An advanced electromagnetic model for rice fields at X-band: Development and interpretation of dual-pol TerraSAR-X images

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Abstract
A generic electromagnetic model for agriculture scenes has been extended and adapted to simulate the X-band SAR response of rice fields during their whole phenological cycle. Simulations of different polarimetric observables have been useful for interpreting time series of dual-pol TerraSAR-X images acquired during 2008 and 2009 over rice fields in Spain at different incidence angles and different polarization channels.

1 Introduction
The imagery provided by the German TerraSAR-X satellite SAR sensor exhibits some characteristics which make it especially suited for agricultural monitoring, such as short revisit time, high spatial resolution, coherent dual-polarization measurements, etc. Interpretation of the data gathered by this sensor relies on the availability of electromagnetic models of the scene which should permit the simulation of the radar data starting from a realistic description of the observed scene. In this context, the use of short wavelengths (X-band) is relatively new, and existing models of vegetated scenes (in general developed for L- and C-band) must be adapted to this frequency band.

In this paper we focus on the direct electromagnetic modeling of rice fields at X-band, with the aim of interpreting time series of dual-pol TerraSAR-X images acquired during 2008 and 2009 over a test site in Spain. A first analysis of this dataset can be consulted in [1], where the physical interpretation of the results was carried out mostly in a qualitative way. Some observables showed clear signatures when compared with the development of the plants, thus suggesting their potential as parameters for monitoring rice crops (particularly the ratio between HH and VV backscattering coefficients and the phase difference between the two copolar channels). However, the physical interpretation of these signatures has to be established and justified properly in order to develop a right monitoring tool. Moreover, an electromagnetic model would serve for assessing the influence of all scene parameters upon the radar observations. Therefore, this work is devoted to develop such a model and to use it for analyzing and interpreting the available data.

2 Model description
With the objective of simulating all possible observations provided by the TerraSAR-X sensor, we have implemented a full wave coherent model, hence delivering the full scattering matrix (with both amplitudes and phases) for a scene. The natural variability of the scene is obtained through a Monte Carlo approach, thus running a high number of realizations and then computing the average values. The model implementation presents two important stages: scene generation and electromagnetic simulation. The scene generation consists in simulating the scene by defining the availability of electromagnetic models of the scene which should permit the simulation of the radar data starting from a realistic description of the observed scene. In this context, the use of short wavelengths (X-band) is relatively new, and existing models of vegetated scenes (in general developed for L- and C-band) must be adapted to this frequency band.

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The first important improvement of the model is the generation of the scene architecture. The new model creates the scene by taking into account the typical morphology of the plants for each phenological stage of the BBCH standard, hence considering all the important parameters as the number, sizes and orientations of stems, tillers, leaves, etc. Therefore, the scenario prepared for the electromagnetic computations is quite realistic and can simulate all the crop conditions found in real cases. This feature is especially important for modeling coherently the responses from all elements, hence enabling also the generation of interferometric observables. Although the final objective of this research is the development of a model adapted to all the stages in the phenological cycle of rice, here we concentrate on the first phenological phase of such crop, named
vegetative, leaving the other two (reproductive and maturation) for future work.

A second change in the model is the incorporation of extinction effects on the electromagnetic scattering. The average extinction coefficient at each layer along the vertical coordinate is computed by the forward scattering theorem, and then used to drive the attenuation of waves through the vegetation volume. In the previous model version extinction was ignored, but we will see in next section the importance of accounting for it and, also very importantly, its notable impact on the polarimetric response as a result of differential extinction between vertical and horizontal channels.

Finally, in order to extend better the range of validity of the model to X-band, we have incorporated the modelling of leaves as dielectric disks (either rectangular or elliptical) with one dimension larger than the wavelength (3 cm for X-band), as other authors have done in the literature [3]. In the previous version, all elements of the plants were modelled as cylinders with arbitrary length (e.g. for the stems) or as ellipsoids (e.g. for the leaves with sizes much smaller than the wavelength, thus analyzed in the Rayleigh scattering region). Instead, the added model of the disks is based on physical optics [4], hence providing the required solutions for disks larger than the wavelength.

3 Results

The first part of the work consisted in adjusting the geometrical parameters of the model at each phenological stage in order to generate the scenes as much similar as possible to the available ground data acquired during the campaigns. Figure 1 shows the overall aspect of a complete typical scene of rice for several BBCH stages during the vegetative phase.

After a realistic geometrical definition of the scene, every element in the scene is associated with its corresponding scatterer (cylinder, disk, etc.) for which its scattering matrix can be computed. In general, stems and tillers are always defined as lossy dielectric cylinders, while branches and leaves can be modelled by means of either cylinders or disks. Besides sizes and orientations, values of dielectric constants are also provided.

Figure 2: Temporal evolution of the backscattering coefficients for HH and VV, and their ratio, for a single rice field at 30° incidence. The vertical lines indicate the sowing date and the approximate dates of transition from vegetative to reproductive phase and from reproductive to maturation phase.

For the moment, instead of just running multiple simulations for many growth stages, we concentrate now on the main scattering mechanisms present in the scene. We can see in Figure 2 the temporal evolution of the HH and VV backscattering coefficients, and their ratio, for a single rice parcel. For vertical polarization we can also study the dependence on incidence angle for the same parcel, as shown in Figure 3. In addition, the phase difference between both copolar channels for all monitored parcels is presented in Figure 4. In all cases there are important dependences of
the observables upon the time, and hence upon the pheno-
logical phase of the plants at each moment.

Figure 3: Temporal evolution of the VV backscattering coeffi-
cient for a single rice field at 22°, 30° and 40° incidences

Figure 4: Temporal evolution of the phase difference between
VV and HH for all the monitored parcels at 30° incidence

The first and simplest model of the rice fields during the
vegetative phase considers only the influence of the stems
and tillers, and for even more simplicity, we can regard
both of them as dielectric cylinders. Therefore, we can
model the scene as a number of clusters of cylinders (each
cluster corresponding to a plant) where cylinders exhibit
a Gaussian distribution of inclinations around the vertical.
Table 1 presents the main parameters of such a scene, and
the simulated values at 9.65 GHz as a function of the av-
erage cylinder length (from 2 cm to 90 cm) are presented
in Figures 5 to 7. Note that in this case the horizontal axis
corresponds to vegetation height, not time (DoY) as in the
plots of the experimental data.

By comparing Figures 2 and 5 we can state that the main
trends and approximate absolute values of the backscatter-
ing coefficients are correctly simulated with such simple
model. We can observe that both HH and VV increase im-
portantly at the beginning as a consequence of the cylin-
ders length growth. From some point (10 cm approx.) the
increase rate is slower, and then from 25 for VV and 40 cm
for HH the received backscattering level decreases as the
cylinders continue to grow. The HH backscattering reduc-
tion is slower than the VV, and hence the ratio HH/VV
increases monotonically (and at a constant rate in the sim-
ulations) during the vegetative phase.

<table>
<thead>
<tr>
<th>Density of plants (clusters)</th>
<th>20 m⁻²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stems and tillers per plant</td>
<td>10</td>
</tr>
<tr>
<td>Cluster radius</td>
<td>7 cm</td>
</tr>
<tr>
<td>Stem/tiller radius</td>
<td>2 mm</td>
</tr>
<tr>
<td>Stem/tiller inclination average</td>
<td>0 deg.</td>
</tr>
<tr>
<td>Stem/tiller inclination std. dev.</td>
<td>15 deg.</td>
</tr>
<tr>
<td>Stem/tiller length std. dev.</td>
<td>10 % of avg.</td>
</tr>
<tr>
<td>Stem/tiller dielectric constant</td>
<td>21.8 + j 9.4</td>
</tr>
<tr>
<td>Ground dielectric constant</td>
<td>60 + j 24</td>
</tr>
</tbody>
</table>

Table 1: Main parameters for the simulation of Figs. 5–7

Figure 5: Simulated backscattering coefficients for HH and VV,
and their ratio, at 30° incidence as a function of the average cylin-
der height

Three key points must be commented about this response:
1) Radar backscattering at X-band and 30 degrees inci-
dence is dominated by the double-bounce interaction be-
tween the flooded soil and the quasi-vertical stems. 2) For
a scene composed by almost vertical very thin cylinders,
extinction coefficient (expressed in dB/m) at vertical polar-
ization is larger than at horizontal polarization, hence there
exists differential extinction between polarizations. 3) As
vegetation height increases, the total attenuation or extinc-
tion (expressed in dB) is stronger for vertical than for hori-
zontal polarization, due to longer propagation paths inside
the vegetation volume and the aforementioned differential
extinction, and this is the mechanism driving the observed
response. The extinction rates provided by the simulations
at 30 degrees incidence are 13.6 dB/m for vertical and 6.6 dB/m for horizontal polarization, respectively.

The main difference between the experimental data and the simulations is observed at the end of the vegetative phase, since both HH and VV simulated levels are approximately 5 dB over the measurements. This evidences the necessity of including the layer of leaves, as in the scenes of Figure 1, which would increase the extinction at both polarizations in a rather similar amount as a consequence of their mostly random orientation.

As for the influence of the incidence angle on the VV channel (see Figure 3), at the very early stages after sowing (days 0 to 25), backscattering is higher for oblique incidences since the presence of very short and scarce plants emerging from the water surface, together with some surface roughness due to the presence of moderate wind, can be observed better at oblique angles than at shallow ones. Then, there is a general increase of the backscattered signal at all angles. Finally, at the end of the vegetative phase there are important differences between incidence angles. At this point the order is the opposite of the early stages, due to a stronger total attenuation at more oblique incidences because the paths of the waves inside the vegetation volume are longer for oblique angles. Simulated values shown in Figure 6 fully confirm these comments.

Simulations shown in Figure 7 provide an almost constant value (approx. 90°) for all cylinder lengths, whereas the experimental data show an initial value around -30° and then a jump to about 60-80° for the rest of the vegetative stage. As previously mentioned, just after sowing the radar response should come from the flooded soil, which may be partially rough due to the wind, and from scarce short plants. The expected phase difference from such scene should be around 0, not -30°, so further investigations are required to interpret this value. Note also that our simulations provide a constant value since the direct response from the ground is not computed and backscattering is always dominated by the double-bounce interaction.

In conclusion, an overall agreement between experimental data and simulations for the vegetative phase has been obtained by a simplified model, hence next steps in this research include: extension of the model to the whole phenology cycle, incorporation of the direct ground response (important just after sowing and in the presence of wind), and analysis of the potential effects of multiple scattering.

Acknowledgments

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