Monitoring Flood Condition in Marshes Using EM Models and Envisat ASAR Observations

Francisco M. Grings, *Student Member, IEEE*, Paolo Ferrazzoli, *Senior Member, IEEE*, Julio C. Jacobo-Berlles, Haydee Karszenbaum, Javier Tiffenberg, Paula Pratolongo, and Patricia Kandus

***Abstract*—This paper discusses the contribution of multipolarization radar data in monitoring flooding events in wetland areas of the Delta of the Paraná River, in Argentina. The discussion is based on the comparison between radiative transfer model simulations and ENVISAT Advanced Synthetic Aperture Radar observations of two types of marshes: *junco* and *cortadera*. When these marshes are flooded, the radar response changes significantly. The differences in radar response between the flooded and nonflooded condition can be related to changes in the amount of emerged biomass. Based on this, we propose a vegetation-dependent flooding prediction scheme for two marsh structures: nearly vertical cylinders (*junco*-like) and randomly oriented discs (*cortadera*-like).**

***Index Terms*—Flood monitoring, modeling, radar, wetlands.**

I. Introduction

THE ability of satellite radar data to provide information about vegetation structure and hydrological conditions in wetlands has been demonstrated extensively over the last decade. Various authors already reported on the characteristics of the backscattering coefficient σ^0 at various frequencies and polarizations for different types of marshes. Pope *et al.* [1] analyzed Spaceborne Imaging Radar-C/X-band (SIR-C) polarimetric radar imagery of wetlands in Central America, and their main conclusions were that water under vegetation could be detected by means of an increase or a decrease of σ^0: the increase is observed in marshes with mainly vertical orientation, while the decrease is observed in short, randomly oriented marshes. In the first case, the increase in horizontal (HH) polarization is greater that in vertical (VV) polarization [1]. Kasischke *et al.* [2] reported comparable results analyzing the radar backscattering coefficients measured from European Remote Sensing 2 (ERS-2) synthetic aperture radar (SAR) in Florida wetlands [2]. Hess *et al.* in their work showed how it is possible to accurately delineate inundation and different vegetation types using multifrequency polarimetric radar (SIR-C) along the Amazon floodplain [3]. This paper addresses a region of wetland marshes in Argentina which was previously observed by different SAR systems [4], [5]. We analyze the sensitivity of the ENVISAT Adavance Synthetic Aperture Radar (ASAR) instrument to flooding effects. The results of this work are based on: 1) multitemporal ASAR data that address different flood conditions in two types of marshes of different structure (*cortadera* and *junco*); 2) a radiative transfer model that represents the backscattering of these marshes; and 3) field work in correspondence of the acquisition dates. The electromagnetic (EM) model simulates marsh backscattering at HH and VV polarization under various flooding conditions. By comparing simulated backscattering coefficients with experimental ones, the water level inside marshes is estimated, and results are compared against ground truth. In this way, the combination of observations, models and field work allows us to develop and test an algorithm to monitor flood condition within marshes.

The final objective of this work is to investigate which knowledge is necessary to develop a robust and general water level retrieval algorithm on marshes, which could be used as an input of a hydrological process model. In fact, some papers show that the water inside the marshes along the rivers can be used as a border condition to correct "pipe type" hydrological models [6]. For the time being, the available dataset is limited. Therefore, what we show is a first approach to the problem of quantitative water level retrieval inside marshes. Further refinements and validations will be possible after more data of present and future spaceborne SARs will be collected.

The paper is organized as follows. Section II describes the area and its characteristics. Section III describes the environmental problem addressed and ASAR observations. Section IV deals with the models used. Section V presents the retrieval scheme to estimate the flood condition within marshes and, finally, in Section VI the main conclusions are given.

II. Study Site: General Description and Vegetation Characteristics

The Delta of the Paraná River is one of the most important wetland systems of Argentina and South America. It extends along 300 km from 32° 5′ S near the city of Diamante, in the Entre Rios Province, to 34° 29′ S near the city of Buenos Aires. The landscape patterns of this region are subordinated to a flooding regime characterized by different sources of water with a different behavior, that is local precipitation, and large rivers whose specific flooding patterns affect particular areas. Sometimes these sources add together provoking large flooding

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F. M. Grings, H. Karszenbaum, and J. Tiffenberg are with the Instituto de Astronomía y Física del Espacio, Ciudad Universitaria, 1428 Buenos Aires, Argentina.

P. Ferrazzoli is with the Facoltà di Ingegneria, Dipartimento di Informatica, Sistemi e Produzione, Università di Roma "Tor Vergata," 00133 Rome, Italy (e-mail: ferrazzoli@disp.uniroma2.it).

J. C. Jacobo-Berlles is with the Departamento de Computación, , Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Ciudad Universitaria, 1428 Buenos Aires, Argentina.

P. Pratolongo and P. Kandus are with the Departamento de Biología, Laboratorio de Ecología Regional, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Ciudad Universitaria, 1428 Buenos Aires, Argentina.

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TABLE I
MARSH PROPERTIES IN THE LOWER DELTA OF PARANÁ RIVER

	Junco marshes	*Cortadera marshes*
Dominant species	*Schoenoplectus californicus*	*Scirpus giganteus*
Relative area	22%	19%
Average plant height	2 meters	2 meters
Plant phenology	Perennial	Perennial
Soil Condition	Permanently flooded (a few centimeters of water)	Saturated (occasionally flooded)

events. The greatest influence comes from the Paraná River, which shows a main flood peak in late summer and a second peak in winter. The final portion is also influenced by the De La Plata River with its daily winds and lunar tides. The De La Plata River is primarily responsible for the regular flooding of the downstream portion of the region. The combined effects of wind and tide result in frequent but short (hours-long or day-long) floods. The Paraná river regime is determined mainly by the precipitations taking place in the watershed. This complex system shows not only seasonal variations but also annual and interannual fluctuations [4].

This paper focuses on the lower part of the Delta of the Paraná River, which covers 2700 km^2. In this area, we consider two types of marshes.

1) The *cortadera* plant is composed of long leaves, with nearly uniform vertical density (with average leaf area index (LAI) equal to about 5) and an average height of 2 m. Plants are located in the inner portion of the delta islands, near the deltaic front. Eight marsh fields are analyzed in this work
2) The *Junco* marshes look like long, nearly vertical, cylinders. It is a patchy ecosystem driven by a complex fire-forced dynamics. Patches range from young stands (height $=$ 25 cm, density $=$ 10 m^{-2}) to mature stands (height $=$ 200 cm, density $=$ 60 m^{-2}). They are also located in the inner portion of the islands, but these islands are located about 50 km upstream the Paraná River. Fifteen mature marsh fields with 200 cm average height are analyzed. Additional details, including photographs, can be found in [4], [5], and [7]. Biological information is summarized in Table I.

III. ASAR OBSERVATIONS AND FLOODING EVENTS

The objective of this work is to investigate the capability of a dual-polarized C-band radar to monitor marsh flooding. To this aim, we have considered a multitemporal set of ASAR observations in alternate polarization (APP) mode, at HH and VV polarization, and at an angle of 19° (S1 configuration). Within the dataset, we have selected two dates, i.e., November 20, 2003 and April 8, 2004, for which detailed information about water level within marshes was available. Details about ASAR data acquisition and processing are given in [7]. On November 20, 2003, due to strong SE winds, the Rio De la Plata water level reached 180 cm and water from the river flowed over the island levees and flooded the *cortadera* marsh sites. At the same time, the Paraná water level also increased (probably related to the De la Plata River increase) and flooded the *junco* sites (water level 100 cm). On April 8, 2004, water levels in cortadera and junco sites were very low (20 cm), which corresponds to a normal flood condition.

The values of backscattering coefficients at HH and VV polarization for the two dates are shown in Fig. 1(a), for cortadera,

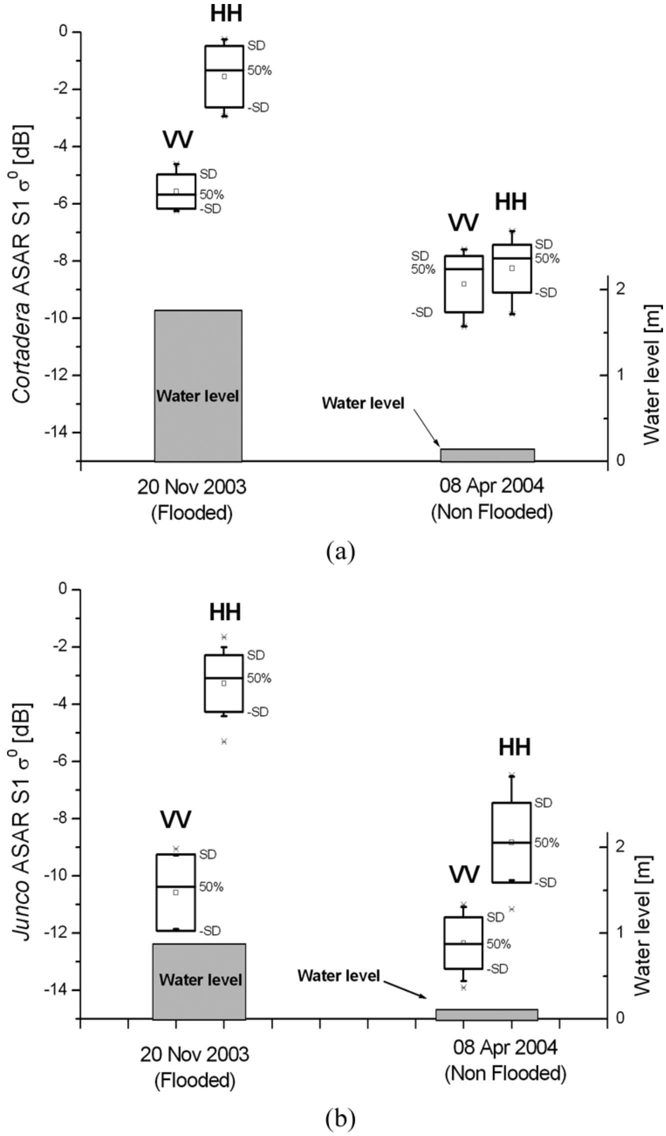

Fig. 1. ASAR signatures and measured water levels for (a) *cortadera* and (b) *junco* marshes.

and Fig. 1(b), for junco. For each date and polarization, average values within the marsh fields are indicated, as well as standard deviations (by boxes) and ranges of values (by error bars). Also the values of measured water level are indicated.

For *cortadera* marshes, it may be observed that σ^0 HH response in the flooded condition is much higher than the response in the nonflooded condition. The σ^0 VV values also are higher on November 20, 2003, but not as high as the HH polarization ones. In *junco*, σ^0 shows a similar pattern: the HH values in the flooded condition are much higher than the HH values in the nonflooded. The difference in VV is less significant.

IV. MODEL

A. General Aspects

The flood monitoring technique proposed in this paper requires to model and explain the effects of flooding events on the backscattering coefficient of the considered marsh areas. To this aim, the scattering processes have been simulated by the EM model developed at the University of Rome "Tor Vergata"

[8]. In its general version, the model describes the soil as a homogeneous half space with a rough interface and the vegetation as a discrete ensemble of lossy dielectric elements. Canonical shapes, such as discs and cylinders, are selected for the elements. Details are given in [8], while the main points are summarized below.

For the soil, the bistatic scattering coefficient is computed by means of the integral equation model [9], and the specular reflection coefficient is computed by the Fresnel formulas corrected for roughness. Inputs required for soil are: permittivity, which is related to volumetric moisture using a well-established semiempirical formula (E.111 of [10]), height standard deviation, and correlation length.

Shoots are described as dielectric cylinders. The "infinite length" approximation [11] is used to compute the bistatic scattering cross section and the extinction cross section. Radius, height, and orientation distributions are given on the basis of available ground truth. Leaves are described as ensembles of dielectric discs. The physical optics model [12] is used to compute their bistatic scattering cross section , and the extinction cross section. Diameter, thickness, and orientation distributions are given on the basis of available ground truth. For both discs and cylinders, the permittivity is related to the moisture by the semiempirical formula given in [13].

The scattering contributions due to the soil and the single vegetation elements are then combined by means of an advanced matrix algorithm, which includes multiple scattering effects of any order [8]. In combining soil and vegetation effects, both specular soil–vegetation reflection and diffuse soil–vegetation multiple scattering processes are considered. The first contribution is important for flat surfaces, while the second one is important for rough surfaces.

Junco marshes are normally flooded. Therefore, the soil permittivity has been set equal to fresh water's one. Vegetation is dominated by nearly vertical shoots, which are cylinders in our representation. A sketch is given in Fig. 2(a). Since water surface is flat, the soil-shoot specular double bounce is the dominant effect, as it will be shown in next sections. Input variables for the *junco* model, based on ground measurements, are given in Table II.

The soil of *cortadera* marshes, in normal conditions, is saturated, but it may be flooded during extreme events. Vegetation is dominated by wide and thick leaves, which are discs in our representation [see the sketch in Fig. 2(b)]. The number of discs per unit area may be computed as the ratio between LAI and single disc area. Input variables for the *cortadera* model, based on ground measurements, are also given in Table II.

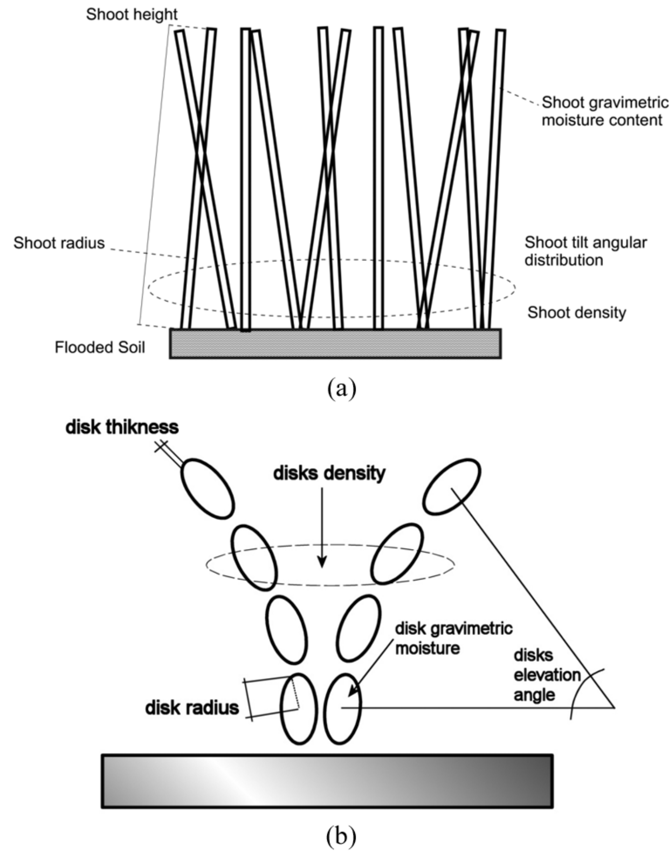

Fig. 2. Schemes of the adopted marsh models. (a) The *Junco* marsh model is based on nearly vertical cylinders. (b) The *Cortadera* marsh model is based on random disks with a preferential tilt distribution.

TABLE II
RADAR PARAMETERS MODEL INPUT VARIABLES

General Parameters			
Frequency		5.3 GHz	
Incidence angle		19° (ASAR APP S1)	
Soil RMS height		0.1 cm	
Soil correlation length		10 cm	
Gravimetric soil moisture		1.0 g/g	
***Cortadera* Parameters**	**Value**	***Junco* Parameters**	**Value**
Disk radius	4.5 cm	**Shoot radius**	0.5 cm
Disk thickness	0.2 cm		
Disk gravimetric moisture	0.7 g/g	**Shoot gravimetric moisture**	0.7 g/g
LAI	5.0	**Shoot plant density**	60 m^{-2}
Disk angular distribution	45-90 deg - uniform	**Shoot angular distribution**	0-10 deg - uniform
Plant height	200 cm	**Shoot height**	200 cm.

B. Application to Flooding

To correctly simulate the flooding events, we need to specify how an increase in water level affects the input variables in our model. This effect is dependent on the marsh species. In the case of *cortadera*, our hypothesis is that observed changes in σ° are related to a reduction of the emerged biomass caused by the flood. This reduction of the emerged biomass implies a reduction of the "emerged LAI."

Taking into account the following:

— vertical leaves density can be considered as uniform;
— *cortadera* leaves angular distribution spans a wide range;
— nonflooded (maximum) *cortadera* LAI (LAIMax) is constant;

we can relate the water level x to the emerged LAI by

$$x = \left(1 - \frac{\mathrm{LAI}}{\mathrm{LAI}_{\mathrm{Max}}}\right) h_c \tag{1}$$

where h_c is the *cortadera* height. Since *cortadera* height can be considered constant for this marsh, we can relate the "emerged LAI" to the water level inside the marsh.

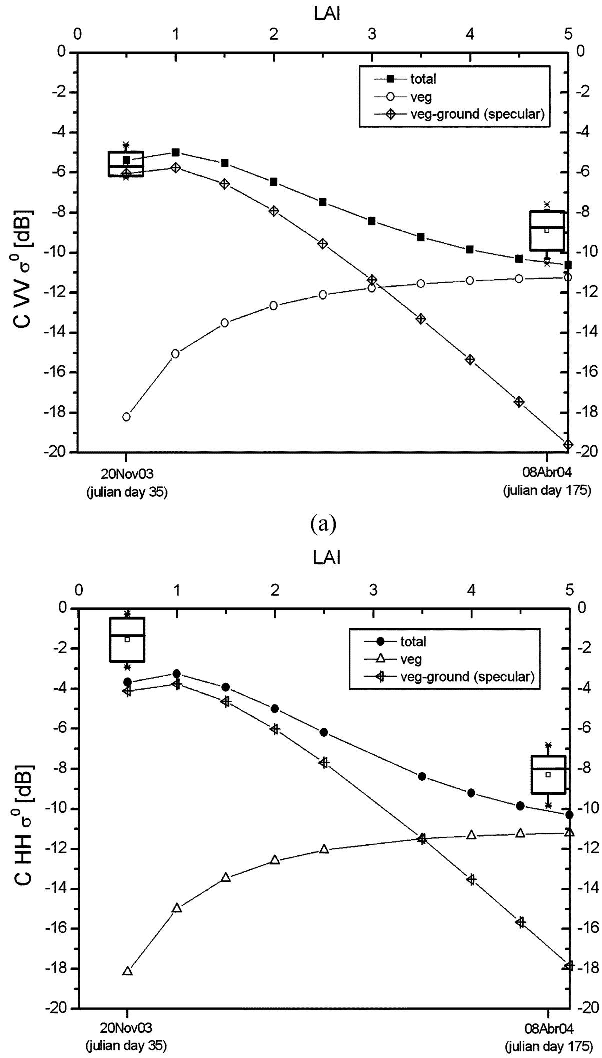

Fig. 3. Backscattering coefficient for *cortadera* marshes in two conditions (flooded and nonflooded). (Box plots) ENVISAT ASAR signatures. (Lines) Model simulations of total backscattering and single components. (a) VV polarization. (b) HH polarization.

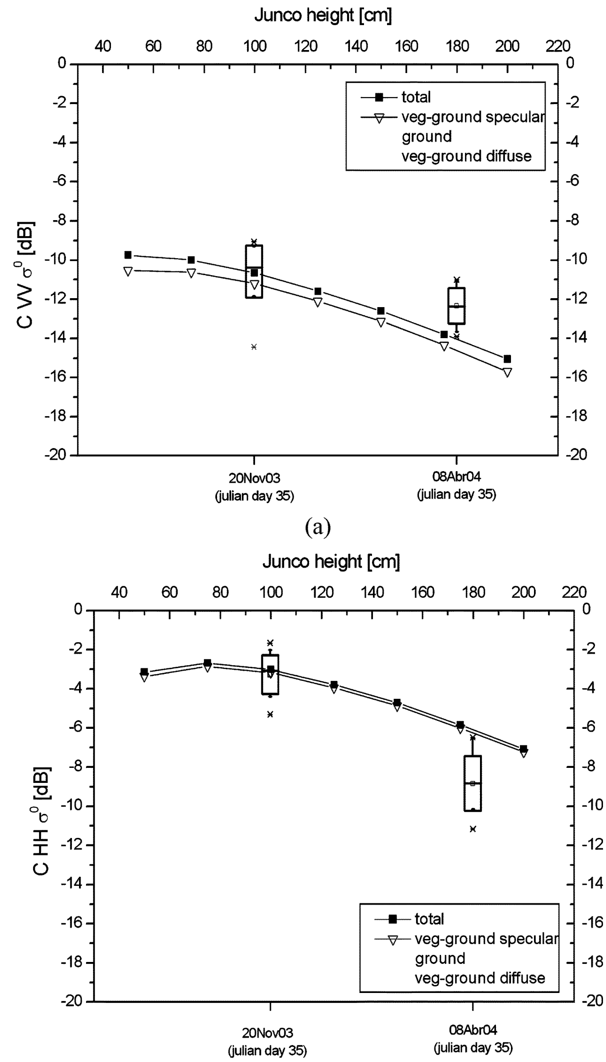

Fig. 4. Backscattering coefficient for *junco* marshes in two conditions (flooded and nonflooded). (Box plots) ENVISAT ASAR signatures. (Lines) Model simulations of total backscattering and single components. (a) VV polarization. (b) HH polarization.

In the case of the *junco*, the observed increase in σ° is related to a reduction of the emerged plant height caused by the flood. This effect was also reported by other authors in similar marshes [1]. In this case, the water level (x) is related to shoots height by the simple relationship

$$x = h_{\mathrm{Max}} - h_j \tag{2}$$

where h_j is the emerged junco height and h_{Max} is the total junco height.

C. Simulation Results

Backscattering coefficients, obtained by using the EM model and the previously described flooding scheme, are shown as a function of water level in Fig. 3, for *cortadera* marshes, and in Fig. 4, for *junco* marshes. Also values of LAI or shoot height, related to water level by formulas (1) and (2), are indicated in the figures. The simulated trends of the total backscattering coefficient, as well as the single contributions (ground, volume, double bounce), are plotted. Experimental values collected by ASAR, already given in Fig. 1, are plotted also here for direct comparison. For both marsh species, HH and VV signatures are considered separately.

The general properties of scattering contributions in vegetation canopies are well known (see, e.g., [10, Sect. 21-5]). For short vegetation, scattering is dominated by the direct soil contribution, while for thick vegetation soil contribution is attenuated, so that direct vegetation contribution tends to dominate. Double bounce is maximum for intermediate growth levels. This contribution may be important for particular radar configurations and for some conditions of soil and vegetation.

For marshes, some specific aspects must be considered, which make their scattering properties partially different from the ones of crops and forests. If the soil is flooded, it shows a small roughness and a high permittivity. Therefore, it produces a small direct backscattering and a strong double bounce which is mostly specular. Moreover, if vegetation components are vertically oriented, such as in the case of *junco* shoots, they produce a low direct backscattering even in case of full growth.

By taking these considerations into account, the trends shown in Figs. 3 and 4 may be interpreted as indicated below.

For *cortadera* (Fig. 3), in case of intense flooding the water level reaches values slightly lower than about 2 m, reducing the emerged LAI to about 1. In these conditions, the backscattering is dominated by the specular double bounce which is close to its maximum value. A decrease of water level produces an increase of leaf attenuation, which on its turn leads to a decrease of double bounce contribution to backscattering. When the emerged LAI is higher than about 3, the direct leaf contribution becomes dominant. As a whole, the trend of the total backscattering coefficient is decreasing, since the increase of the direct leaf scattering does not compensate the decrease of the specular double bounce. A comparison between Fig. 3(a) (VV) and Fig. 3(b) (HH) indicates that the two trends are basically similar and polarization effects are moderate. This is due to the wide range of leaf orientation angles (see Table II). When comparing model simulations with ASAR signatures, it is observed an underestimation of about 1.5 dB (on average) in normal conditions at both polarizations, and of about 2 dB for the flooded case at HH polarization. A possible explanation of these discrepancies lies in the difficulty to fully represent the geometry of *cortadera* leaves. In particular, the orientation distribution was selected on the basis of visual inspections, but detailed quantitative information is not yet available.

For *junco* (Fig. 4), the vertical structure and the dimensions of shoots make the specular double bounce dominant in all situations. This result was already obtained in [14], where the problem of regrowth monitoring after burning was studied. In the flooded case, the specular double bounce produces a high backscattering, particularly at HH polarization. A decrease of water level produces mostly an increase of shoot attenuation, which leads to a decrease of backscattering. Differently from the *cortadera* case, a comparison between Fig. 4(a) and (b) indicates that polarization effects are important in *junco* marshes. This is due to the vertical orientation of shoots, making both attenuation and shoot contribution to double bounce strongly affected by wave polarization. A comparison with ASAR signatures indicates that the backscattering in flooded conditions is well represented. Also the σ° decrease when increasing water level is confirmed by experimental data. However, the model overestimates the HH polarization backscattering for the case of low water levels. In the reality, the assumption of near vertical shoots is realistic for the short emerged sections during flooding, but a wider range of orientations should be considered for the lower parts. A more realistic representation of the orientations requires further experiments and more detailed *in situ* measurements.

V. Water Level Estimates

For both November 20 and April 8 observations, an estimate of water level in *cortadera* and *junco* sites has been obtained with the aid of model simulations. First, we have simulated the σ^0 at VV and HH polarization for all water level (WL) values between 1 and 180 cm (step 1 cm). Then we have selected as "estimated water level" the WL value minimizing the cost function

$$\mathrm{CF} = \sum_{m=1}^{Ms} \sum_{p=1}^{2} \left[\sigma^0_{ppS}(WL) - \sigma^0_{ppEm}\right]^2 \qquad (3)$$

TABLE III
Water Level Estimation Results

Date	Marsh	Measured water level	Estimated water level	SD	Number of fields (*Ms*)
11/20/03	*Cortadera*	1.80 m	1.60 m	1.51 dB	8
11/20/03	*Junco*	1.00 m	0.98 m	1.14 dB	15
04/08/04	*Cortadera*	0.20 m	0.65 m	0.87 dB	8
04/08/04	*Junco*	0.20 m	0.10 m	2.51 dB	15

where $\sigma^0_{pp}S\,(WL)$ 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. In the way it is stated, this algorithm chooses the WL that performs the best fit of HH and VV simultaneously.

Finally, estimated water levels have been compared with measured water levels. Results are shown in Table III. For *junco* marshes and flooded *cortadera* marshes there is a general agreement. For nonflooded *cortadera* a systematic error is observed. This is due to a model underestimation of direct vegetation scattering from *cortadera* leaves. Indeed, *cortadera* leaves have a complex curved structure, which is partially represented by the disc approximation. Moreover, the trend of total backscattering coefficient in Fig. 3(a) is rather flat for low water levels, so that an error of 0.5 dB in σ^0 corresponds to a water level error of about 30 cm.

Overall, results are promising, in view of future applications. However, further work aimed at improving the proposed technique is required. More ASAR measurements will allow us to consider a wider amount of water level conditions and higher angles. New extensive ground measurements will lead to a more detailed description of marsh structure. Also the use of longer wavelengths is promising to make the algorithm more reliable. Preliminary simulations indicated that the σ^0 trends versus water level of an L-band radar are appreciably different with respect to the C-band case [15]. For the time being, there are no experimental data to confirm these results, but the potential will be exploited in the future.

VI. Conclusion

Variations of dual-polarization signatures observed by ASAR in marshes of Paraná River have been simulated by means of a theoretical scattering model. Two vegetation types, characterized by different geometrical structures, have been considered. By using ASAR signatures and model simulations, a simple water level retrieval scheme has been proposed. Estimated water level values are in general agreement with measured ones, except for the case of nonflooded *cortadera* marshes. Further efforts aimed at representing and modeling *cortadera* complex leaves are required.

It is important to state that, since the flooding regime of the wetland system is very complex, only two of our ASAR images meet all the characteristics to be used in the validation of this retrieval scheme. Future acquisitions and field work will allow us to refine and further validate the retrieval model. The sensitivity of multifrequency systems should be also investigated, particularly including L-band. As future work, in order to advance in the direction of an operational water retrieval algorithm based on SAR observations, it is also important to validate the retrieval algorithm using other ASAR images, particularly with higher incidence angles (S2-S6 ASAR operational modes). In spite of some present limitations, the obtained results are promising for flood monitoring in marshes using radar data. As stated in the Introduction, the future goal is to use marsh water level as a border condition for "pipe type" hydrological models.

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Francisco M. Grings (S'05) graduated in medical physics from UNSAM University of Buenos Aires, Buenos Aires, Argentina, in 2003. He is currently pursuing the Ph.D. degree at the Astronomy and Space Physics Institute (IAFE), Buenos Aires, studying "the retrieval of biophysical variables from coastal wetlands using SAR systems and EM modeling."

In 2002, he joined the Remote Sensing group of the Astronomy and Space Physics Institute. In 2003, as a part of the IAFE Remote Sensing Group cooperation with DISP—Tor Vergata, he was in Rome with Paolo Ferrazzoli for one month, adapting marsh radiative transfer models to simulate ASAR radar response. He is currently involved in a collaboration project related to the Argentine SAOCOM SAR mission.

Paolo Ferrazzoli (M'95–SM'06) graduated from the University of Rome "La Sapienza," Rome, Italy, in 1972.

In 1974, he joined Telespazio S.p.A., Rome, Italy, where he was mainly active in the fields of antennas, slant-path propagation, and advanced satellite telecommunication systems. In 1984, he joined the University of Rome "Tor Vergata," Rome, where he is presently working, teaching microwaves and propagation. His current research is focused on microwave remote sensing of vegetated terrains, with particular emphasis on electromagnetic modeling. He has been involved in international experimental remote sensing campaigns such as AGRISAR, AGRISCATT, MAESTRO-1, MAC-Europe, and SIR-C/X-SAR. He has participated with the coordinating team of the ERA-ORA Project, funded by the EEC, establishing an assemblage among several European researchers working in radar applications. He has been a member of the Science Advisory Group of the European Space Agency SMOS Project.

Julio C. Jacobo-Berlles received the Eng. degree in electronics and the Ph.D. degree in computer science from the University of Buenos Aires, Buenos Aires, Argentina, in 1983 and 2005, respectively.

Since 1996, he has worked on statistical models for synthetic aperture radar data and on image processing. His current research interests include microwave remote sensing, image processing, and computer vision. He is currently an Adjoint Professor at the Computer Science Department, Faculty of Exact and Natural Sciences, University of Buenos Aires and is currently involved in a collaboration project related to the Argentine SAOCOM SAR mission.

Haydee Karszenbaum graduated in physics from University of Tennessee, Knoxville.

In 1979, she joined the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Buenos Aires, Argentina. In 1982, she began doing Remote Sensing work at University of Delaware, Newark, in coastal applications. Since then she has participated in several projects related to the study of Argentine coastal areas using optical and thermal remote sensing data. From 1997 on, she has been working in radar remote sensing, mainly in wetland applications. She was the Principal Investigator (PI) of a Radarsat 1 Globsar 2 project and of an ESA ERS-2 AO3 232 project. She is currently PI of ENVISAT ASAR AO 667 project and of a national project on radar remote sensing financed by the Secretaría de Ciencia y Tecnología, Argentina. Since 1994, she has been collaborating with the National Commission on Space Activities (CONAE). She is currently involved in a collaboration project related to the Argentine SAOCOM SAR mission.

Javier Tiffenberg is currently studying physics in the University of Buenos Aires (UBA), Buenos Aires, Argentina.

In 2000, he joined the Remote Sensing Group of the Astronomy and Space Physics Institute (IAFE), Buenos Aires, where he is currently working in the retrieval of biophysical variables from and EM modeling. He is currently involved in a collaboration project related to the Argentine SAOCOM SAR mission.

Paula Pratolongo received the Licenciatura degree in biological Sciences and the Ph.D. degree from the University of Buenos Aires, Buenos Aires, Argentina, in 1998 and 2005, respectively.

Since 2000, she has worked on tidal freshwater marsh ecology linking local dynamic and landscape patterns with optical remote sensing. Her current interests include wetland ecology and remote sensing.

Patricia Kandus graduated from the University of Buenos Aires, Buenos Aires, Argentina, in 1985.

At that time, she joined the Laboratory of Regional Ecology at the Faculty of Sciences and started working in wetland ecology. She focused her ecological studies in the Parana River Delta Region and Team at Astronomy and Space Physics Institute (IAFE), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Buenos Aires. At present, her research is focused on wetland vegetation structure and dynamic with particular emphasis on classification and monitoring using optical and microwave remote sensing.