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Potentials of polarimetric SAR interferometry for agriculture monitoring

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[1] This paper is aimed to define the main specifications and system requirements of a future spaceborne synthetic aperture radar (SAR) mission with polarimetric and interferometric capabilities, to be applied in agriculture monitoring. Firstly, a previous discussion concerning the applications of remote sensing to agriculture and the requirements demanded by end users is introduced. Then, a review of polarimetric SAR and interferometric SAR techniques employed in agriculture is performed in order to explore and justify the potential contributions to crop parameter retrieval of polarimetric SAR interferometry (PolInSAR). The current status of the research about PolInSAR when applied to the retrieval of biophysical parameters of agricultural crops is also addressed, covering recent advances in theoretical modeling aspects (both direct and inverse models), the validation carried out so far with indoor data, and complementary information provided by other different but related experiments. From this experience, we describe some system specifications that will be important for the success of this technique. Among them it is emphasized the need of baselines larger than usual, medium-high frequency band, and a mandatory single-pass mode for overcoming temporal decorrelation. Finally, a set of future experiments is also proposed for additional testing and confirmation of observations made so far regarding minimum baseline requirements, temporal evolution of observables and modeling issues, among others.

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1. Introduction

[2] Since the first proposal of polarimetric SAR interferometry (PolInSAR) in 1997 by *Cloude and Papathanassiou* [1997, 1998], a number of advances have been achieved in many aspects of the development of this remote sensing technique, covering theoretical formulation, technological requirements, final applications in different fields, etc. In parallel, many contributions have shown potentials and limitations of this technique. The most recently launched satellite SAR sensors (ALOS-PALSAR (http://www.eorc.jaxa.jp/ALOS/about/palsar.htm), TerraSAR-X (http://www.dlr.de/tsx), and Radarsat-2 (http://www.radarsat2.info)) provide polarimetric and/or interferometric capabilities, but none of them is specially designed for agricultural crop parameter estimation by PolInSAR. Therefore, it is pertinent to make the exercise of studying the potential of PolInSAR when applied to agriculture monitoring, as well as the requirements of a future sensor to be useful for this application. In short, this paper is aimed to provide some information for answering the following two questions: (1) can PolInSAR contribute in different agriculture applications of remote sensing?, and (2) which system configuration would be required for these applications?

[3] During the last years, a number of experiments have been conducted in order to study the correlation of different radar observables to crop parameters, as well as to analyze the temporal evolution of such observables and compare it with the evolution of the biophysical parameters of interest (biomass, phenological stage, soil moisture, etc.). An excellent review of advances achieved in active remote sensing of agriculture by means of polarimetric data at C band can be consulted in the work of *McNairn and Brisco* [2004]. Unfortunately, there does not exist any experiment on agricultural crops providing a complete data set with PolInSAR information along the whole growth period of a crop type. Instead, contributions consist of results provided by observables acquired in simpler radar configurations, such as backscattering coeffi-

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cients and ratios among them when measured at different polarization channels, different frequencies and/or different incidence angles [see *Boerner et al.*, 1998]. Some of the conclusions from these experiments are not perfectly extrapolable to PolInSAR, since the added value of combining polarimetry with interferometry plays an important role in many cases. However, the mentioned experiments do offer a wealth of information about the sensitivity of microwaves to crops scenarios and about the influence of both system and scene parameters. In this paper, we make use of this information, together with the conclusions of the experiments carried out with PolInSAR data on single samples of crops in laboratory conditions.

[4] In this study we also review past and current scene models employed for this purpose, mainly focused on the models specially tailored for PolInSAR data developed in the works of *Treuhaft et al.* [1996] and *Treuhaft and Siqueira* [2000]. The complexity of modeling agricultural scenes is analyzed, pointing out the presence of multiple scattering effects, vertical heterogeneity, clustering of vegetation elements, polarization dependent extinction, etc. Then, for defining the configuration of the best suited sensor, we discuss many topics: frequency band selection, influence of the baseline and the interferometer mode (single-transmit versus ping-pong) to provide enough sensitivity, the proper range of incidence angles, signal bandwidth in relationship to the subsequent multilooking processing and required spatial resolution to provide both estimation accuracy and local information, revisit cycle for the end user needs, strong limitation of temporal decorrelation, etc. Additionally, we also propose several campaigns, mainly with indoor or laboratory systems, which may contribute to the development of this application before new satellite systems are proposed and devised for such purpose.

[5] The text is organized as follows. As a starting point, section 2 presents a discussion about the possible applications of remote sensing to agriculture, defined from the viewpoint of the end users, and some requirements associated with these applications. This discussion will be used later on the text to propose an appropriate configuration for future spaceborne PolInSAR systems. Since PolInSAR is a technique developed from SAR polarimetry (PolSAR) and interferometry (InSAR), a comparison between agriculture applications of PolSAR, InSAR and PolInSAR techniques is provided in section 3. This comparison is aimed to highlight the potential contributions or advantages of using PolInSAR instead of PolSAR or InSAR. Once the applications are discussed, in section 4 the state of the art about direct models for PolInSAR and associated inversion approaches are described. Limitations of current models and suggestions for improved ones are also discussed. Then, from the conclusions about applications requirements, a description of the main technical requirements for a future PolInSAR system applied to crop monitoring is presented in section 5. Experiments for improving the understanding about this technique and for estimating its limits and capabilities are proposed in section 6. The paper ends summarizing the main points in section 7.

2. Agriculture Applications and End Users Requirements

[6] As stated above, a primary objective of this paper is to discuss the potentials of PolInSAR as a tool for monitoring agricultural crops. For such a discussion, a previous step is the definition of the potential users interested in the parameters derived from the acquired data (also known as end users), and the specification of the information required by them.

[7] In general, there are two groups of end users requiring information related to agricultural crops: government agencies or authorities competent at national/regional/local scales, and farmers with extensive fields. Both groups are interested in disposing of data which can be directly used to perform actions that lead to an optimization of the resources management. On the one hand, public authorities are mainly focused on crop-type mapping and classification (e.g., for justification of subsidies and fraud detection), water resources consumption (e.g., in regions suffering droughts or with scarce water resources) and yield prediction (e.g., for economic and market predictions, price regulations, etc.). On the other hand, owners of wide agricultural fields are concerned with timely information about crop condition (e.g., particular phenological stages, such as time of emergence, for irrigation and fertilization purposes, and diseases detection), water requirements (e.g., for irrigating only when and where necessary) and final crop productivity. This information, required at high spatial and temporal resolutions, leads to farming practices usually named precise crop management or precision agriculture [*Srinivasan*, 2006].

[8] Reviews of the possible contributions of remote sensing to precise crop management can be consulted in the works of *Moran et al.* [1997] and *Pinter et al.* [2003], where examples of applications and user demands illustrate the general requirements of spaceborne and airborne remote sensing systems for supporting crop management. Most important applications pointed out in these references are still object of intense research, specially in microwave remote sensing due to the advantages of this technology over optical systems, since they constitute the basis of the current requirements demanded by end users.

[9] The derivation of the information demanded by the end users, from remote sensing data, is founded on existing direct relationships, known from ecology and agronomy fields, among the final information and other physical and/or agronomic parameters, which in turn can be linked to remote sensing observables. These physical parameters

are manifold and their role and importance for the monitoring procedure differs depending upon the type of crop and scenario. Next, a short description of the most important physical parameters and their utility is introduced.

[10] 1. Crop biomass is a main indicator of crop condition and potential yield. Unlike forest applications, where the vegetation height is directly related to biomass by means of quite general allometric equations, it is not so straightforward to relate crop biomass to a single physical parameter. Biomass exhibits specific ranges of values for each type of crops at different phenological stages, so it is also useful for classification purposes. In many cases, yield and crop growth models employ other auxiliary input parameters, such as Leaf Area Index (LAI), in order to estimate biomass.

[11] 2. Leaf Area Index (LAI), defined as the one-sided green leaf area per unit ground area, is an important source of information for final users since it is related to organic processes that affect crop development, and it is widely employed as input data of crop models [*Bach and Mauser*, 2003]. During the growing season it reaches its maximum value approximately one month or one month and a half before harvesting, depending on the crop type. Hence, this is a key moment to estimate the final yield [*Baez-Gonzalez et al.*, 2005] of the crop by means of the retrieved value of LAI.

[12] 3. Regarding water content of plants, from the ecological point of view, the interest is actually focused on water potential of plants, which in turn is a function of the water content and is also related to a key parameter of hydrological cycle and energy balance of ecosystems called evapotranspiration, ET, which quantifies the water loss due to evaporation and plant transpiration. Among all the definitions of ET, the so-called reference ET (ETo) has been established as the preferable one because of its direct relationship to water requirements of crops. It is defined from a 8–15 cm high reference crop (i.e., cereals) in an active growing stage, occupying completely the soil and with the necessary water supply. This parameter (which can be estimated by optical remote sensing systems, as shown by *Caselles et al.* [1998]) is important for optimization of crop irrigation, prediction of drought seasons, and plant pathology detection. Indeed, if one knows the ETo, the amount of water for irrigation of that crop is automatically known.

[13] 4. Fractional crop coverage gives the proportion of soil which is covered by vegetation. This parameter, also related to evapotranspiration, is employed to obtain estimates of productivity and water requirements. Fractional crop coverage, which can be also expressed in terms on surface density of plants, is also important for monitoring tillering practices.

[14] 5. Regarding phenological stage, the growth cycle of crops is modeled as a sequence of stages characterized by different features of the plants. These stages, classified by crop type, are well known and standardized [see *Meier*, 2001]. In first instance, end users are interested in knowing, at daily to weekly basis, the phenological stage of the crops in order to check the expected development of plants during the full cycle, from sowing to harvest. More importantly, farmers are mainly concerned with knowing exactly the time at which the fields reach some particular phenological stages, which are important for irrigation and fertilization procedures associated with the corresponding crop types and scenarios. Two important phenological stages to be monitored are the following:

[15] Regarding time of emergence, the detection of the emergence of plants from the soil is important for irrigation and fertilization in many crop types. Besides, this indicator is also useful in reforestation programs to estimate the percentage of germination after aerial sowing.

[16] Anthesis is the flowering moment, which serves as an indicator for quantifying the future productivity in cereals.

[17] 6. The role of plant height by itself for crop monitoring is limited, but it can be used as an indirect measure of other features. Firstly, in most crop species, height is directly related to biomass and phenological stage during the first period of the plants growth, until maturity is reached. Secondly, height may be also used for detecting problems in the crop condition, such as lodging. For example, it is known that rice fields in Andalucia (Spain) suffer from the effects of the eastern wind (called Levante). When this wind blows, rice stems bend down and their upper parts come into contact with water and, hence, they decay. In this case, the height estimation could be used to identify which zones have been affected by this problem.

[18] 7. Regarding soil moisture, for most crops (all but those irrigated by inundation, such as rice) this key parameter [*Denmead and Shaw*, 1960], closely related to the water balance parameters discussed above, serves as an indicator of the irrigation requirements, since the quantity of moisture in the soil at a given time hints whether additional water must be provided or not. Therefore, soil moisture estimations are useful when acquired with short revisit times (e.g., daily measurements). The required precision, spatial resolution and temporal sampling depend on the crop type and scenario.

[19] The demanded precision in the estimation of these parameters by a remote sensor is variable and depends on the application. In some cases, especially when the parameter estimates are used as inputs for complex models of crop condition or yield prediction (e.g., LAI and biomass), which usually incorporate many other data sources, it is more important to dispose of confidence intervals or precision ranges than a extremely high precision by itself. On the other hand, temporal parameters, such as detecting the time of emergence, flowering moment or a decrease of soil moisture below a predefined threshold, may impose a tight temporal restriction in the system because the con-

sequence of their detection should be immediate (e.g., to irrigate or fertilize). Anyway, a general agreement in all the requests provided by the end users is that useful estimates should be around ±15% of their true value (i.e., unbiased). This confidence interval matches in many cases the intrinsic variability of the parameter itself. For instance, in a recent ground-truth campaign [see *Gerighausen et al.*, 2007], variations of 20% in LAI, 20% in vegetation height, 10% in soil moisture and 40% in biomass were measured within the same maize field, and variations of 10% in LAI, 15% in vegetation height, 10% in soil moisture and 25% in biomass were measured within the same winter rape field. Variability of the same order was observed also in wheat, soybean and other crop fields.

[20] The required spatial resolution will depend on the application. On the one hand, large swaths will be preferred for wide area observations and, hence, this will reduce the spatial resolution. On the other hand, local scale agriculture management will require a resolution of tens of meters for accounting for small-scale variations [see, e.g., *Sadler et al.*, 1998].

3. Crop Parameter Retrieval by PolSAR and InSAR

3.1. Review

[21] After reviewing parameters requested by different end users, we analyze in this section their retrieval by means of SAR systems, including PolSAR and InSAR, in order to detect potential contributions of PolInSAR in this application. As already cited in the Introduction, the interested reader is referred to the work by *McNairn and Brisco* [2004] for a comprehensive review of PolSAR applied to agriculture. We have extracted the following summary from that paper and other complementary references.

[22] It is well known that microwaves respond to the crop structure (size, shape, and orientation of leaves, stalks, and fruits), the dielectric properties of the canopy (related to the water content), and the physical properties of the underlying soil (roughness and moisture). Crop structure and plant water content vary as a function of crop type, growth stage and crop condition. Consequently, SAR sensors are expected to provide useful information about most of the parameters introduced in section 2. In addition, cloud cover does not affect radar data acquisition, so SAR's present a significant operational advantage over optical sensors for time-critical applications. The challenge, however, is still to establish robust links between the physical parameters of crops and soils and the data recorded by these sensors.

[23] Traditionally, methods for retrieving these parameters by using SAR data have been focused on analyzing their correlation with backscattering coefficients. SAR sensors that acquire imagery at a single combination of transmit and receive polarizations provide one-dimensional data sets. When comparing one-dimensional radar data with the complex nature of the observed scenes, described with many parameters, it is evident that imagery with higher dimensionality (also known as multichannel SAR data) is required to provide meaningful crop information. There are four general ways of obtaining multichannel SAR data, namely:

[24] 1. With multifrequency, data are acquired at different frequency bands, generally combining low and high microwave bands, thus becoming sensitive to different properties of the plants and different scales of their components.

[25] 2. With multipolarization, data are acquired with different combinations of transmit-receive polarizations. This technique, generally named SAR polarimetry (PolSAR), exploits the sensitivity of the wave polarization to the orientation, shape and dielectric properties of the elements in the scene.

[26] 3. With multitemporal, the scene is observed for a period of time, providing time series of images corresponding to the temporal evolution of SAR data.

[27] 4. With multiangle, data are acquired over the same area but from different incident angles, thus becoming sensitive to different crop and soil properties. There exists a particular case of special interest, named SAR interferometry (InSAR), which consists in combining two complex images with slightly different incidence angles. InSAR provides observables related to the vertical distribution of scattering centers.

[28] The use of multichannel data increases the set of possible observables to be related with the crop parameters, so many studies have analyzed correlations between different observables and different physical parameters. Indeed, the use of multipolarized and multifrequency SAR data has yielded successful results in a wide variety of applications, such as crop classification and crop-type mapping, crop condition assessment, plant pathology detection, biomass estimation, soil moisture retrieval, soil tillage and crop residue mapping [*McNairn and Brisco*, 2004; *Boerner et al.*, 1998].

[29] Biomass exhibits high correlations with the HV channel at C band and 35° incidence angle for colza, wheat and alfalfa crops, but the presence of signal saturation effects disables the biomass estimation of other crops, such as corn, sunflower and sorghum, as shown by *Ferrazzoli et al.* [1997]. A similar limitation was also reported by *McNairn et al.* [2000], where HH data at C band saturates for corn crop when it is 1 m high. Polarimetric ratios have demonstrated good performances for estimating biomass in some conditions, as shown in the works by *Bouman et al.* [1999] and *Ferrazzoli et al.* [1999]. Another example can be found in a simulation

study [*Blaes et al.*, 2006] where it was shown that the VV/VH ratio correlates well (i.e., shows relationship) with maize biomass up to 6.5 kg/m^2.

[30] A second parameter of interest, closely related to biomass in many cases, is LAI. Due to its definition, LAI is intrinsically well estimated by optical sensors. In the case of radar remote sensing, some authors have reported correlations with different observables. HH and VV backscattering coefficients at C band were related to this parameter [*Ferrazzoli et al.*, 1992], but both saturate for 2–3 m^2/m^2. The same saturation value is reported for the VV/VH ratio by *Blaes et al.* [2006].

[31] In general, conclusions depend heavily on the crop type. The sensitivity of C band to different features of a wide range of crop types has been also verified by *Picard et al.* [2003], where a direct relationship was found between the VV channel and the wheat crop height for a 23° incidence angle. Another example of the capability of PolSAR data for crop condition assessment by detecting changes on height and density is reported in a contribution by *McNairn et al.* [2002].

[32] Interesting results for paddy rice fields were acquired with an exhaustive campaign by a ground-based system [*Inoue et al.*, 2002]. Among all the data sets considered (fully polarimetric acquisitions from L to Ka band and incidence angles of 25°, 35°, 45° and 55°), it was shown that HH and HV channels at C band correlate very well with LAI, whereas HH and HV at L band were best correlated with biomass. Additionally, these measurements showed also a high correlation with rice height. This is an important result to take into account since it is in agreement with the agronomic principles that describe the relationship among biomass, LAI and crop height.

[33] Regarding the frequency dependence, shorter wavelengths such as Ka, Ku, and X band have shown to be quite sensitive to canopy architecture and/or critical moments of plant development. These bands have shown capability of detecting rice seedlings just after transplanting, specially at large incidence angles (45–55°), and backscattering data at different polarizations and incidence angles at Ka and Ku bands were highly correlated with the weight of heads of rice plants [*Inoue et al.*, 2002]. Besides, Ku and X bands are useful for separating crop types, as reported by *Bouman and Hoekman* [1993] and *Brown et al.* [1992], as well as for providing biomass information on high-density crops [see *Ferrazzoli et al.*, 1997].

[34] In a different campaign with an X band airborne system over rice fields, *Le Toan et al.* [1989] found that the HH/VV ratio showed a clear signature correlated with time and with the crop growth. In the case of rice, this signature is a consequence of the flooded soil condition and the morphology of the rice stems.

[35] Water content of crop plants has been also estimated with SAR since the first works about this remote sensing tool [see, e.g., *Ulaby and Bush*, 1976]. Again, the influence of frequency and incidence angle, together with the specific characteristics of the observed crop type, influence the potential of different observables to retrieve this parameter.

[36] The sensitivity of PolSAR data to the physical properties of crop and soil has been also exploited for crop-type mapping and different classification approaches (see *McNairn and Brisco* [2004] for more details). Recent works have concluded that classification accuracies better than 90% can be achieved if fully polarimetric information is provided at L or C band and, more importantly, that the best performance is obtained when time series of observations are available [see *Skriver et al.*, 2007]. This is in agreement with other works addressing soil moisture estimation such as the one provided by *Mattia et al.* [2006], where C band SAR data at copolar polarizations is used yielding an accuracy up to 5%. As the authors of that work state, the main contribution of SAR data to soil moisture monitoring is probably through their multitemporal information content. The same study concludes that C band SAR data restricts the soil moisture retrieval application to bare or nondense vegetated soils. Other works have been also aimed to estimate surface parameters (roughness and moisture) by PolSAR data, as shown by *Hajnsek et al.* [2003] and *Hajnsek et al.* [2007]. It is stated that the main difficulty found is the correlation among parameters and the dependence on the response of the aboveground volume.

[37] As cited in the previous paragraph, the importance of the time coordinate, i.e., to increase the observation space with multitemporal SAR data, is especially evident for crop applications because the phenological cycle exhibits a temporal signature for each crop type. The availability of temporal data sets accounting for the whole growing season, and with an appropriate sampling period, allows a better analysis of the correlation between the plant parameters and radar measurables. Clear examples are reported, for instance, by *Le Toan et al.* [1989, 1997], *Saich and Borgeaud* [2000], *Inoue et al.* [2002], *Mattia et al.* [2003], and *Blaes et al.* [2006]. The contribution of the temporal information is also necessary for detecting particular phenological stages. For instance, the C band VV/HH ratio at low incidence angle allows to detect the emergence of maize plants, as reported by *Blaes et al.* [2006]. In conclusion, there is a general agreement in the necessity of time series of PolSAR data in order to provide enough information to cover the main requirements of end users [*McNairn and Brisco*, 2004].

[38] With respect to SAR interferometry, its sensitivity to the vertical profile of the scene scattering has been widely exploited in forest applications, but not in agriculture monitoring. InSAR provides two observables: interferometric phase, which is directly related to the vertical position of the scattering phase centers in the scene, and

coherence, which depends on scene structure and properties in a rather complex way. To our knowledge, the literature concerning interferometry applications to agriculture is scarce. A first potential agriculture application reported by *Gabriel et al.* [1989] was a study of the expansion and contraction of the soil (composed by clays and salts) in some fields as a consequence of the presence of water. The sensitivity of the interferometric coherence to fractional crop coverage and crop growth was studied for several crops with ERS images by *Wegmüller and Werner* [1997], where the importance of the time interval between acquisitions was demonstrated for this type of changing scene. Later on, crop height estimation was addressed by *Engdahl and Borgeaud* [1998] and *Engdahl et al.* [2001], where it was found a quasi-linear relationship between the interferometric coherence and the height of a variety of crops, such as beet, wheat and potatoes, during the first part of the growth cycle. The main reason of the reduced number of InSAR studies about agriculture, as it will be explained later in the text, relies on the extreme temporal decorrelation of agricultural scenes due to the rapid growth of crops and their associated fast changes in vegetation and soil conditions, hence imposing the necessity of single-pass interferometric systems.

3.2. Potential PolInSAR Contributions

[39] At this stage, one can anticipate several potential contributions of PolInSAR to remote sensing of agriculture, which may overcome some limitations of PolSAR or which may provide complementary information. They are described in this section.

[40] PolInSAR observables (complex interferometric coherences at different polarization combinations) yield information not only about the dielectric properties, shape and orientation of the whole plant constituents (as PolSAR does), but also about the vertical structure of the plant by means of information about the localization of the scattering centers. This is a key feature of PolInSAR.

[41] In first place, PolInSAR may overcome the saturation effects shown for all PolSAR observables when estimating biomass, LAI and crop height. These physical parameters are correlated with PolSAR data because their increase during the growth part of the phenological cycle generates an increase (up to some saturation) in some backscattering coefficients or a particular signature in the ratio of backscattering coefficients at different polarizations. In short, changes of biomass and height correspond to absolute or relative changes of SAR backscattering level, and this correspondence is also limited to some range. Contrarily, PolInSAR provides a direct measure of vegetation height, which in turn can then be assimilated to the phenological stage, and also to biomass for specific crops. Afterwards, when the plants reach their maximum height, subsequent changes in crop condition will cause different distributions of vegetation elements and, consequently, different signatures in coherences. This variation of PolInSAR observables may be used to address biomass estimation and the retrieval of phenological stage information.

[42] Together with the independence from saturation, height estimates provided by PolInSAR can be utilized as complementary information for avoiding ambiguities in parameters retrieved by PolSAR alone. For instance, tall and sparse crops can provide the same PolSAR observables (at a single frequency band) as short and dense crops. In this case, the extra information provided by PolInSAR should help PolSAR to work under the right assumptions and, therefore, to proceed to an unambiguous parameter retrieval.

[43] More importantly, PolInSAR enables a separation of different scattering contributions associated with different parts of the scene, such as soil and crop canopy. This capability may be exploited by retrieval approaches to distinguish the origin of different features in the data and, as a result, for inverting correctly parameters associated to different parts of the scene (e.g., soil moisture and vegetation biomass).

[44] As commented before, many agriculture applications with PolSAR data require to dispose of temporal series of data in order to perform the parameter estimation correctly or more accurately. This requirement of PolSAR may be overcome in many cases by PolInSAR because it is able to provide not only physical estimates such as crop height (other parameters will be detailed below) from a single interferometric acquisition, but also the distribution of scattering mechanisms along the vertical dimension of the volume, as pointed out above. This is indeed the key point of PolInSAR that potentially represents an added value over PolSAR systems. For instance, this feature becomes evident in rice crops. In the work by *Inoue et al.* [2002] was shown that X band polarimetric data at different incidence angles was only useful for detecting rice seedlings after transplanting. The first impression of this result is that X band should not be used at later stages of development due to the poor capability of penetration of such a wavelength. Nevertheless, as demonstrated in the work by *Lopez-Sanchez et al.* [2007], PolInSAR observables are sensitive to the vertical structure of rice crops even at X band.

[45] Evidently, PolInSAR provides more data channels than PolSAR and, hence, provides additional or complementary information. With this argument, time series of PolInSAR observables may contribute also to many agriculture applications. The detection of plant pathology due to plagues or water stress can be also addressed with a single set of PolInSAR observables acquired in a single date, by observing an unexpected localization of scattering centers related to changes in the plant morphology due to the disease, or with temporal series of PolInSAR data, by detecting modifications of the distribution of scattering centers during the season.

[46] Despite these potentialities, the utility of PolInSAR systems goes beyond the biophysical parameter estimation procedures. Recently, the polarization coherence tomography (PCT) approach by *Cloude* [2006] [see also *Cloude*, 2007] has been introduced as a method for obtaining the backscatter vertical profile function of the crop sample for different polarizations, which enables the identification and relative importance of the main scattering centers inside the target. Hence, it also constitutes an effective tool for aiding in research about electromagnetic modeling of crops and for improving the knowledge about scattering processes present in crop scenes.

4. Direct and Inverse Model

[47] Once the agricultural applications and end users requirements have been identified and the potentials of PolInSAR introduced, the electromagnetic models that account for the relationships between biophysical parameters and the measurables of a PolInSAR sensor will be addressed.

[48] Apart from purely empirical fits or other approaches only based on mathematical correlations, in most remote sensing applications the scene parameters of interest are retrieved from the sensor observations through an inversion of an appropriate direct model of the scene. The direct model must be well defined from the physical viewpoint in order to ensure a reliable relationship between biophysical parameters (inputs) and predicted observables (outputs). At the same time, the direct model should be simple enough to guarantee an affordable inversion.

[49] To date, the best example of a vegetation cover model specifically developed for PolInSAR is the one introduced by *Treuhaft et al.* [1996] and *Treuhaft and Siqueira* [2000]. In that model, the interferometric cross products in the different polarization channels were linked to the physical structure of various types of scenes: a random volume without ground (RV), a random volume over the ground (RVoG), and an oriented volume without ground (OV). This model provides analytical expressions of the complex interferometric coherence at different polarization combinations, which are the most general PolInSAR observables.

[50] The main characteristics of the mentioned direct model are outlined in the next section. Then, some experimental results used for validating the direct model are reviewed, and its use in retrieval of physical parameters of agricultural crops is also described. Finally, potential improvements to the model are suggested and justified.

4.1. Direct Model Features

[51] The geometry of the aforementioned direct model is depicted in Figure 1. In general, the vegetation cover is considered as a two-layer structure. The upper layer corresponds to the volume occupied by the plants above the ground. This vegetation volume is modelled as a homogeneous medium with many particles inside, all located in a random fashion. The volume is assumed as uniform along the vertical coordinate, and its constitutive parameters are the vegetation depth h_v and the extinction of the wave σ. Consequently, the backscatter from the volume is distributed along its vertical extent, but it is affected by an exponential attenuation. The lower layer is used to model the ground response. The ground response consists of a localized backscattering coming from the airground interface, located at position z_0.

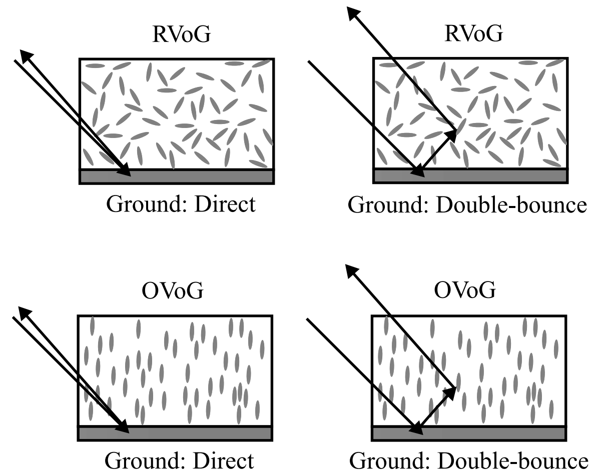

Figure 1. Representation of different model variants for agricultural crops (RVoG and OVoG) specially designed for PolInSAR.

[52] If the particles in the vegetation volume do not exhibit any preferred orientation, the volume is named random (see RVoG in Figure 1), and it entails a polarization independent extinction σ_x. On the contrary, if they are mostly oriented along a particular direction, the propagation of the electromagnetic waves through the volume becomes anisotropic and, hence, it depends on polarization. In this second case, the volume is named oriented (see OVoG in Figure 1), and we must employ two different extinctions in the formulation, which correspond to the eigenpolarizations [see *Tsang et al.*, 1985; *Treuhaft and Siqueira*, 2000] of the medium (σ_a and σ_b).

[53] The direct model is adapted to two common interferometric modes of operation: single-transmit (one antenna transmits and both antennas receive) and alternate-transmit or ping-pong (one antenna first transmits and receives, and then the other), yielding different formulations for each case. When deriving the expression of the interferometric coherence, the ground response is assumed to be dominated by one of its two main contribu-

tions, namely the direct backscattering from the surface or the double-bounce contribution originating from the ground-stem interaction. Expressions are obtained for both types of ground response by assuming the other as negligible. This idea is also illustrated in Figure 1 by considering them as different model variants. The type of ground response and the interferometric mode are two factors with important signatures in the predicted coherences, as recently studied [*Ballester-Berman and Lopez-Sanchez*, 2007].

[54] Despite the complexity of the formulas derivation, the final expressions of the interferometric complex coherence can be explained in a simple way when the coherences at different polarizations are displayed on the complex plane. For example, the coherences of the RVoG are arranged along a line which intersects the unit circle at the ground topographic phase. This feature has been demonstrated to be very useful for both understanding the direct model and designing robust inversion algorithms, as shown by *Papathanassiou and Cloude* [2001] and *Cloude and Papathanassiou* [2003].

4.2. Experimental Validation of the Direct Model

[55] The RVoG variant has been successfully employed for the retrieval of height and biomass of forest covers, with the use of airborne data at P and L band [*Mette et al.*, 2004], and even at X band [*Garestier et al.*, 2008]. The RVoG is well adapted to the randomness of the vegetation layer in most forest covers. However, in many agricultural crops, the morphology of the plants is dominated by the vertical stems. As a result, the oriented volume over ground (OVoG) model variant appears to be better suited for crops modeling. On the basis of the same framework of the original papers, the complete formulation of the OVoG was presented by *Ballester-Berman et al.* [2005] and *Ballester-Berman and Lopez-Sanchez* [2007].

[56] To date, two different attempts have been presented for analyzing the fidelity of the OVoG direct model. Both of them have worked with PolInSAR data gathered in laboratory conditions at the European Microwave Signature Laboratory (EMSL), JRC-Ispra, Italy. Experiments were conducted with a fully polarimetric radar, from 1.5 to 9.5 GHz, with several baselines obtained in alternate-transmit configuration. Two agricultural samples were measured: maize (1.8 m high) and rice (0.75 m high).

[57] The first analysis is based on the application of the polarization coherence tomography [*Cloude*, 2006] to data obtained from the maize sample [*Cloude*, 2007]. From the results presented by *Cloude* [2007], the assumption of a homogeneous volume with a uniform vertical structure and an exponential attenuation (extinction) is not fully justified, since the maximum scattered power does not always originates from the top of the plants.

[58] A second validation of the direct model with experimental data is presented in the work of *Lopez-Sanchez et al.* [2007]. In this case, the validation is performed by comparing the position (on the complex plane) of the coherences predicted by the model and the ones resulting from the experimental data, since the true vegetation height and topography were known. The two data sets, from maize and rice samples, were employed in this comparison. The main conclusions are the following:

[59] 1. The relative position of the experimental coherences does not fit the theoretical model predictions regarding the influence of extinction. The model predicts that the possible positions of the coherences lie on lines with larger distances to the origin for the lower extinctions. As a result, the most external line should correspond to the HH polarization channel and the most internal to the VV channel. The cross-polar channel should produce a coherence located between the other two lines. In the results obtained from rice and maize at several frequency bands, the copolar coherences exhibit the right relative order, but the cross-polar coherence falls outside the expected range of positions.

[60] 2. The region of lines corresponding to the true vegetation height and extinctions above 0 dB/m does not match the experimental data. Only if one reduces the vegetation depth and extends the maximum extinction, the modelled and the experimental regions overlap.

[61] 3. The model is not very sensitive to extinction, since a change in several dB/m does not modify much the position of the coherences on the complex plane.

[62] The discrepancies between model predictions and experimental data can be explained by several characteristics of the model which make it specially simple. For instance, the vegetation layer is assumed to be homogeneous and it is not true, since in the case of maize plants they do not bear leaves in their lowest part (about 40 cm from the ground). On the other hand, in the case of rice, the stems depart from a point of the ground surface but they separate each other as one moves towards the upper part of the plants, and the top part of the rice plants is bent. Additionally, it must be taken into account that these considerations depend strongly on the size of the scattering particles inside the volume relative to the wavelength. Hence, the arrangement of PolInSAR observables will be modified differently for different frequency bands.

[63] Another simplified aspect is the modeling of the interaction among vegetation elements, since it has been taken into account only partially by means of a statistical approach of the total first order backscattering response of the medium. Actually, this interaction leads to multiple scattering effects, which have been demonstrated with simulations of rice fields by *Tsang et al.* [1995] and experiments with high resolution radar images of wheat samples by *Brown et al.* [2003]. The presence of second-order volume scattering events may explain the anomaly in the position of the HV coherence. Note also that the position of the phase center at the HV channel has been also studied

in the work by *Cloude* [2007], showing that the crosspolar channel has a lower scattering center than the copolar channels, which is again a consequence of the simplicity of the model.

[64] However, despite the mismatches in the comparison between model and data, we will see in the next section that its inversion is possible and that it provides accurate estimates in many situations.

[65] Finally, it is also important to note that the single-transmit formulation of both RVoG and OVoG variants has not been validated yet because there are no data available with this type of acquisition.

4.3. Retrieval Algorithms

[66] Several algorithms have been proposed in the literature in order to solve the inversion of the OVoG model for PolInSAR data. First, a geometrical approach [*Ballester-Berman et al.*, 2005], which was designed for inverting only the ground topography and the vegetation depth, is based on the almost linear shape of the coherence region under the assumption of the random volume [*Cloude and Papathanassiou*, 2003]. It was applied successfully when the $k_z \cdot h_v$ is below certain limit, i.e., with low volume decorrelation. Note that k_z is the vertical wave number, defined as:

$$k_z = \frac{4\pi \cdot \Delta\theta}{\lambda \cdot \sin\theta} \quad (1)$$

where λ is the wavelength, θ is the incidence angle, and $\Delta\theta$ is the angular separation between the antenna positions [*Cloude and Papathanassiou*, 2003].

[67] Retrieval results obtained from laboratory data acquired on samples of maize and rice showed an accuracy about 10% in both vegetation height and topography estimations, for a wide frequency range and baselines. For the rice sample, the topography was extremely well estimated. In addition, accurate estimates of topography and vegetation height were also obtained by applying the RVoG variant of the model and assuming a null extinction.

[68] The geometrical algorithm is also able to provide correct estimates with a reduced set of polarization channels. In particular, the selection of polarization channels corresponding to a physics-based interpretation, such as the direct and dihedral-type mechanisms, produces similar results to those obtained with a larger set of coherences (e.g., linear, Pauli and optimized).

[69] Although the geometrical procedure only provides a partial inversion, i.e., not all the model parameters, it would be the preferred approach if the interest is only focused on topography and vegetation height, due to its simplicity of implementation and low computational cost.

[70] A second geometrical approach, devoted to retrieve differential extinction, i.e., the difference between extinction at V and H polarizations, was proposed and tested by *Hajnsek and Cloude* [2005] with airborne data acquired on agricultural fields.

[71] The inversion of the full set of model parameters has been solved by *Lopez-Sanchez et al.* [2007] by combining the previous line fit of the complex coherences and a numerical minimization algorithm. Results of the so-called hybrid approach correspond to similar accuracies than before on ground topography and vegetation height. The extinction estimates obtained for the maize sample agree with the qualitative behavior predicted by scattering physics in an oriented volume and are of the same order than measurements provided by the work of *Ulaby et al.* [1987], but show a large variability, which is even worse for the rice. The trends of ground-to-volume ratios for every channel as well as their relative ordering follow the predictions of theoretical models. Nevertheless, this parameter must be carefully treated and also further investigated since it depends on many other parameters, namely soil roughness and dielectric constant as well as ground and volume scattering. A recent work by *Hajnsek et al.* [2007] has performed a related analysis over the AgriSAR data set [*AgriSAR-web*, 2007]. Assuming that the Freeman-Durden three-component decomposition retrieves the actual direct surface contribution (which is not always true) a procedure to estimate the direct ground and the double-bounce contributions was proposed. They found that the dynamic range for these parameters goes from 20 dB for bare surface to 10 dB for vegetated zones.

4.4. Future Work in Modeling

[72] As discussed in section 4.1, the expressions of the interferometric coherence provided by the formulation of the direct model (for both the RVoG and the OVoG cases) are derived under the assumption that the ground response is dominated by one of the two possible contributions: direct return from the surface or double-bounce interaction with the stems. In many situations this assumption is valid, but it depends on the crop type, crop development stage, frequency band and incidence angle. For example, at 40–45 degrees of incidence angle and when the ground is not specially rough the direct ground response is negligible when compared to the double bounce. A clear example is rice fields because of the flooded condition of the soil. However, there are also many cases were one can not assume that any of the two contributions is small compared with the other. For instance, if steeper incidence angles are used, such as 23 degrees used in ERS and Envisat, the direct ground backscatter is strong and shows a clear dependence on soil moisture and roughness. Consequently, the extension of the model formulation to consider the general case of two types of ground response contributing simultaneously is required. A scheme of the extended model is depicted in Figures 2a and 2b. This extension entails the enlargement of the parameters set,

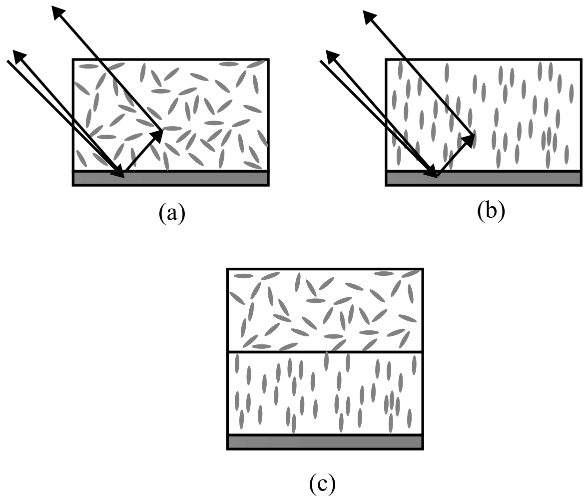

Figure 2. Representation of improved direct models for agricultural crops: (a and b) RVoG and OVoG with two simultaneous contributions from the ground (direct and double bounce); (c) model with a two-layer vegetation volume (random at top and oriented at bottom).

since two ground-to-volume ratios for every polarization channel will appear instead of only one and, consequently, formulation will be more complex. Note that the inclusion of the direct ground contribution will contribute in the final complex interferometric coherence expression as an additional real term, so the effect will be a modification in the arrangement of coherences on the complex plane which, in principle, would lead both to a better matching of the direct model with the data and to an improvement in the estimation performance.

[73] A second feature which may improve the predictions of the direct model when compared to the observations is the inclusion of some heterogeneity in the volume, specially along the vertical coordinate. The modification of the vertical homogeneity can be obtained by different strategies, some of them already proposed for forests. For instance, attending to the density and type of scatterers at different heights, the extinction coefficient can be modeled as a function of the vertical coordinate z. This approach was employed by *Sarabandi and Lin* [2000] through an extinction defined for each z by the wave transmissivity computed from Monte Carlo simulations and a realistic tree structure. A linear function for extinction has been also proposed by *Garestier and Le Toan* [2007] for simulating the biomass vertical distribution of some forests. A recent study by *Woodhouse* [2007] has stressed the importance of linking this electromagnetic modeling with the allometric equations defining the tree structure and, more importantly, with macroecological models commonly used in botany. The information necessary for defining the vertical distribution of scattering can be obtained from alternative microwave experiments such as scatterometry [see *Martinez et al.*, 2000], high resolution radar images [see *Lopez-Sanchez*, 2000; *Cloude et al.*, 1999; *Lopez-Sanchez et al.*, 2000] or tomography [see *Reigber and Moreira*, 2000; *Cloude*, 2006]. All the previous experiences in forest modeling should be adapted to agriculture for increasing the fidelity of the final electromagnetic models. The most simple introduction of vertical heterogeneity for crops would consist in assuming a two-layer vegetated volume. For instance, mature maize plants correspond to an upper layer with randomly oriented leaves and a lower layer with vertical stems and without leaves. This simplified geometry is shown in Figure 2c. This idea was already present in classical vegetation models like MIMICS by *Ulaby et al.* [1990], but it was used for backscattering measurements, and not for PolInSAR observables.

[74] The introduction of vertical heterogeneity will lead to a parameter set larger than for the homogeneous case, since we should deal with different extinctions and depths for each layer (for the two-layer model) or with parameters defining the vertical functions of extinction and/or scattering.

[75] A third important aspect of the direct model to be incorporated is the presence of multiple scattering effects in the vegetation volume. Multiple scattering, as outlined in section 4.2, changes markedly the electromagnetic response of agricultural crops with respect to its absence. Therefore, within the framework of the model proposed by *Treuhaft et al.* [1996] and *Treuhaft and Siqueira* [2000], multiple scattering should be accounted for by considering other propagation terms inside the volume integrals which would modify the current expression for the received field by adding new contributions. These contributions are expected to increase the number of parameters involved in the coherence expressions. The impact of this feature on the final model formulation has not been yet quantified and should be addressed in a future work.

[76] Finally, all the available agriculture models for PolInSAR have shown a severe sensitivity limitation for treating extinction. Extinction is an important parameter which has a close relationship with water content of the plants and plants architecture. However, the short vegetation depth reduces its influence in the interferometric coherence, since the backscattered power is normalized by definition. An alternative way to increase the observation space, and hence the robustness of extinction retrieval, may be the introduction of additional polarimetric observables, such as backscattering coefficient σ_0, cross correlations between different channels and phase differences. The counterpart of such a strategy is the enlargement of the complexity of the inverse problem since we would

become sensitive to additional scene parameters (currently normalized in the coherence derivation).

5. System Requirements

[77] Observations obtained from the previous analysis with direct models, retrieval algorithms and real data from laboratory experiments are useful in order to study the sensor parameters required for this application. They are discussed in the following sections. In some cases, parameters of current and planned spaceborne systems are taken for comparison.

5.1. Baseline

[78] The application of any interferometric system entails the definition of the required range of baselines. When applied to vegetation parameter retrieval, minimum and maximum baseline values are constrained by vertical sensitivity and by extreme volume decorrelation, respectively. Small baselines provide poor sensitivity to the vertical distribution of scattering, due to low values of the vertical wave number k_z. On the other hand, too large baselines produce decorrelation (both volume and geometrical) and, consequently, a decrease in coherence that is related with bad quality of the interferometric observables.

[79] To choose the baseline range, we have analyzed the retrieval results published by *Ballester-Berman et al.* [2005] and *Lopez-Sanchez et al.* [2007], obtained from a sample of maize with 1.8 m height and a sample of rice with 75 cm height.

[80] For the maize sample, correct estimates are obtained even with a coherence as low as 0.3, measured at 5.3 GHz for a 0.5° angular baseline. This corresponds to a vertical wave number of 2.74. On the other hand, from this data set, the lowest bound on the wave number is set to 0.52, which happens at 2 GHz and for a 0.25° angular baseline. This configuration yields a 0.95 coherence. Note that there are not data acquired at frequencies lower than 2 GHz or with baselines smaller than 0.25°. Moreover, no univocal relationship exists between high coherence and sensitivity of the interferometer to a vertically distributed target, so this value has been regarded here as the limit for the system to be sensitive enough to this specific maize target.

[81] Assuming these experimental values as limits for a correct parameter retrieval, and considering a 45° incidence angle and an orbit with a height of 550 km, which corresponds to TanDEM-X system [see *Krieger et al.*, 2007], the normal baseline requirements as a function of frequency for a given volume height (1.8 m) are shown in Figure 3. The dashed thick line is obtained by considering the minimum experimental coherence, i.e., 0.3, for a successful retrieval, whereas the solid thick line corresponds to a lower baseline limit related to the vertical sensitivity. Both curves represent the upper and lower bounds of the normal baseline and, consequently, the design of the interferometer is constrained by the region contained between both lines.

[82] In the same plot, thin lines correspond to the critical normal baseline for several bandwidth values (15, 40 and 70 MHz) for the alternate-transmit case, the same assumed so far, which is given by *Gatelli et al.* [1994]:

$$\Delta f = \frac{f B_n}{r_0 \tan(\theta - \alpha)} \quad (2)$$

where f is the carrier frequency, r_0 is the distance between antennas and target, B_n is the effective or normal baseline, and α the local slope of the surface.

[83] As is observed, the constraint of minimum coherence (volume decorrelation) is not restrictive at all since it corresponds to very large normal baselines. On the other hand, the lower bound (vertical sensitivity) restricts the minimum baseline to about 2500 m for S band, 1500 m for C band and about 700 m for X band. These minimum baselines, which are by far larger than the common values in current systems, are requested by this technique for providing enough sensitivity to the vertical coordinate of the target. This is a consequence of the shortness of the target to be monitored, since we must be able to estimate the position of scattering centers (through the interferometric phases) with extreme accuracy (a few centimeters) to provide a useful monitoring tool.

[84] From Figure 3, it is observed that the critical baseline is not a limiting factor for systems with a signal bandwidth greater that 40 MHz. The corresponding values for S, C and X band, and assuming an alternate-tx interferometer, are very high values, i.e., 12400, 5870 and 3240 m, respectively. This would be even more evident for a single-tx interferometer, since the spectral shift is half the alternate-tx case and, hence, the critical baseline doubles.

[85] The same procedure has been replicated for the retrieval results from the 75 cm tall rice sample, which could be also assimilated somewhat to a maize sample in an early stage of development. From our experimental observations, the minimum useful coherence, due to volume decorrelation, is 0.4, whereas the coherence corresponding to the minimum required sensitivity to the target is 0.8. Note that in this case we have at disposal a narrower dynamic range of the coherence, as a consequence of the target structure. Backscattering from the aboveground volume is weak, especially at low frequencies, and the main contribution to backscattering is the double-bounce interaction between stems and ground. The lack of enough response to the radar from the upper layers of the target reduces even more the effective volume seen by the sensor. The normal baseline range as a function of frequency is plotted in Figure 4 for the rice case. The minimum

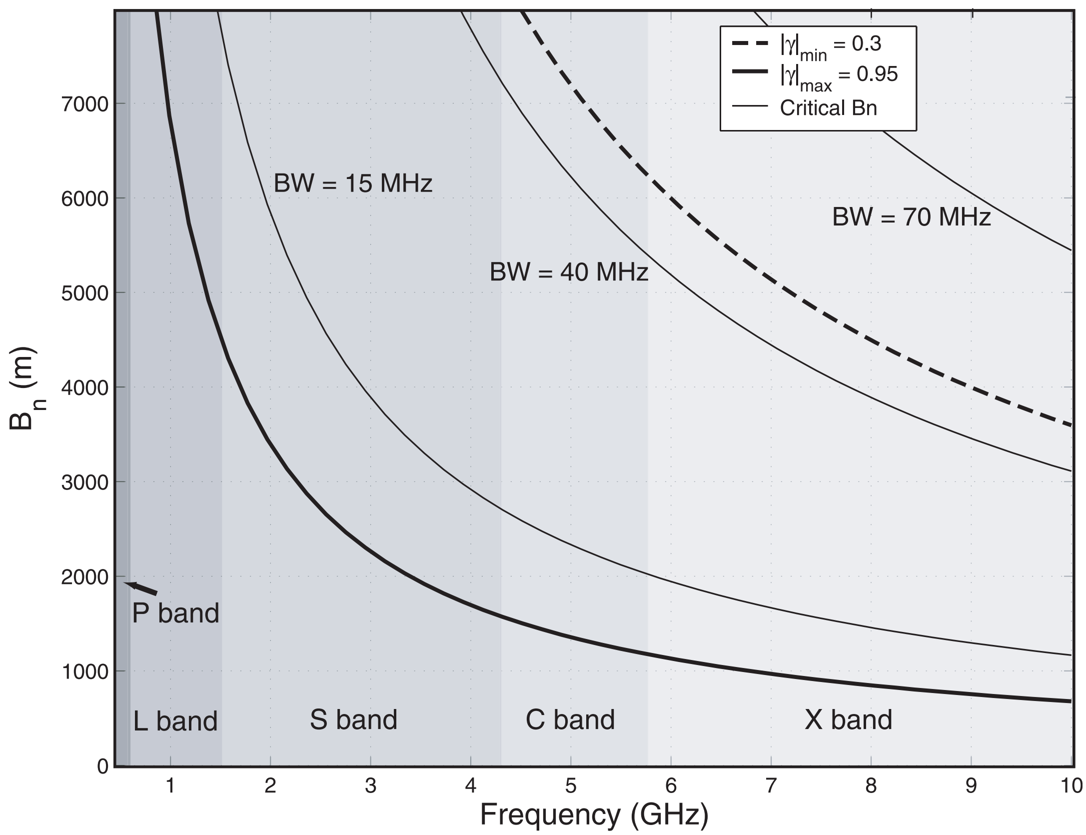

Figure 3. Valid range of normal baseline as a function of frequency, derived from results with a 1.8 m tall maize sample. Thick lines show the limits by low coherence (dashed) and volume sensitivity (solid). Thin lines represent the critical baseline for different bandwidths. Parameters: $\theta = 45°$, $H = 550$ km.

baseline is 7000 m for S band, 5500 m for C band and about 3000 m for X band.

[86] It is important to note that in this case we will need larger bandwidths for ensuring enough range resolution and avoiding to be too close to the critical baseline. The critical baseline for 40 MHz is very close to the smallest useful baseline, so the bandwidth should be increased to, for instance, 80 or 90 MHz. Regarding the expectations about near future PolInSAR sensors due to the availability of high signal bandwidth, it must be pointed out that problems could arise even with baselines less than critical, depending on the application. The mandatory range spectral filtering entails a broadening in range resolution and hence a decrease in the available number of looks, which could be a limitation for agricultural monitoring on small areas.

5.2. Frequency Band

[87] Another key aspect in the design of a radar sensor is the selection of the frequency band. It is evident that low microwave frequencies (P and L band) are not suited for retrieving agriculture parameters by means of PolInSAR because backscattering from the volume of this short vegetation target is very low. In contrast, both C and X band are better adapted to this application because they guarantee enough radar response from the plants. It can be stated that C band provides a good compromise for operation on short and tall crops. To date, promising retrieval results have been obtained with PolSAR data at C band, as already reviewed in section 2. From the PolInSAR laboratory experiments, excellent results were obtained at C band for the maize sample, but not as accurate for rice. The shorter and more tenuous structure of the rice target produces a low backscattered response from the vegetation volume than for the maize case, hence making more difficult (not impossible) the inversion. From the available PolInSAR experiments, X band guarantees enough backscattered signal from short and/or tenuous crops. In addition, X band needs shorter baselines for providing the same sensitivity. Therefore, provided that the crop is not so tall to produce excessive decorrelation, an X band PolInSAR system would be preferred.

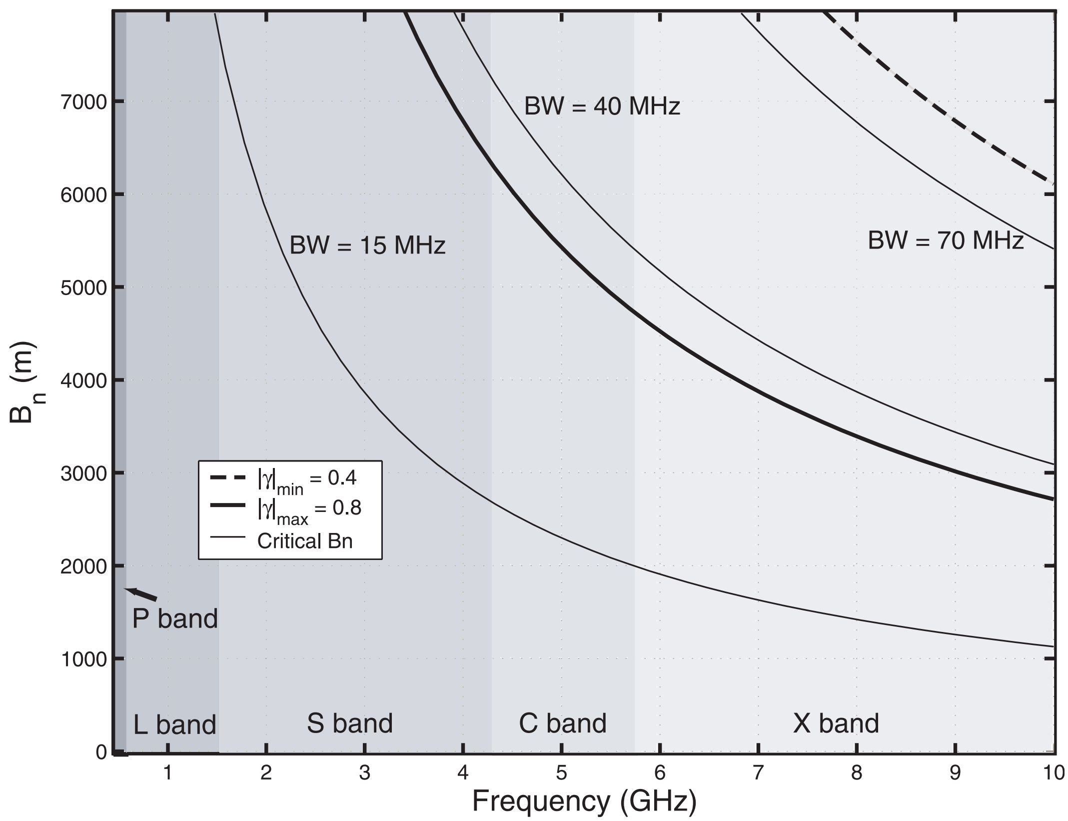

Figure 4. Valid range of normal baseline as a function of frequency, derived from results with a 75 cm tall rice sample. Thick lines show the limits by low coherence (dashed) and volume sensitivity (solid). Thin lines represent the critical baseline for different bandwidths. Parameters: $\theta = 45°$, $H = 550$ km.

[88] In this context, data provided in the very next future by Radarsat-2 at C band and TerraSAR-X at X band (in experimental mode during part of the mission) will contribute partially to this decision by providing the first fully polarimetric data sets acquired by satellites in continuous mode. Unfortunately, the comparison between data from both satellites will be limited to polarimetry, so the final decision about the best band for PolInSAR applied to agriculture should be investigated with additional experiments with indoor, ground-based and airborne sensors (see next section).

5.3. Bandwidth

[89] In first place, the signal bandwidth of the radar should be large enough to avoid critical baseline limitations (see discussion in section 5.1). In second place, the application of PolInSAR requires an important multilook processing of the data, which degrades the spatial resolution (which depends on the bandwith) with respect to the single-look images. The evaluation of the minimum number of looks required to obtain accurate estimates of PolInSAR observables constitutes an ongoing research field. To date, there is not a definite or closed solution to this specific issue. An analogous study has been carried out for PolSAR and InSAR observables, and the general consensus during years has been that a minimum size of 7×7 or 9×9 averaging windows (i.e., about 50 to 80 samples) are required for these techniques to obtain unbiased estimates [see *Touzi et al.*, 1999; *Lopez-Martinez et al.*, 2005]. More recently, a study performed on PolSAR data on different media (grassland, urban and forest areas) by *Lee et al.* [2007] has revealed that smaller multilooking windows of 5×5 (25 looks) and 7×7 (49 looks), together with a bias removal procedure, achieve non-biased estimates of entropy and anisotropy, respectively. For the moment, the larger dimensionality of PolInSAR data with respect to both InSAR and PolSAR alone is expected to impose a larger number of looks, but the quantitative evaluation is still pending.

[90] Since the system must deliver certain number of independent samples for averaging, this constraint is solved by ensuring a high resolution in the images, which is provided by large bandwidths. Note that the samples to be averaged must correspond to the same uniform scenario,

and agricultural fields in some regions are not very large. Moreover, range spectral filtering must be applied, thus degrading the spatial resolution. In conclusion, the larger the bandwidth, the easier the processing and the better the retrieval results. An affordable value of 100 MHz, already provided by current systems, would be a minimum but enough bandwidth for this application.

5.4. Incidence Angle

[91] The selection of the incidence angle affects different aspects of the system sensitivity to the scene. First, the incidence angle modulates the dominant type of ground response, i.e., direct ground versus double bounce, as demonstrated by *Lin and Sarabandi* [1995]. Moreover, steeper angles increase the influence of ground conditions (soil moisture, roughness, etc.) in the backscatter response with respect to more oblique ones, which emphasize the vegetation volume contribution. From the interferometric viewpoint, the vertical wave number, which drives the sensitivity to the vertical structure of the target, is also affected by the incidence angle. For the same baseline, steeper incidences produce larger vertical wave numbers than more oblique ones (see equation (1)).

[92] Unfortunately, the PolInSAR data provided by the available laboratory experiments were collected only at one incidence (44–45 degrees), so we cannot draw any definite conclusion from this data set about the incidence angle requirements.

[93] Other results published in the literature, obtained by scatterometers by *Inoue et al.* [2002] and *Mattia et al.* [2003], evidence that some crop parameters are better monitored either at steeper or at more oblique incidence angles, whereas other parameters are insensitive to incidence angle. In addition, this sensitivity or insensitivity depends also on the frequency band. In general, provided that a PolInSAR system generates observables with information of the whole structure of the target, it seems that incidence angle is not a key parameter but for very specific cases, such as very short or very tall crops.

5.5. Acquisition and Interferometric Modes

[94] When dealing with vegetated scenes, temporal decorrelation is a major issue in interferometry. Decorrelation is produced by changes in the scene between the two acquisitions employed in the interferogram. There are different timescales for these changes, from the fast movement of plant leaves and branches due to wind to the slow modification of the scene due to plant development and growth. The presence of temporal decorrelation in the data obscures the information to be retrieved and may lead to important errors in retrieval results. In principle, in the agriculture case, the fine interferometric sensitivity required for such a short target makes almost useless interferograms acquired in repeat-pass mode. Hence, a single-pass acquisition is regarded as mandatory for avoiding temporal decorrelation.

[95] This single-pass acquisition can be implemented in a satellite sensor by using a tandem configuration (i.e., two satellites flying in close parallel orbits). In some cases, a possible alternative is to reduce to the minimum the time interval between acquisitions in a repeat-pass system by using two satellites flying with a short delay between them (e.g., a few minutes). In the second case, the system will work properly for all cases but for windy or rainy conditions. Therefore, the only configuration guaranteeing the right operation in all conditions is a single-pass system.

[96] For a discussion of different schemes of transmission and reception of signals in a single-pass interferometer formed by a tandem of satellites, we refer to the solutions proposed for the future TanDEM-X [*Krieger et al.*, 2007].

[97] In close relationship to this topic, we have to decide between the single-transmit mode (one antenna transmits and the two antennas receive simultaneously) and the alternate-transmit mode, also known as ping-pong, where the first antenna transmits and receives and then the second one transmits and receives. The single-tx mode presents the advantage of a reduced hardware (only one transmitter is required), but the resulting effective baseline is half the one provided by the alternate-tx mode and, therefore, the physical baseline in the single-tx case must be twice the one in alternate-tx mode for ensuring the same vertical wave number (see section 5.1). This last point, which has to do with the sensitivity of the system to the vertical distribution of scattering in the crop, suggests that the alternate-tx mode would be recommended. Note also that this means that the normal baselines presented in Figures 3 and 4 (actually very large) should be multiplied by 2 in single-tx case.

[98] Regarding the previous experience with this topic, the alternate-tx mode has been successfully tested with the experiments provided by the EMSL, since in that case the system worked with a repeat-pass acquisition without temporal decorrelation (thanks to the controlled conditions in the anechoic chamber). On the contrary, there does not exist any PolInSAR data set over agriculture acquired in single-tx mode for validation.

[99] Finally, it is important to recall the conclusions derived from the formulation of the direct model, for both RVoG and OVoG versions, when employing the single-tx mode [see *Treuhaft and Siqueira*, 2000; *Ballester-Berman and Lopez-Sanchez*, 2007]. If the ground response is dominated by the double-bounce contribution, there appears an extra decorrelation term in the single-tx mode. This term reduces the coherence below one for an infinite ground-to-volume ratio, so the line fitting procedure commonly employed in the inversion algorithms is not applicable any more for retrieving ground topography.

Consequently, the single-tx mode may also complicate the estimation of biophysical parameters of the scene in some cases.

5.6. Revisit Time

[100] Among the special features of agriculture as a scenario to be monitored, the fast development of plants must be taken into account when designing the acquisition plan of the sensor. The full phenological development of crops, from sowing to harvest, spans from 1 to 3 months, depending on the crop type. Consequently, typical revisit times of satellite systems (ERS, Envisat, Radarsat-1, ALOS-PALSAR) exceed the sampling rate required for following the development of the crop. The question is: what should be the revisit time to ensure a useful monitoring and, at the same time, not to compromise the rest of system parameters (spatial coverage, for instance)? The answer is not straightforward, also because it will depend strongly on the final application.

[101] If the final user requires timely or frequently updated information, such as detecting the time of emergence of plants after sowing or noticing slight differences in crop condition, usually demanded for precision farming [*Srinivasan*, 2006], the time interval between successive acquisition must be reduced as much as possible. Other applications, however, need just to follow the crop development at a wide phenological scale.

[102] From the viewpoint of the signal variation, it is interesting to observe the temporal evolution of radar observables obtained in previous experiments and campaigns over agricultural fields. For instance, backscattering coefficients at all linear polarizations (HH, VV and HV), incidences from 25 to 55 degrees, and bands from L to Ka, were measured daily for the whole season at a paddy rice field [*Inoue et al.*, 2002]. Apart from crop-type specific correlations, this campaign is useful for observing the change rate in these observables. Plots show slow variations in all measurements, with extreme changes of 10 dB in 3 weeks, and common variations below 5 dB in 2 weeks. Although more limited in scope, the measurement campaign presented by *Mattia et al.* [2003] provides some useful hints. In this case, a wheat field was monitored at C band with a regular interval of two weeks between successive data acquisitions. There appear several discontinuities in the resulting time series, so one can conclude that a revisit period shorter than 2 weeks should be employed for ensuring a satisfactory monitorization, although it may depend on the final application. More recently, an ESA funded campaign, named AgriSAR 2006 [*AgriSAR-web*, 2007], was conducted in Germany. Radar data were acquired by the E-SAR DLR airborne sensor on a weekly basis from April to August over a test site with 9 types of crops. There was an intensive ground-truth campaign for validation. The first analysis of the temporal evolution of polarimetric observations at L and C band shows important correlations against biophysical parameters and, importantly for our study, demonstrates that a 1 week revisit period is well adapted to this application, since we have not found important discontinuities in the data.

[103] Finally, it is very important to emphasize again that the strategy in retrieval procedures could be different if enough sampling rate (revisiting time) is provided. A high sampling rate enables the fitting of the radar data to the temporal evolutions of parameters of interest (crop height, phenology, biomass) and, consequently, to derive more accurate estimates.

[104] In conclusion, a revisit time of one week is suggested for the PolInSAR system in order to cover most agriculture applications. However, specific time-critical requirements of the end users (see section 2) should be taken into account to define better this parameter.

5.7. Full Versus Partial Polarimetry

[105] The usefulness of polarimetry is evident in this application because agriculture scenes exhibit clear polarimetric signatures. The important radar response from the ground and the orientation of plants are the main contributions to the polarimetric information content. In this context, a system with full polarimetric capability will enable the exploitation of the complete information without any kind of symmetry assumption. On the contrary, if partial polarimetry is employed, some assumptions about symmetries in the scene must be accepted. Note that common assumptions in other natural scenarios (such as azimuthal symmetry in forests) are not applicable to agricultural fields because plows and plantation practices induce clear geometrical patterns on the scene.

[106] Anyway, previous experiments with PolInSAR data have proved that some partial polarimetry combinations provide accurate estimates of several physical parameters. For instance, if a partial inversion of the RVoG/OVoG model is used to retrieve topography and vegetation depth, it has been demonstrated (with the rice and maize targets measured in laboratory conditions) that a system acquiring HH and VV channels, with relative phase information, produce results similar to the ones obtained with full polarimetry [*Ballester-Berman et al.*, 2005]. In this case, we can work with the two first Pauli channels: HH+VV for direct scattering from the volume and HH-VV for dihedral-type scattering from the ground-stem interaction. After these conclusions from data gathered in laboratory conditions, more experiments with ground-based and airborne systems should be conducted to fully confirm the necessity of fully polarimetric modes or, alternatively, the best partial polarimetric combinations adapted to these applications (see section 6).

5.8. Scene Variability

[107] Finally, a note of caution about agriculture monitoring by PolInSAR must be stated. By definition, agri-

culture comprises many types of plants and species, showing a vast variability between crop types. Consequently, successful models and inversion techniques for a kind may be useless when applied to a different one. Moreover, the same plant evolves and exhibits different morphology for different growth stages (tillering, booting, heading, ripening, etc.). Therefore, an observable may be sensitive to plant characteristics at a period of time or growth stage, but not at others. For instance, as reported by *Mattia et al.* [2003], important differences appear in the relationship between HH/VV (C band, 23° incidence) and biomass for wheat before and after heading.

[108] It is also important to remind that different plantation and irrigation practices usually generate completely different patterns in the radar observation of crop scenes of the same type (clear examples have been reported in the literature for paddy rice fields, as shown by *Rosenqvist* [1998]).

[109] Despite of this, the potential of PolInSAR is evident because this remote sensing technique is sensitive to the full morphology of the scene, so it yields physical information not provided by other techniques with more limitations (polarimetry, interferometry, or backscattering only).

6. Future Experiments and Validation Tests

[110] Most of the system specifications defined in section 5 have been established from the conclusions derived from the experiments carried out so far, which in the case of PolInSAR over agriculture consist of only two data sets acquired in laboratory conditions over two crop types at a particular development stage. Consequently, it is evident that more experiments specifically designed for this purpose should be conducted to confirm all the previous conclusions and to define better all system requirements. Moreover, new experiments with PolInSAR may provide additional information about new potentials of this technique which have not been tested yet. The open issues that should be addressed with future experiments can be summarized as follows.

[111] 1. Modeling issues are the following:

[112] Validation of the formulation developed for the single-tx interferometric mode, both in the RVoG [*Treuhaft and Siqueira*, 2000] and OVoG [*Ballester-Berman and Lopez-Sanchez*, 2007] variants of the direct model, by inspecting the positions of the resulting coherences on the complex plane. Once the validation of the single-tx formulation is completed, advantages and disadvantages of the model inversion have to be analyzed when compared with the alternate-tx case. The application of full-wave scattering models could be very useful in this task. One example is found in the work of *Thirion et al.* [2006], where a Coherent Scattering Model (COSMO) was designed for simulating the backscattered fields of forested areas from P to L band. A model version adapted to agricultural fields and higher frequency bands should be developed for such purpose. Note that although this type of models does not provide an analytical expression to be inverted for parameter estimation, they will be very useful to understand the scattering processes present in this problem and the potentials and limitations of this remote sensing tool.

[113] Isolation of soil and canopy effects. An improved understanding of the separate contribution to the overall scattering response of soil and vegetation is required for modeling and retrieval purposes. A possible approach to address this question consists in deploying artificial electromagnetic absorber on ground, since it would isolate the vegetation response from ground backscattering. This scheme would help the study of the differential extinction effect by avoiding the strong response from the ground. Alternatively, the use of small canonical metallic targets could be useful to investigate also the attenuation produced by vegetation. In experiments carried out under controlled conditions, it is possible to place small calibration targets inside the vegetation sample without modifying significantly the vegetation elements and with an acceptable backscattering power on receive. Comparison of these measurements with those corresponding to the canonical targets on the bare surface should yield conclusions about the response of the aboveground volume.

[114] 2. System requirements are the following:

[115] Definition of the minimum required baseline (vertical wave number) for PolInSAR to become sensitive enough for successful parameter inversion. This is a key parameter for the feasibility of a future interferometric system, since the values predicted from our analysis (see section 5.1) are very large when compared with current systems. We did not dispose of really short baselines to evaluate in our analysis, so it is important to confirm this minimum. The required experiments would comprise acquisitions with progressive baselines, in order to characterize this sensitivity and to decide a threshold.

[116] Confirmation of the dependence of this technique on incidence angle, frequency band, revisit time, etc. All this parameters have to be studied with extensive campaigns.

[117] 3. The third issue is analysis of the temporal evolution of PolInSAR observables and their correlation with crop parameters. This would include a comparison among crop types and among different phenological stages.

[118] 4. The fourth issue is assessment of possible contribution of multibaseline techniques designed for PolInSAR, such as the PCT [*Cloude*, 2007] and a recently proposed coherence optimization by *Neumann et al.* [2008].

[119] To address these tasks a complete experimental campaign in laboratory conditions would consist in acquiring wideband (C and X band) fully polarimetric and

interferometric data as a function of the angular baseline for all development stages of vegetation, i.e., from emergence to harvest. According to our observations, the angular baseline should range from 0° to 1° in steps of 0.05°. This experiment should be performed at various incidence angles (e.g., 20, 35 and 45 degrees) for testing different observation conditions which may lead to different combinations of ground responses (direct and double bounce). Typical crop targets, such as rice, wheat and maize, should be measured in this campaign. Despite the advantages of laboratory experiments from the radar system point of view, a note of caution must be pointed out regarding the target itself. Indoor campaigns covering an extensive time interval complicate notably the right development of the plants, because it is quite difficult to resemble inside the laboratory the natural conditions of a real agriculture field during the whole phenological cycle. Therefore, an appropriate design of the campaign and an accurate monitoring of the physiological variables of the crop samples during the development of the campaign must be carried out.

[120] Apart from these indoor experiments, campaigns on real agriculture fields with airborne fully polarimetric SAR sensors should be performed. A number of consecutive flights over the same area (with a short time interval and progressive baselines) would produce interferometric pairs for validation with outdoor data of all comments and parameter selections made so far. This is important also to confirm whether the possible artifacts present in indoor data, induced by the finite size of the samples and the shape of the platforms containing the vegetation, are relevant or not from the PolInSAR point of view.

[121] Outdoor measurements with a ground-based SAR in a single-pass interferometric configuration for avoiding temporal decorrelation would be also helpful for validation and research. The main limitation with a ground-based system when applied to PolInSAR is that the required processing of data for natural cover applications entails a large amount of multilooking (usually computed by a spatial averaging over many resolution cells). Unfortunately, it is very complicated to get enough number of independent samples (looks) with a ground-based SAR system deployed in an agricultural field, because resolution is limited by the synthetic aperture (the size of the rail for a linear SAR or the angular displacement of the antennas for a circular SAR) and, more importantly, because incidence angle must remain uniform for all averaged samples (limited by the height of the tower or boom employed to elevate the SAR system). As a result, experiments with ground-based SAR would be applicable only under certain conditions.

[122] In summary, from our point of view, the current priorities for assessing the potentials of PolInSAR for agriculture applications are two: the definition of the minimum baseline (or vertical wave number) and the disposal of measurements during the whole phenological cycle.

7. Conclusions

[123] The potential future application of PolInSAR to agriculture monitoring has been discussed in this paper. We have reviewed the main demands of end users and the corresponding physical parameters of interest which have to be measured by remote sensing systems. Then, the current status of agriculture monitoring based on SAR data has been summarized, and potential contributions of PolInSAR for improving this approach have been identified. The available PolInSAR models and experiments, together with the previous review, have been used for discussing a number of technical parameters of a future satellite sensor with this goal.

[124] From our observations, we have pointed out that baselines larger than usual are required for crop monitoring, C and/or X band are needed (not lower frequencies), and a single-pass mode is mandatory for overcoming temporal decorrelation. In principle, the precise estimation of crop height and the sensitivity to the vertical structure of plants are the key contributions of PolInSAR. Improvements of the direct models by adding the combination of direct ground and double-bounce responses, and multiple scattering effects are also necessary.

[125] A set of experiments has been also proposed for improving the knowledge about this technique and this particular application. The current priorities are the definition of the minimum baseline for ensuring system sensitivity to the scene properties and the acquisition of measurements during the whole phenological cycle for enabling a complete study of all aspects.

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