Model investigation about the potential of C band SAR in herbaceous wetlands flood monitoring

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Wetlands are areas where the presence of water at or near the soil surface drives the natural system. Imaging radars (SARs) have distinct characteristics which make them of significant value for monitoring and mapping wetland inundation dynamics. The presence or absence of water (which has a much higher dielectric constant than dry or wet soil) in wetlands may significantly alter the signal detected from these areas depending on the dominant vegetation type, its density and height. The objective of this paper is to present our current research efforts to explain and correctly simulate the radar response of wetland vegetation/inundation mixtures, and use simulations as an aid for retrieval applications.

The radar response of junco marshes under different flood conditions and vegetation stages is analyzed using a set of 13 multipolarization ENVISAT ASAR scenes acquired over the Paraná River Delta marshes during the period 2003-2005. The main aspect of the approach followed is the simulation of SAR wave interactions with vegetation and water, using an adapted and improved version of the EM model developed at Tor Vergata University. Obtained results indicate that with the refined EM model, it is possible to represent with a good accuracy VV and HH SAR responses of junco marshes for a variety of environmental conditions. Further work and data are needed to explain measured HV backscattering. The general agreement obtained between simulations and observations permitted the development of a simple retrieval scheme, and estimates of water level below the canopy were obtained for different environmental conditions. RMS errors of forward simulations and retrievals are reported and discussed.

Keywords: *SAR, Wetlands, hydrology, radiative transfer models*

1. Introduction

Wetlands are areas where the presence of water at or near the soil surface primarily drives the structure and dynamic of the ecosystem. Due to their variability, monitoring efforts limited to a single date of remote sensing observation are usually insufficient to capture the dynamic related to critical hydrologic processes or other dynamic conditions, named phenology or disturbances. Through monitoring of wetland regions, an improved understanding of the water balance and stability of regional watershed systems can be obtained.

Imaging radars (SARs) have distinct characteristics which make them of significant value for monitoring and mapping wetland inundation dynamics. For several wetland canopies and at frequencies lower than about 5 GHz, the microwave energy transmitted by the radar penetrates the vegetation and interacts with both the canopy and the underlying soil. Therefore, the backscattering coefficient is influenced by vegetation structure and soil condition. The presence or absence of water (which has a much higher dielectric constant than dry or wet soil) in wetlands may significantly alter the signal detected from these areas depending on the dominant vegetation type, its density and height. Several authors already investigated the characteristics of the backscattering coefficient σ^0 at various frequencies and polarizations for different types of wetland marshes. Among the relevant ones, we can mention the works of Pope *et al* (1997), Kasischke *et al.* (2003), and Hess *et al.* (1995). The first one analyzed SIR-C polarimetric radar imagery of wetlands in Central America, and its main conclusions were that water under vegetation could be detected by an increase or a decrease of σ^0: increase in marshes with mainly vertical orientation, decrease in short, randomly oriented marshes. In the first case, the increase in HH is greater that in VV. Kasischke *et al.* (2003) presented comparable results analyzing the radar backscatter measured from ERS-2 imagery in Florida (USA) wetlands. In Hess *et al.* (1995) paper, the authors showed how it is possible to accurately delineate inundation and different vegetation types using multi-frequency polarimetric radar (SIR-C) along the Amazon floodplain.

This paper addresses a large region of marshes in Argentina which was observed by different SAR systems. Parmuchi *et al.* (2002), discussed RADARSAT 1 data that was acquired during 1998 El Niño event. Inundated areas were mapped using supervised and unsupervised procedures based on multitemporal images that combined two extreme episodes, normal flood conditions and extreme floods (vegetation covered by water). Karszenbaum *et al* (2000) compared observations of HH and VV polarizations using two SAR systems, RADARSAT 1 and ERS-2, in two type of marshes and in forests. Grings *et al*, (2005) introduced EM models for junco marshes and successfully explained an ERS-2 VV multitemporal data set that showed the re-growth of *junco* marsh patches after an intense burn, based on restricted scattering and biophysical assumptions. More recently, we used two versions of the model (Grings *et al.*, 2006) to interpret the radar response (VV and HH) of *junco* and *cortadera* marshes in occasion of an extraordinary flooding event observed with ENVISAT ASAR APP S1 mode. A preliminary water retrieval scheme was also presented.

Additional radar data, provided through ESA ENVISAT ASAR AO 667 project, included observations of the Paraná delta marshes under different environmental conditions using HH, VV and HV polarizations, and steep and slant incident angles became available. To be able to explain these observations, the model required further refinements, particularly in the input data characterization, based on more detailed biophysical measurements and their statistical description. The objective of this paper is to present our current research efforts to explain and correctly simulate the *junco* marsh radar response for a set of ASAR acquisitions over the area (different incidence angles, polarizations, vegetation phenology and water level conditions) with the main goal of implementing an operational scheme to retrieve water level inside marshes.

Section 2 describes the experimental site. Section 3 describes the satellite observations, the field work and and the auxiliary data. In Section 4, the main improvements applied to the model to correctly simulate the complete set of ASAR data are illustrated, and the results of a comparison between observed and simulated backscattering coefficients of *junco* marshes are shown. Section 5, describes a water level retrieval scheme based on the minimization of a cost function (CF) and discusses the uncertainties in the estimated water level

2. Site description

The Paraná river Delta Region is a vast macro-mosaic of wetlands types located at the terminal area of that river in Argentina. It stretches through the final 300 km of the Paraná basin, covering approximately 17,500 km^2 (Kandus *et al.*, 2006) and is located between 32º05'S, 60º48'W, and 34º29'S, 58º30'W, close to Buenos Aires City (Figure 1**).** It has a complex hydrological regime determined by the influence of the Paraná and Uruguay rivers and De La Plata estuary. The De La Plata River is primarily responsible for the regular flooding of the downstream portion of the region. In this case, the combined effects of wind and tides result in frequent but short (hours-long or day-long) floods. The regime of the Paraná river is determined mainly by the precipitations that take place across its whole watershed, producing seasonal floods that affect the whole region. The Uruguay river also has a seasonal behavior but it only has influence over its proximities. A large portion of the region is occupied by marshes, mainly dominated by *Schoenoplectus californicus* (junco). It is well known that this type of ecosystem functions as a water buffer, a key phenomenon for flood control and a common argument for wetland conservation policies. In order to fully understand this buffer effect, marsh water storage capacity needs to be assessed and monitored at a regional scale.

Figure 1 shows an ENVISAT ASAR Wide Swath mode image (HH polarization) of the Paraná River Delta (study area is marked in green). It is possible to identify different structures through the different radar responses. Inside the study area, there are two easy differentiable structures: forests with intermediate backscattering coefficients and *Junco* marshes, with their characteristic strong backscattering at HH polarization (Parmuchi et al., 2002). As explained previously (Grings et al., 2005), this particular response is due to the fact that *Junco* plant is basically a near-vertical shoot over a flooded soil. In order to illustrate the structure of this plant community, Figure 2 shows a photograph of *Junco* marsh where it can be seen that it is dominated by near-vertical shoots. The differences in geometry between *Junco* and forest produce strong differences in radar backscattering.

3. ASAR data and field work

This study uses ENVISAT ASAR precision image products in Alternating Polarization mode (AP). For each date, there is a multi-look ground range digital image. Data are similar to image mode products, but include a second image acquired using a second polarization combination. The raw data are acquired in bursts of alternating polarizations. The polarization combinations are: the co-polarized sub-mode (one image HH and one image VV), the cross-H polarized sub-mode (one image HH and one image HV), and the cross-V polarized mode (one image VV and one image VH). APP products contain two images corresponding to one of the three polarization combination sub-modes. Each sub-mode can be acquired under different incidence angles (ESA ASAR Handbook, 2002). Table 1 lists the 13 ASAR images that were processed and analyzed for this work. In addition, several RADARSAT 1 and ERS-2 images were also acquired and used in previous works (Kandus et al., 2001, Grings et al., 2005). Although results presented here are based only on ASAR data, the complete data set was used to check the consistency of observations and models.

Extraction of quantitative information from multitemporal radar images involves several tasks. ESA BEST software was used for calibration of the alternating polarization data. Co-registration was done manually and a precise geometrically corrected optical image was used as a reference for geolocation of the ASAR data set (Karszenbaum et al., 2004).

Four sample images of our SAR time series are shown in Figure 3. These images correspond to very close ENVISAT ASAR acquisitions (5 and 8, April 2004) with different incidence angles (mean incidence angle = S1: 19º, S3: 28º). During these dates, no extraordinary environmental conditions were observed.

A comparison between S1 and S3 images indicates that an increase in incidence angle produces a strong decrease of backscattering coefficient in the river, while angle effects over marshes and juncos are moderate. But other than the differences in river response, ASAR S1 and ASAR S3 images of the same polarization look very similar (despite the expected absolute intensity differences). This observation leads us to two related remarks. First, due to the interaction mechanisms that take place, Junco and forest show a more stable backscattering with incidence angle than water surface. Second and more important, this stability with incidence angle (S1-S3) is a key factor to use these images to increase the temporal frequency for monitoring surface water level below vegetation.

As far as the polarization is concerned, a comparison between HH and VV images indicates that there is a strong polarization difference in juncos, while the backscattering of forests is almost unpolarized.

Although this wetland is close to Buenos Ares city, marshes are not friendly environments for developing field work due to the difficulties in accessibility, and environmental conditions (insects, inundated areas, etc). The area remained almost unknown until the 90´s when several field work campaigns took place. In particular, since 1998, an intense field work has been carried out in order to characterize several structural parameters and the ecological functioning of the junco marsh and other herbaceous wetlands in the delta area (Kandus et al 2003, Kandus 1997, Pratolongo 2005a, Pratolongo et al 2005b, -c).

With the objective of describing and simulating junco marsh radar signatures, for several flood conditions, incidence angles, and polarizations, in 2004 we started to use a detailed field work methodology simultaneously with ENVISAT data acquisitions. A rigorous and systematic characterization of the target made it possible to analyze the statistical distribution of target parameters. Field methods were adapted from previous works. Five quadrates of 50cm side were established in each of two stands representative of S. californicus marsh (junco marsh). After counting stems inside the plots, and measuring water level, a complete harvesting and weighting of plant material was performed. In the laboratory, the collected material was rinsed, and diameter and length of each stem was measured. All collected material was dried for 72 hours at 60 oC and weighted. Mean stem biomass (green and dead) per quadrant and per sampling period was estimated as well as gravimetric and volumetric moisture content. This was repeated for subsequent satellite data acquisition.

In order to asses the biomass production and recruitment of junco marsh five permanent plots were also placed in each of the same two stands. In each plot all live stems were tagged with a plastic strapping and their diameter and height were measured. On the subsequent visits, each labeled stem was measured and new shoots were labeled and measured too. To asses stem distribution and orientation, two meters side photographs were taken for each junco plot in each visit. As a result, an asymmetrical junco tilt angle distribution was obtained (mode=5º, mean=28º, SD=39º).

Statistical analysis of model input parameters resulted from a careful description of stem orientation, height, radius and density based on ground measurements and a more precise evaluation of stem permittivity, based on dry matter density measurements (0.15 g/cm^3).

4. The forward model

In this work, we have used as inputs to the model the statistical distributions of height, diameter, density, orientation, and moisture of the evaluated *junco* plants. Also, surface water level measurements were obtained (Table 2).

For those dates when field work was not accomplish, vegetation input parameters to the model were establish considering criteria such as field measurements of the closest date available and/or same season for a different year assuming the stability of vegetation structure seasonal variability. Regarding soil condition, rivers water table and precipitation data were used for an estimate of water level inside marshes. It is well known the scarcity of observations and the difficulties to quantify responses of vegetation/inundation mixtures over wetlands.

After establishing the input parameters for the model, the backscattering coefficient was simulated using the multiple scattering model described by Bracaglia et al. (1995). The main steps, as well as the specific aspects related to juncos, are summarized below.

- The medium is described as a lower half-space overlaid by discrete dielectric elements. The lower half-space represents soil or water, depending on flood conditions. Junco marshes are always flooded, although water level may suffer variations. Therefore, the permittivity of the half-space is equal to water permittivity. The discrete dielectric elements represent vegetation. They are cylinders in the case of juncos.
- Phase and extinction matrices of single elements are computed by using suitable electromagnetic approximations. In particular, *junco* shoots are described as cylinders under the “Infinite length” approximation (Karam *et al.*, 1988). Permittivity is computed as a function of measured gravimetric moisture.
- Effects of single vegetation elements are combined by using a numerical matrix algorithm.
- Overall vegetation effects are combined with soil (or water) effects, also using a matrix algorithm.
- The backscattering coefficient of the whole medium is finally obtained.

Details about the electromagnetic model are available in Bracaglia *et al.*, 1995.

In figure 4 the results of comparing junco marshes model simulated backscattering coefficients with measured ones can be seen, for different incidence angles, polarizations and environmental conditions. Dates and ground truth parameters of junco marshes are listed in Table 2. Two general conclusions can be extracted from figure 4:

- At HH and VV polarization, the model represents well the absolute backscattering values and the effects due to variations of angle and/or environmental condition.
- At HV polarization the model overestimates experimental data.

A detailed analysis of single components indicated double bounce to be the most important contribution for all samples. Simulations and measurements indicate backscattering to be higher at HH polarization than at VV polarization, since HH shows lower attenuation and higher soil reflectivity. At both polarizations, higher backscattering values are obtained for higher water levels (i.e. lower emerged heights) due to lower attenuation. The overall standard error is equal to 2.5 dB considering the complete set of points in figure 4 and decreases to 1.76 dB if the VH samples are excluded.

Regarding polarization information, it can be seen that at HH and VV the model simulated correctly the *Junco* backscattering, and the expected σ^0HH/ σ^0VV power ratios observed previously (Grings et al., 2006). However, at HV polarization, the model leads to an evident overestimation. Previous theoretical investigations demonstrated that, for computation of double bounce with inclined cylinders, the “Infinite Length” approximation does not keep the reciprocity between HV and VH (Tsang et al., 1992). This problem has been found also in our simulations. For cross-pol samples (i.e. 21-23) the simulated values have been obtained as averages (in power) between HV and VH backscattering coefficients computed by the model. However, this does not lead to an accurate representation of experimental data. This problem needs further investigation.

Concerning angular information, this figure shows that both ASAR S1 and ASAR S3 angular configurations are correctly simulated, at both HH and VV polarizations. As expected, the S1 values are higher than the S3 values. Anyway there is a slight overestimation of ASAR S3 VV data and a underestimation of ASAR S3 HH data (more clearly shown in figure 4). S2 data is poorly simulated, but this is due to the fact that all the S2 images shown here are of HV polarization. Further simulations (not shown here) indicate that the model works correctly for ASAR S2 configuration for HH and VV polarizations.

5. Water level retrieval within junco marshes

For ENVISAT-ASAR S1-S3, HH, VV observations, an estimate of water level in *junco* sites has been obtained with the aid of model simulations. First, we have simulated the σ^0 at VV and HH polarizations for all water level (*WL*) values between 1 and 180 cm (using 1 cm steps), for all the environmental condition of the acquired scenes. For each value of water level, the average values and SDs of other variables have been given using empirical relationships obtained by fitting measured data available to us. Then we have selected as "estimated water level" the *WL* value minimizing the Cost Function given by

$$CF = \sum_{m=1}^{Ms} \sum_{p=1}^{2} \left[\sigma^0_{ppS}(WL) - \sigma^0_{ppEm} \right]^2$$

where σ^0_{ppS} (*WL*) is the simulated backscattering coefficient at *pp* polarization for *WL* water level, σ^0_{ppEm} is the backscattering coefficient at the same polarization collected by ASAR over the marsh field and *Ms* is the number of marsh fields within the site (*Ms*=15). In this way, this algorithm chooses the *WL* that performs the best fit of HH and VV simultaneously.

Figure 5 shows the results obtained by comparing the retrieved water level with observed ones. Error bars indicate uncertainties in estimated water level due to the radiometric uncertainties of the measured σ^0. Uncertainties are relatively large, because they are the result of propagating the radiometric errors of the measurements through the retrieval model. The measurement uncertainties are relatively large (+/- 1 dB), because junco patches within the islands are small (~200 pixels) and, as a result, samples should be necessarily smaller, leading to a large radiometric error.

In spite of this problem, figure 5 shows a general agreement between measured and retrieved average water levels, leading to an estimated RMS error, based on average simulated water levels, of 22 cm. The relative error is larger at low water levels, where there is a systematically overestimation of the retrieval model. This result is not completely unexpected, since small water variations have almost no effect on *Junco* backscattering.

6. Final remarks

Despite the recognized importance of wetlands in climate and biogeochemical cycles, and the large volume of satellite observations available, the potential of satellite techniques to detect inundated wetlands and to quantify their seasonal and spatial dynamics (Prigent *et a*l., 2001) has not yet been systematically assessed. Estimates of vegetation/inundation mixtures are even more difficult to determine and very few publications address this subject.

Active microwave systems have been successfully used to map inundated areas, but effective algorithms to estimate certain aspects of surface hydrology of wetlands such as water below the canopy, are not yet available. In this subject, this investigation shows that the retrieval of surface water level can be obtained with the use of electromagnetic models that correctly address the structural characteristics of vegetation and the interaction mechanisms taking place. Although it is clear that this is not a straight forward task, and, appreciable errors are still encountered, the correct simulation of a set of observations addressing different SAR configurations (polarization and incidence angles) constitutes a useful contribution for understanding radar-water-vegetation interactions and for future operational uses of active systems.

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