Modeling backscattering variations due to flooding over vegetated surfaces

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Abstract
The objective of this study is to evaluate the possibility to identify floods when soil is covered by vegetation, recognizing differences in backscattering between SAR measurements acquired before and after the event. To this end, the electromagnetic model developed at Tor Vergata University is run for an early stage and a fully grown wheat field, at L, C and X band. Theoretical results show that flooding can be detected at all frequencies in presence of short vegetation, while L band is the most suitable one for developed crops. Results obtained in the case of early stage are in reasonable agreement with ERS data collected over grass fields before and after the strong flooding occurred in Alessandria (North Italy) in 1994.

Keywords: Soil Moisture, Flooding, Electromagnetic Model, SAR.

Introduction
Extreme hydrologic events cover a wide scale of spatial and temporal scales, such as flash floods or long-duration widespread floods. In all cases, they can cause significant economic losses, as well as social and environmental stresses. One of the biggest problems during
these emergencies is obtaining an overall view of the phenomenon, in order to evaluate the extent of the flooded area and to predict its development. Detailed maps of the event are necessary both for hazard assessment and as input to hydrological models which are run to schedule eventual interventions. **Airborne observation is often impossible, due to prohibitive** weather conditions and, if the phenomenon is widespread, it would be too expensive. In this framework, space-borne SAR acquisitions stand as a useful tool in early warning of flooding events [Henderson, 1995]. **Their combined characteristics of high resolution** and cloud penetration capability offer a unique opportunity of damage inventory and flood propagation forecasting [Pierdicca et al., 2008]. Many theoretical and experimental studies have demonstrated the sensitivity of SAR to the moisture content of soil up to its complete coverage by water [Wang et al., 1995; Tholey et al., 1997]. This sensitivity is driven by the dielectric constant of the observed surface, which is a function of its water content and which determines its reflection property. However, both surface roughness and vegetation cover make the interaction between the electromagnetic wave and the surface a complex phenomenon. Indeed, flood may make the soil surface smoother - or rougher, if wind is present - so that the imprint of the natural disaster on the radar response changes as a function of frequency and incidence angle. **On its side, vegetation attenuates scattering** from underlying soil but, when stems or trunks are present, introduces a “double bounce” effect as well, which can be enhanced by a flooded surface [Wang et al., 1995; Grings et al., 2006]. In this case, the radar response depends on frequency but also on the vegetation biomass and on the geometry of the scattering elements. **Due to the large variability of scenarios, empirical approaches are not suitable to reach a complete understanding of the scattering processes which arise in such conditions. On the contrary, models are able to single out the effects due to different variables, thus allowing a parametric analysis of the radar response of flooded land.**

In this paper, the electromagnetic model developed at Tor Vergata University has been employed to simulate the effect of soil moisture on the backscattering coefficient of a vegetated surface. Then, a surface with a dielectric constant equal to the one of water has been supposed to lie beneath vegetation, in order to simulate the case of total flooding. A wheat field at two different stages of growth is considered: a very early and a late stage. The first one corresponds to a small plant with short vertical stems and narrow leaves, and can be also considered representative of a grass field; the second one corresponds to a well developed crop with typical morphological properties of wheat. The electromagnetic behaviour at three different frequencies (1.2, 5.3 and 10 GHz) will be studied, in order to identify the frequencies and polarizations with the best sensitivity. Finally, a comparison with ERS data, collected before and after a flooding event in Northern Italy in 1994, will be presented.

**The electromagnetic model**

The model developed at Tor Vergata is based on the radiative transfer theory, and adopts a discrete approach [Bracaglia et al., 1995]. The latter is recognized as reliable and widely accepted within the scientific community. It is suitable to simulate the backscattering of crops, provided the model inputs are given using detailed, complete and reliable ground truth. The first step consists in selecting a suitable crop geometry. For wheat, we have considered a homogeneous half space with rough interface, representing the soil, overlaid by a lower layer filled with discrete dielectric scatterers, representing stems and leaves, and
an upper layer of ears, when present. The electromagnetic behaviour of leaves are modeled by means of randomly orientented thin circular discs [Le Vine et al., 1983; Eom and Fung, 1984]; stems and ears are modelled by means of vertical cylinders [Karam and Fung, 1988]. The bistatic scattering coefficient of soil has been computed through the Integral Equation Model (IEM) [Fung, 1994]. The extinction cross sections and bistatic scattering cross sections of single elements have been computed using suitable permittivity models [Ulaby and El-Rayes, 1987] and electromagnetic approximations [Del Frate et al., 2004; Della Vecchia et al., 2006]. In order to combine vegetation contributions, the Tor Vergata model adopts the Matrix Doubling algorithm [Bracaglia et al., 1995]. This is an advanced method, in that it includes multiple scattering effects of any order which take place between vegetation elements and vegetation and soil. A further peculiarity of the developed model is that it yields the overall backscattering coefficient of the vegetation-soil canopy, and it can also separate contributions coming from the vegetation elements, the soil (attenuated by the above lying vegetation), interactions between them and double bounce effects between stems and soil. A thorough description of the model, as it has been applied to simulate backscattering from wheat, can be found in Del Frate et al. [2004] and Della Vecchia et al. [2006].

Theoretical Simulations

The objective of this study is to evaluate the possibility to identify floods when soil is covered by vegetation, recognizing differences in backscattering between SAR measurements acquired before and after the event. To this end we have considered wheat fields at two different stages of development, that is:

1. Wheat at a very early stage, which, with a reasonable approximation, can be assimilated to a grass field;
2. Wheat at a well developed stage.

Information relative to plant dimensions and moisture, requested as input to the model, has been derived from experience gained in previous experimental campaigns and ground truth collection [Del Frate et al., 2004]. In Table I the most relevant vegetation parameters, used in the simulations and linked to the vegetation development, are reported. They were derived from experimental measurements performed in the past [Ferrazzoli et al., 2000] and they were used as input to the Tor Vergata model.

<table>
<thead>
<tr>
<th>Case</th>
<th>Leaf Area Index</th>
<th>Plant height [cm]</th>
<th>Biomass [kg/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Early stage</td>
<td>0.32</td>
<td>15</td>
<td>0.5</td>
</tr>
<tr>
<td>2 Well developed</td>
<td>3.2</td>
<td>72</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Vegetation moisture has been fixed around 85%, a typical value for wheat crops during the green period [Ferrazzoli et al., 2000], while the soil roughness parameters were fixed to a height standard deviation \( \sigma = 1 \) cm and correlation length \( l = 5 \) cm. In the simulations concerning complete water coverage due to flooding, a height standard deviation \( \sigma = 1 \text{mm} \) has been considered in order to simulate a smoother surface below vegetation.
In view of hydrological applications, in this paper we study the dependence of the backscattering coefficient $\sigma^0$ on Soil Moisture Content. The latter determines the dielectric constant of soil, which is modelled by the semi-empirical formula of Dobson et al. [1985]. Soil Moistures between 5 and 40% have been taken into account, since typical values are contained within this range in temperate regions. Flooding has been simulated substituting the soil with a semi-infinite layer having a dielectric constant equal to the one of water. The latter has been derived by Ulaby et al. [1986]. In the following Figures, the Soil Moisture Content of a flooded surface has been conventionally represented by values in the range 80-100%.

In Figures 1 to 6, the trends of the backscattering coefficient as a function of soil moisture are presented. Simulations were performed at VV and HH polarizations and at the three frequencies which are typically used in present SAR systems: L-, C- and X-band. An observation angle of $20^\circ$ has been fixed (this value is close to the ERS observation angle of the experimental data available for comparison and presented in the next section). The plots report, besides the total backscattering coefficient, the single contributions due to vegetation volume, soil attenuated by vegetation and soil-plant double bounce.

When the plant is small, backscattering is completely dominated by soil contribution at L-band (Fig. 1): the backscattering coefficient $\sigma^0$ increases with soil moisture but, in correspondence of flooding, a drop in $\sigma^0$ is observed because of the smooth surface, simulating water, which reflects specularly but does not backscatter significantly.

![Figure 1 - Simulated Backscattering coefficient of the wheat field of Case 1 vs. Soil Moisture Content. L-band, $\vartheta_i=20^\circ$, VV polarization (left), HH polarization (right).](image)

At C-band (Fig. 2), a similar behaviour is observed, with a slightly reduced difference between flooded and non flooded case at vertical polarization, due to a small contribution coming from double bounce originating from the interaction of the thin vertical stems and the vertically polarised electric field. The latter becomes more important at both polarizations at X-band (Fig. 3), when standing water is present. At this frequency, a flooding event would still cause a decrease of backscattering but to a more limited extent.

In presence of a well developed plant, backscattering response is more differentiated in frequency, since the relative weight of the various contributions is appreciably variable from low to high frequencies. At L-band (Fig. 4), soil moisture content can still be monitored: the vertical structure of wheat does not give rise to a significant volume scattering at low
frequency. In case of flooding, a decrease in backscattering can be still observed, but the $\sigma^0$ value is now determined by the combination of the various contributions. In particular, double bounce effect is important at vertical polarization.

Figure 2 - Simulated Backscattering coefficient of the wheat field of Case 1 vs. Soil Moisture Content. C-band, $\theta_i=20^\circ$, VV polarization (left), HH polarization (right).

Figure 3 - Simulated Backscattering coefficient of the wheat field of Case 1 vs. Soil Moisture Content. X-band, $\theta_i=20^\circ$, VV polarization (left), HH polarization (right).

Figure 4 - Simulated Backscattering coefficient of the wheat field of Case 2 vs. Soil Moisture Content. L-band, $\theta_i=20^\circ$, VV polarization (left), HH polarization (right).
At C-band (Fig. 5), an increase of $\sigma^0$ after flooding is obtained at VV polarization, while the backscattering coefficient, after a first increase due to increasing soil moisture, remains approximately constant at HH polarization. At this polarization, soil contribution is dominant before flooding, but it becomes negligible when water is present. In this situation, double bounce and volume scattering are the largest contributions, but their combination leads to an invariant total backscattering with respect to the case of soil moisture equal to 40%. At X-band (Fig. 6), the two polarizations show a reversed sensitivity to floods: total backscattering is constant at Vertical polarization, whereas Horizontal polarization shows an increase. At high frequencies, volume scattering is the dominant contribution at both polarizations, so that soil moisture monitoring is hampered by a complete masking coming from vegetation (soil contribution is missing from the plots in Figure 6 since its value is lower than -35 dB). Only in case of a complete water coverage some effects are apparent at Horizontal polarization, where the double bounce gives a significant contribution, leading to an overall increase of the backscattering coefficient.

**Figure 5** - Simulated Backscattering coefficient of the wheat field of Case 2 vs. Soil Moisture Content. C-band, $\vartheta_i=20^\circ$, VV polarization (left), HH polarization (right).

**Figure 6** - Simulated Backscattering coefficient of the wheat field of Case 2 vs. Soil Moisture Content. X-band, $\vartheta_i=20^\circ$, VV polarization (left), HH polarization (right).
Experimental data

The model results described in the previous section were compared against data extracted from two ERS (5.3 GHz, VV polarization) images acquired in 1994. In particular, the area surrounding Alessandria, in Northern Italy, was observed on October 3 and on November 9, after the river Tanaro inundation that occurred on November 6. A land cover CORINE map of the same area was available, which allowed us to identify some vegetated fields, and also a digital thematic map of the flooded areas after the disaster. A deeper overview of the data set and pictures with the images and maps are reported in Pierdicca et al. [2008]. Since the event occurred in autumn, crops were not growing, and the CORINE class named “grass fields” was selected for the following analysis. Then, only those grass fields which underwent flooding were extracted from the intersection of the CORINE map with the digital map of the inundation. The histograms related to those fields (about 20000 pixels), and worked out from both images, pre- and post-event, are shown in Figure 7. The horizontal axis of the histograms represents the backscattering coefficient. The continuous lines represent the frequency histograms of values measured by ERS, while the superimposed vertical bars represent the model results. In order to consider two different scenarios of grass fields, another case of wheat at early stage has been added to the previous simulations, i.e., wheat at 28 cm height has been considered besides the one at 15 cm. Other vegetation parameters have been derived from previous campaign data [Ferrazzoli et al., 2000], while Soil Moisture Content has been fixed equal to 20% and the observation angle to 20°.

From the pre-event histogram, it can be observed that the peak value is very close to the ones obtained simulating backscattering from early wheat. Indeed, at the two simulated stages, wheat is very similar to grass, being a plant with an essentially vertical structure and with small values of LAI and biomass. The post-event histogram shows that the ERS backscattering coefficient has undergone a significant reduction. Since the digital map of the flooded areas refers to the maximum extension of the flood, whereas the SAR image
has been collected few days after, the presence of pixels classified as flooded, but without standing water, can be envisaged in the post event ERS image. This means that a large distribution of values can be observed, indicating a large variability of surface conditions, e.g. due to the presence of standing water in some pixels or to plants, with different condition of emerged vegetation, in other pixels. However, also in this case, simulated results fall in the experimental range.

Conclusions
In this paper, the electromagnetic model developed at Tor Vergata was applied to perform simulations of flooding events over vegetated fields. The theoretical results indicate that, for wheat fields at early stage (which can represent grass fields), floodings can be detected at at L-, C- and X-band, at an angle of 20°. Model results at C-band are in reasonable agreement with ERS data collected before and after a flooding event in Northern Italy over grass fields.

For developed wheat fields, simulations indicate that the L-band performances in the detection of flooding are much better than the ones at higher frequencies. Depending on frequency and polarization, an increase of backscatter can be even expected in presence of standing water, due to the enhancement of the double bounce mechanism.

Analysis of more SAR data at different frequencies, polarizations and incidence angles is planned to verify the above conclusions and to identify the best system configurations for flood mapping.

Acknowledgments
Work partially supported by ASI.

References
Artech House, Norwood.

Received 22/04/2009, accepted 24/07/2009.