\text{ cm}^{-3}$, bars are averaged 68% confidence intervals. Lines are simulation results $P_{rxs}$ for found optimal parsets of 1- (solid) and 3-volume model (dashed).

morphology is known as tufting and is a feature of *Festuca ovina* [29]. When letting ten or more thin cylinders, as used in our simulations, 'merge' into a smaller number of thicker cylinders (main stems) with about four times larger radii, i.e. $N_A^{stem} = N_A^3 / 10$ and $r_{stem} = 4r$, with the 1-volume model, this indeed results in $L_{hh} > L_{vv}$. This change would of course result in mismatch for the higher frequencies. Using the M-volume approach, however, would allow for implementing tufting without the higher frequencies being affected, as these do not penetrate deep enough to encounter the thicker cylinders. Unfortunately, during the in-situ measurements too little attention was paid to the precise morphology of the grass plants. On photographs taken during the measurements (Fig. 2 for example) tufting phenomena could not clearly be identified. An alternative explanation for the strong difference between $L_{hh}$ and $L_{vv}$ could be that the soil was not modeled properly. It is possible that features other than surface roughness, as covered by for example AIEM, play an important part.

C. Effect of leaf inclination

The found optimal parset of the 3-volume model for matching the measurements has a $\beta_m$ configuration of $60 - 75^\circ$, $30 - 90^\circ$, and $0 - 75^\circ$ for volumes 1 (top) to 3 respectively. Here we explore the $\sigma_{pq}^0(\theta)$ curves of alternative $\beta_m$ configurations to illustrate the effect of the leaf (segment) inclination angles. Other parameter values are as in Table V.

In Table VI six scenarios for the angular geometry of a 3-volume canopy are described in terms of $\beta_m$. We have canopies where all plants are predominantly vertical: scenario A 'straight' and scenario B, or mostly horizontal: scenario F 'lodging', where due to wind and heavy rain the plants are lodged over. The scenario C 'gradually hanging' configuration mimics plants that bend over further as they grow longer. Then there is the scenario where the plants of medium height hang over while the longest plants are upright: scenario D. Finally, scenario E 'uniform' represents the commonly used configuration where all inclinations are present. Figure 6 shows the simulated $\sigma_{pq}^0(\theta)\beta_m$ curves for each of these scenarios.

The effects of varying $\beta_m$ are strongest for X-band in general, except with hh polarization. This is because with X-band the cylinder segments are larger compared to the wavelength, causing their $\langle \sigma_m(\theta_s, \theta_i, \Delta \phi) \rangle$ and $\langle \sigma_m(\theta_i) \rangle$ to be stronger and more directional, so that more change
in $\sigma^0_{pq}(\theta)$ may be expected when changing the inclination angles. The two 'straight' scenarios A and B clearly don’t match with the measurements, neither does the scenario D. The uniform configuration already performs much better. The lodging scenario also comes close, though we did not observe such strong lodging on site during the measurements. For Xhh the performance is in-fact the best with scenario F. For Xvv, however the performance of scenario’s E and F is worse than with the found optimal 3-volume parset. With the ‘gradually hanging’ scenario C the Xvv performance is also quite good, but for C-band it is far from optimal. For completeness we mention here that the simulated $P_{pq}^{rx}$ for all bands of the 6 considered scenarios matched less good than with the found optimal 3-volume parset. Except for the 'lodging' and 'uniform' configurations, whose performance was comparable.

**D. Bistatic scattering coefficient**

For simulating microwave emission from a vegetation-covered surface the bistatic scattering coefficient $\sigma^0_{pq}(\theta_s, \theta_i, \Delta \phi)$ or $\sigma^0_{pq}^{bi}$ of the vegetation is required, see for example [49], [50]. Also with global navigation satellite system (GNSS)-reflectometry [51], [52] $\sigma^0_{pq}^{bi}$ of vegetation can become relevant. In many applications the coherent specular reflection of the underlying soil is the main signal of interest and is also the strongest [53]. For optically thick vegetation however, the incoherent vegetation scattering can become dominant at, or close to, the specular direction [54] [55]. With both techniques, the M-volume approach may result in better simulation results of $\sigma^0_{pq}^{bi}$. Although $\sigma^0_{pq}^{bi}$ was not measured in this study we demonstrate here important differences in $\sigma^0_{pq}^{bi}$ simulations than may occur when the height-variable vegetation morphology is not considered.

In this analysis we only consider incoherent scattering. As explained in [53] coherent soil scattering (particularly, the specular direction) is not accounted for in the TVG model as used in this paper. Modeled co-polar scattering at, or near, the forward direction ($\Delta \phi = 0^\circ, \theta_i = \theta_s$) is therefore invalid. For X-band, however, we can use the simulated results because incoherent soil scattering is dominant, given the used roughness; $k_s = 2, k_l = 18$. The AIME specular predictions are 4.1 dB for vv and 10.4 dB for hh, exceeding the plane-wave coherent upper limit, -22.6 dB and -18.0 dB respectively [17], by more than 27 dB. Figure 9 shows simulated X-band $\sigma^0_{pq}(\theta_s, \theta_i = 55^\circ, \Delta \phi)$ patterns of the found optimal parsets of the 1- and 3-volume model discussed earlier (Table V). From the perspective of the known, i.e. measured, in-situ vegetation parameters both model approaches can be considered equivalent. The total fresh biomass $BM_F$ and $r$-values of both parsets are comparable.

For Xvv the 3-volume model predicts up to 2 dB higher scattering than with the 1-volume model for most of the angles. For $\Delta \phi = 0^\circ$ and in the backscattering plane ($\Delta \phi = 180^\circ$) the 1-volume model scattering is, respectively, up to 1 dB and 2 dB higher for larger $\theta_s$-angles. An up to 3 dB higher scattering with the 1-volume model is predicted in the forward direction of the Xhh channel. With the other $\Delta \phi$ -planes the 1-volume model value is up to 1.5 dB higher than with the 3-volume model. The overall differences between the two cross-polarization channels are larger with the 1- than with the 3-volume model. Although AIME also predicts differences between Xhv and Xvh, what we see here is for the major part due to vegetation-volume scattering. This is further illustrated by the close-to-zero one-way canopy transmission for both v- and h-polarized radiation shown in Fig. 8. In particular, for Xvh the 3-volume model predicts an overall stronger scattering of up to 2 dB higher than the 1-volume model while for Xhv both models’ values are more similar, except for $\Delta = 0^\circ$ and $45^\circ$. An example of the relevance of the described differences may be found in [56], where the authors describe the idea of using the co-polarization channels of $\sigma^0_{pq}^{bi}$ in the plane $\Delta \phi = 90^\circ$ for vegetation monitoring, as it is more sensitive.

---

**TABLE VI**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Volume 1 (top)</th>
<th>Volume 2</th>
<th>Volume 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A straight</td>
<td>0 – 30</td>
<td>0 – 30</td>
<td>0 – 30</td>
</tr>
<tr>
<td>B straight, bit hanging</td>
<td>0 – 45</td>
<td>0 – 30</td>
<td>0 – 30</td>
</tr>
<tr>
<td>C gradually hanging</td>
<td>45 – 90</td>
<td>30 – 60</td>
<td>0 – 30</td>
</tr>
<tr>
<td>D middle hanging, longest plants straight</td>
<td>0 – 30</td>
<td>15 – 60</td>
<td>0 – 30</td>
</tr>
<tr>
<td>E uniform</td>
<td>0 – 90</td>
<td>0 – 90</td>
<td>0 – 90</td>
</tr>
<tr>
<td>F lodging</td>
<td>75 – 90</td>
<td>45 – 90</td>
<td>0 – 90</td>
</tr>
</tbody>
</table>

**Fig. 8.** Components of simulated $\sigma^0_{pq}(\theta)$ for L- and X-band of found optimal - and 3-volume parsets: vegetation volume scattering, attenuated soil surface backscatter and soil surface backscatter. Values extinction coefficient $E$ (or one-way canopy transmission) shown on right ordinate.
to vegetation- than to soil scattering there. Our simulations show a difference up to 2 dB between the two models with the co-pol channels.

The simulation results for the other bands are not shown here, but are available as supplementary material at https://doi.org/10.1109/TGRS.2022.3229749/mm1. With Cvv the 3-volume results are up to 2 dB higher than with the 1-volume model ($\Delta \phi = 0^\circ$ is not considered here). For Chh it depends on the $\Delta \phi$ -plane which model gives higher values, overall differences are up to 1 dB. For cross-polarization the 3-volume model, in general, gives higher values up to 2 dB. As expected, the differences at S- and L-band are smaller, as the vegetation becomes more transparent for the longer wavelengths and soil scattering will be dominant. For Svv, Svh, and Shv the 3-volume scattering is up to 1 dB higher in general. For Shh the overall difference between the models is up to 1 dB. In the backscattering plane both models’s predictions are similar for all $\theta_s$. Finally, with L-band, the differences are less than 0.5 dB for all polarization and angles.

Due to absence of measurement data we cannot rule in favor of any model, but this example does show that considering the vegetation’s geometric structure in greater detail than with the default (1-volume) case does have influence on the scattering patterns, both in mono-static (backscatter) and bistatic case.

E. Further considerations
A possible reason we could not find better matches to measured $\sigma_{pq}^0(\theta_s)$ and $\mathcal{P}_{pq}^{rx}$ using the 3-volume model, for example with the X-band $\sigma_{pq}^0(\theta_s)$, is that the number of volumes used (three) is not yet sufficient. With more volumes the plant structure, for example in terms of inclination of segments, can be reproduced better and thus may result in more accurate simulation results. Furthermore, one has to consider the possibility that amount of measurement data at our disposal was insufficient. Angles smaller than $\theta = 35^\circ$ and above $\theta = 70^\circ$ were not measured, while for these ranges predicted differences between the 1- and 3-volume models are large (Fig. 6). Also the number of statistically independent $\sigma^0$ measurements was on the low side. Actual measurements on L- and S-band $\sigma^0(\theta)$ with higher gain antennas rather than simulated $\mathcal{P}_{rx}^{fx}$ could have also helped in identifying the proper height-dependent structural configuration of the canopy.

The AIME surface roughness parameters were fixed to $s = 1$ and $\ell_{corr} = 9$ cm with an exponential correlation function as described in section IV-D in accordance to the empirical settings found in [41] for the Maqu area. Other roughness settings can lead to very different simulation results, in particular for L- and S-band. Upon trying alternative roughness settings ($s = 0.5, 1, 1.5, 2.5$ cm and $\ell_{corr} = 3, 9, 18, 30$ cm) with the optimal parsets (Table V) we found that the used values offer the best compromise for all channels. Actual measurements of surface roughness are required to actually validate used settings.

Finally, we realize that the type of vegetation used in this paper: alpine meadow grassland, did not turn out to be the best choice for comparing the M-volume TVG approach to the default model. Compared to crops its VWC is on the low

![Fig. 9. Angular plots simulated $\sigma_{pq}^0(\theta_s, \theta_i, \Delta \phi)$ for the found optimal 1- , (left plots) and 3-volume TVG model (right plots) at X-band. Lower four graphs show cross sections $\sigma_{i}^0(\theta_s)$ of both models at different azimuth planes ($\Delta \phi$). Solid lines represent 1-, and dashed lines 3-volume cross sections. Incidence angle $\theta_i = 55^\circ$ (black triangle in the contour plots).]
side, 60% compared to for example 85% for sunflower [14], yielding only a moderate dielectric contrast: \( \varepsilon_r = 20 - i7 \) compared to \( \varepsilon_r = 44 - i10 \) respectively for C-band. Also its canopy element dimensions are small compared to for example the branches and stems of a forest canopy. Larger dimensions of the elemental scatterers, compared to the wavelength, will result in stronger and more directional radiation scattering patterns, see for example [19]. A supplementary document is available under https://doi.org/10.1109/TGRS.2022.3229749/mm1, in which we give a demonstration of how a stronger scattering vegetation volume would behave. Taking the found optimal 1- and 3-volume parset as starting point, an increment of the cylinder radii to twice- or four time its found value (Table V) will yield stronger differences in \( \sigma_{pq}^0(\theta) \) and \( \sigma_{pq}^{0,bi} \) between the two models, also for the lower bands. We expect that using the M-volume TVG approach with, for example, a forest or soybean crop will show a stronger improvement in modeling microwave scattering compared to the default TVG than we have demonstrated here with alpine meadow grassland.

VII. CONCLUSION

In this paper we performed simulations of multi-frequency and fully polarimetric microwave scattering from a Tibetan Alpine meadow using the Tor Vergata (TVG) model based on the Matrix Doubling Method (MDM). The effect of vertically heterogeneous canopy structure of the grass was investigated by extending the TVG model to accommodate height-dependent variation in structure and constituency for every one type of scattering element by the M-volume approach. Simulations of both the default (1-volume) TVG model and the new M-volume approach with 3-volumes were compared against backscatter measured by a ground-based scatterometer over 1 – 10 GHz. Measurements included angle-dependent backscattering \( \sigma_{pq}^0(\theta) \) for C- and X-band taken on 25 August 2017 and 19 August 2018, and full polarimetric radar return power \( P_{pq}^{rx} \) for L-, S-, C-, and X-band measured over 13 July – 13 August 2018. In-situ measuremens of fresh/dry biomass and plant dimensions were used to constrain the model. The 3-volume model was considered to better mimic reality.

We managed to reproduce the measured \( \sigma_{pq}^0(\theta) \) for C- and X-band and the 31-day average of \( P_{pq}^{rx} \) for L-, S-, C-, and X-band within, or close to, the measurement uncertainty with both the 1- and 3-volume model. Our analysis, based on the measurement data we had and TVG simulations performed, was inconclusive on whether the 3- or 1-volume approach could better reproduce the measured backscatter of an Alpine Meadow. We argued that this result might have been due to an insufficient amount of backscatter-measurement data and/or because the number of volumes used to represent the vertical canopy structure was too low. Furthermore, in the process of comparing simulated- with measured \( P_{pq}^{rx} \) no notable differences in sensitivity to varying soil moisture content between the 1- and 3-volume model were found.

We did find that the 3-volume approach allows for more flexibility in reproducing the actual \( \sigma_{pq}^0(\theta) \) of the scene for multiple frequencies than the 1-volume model. We hypothesize that at some point, when more (also bistatic) angles are considered the default (1-volume) approach might reach its limits in reproducing the scattering behavior. Simulations on the bistatic scattering behavior of both models show that, although similar constraints on canopy biomass and plant dimensions were used, the 1-, and 3-volume model predictions differed substantially for X-band (up to 3 dB in specular direction for hh-polarization) and also for C-band (up to 2 dB for vv, vh and hv). This predicted difference in bistatic vegetation scattering may prove relevant for applications in the fields of microwave emission and GNSS-R.

The difference between the two approaches would have been more apparent in case of a vegetation canopy with stronger scattering behavior. This was demonstrated by artificially increasing the scattering strength of the two model canopies.

Measured \( P_{pq}^{rx} \) for Lhh exceeded Lvv by 5 dB on average. The TVG model was not able to reproduce this difference both with the 1- and 3-volume approach. We argued that this discrepancy is either due the absence of thicker main plant stems at the bottom of the TVG model canopy or due to a inadequate treatment of the soil scattering in the TVG model. In the former case, the M-volume approach would be able to accommodate this.

Further research on the effects of considering canopy vertical heterogeneity in microwave scattering modeling, including bistatic measurements, is needed to give a (more) definite answer on whether adding more complexity to the TVG model through the M-volume approach will pay of.

APPENDIX A

STATISTICS FOR \( \sigma^0(\theta_0) \) COMPARISON

The following statistics were used for comparing the simulated- and measured \( \sigma_{pq}^0(\theta_0) \) values, for C- and X-band channels of every parset. All below statistics were used with the dB values of the measurements and simulations to prevent high-value sets overruling the low-value ones [57]. The RMSD is calculated as

\[
RMSD = \sum_{i=1}^{8} w_i [m_i - s_i]^2
\]

with \( m_i \) and \( s_i \) being the measured- and simulated \( \sigma_{pq}^0(\theta_0) \) respectively (there are eight \( \theta_0 \)-angles to compare) and \( w_i \) the normalized weight, i.e. sum of all weights equals 1. The correlation coefficient is calculated by

\[
R = \frac{\sum_{i=1}^{8} w_i [m_i - \bar{m}] [s_i - \bar{s}]}{\sqrt{\sum_{i=1}^{8} w_i [m_i - \bar{m}]^2} \sqrt{\sum_{i=1}^{8} w_i [s_i - \bar{s}]^2}}
\]

where also the averages \( \bar{m} \) and \( \bar{s} \) are weighted.

The skill score \( S \) combines the \( R, \) RMSD, and \( \sigma_{rar} \) of a set of measured and simulated \( \sigma_{pq}^0(\theta_0) \) values into one number ranging from 0 (very poor match) to 1 (identical). It is an extension of the equations stated in [35].
where powers $U$, $V$, and $W$ can be used to scale the importance of the different parts. We used 2, 1, and 1 respectively.


Jan Hofste obtained his BSc-degree in Engineering Physics at the Saxton Hogeschool Enschede in 2007, after which he was employed for five years at Thales Nederland B.V. in Hengelo where he worked as Antenna Engineer on the design and experimental verification of (phased array) antennas and other passive microwave components used in military radar systems. Next, he continued his study on physics at the University of Twente, where he obtained his MSc-degree Applied Physics in 2016 on light scattering by photonic crystals. Currently he is pursuing his Ph.D. degree on the subject of microwave remote sensing of vegetation- and soil. His research interests lie with scattering of electromagnetic waves by complex media.

Rogier van der Velde earned a M.Sc. degree in hydrology from Wageningen University, Wageningen, The Netherlands, and a Ph.D. degree in soil moisture remote sensing and land surface hydrology from the University of Twente, Enschede, The Netherlands. He has held Assistant and Associate Professor positions in Earth Observation and Land Surface Hydrology at the Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, with a focus on soil moisture estimation from active as well as passive microwave observation for the understanding of hydrometeorological processes. Currently he is Specialist Hydrology at the Water Expertise Centre (WEC) of Vitens where he contributes with his research to a sustainable drinking water production.

Paolo Ferrazzoli (Senior Member, IEEE) graduated from the University “La Sapienza” of Rome, Rome, Italy, in 1972. In 1974, he joined Telespazio s.p.a., Rome, where he was mainly active in the fields of antennas, slant-path propagation, and advanced satellite telecommunication systems.

In 1984, he joined Tor Vergata University of Rome, Rome, where he taught microwaves, radiowave propagation, and electromagnetic fields. His research was focused on microwave remote sensing of vegetated terrains, with particular emphasis on electromagnetic modeling. He was involved in international experimental remote sensing campaigns such as AGRISAR, AGRISCATT, MAESTRO-I, MAC-Europe, and SIR-C/X-SAR. He participated in the coordinating team of the ERA-ORA Project, funded by EEC, establishing an assemblage among several European researchers working in radar applications.

Mr. Ferrazzoli was a member of Science Advisory Group and a member of Quality Working Group in the framework of the European Space Agency (ESA) SMOS Project. He was Chair of MICRORAD 2012 International Meeting, and a member of the Technical Program Committee of IGARSS Conferences from 2012 to 2018.
Zhongbo (Bob) Su received the B.Sc. degree (1984) in hydraulic engineering from the Taiyuan University of Technology, China, the MSc. degree with distinction (1989) in hydrological engineering from IHE Delft Institute for Water Education, the Netherlands, and the Ph.D. degree (1996) in civil engineering from the Ruhr University, Bochum, Germany.

He currently holds the chair of Spatial Hydrology and Water Resources Management at the Faculty of Geo-Information Science and Earth Observation of the University of Twente. His current research focuses on integrating radiative transfer, photosynthesis and energy fluxes with simultaneous transfer of energy, mass and momentum in unsaturated soil via the water-soil-plant-atmosphere pathway as a component of earth system model, modelling microwave signature of land surface and retrieval of soil moisture and vegetation properties, and developing data driven machine learning algorithms for digital twin earth. Prof. Su is a member of GEWEX Scientific Steering Group (SSG) and a member of COSPAR Capacity Building Panel.