Signatures of ERS–Envisat Interferometric SAR Coherence and Phase of Short Vegetation: An Analysis in the Case of Maize Fields

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Abstract—Interferometric observations between the European Remote Sensing, ERS-2, synthetic aperture radar (SAR) and the Envisat Advanced SAR (ASAR) are unique since they are characterized by a short repeat-pass interval (28 min) and a perpendicular baseline of approximately 2 km. In vegetated areas, this configuration should preserve from strong temporal decorrelation and enhance the sensitivity of coherence and SAR interferometric (InSAR) phase to volumes with small heights. This assumption could be tested with the data acquired during the dedicated ERS–Envisat Tandem mission on October 15, 2007, over the Seeland region, Switzerland. Five maize fields and one sunflower field presented lower coherence and offsets of the interferometric phase, i.e., height, with respect to neighboring bare fields. To gain understanding on the interferometric signatures, the interferometric water cloud model was used to simulate coherence and InSAR height for the maize fields. Both the coherence and the InSAR height present clear dependence upon vegetation height and exhibit strong consistency. Simulations showed that the modeled coherence and InSAR height are most sensitive to the two-way attenuation and the temporal coherence of the vegetation. The best correspondence between the observed and modeled InSAR parameters was obtained with two-way attenuation values between 2 and 4 dB/m (corresponding to an extinction between 1 and 2 dB/m) and high temporal coherence of the vegetation (above 0.6), with this being due to the very stable conditions of the weather during the 28-min interval between image acquisitions.

Index Terms—Coherence, cross-interferometry, Envisat, ERS-2, interferometric water cloud model (IWCM), maize, phase, vegetation.

I. INTRODUCTION

ONE OF the prominent features of synthetic aperture radar (SAR) interferometry (InSAR) is the capability to sense the 3-D structure of vegetation. The information contained in the interferometric observables, i.e., the coherence and the interferometric phase, depends on the characteristics of the interferometric system, namely, the radar configuration (i.e., wavelength, polarization, spatial resolution, and look direction), the interferometric baseline, and the temporal interval between two images forming the interferometric pair. The interpretation of InSAR observations of vegetated areas and, consequently, the development of methods for the estimation of vegetation parameters require knowledge of the specific interplay between the InSAR system characteristics and the vegetation properties.

The interferometric configuration formed by the European remote sensing satellite ERS-2 and the Environmental Satellite Envisat consists of two spaceborne SAR instruments: the ERS-2 SAR and the multimode Envisat ASAR. In this configuration, ERS-2 SAR and Envisat ASAR operate at C-band, VV-polarization, with a 23° incidence angle and have a minimum temporal interval between acquisitions of 28 min. At C-band, the signatures of the interferometric coherence and phase of vegetation are strongly affected by temporal decorrelation. This, in turn, depends on the environmental conditions at and between image acquisitions. Several studies have highlighted that interferometric observations characterized by “stable” environmental conditions throughout the acquisition period can be related to biophysical parameters of forests (see, e.g., [1]–[8]) and agricultural crops [2], [9], [10]. Constant dry conditions limit temporal decorrelation, which is then mainly determined by wind-induced effects because of the motion of a large part of the scatterers within the resolution cell (twigs, leaves, and small branches). Moisture variations due to precipitation or snowmelt are, instead, deleterious because they cause almost total decorrelation regardless of the specific target [4], [11], [12]. In this respect, the 28-min ERS–Envisat repeat-pass interval is extremely appealing since the probability of obtaining image pairs acquired under stable environmental conditions is higher compared to configurations with a repeat pass on the order of a day or more (e.g., ERS-1/2 tandem mission or ERS-1 three-day mission).

The other salient aspect of the ERS–Envisat constellation with respect to conventional interferometric systems is the slightly different frequencies at which the two radars operate (Δf = 31 MHz). To maintain coherence, the two satellites must have a specific distance. The spatial separation quantified in terms of the perpendicular component of the InSAR baseline has its optimal value at about 2 km for a flat terrain [13]–[15]. The sign of the baseline is such that Envisat looks at the
same target on the ground under a slightly steeper look angle compared to ERS. Long baselines imply higher sensitivity of the InSAR phase to height variations and cause volume decorrelation, which, in turn, increases the sensitivity of the coherence and the InSAR phase to vegetation parameters. The drawback of the long baseline is that strong spatial decorrelation occurs in areas of moderate and steep slopes as demonstrated in [15].

Due to the short repeat-pass interval and the long baseline, ERS–Envisat InSAR observations should be particularly sensitive to small elevation changes and to biophysical parameters of short vegetation. The possibility to demonstrate the capability of ERS–Envisat cross-interferometry to map small elevation changes was the driver of the dedicated ERS–Envisat tandem mission that lasted from September 2007 to February 2008. For three 35-day repeat-pass cycles, the two satellites flew over the Northern Hemisphere with a nearly 2-km-long perpendicular baseline, and orbits were controlled to maintain a similar attitude. In this way, a small Doppler frequency difference could be achieved. Previously, only a small number of image pairs were found to be suitable for cross-interferometry because of the variable baseline between the two satellites and the often-different Doppler frequencies [15].

The interferometric image pairs acquired during this tandem mission were primarily used to demonstrate the capability to generate digital elevation models (DEMs) with high vertical precision. For a 2-km perpendicular baseline, the ambiguity height, i.e., the elevation difference corresponding to a $2\pi$ phase difference in the interferogram, is approximately 5 m. ERS–Envisat DEMs generated for predominantly flat terrain regions, e.g., The Netherlands, the Po river delta, Italy, and the Seeland region, Switzerland, did not only agree remarkably well with the widely used three-arc-second Shuttle Radar Topography Mission (SRTM-3) DEM but also showed fine-scale topographic features such as old riverbeds and alleys that are not visible in the SRTM-3 DEM [16]. The long baseline and the high resolution of the ERS and Envisat interferometric configuration explain the higher level of details with respect to the SRTM-3 DEM.

In the interferogram acquired on October 15, 2007, over the Seeland region (also known as Central Plain), six agricultural fields showed lower coherence and phase offsets with respect to the large majority of the fields. Information from local authorities managing these fields reported that they were still covered by mature vegetation (maize and, in one case, sunflower) at the time of the image acquisition, whereas the other fields had already been harvested. These observations motivated an in-depth analysis of the interferometric signatures of the six fields and an investigation aiming at assessing to what extent a simple model and associated physical constraints can explain the interferometric observations. In Section II, the study area and the InSAR data set are presented. In Section III, we present the observations of coherence and interferometric height, obtained from the interferometric phase. In Section IV, the model linking the interferometric observables and the vegetation parameters is introduced. References to investigations dealing with backscatter and interferometric observations of maize and sunflower are included here. Results from observations and model simulations are discussed in Section V. We conclude with a summary of the main findings and an overview of possible implications in Section VI.

II. SATELLITE DATA AND STUDY AREA

The Seeland region is located between the lakes of Neuchâtel, Biel, and Murten in the western part of Switzerland. The central part of the Seeland region includes primarily agricultural fields and a few small forest stands. The topography here is mostly flat with elevation differences on the order of a couple of meters. Small hills with moderate topography are located nearby Lake Neuchâtel on the northern edge of the region. An overview of the Seeland region as seen by the ERS–Envisat interferometric coherence and phase is given in Fig. 1(a). Details on this image will be given at the end of this section.

Of the three possible acquisitions during the ERS–Envisat cross-interferometry experiment, only one turned out to be useful. This image pair was acquired during the first of the three cycles, on October 15, 2007, with a perpendicular baseline of 1890 m and a difference of the Doppler centroids $\Delta f_D$ of 237 Hz. For the second date (November 19, 2007), the Envisat image was not available. For the third image pair acquired on December 24, 2007, the Doppler spectra were completely disjoint ($\Delta f_D = 3720$ Hz) which resulted in total decorrelation.

For the October 15, 2007, image pair, the differential interferogram and the coherence image were generated. The differential interferogram was obtained after the following: 1) coregistration of the images at a subpixel level; 2) spatially adaptive range common-band filtering in order to deal with the long baseline and frequency offset effects; 3) azimuth common-band filtering; and 4) removal of the topographic component from the interferogram [17], [18]. The topographic phase was simulated using the SRTM-3 DEM. Visible local errors of the SRTM-3 DEM, also due to the oversampling to the $20 \times 20$ m$^2$ pixel size of the interferometric images, were masked out in order to avoid erroneous computation of the differential interferometric phase. Iterative filtering of the interferogram [19], phase unwrapping [20], and further masking in areas of low coherence were applied to obtain the unwrapped differential interferometric phase. At this stage, the differential interferogram could be assumed to contain primarily residual heights with respect to the SRTM-3 DEM. It is very unlikely that neither displacements occurred over the 28 min between the acquisitions nor we could detect clear signs of atmospheric artifacts in the interferogram. The differential interferogram was therefore inverted to elevation. We will refer to this image as “InSAR DEM.” The coherence was computed using an adaptive estimation method, which represents a tradeoff between accurate estimation of the coherence and loss of spatial resolution [18]. Finally, all images were geocoded to a $20 \times 20$ m$^2$ pixel size using an automated procedure based on a geocoding lookup table linking the radar and the map geometries [21].

The weather statistics from several stations located nearby the Seeland region reported stable weather conditions, no precipitation, very low wind speed (0.5 m/s), and a temperature of...
Fig. 1. (a) Geocoded ERS–Envisat “coherence product” ($R = \text{coherence}, \ G = \text{SAR backscattering coefficient}, \ \text{and} \ B = \text{SAR backscattering coefficient difference}$). (b) ERS–Envisat InSAR DEM of the Seeland region, Switzerland. The area is 17.6 km wide and 18.6 km long. In (b), a cyclic color scale (10-m height per color cycle) is used to highlight local height variations. The average backscattering coefficient is used for the image brightness in (b); areas with coherence below 0.3 were masked out during phase unwrapping.

8 °C at acquisition time (9:52 A.M. for Envisat and 10:20 A.M. for ERS-2).

Fig. 1 shows the ERS–Envisat “coherence product” and the InSAR DEM for the Seeland region. Our interest concentrated on the agricultural area, which appears predominantly in orange in Fig. 1(a). Most fields had high coherence and high backscatter, thus appearing in orange, which implied that they were bare, with a rough surface, on the day of acquisition. Forest stands appeared in green as a consequence of the low coherence, the high backscatter, and the low backscatter change between acquisitions. They are clearly visible in the middle of the image. Other features in green correspond to hilly terrain, which caused geometric decorrelation and high backscatter. The lakes of Neuchâtel (top), Biel (bottom), and Murten (left) appear in black or dark blue. This is a consequence of the incoherence of capillary/gravity waves in combination with different backscatter variations due to different wind speed and direction. The InSAR DEM in Fig. 1(b) shows that the agricultural area is characterized by a very gentle topography. A comparison of the two images in Fig. 1 reveals the correspondence between the areas with low coherence appearing as green in the “coherence product” and the topographic features that are visible in the background image in Fig. 1(b). For these areas, phase unwrapping was avoided due to the low coherence, and, therefore, no elevation was determined.

Fig. 2. Subset in Fig. 1(a) highlighting the six fields that showed lower coherence and offsets of the interferometric height compared to neighboring fields.

III. OBSERVATIONS OF COHERENCE AND INTERFEROMETRIC PHASE

Within the agricultural area, a number of fields showed lower coherence and an offset of the interferometric height compared
Fig. 3. Temporal evolution of the vegetation parameters for a maize field in the Seeland region (reproduced from [22]). The plants reach very rapidly the level of 2.2 m at the end of June. Crops are typically harvested during the month of October. The day of acquisition of the ERS-2 and Envisat image corresponds to day of year 288. The symbols $H$, $m_v$, $mdot$, $mwet$, and $mdry$ stand for canopy height, volumetric moisture content, total biomass, wet biomass, and dry biomass, respectively.

to the majority of the fields. These fields have been highlighted in Fig. 2, which represents a subset of the “coherence product” shown in Fig. 1(a). In total, we identified six fields with clearly lower coherence and offsets of the interferometric height with respect to neighboring fields. Information on the vegetation status at the time of image acquisition was acquired from local authorities managing the fields. Fields labeled 1 to 5 in Fig. 2 were covered by mature maize plants; field number 6 was covered by sunflower plants undergoing senescence. While it is common that, around mid-October, some maize fields have not undergone harvesting yet, the presence of sunflowers is seldom. In this case, the plants were left on the field until the end of October for a research on the evolution of senescence of sunflower plants. On the day of the image acquisition, the crop height was, on average, 2.5 m. For each of the six fields, the neighboring fields were reported to be bare on the day of the image acquisition, this being consistent with the high coherence shown in Fig. 2.

Additional information on maize growth and maize conditions at the end of the growing season in the Seeland area was derived from literature and in situ measurements not simultaneous to the day of the image acquisition. References [22] and [23] reported that, for mid-October, plants are approximately 2.2 m high (see Fig. 3) and that their canopy covers almost entirely the ground. The phenological stages of a maize field in the area have been reported in [24]. On October 1, yellowing of leaves has been reported. Harvest took place on October 24. An example showing the conditions of the maize fields around mid-October is shown in Fig. 4. The stalk extends up to approximately 2 m from the ground, becoming thinner for increasing height. The cob is located between 1- and 1.5-m height. Leaves start at about 50 cm from the ground. For the growth stage illustrated in Fig. 4, the leaves extend practically along the entire length of the stalk. The height of the plants shown in Fig. 4 was estimated to be on the same order as the measurements reported in [22] and [23]. Fig. 4 also shows that leaves are yellowing around this time of the year. For sunflower crops, no further information was gathered considering the rather unique case found.

For each of the six fields and corresponding neighboring fields, the size and the number of pixels in the geocoded SAR images are reported in Table I. The neighboring fields corresponded to the fields that are directly adjacent to the sides of each vegetated field. For all fields reported in Table I, the mean value and the standard deviation of the coherence and height from the InSAR DEM were computed. Table I shows that the fields were large enough to allow considering the statistics to be reliable. The coherence observations for the six vegetated fields and the neighboring fields are shown in Fig. 5. In a similar manner, the elevation from the InSAR DEM is illustrated in Fig. 6. The difference between the height at the specific field and the mean height for the corresponding neighboring fields represents the InSAR height of the maize. Fig. 7 shows the InSAR height for each of the six fields. Finally, Table II lists the mean coherence and the InSAR height from the InSAR DEM for each of the six fields. The average coherence of the corresponding neighboring fields is reported as well.

Table II and Fig. 5 show that the coherence of the six fields under investigation was clearly below the level found for the bare fields. While the bare fields presented a rather constant level (mean level of 0.75) and a small range of coherences, the six vegetated fields were characterized by more variable mean values and larger spread, as shown by the longer vertical bars.

Fig. 6 shows that the elevation in the interferometric DEM is consistently higher for the vegetated fields compared to the neighboring fields. The elevation of the bare fields neighboring the vegetated fields varied by less than 1 m (mean value), this being in agreement with the values reported in 1:25 000 topographic maps of the area. The InSAR elevation of the
TABLE I
DESCRIPTION OF THE SIX FIELDS UNDER INVESTIGATION IN TERMS OF CROP TYPE, SIZE, AND CHARACTERISTICS OF NEIGHBORING BARE FIELDS

<table>
<thead>
<tr>
<th>Field no.</th>
<th>Crop type</th>
<th>Size [ha] (number of pixels)</th>
<th>Field no.</th>
<th>Size [ha] (number of pixels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Maize</td>
<td>13.0 (324)</td>
<td>1</td>
<td>5.6 (140)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>13.0 (324)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10</td>
<td>34.2 (856)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>11</td>
<td>81.5 (2037)</td>
</tr>
<tr>
<td>2</td>
<td>Maize</td>
<td>4.2 (104)</td>
<td>3</td>
<td>14.5 (364)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td>10.5 (262)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5</td>
<td>9.9 (247)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td>16.2 (404)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7</td>
<td>3.4 (85)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8</td>
<td>27.0 (675)</td>
</tr>
<tr>
<td>3</td>
<td>Maize</td>
<td>8.2 (205)</td>
<td>16</td>
<td>11.1 (277)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>17</td>
<td>3.8 (95)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>18</td>
<td>5.7 (142)</td>
</tr>
<tr>
<td>4</td>
<td>Maize</td>
<td>10.5 (262)</td>
<td>12</td>
<td>11.1 (278)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>13</td>
<td>19.4 (484)</td>
</tr>
<tr>
<td>5</td>
<td>Maize</td>
<td>5.1 (127)</td>
<td>14</td>
<td>22.6 (566)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15</td>
<td>13.7 (344)</td>
</tr>
<tr>
<td>6</td>
<td>Sunflower</td>
<td>1.5 (37)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5. For each vegetated field, (◦) the mean coherence, (∗) the mean coherence of each of the neighboring bare fields, and (×) the mean coherence of all neighboring bare fields grouped together are shown. The vertical bars represent one standard deviation.

Vegetated fields was characterized by a larger range of values, which could be due to the higher phase noise, i.e., the lower coherence, compared to the bare fields. Considering the high sensitivity of the ERS–Envisat interferometric phase to elevation, we cannot exclude that part of the variation of the elevation, in particular, for the bare fields, could be ascribed to small elevation variations within the fields. Table II and

TABLE II
MEAN VALUE OF THE COHERENCE AND THE INSAR HEIGHT FOR THE SIX FIELDS UNDER INVESTIGATION. (IN BRACKETS) THE MEAN VALUE OF THE COHERENCE FOR THE ENSEMBLE OF BARE FIELDS NEIGHBORING EACH VEGETATED FIELD

<table>
<thead>
<tr>
<th>Field no.</th>
<th>Coherence</th>
<th>InSAR height [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.52 (0.74)</td>
<td>0.49</td>
</tr>
<tr>
<td>2</td>
<td>0.48 (0.78)</td>
<td>0.85</td>
</tr>
<tr>
<td>3</td>
<td>0.43 (0.76)</td>
<td>0.30</td>
</tr>
<tr>
<td>4</td>
<td>0.56 (0.75)</td>
<td>1.08</td>
</tr>
<tr>
<td>5</td>
<td>0.40 (0.71)</td>
<td>0.58</td>
</tr>
<tr>
<td>6</td>
<td>0.37 (0.74)</td>
<td>0.94</td>
</tr>
</tbody>
</table>

Mean of all fields 0.46 (0.75) 0.71

Fig. 6. For each vegetated field, (◦) the mean elevation from the InSAR DEM, (∗) the mean elevation of each of the neighboring bare fields, and (×) the mean elevation of all neighboring fields grouped together are shown. The vertical bars represent one standard deviation.

Fig. 7 show that the InSAR height was between 0.3 and 1.08 m for the five maize fields and 0.91 m for the sunflower field, thus being well below the typical height of these plants in the area. It should be noted that, for the Seeland region, the SRTM-3 DEM represents the surface elevation since data were acquired in February 2001 when all fields were bare so that the estimates of the InSAR height do not include systematic biases that are related to vegetation-induced effects in the reference DEM. While it seems clear that the presence of vegetation on the ground introduces an elevation bias in the ERS–Envisat interferometric phase and, thus, in the interferometric elevation with respect to bare surfaces, the interpretation of the InSAR height is difficult.
Because of the lack of detailed \textit{in situ} measurements on plant density and status at the time of image acquisition, it has not been possible to investigate to which extent the different signatures of the coherence and the InSAR height measurements were related to the plant-specific scattering characteristics, structural properties of the individual fields, or phase noise.

IV. Modeling Approach

The evidence that both the ERS–Envisat coherence and the InSAR height of vegetated fields are different compared to bare fields suggested investigating the possibility of using a simple model to explain the behavior of the complex coherence of the vegetated fields.

In [9] and [10], linear models relating the coherence to crop height were introduced, with the aim of crop height retrieval. These models have been developed for ERS tandem coherence with short perpendicular baselines (< 100 m). For such interferometric geometry, the volume decorrelation can be considered negligible, and the relationship between the coherence and biophysical parameters becomes practically linear. In the case of ERS–Envisat interferometry, there are two aspects that speak for a more advanced modeling solution attempting to describe the relationship between the interferometric observables and vegetation parameters. The non-negligible volume decorrelation introduces nonlinearity in the relationship between the height and interferometric observables. Second, while, in [9] and [10], only the coherence was considered, here, the observations indicate that both interferometric observables contain information related to the structure of the vegetation. Therefore, a modeling approach that should try to explain the ERS–Envisat interferometric observables should express both the coherence and the interferometric phase (or the interferometric height) as a function of crop parameters and include both temporal and volume decorrelation terms. Considering the small number of fields under investigation and the lack of detailed \textit{in situ} measurements, the modeling approach that could be considered was limited to a rather simple formulation.

A. IWCM

To pursue the modeling of the complex coherence, we have investigated to what extent the interferometric observations of the vegetated fields can be understood and explained by means of the interferometric water cloud model (IWCM). This is a semiempirical model that includes the main scattering and decorrelation mechanisms in vegetated areas [25]. The background to the IWCM and its formulation have been presented in [4] and [25]–[27]. An initial assessment on the use of the IWCM to explain the ERS–Envisat interferometric observations of vegetated and unvegetated areas has been presented in [15]. The rather special condition of the sunflower field and the fact that only one field in the Seeland region was covered with sunflowers at the time of image acquisition suggested focusing on those aspects of the model that are relevant to the modeling of the interferometric observables in the case of maize fields.

The IWCM expresses the complex coherence \( \gamma_f \) as a function of vegetation height \( h \) and canopy cover \( \eta \), i.e., the percentage of ground covered by the canopy. In previous publications, the term “area fill factor” has been used as a synonym for canopy cover. This parameter spans between zero and one, with zero indicating no cover and one indicating a canopy without gaps. For consistency reasons with publications on maize structural properties, we will use the expression “canopy cover”

\[
\gamma_f = (1 - \eta)\gamma_{gr} \frac{\sigma^0_{gr}}{\sigma^0_f} + \eta\gamma_{gr} \frac{\sigma^0_{gr}}{\sigma^0_f} T + \eta \gamma_{vol} \frac{\sigma^0_{vol}}{\sigma^0_f} (1 - T).
\]

(1)

The three terms in (1) correspond to the coherence of the ground seen through the canopy gaps, the coherence of the ground seen through the canopy, and the coherence of the vegetation layer, respectively. While the first two terms are related to the temporal decorrelation of the ground, the latter term contains both the temporal and volume decorrelation components of the vegetation. The model parameters \( \gamma_{gr} \) and \( \gamma_{vol} \) express the temporal coherence of the ground and of the vegetation layer, respectively. Similarly, \( \sigma^0_{gr} \) and \( \sigma^0_{vol} \) express the SAR backscattering coefficient of the ground and the vegetation layer. The parameter \( \sigma^0_f \) represents the total SAR backscatter of the vegetation, which has been modeled as a water cloud with gaps as a function of \( \sigma^0_{gr}, \sigma^0_{vol}, \eta \), and \( T \) [25]. \( T \) represents the plant transmissivity, which can be expressed as \( \exp(-\alpha h) \). The coefficient \( \alpha \) represents the two-way attenuation of the plant per meter.

The volume decorrelation \( \gamma_{vol} \) is expressed as (see [4] and [26])

\[
\gamma_{vol} = \left( \frac{\alpha}{\alpha - j \omega} \right) \left( e^{-j\omega h} - T \right) \frac{1}{1 - T}
\]

(2)

where \( \omega \) represents the InSAR system geometry coefficient and is related to the perpendicular component of the baseline \( B_n \), the slant range distance \( R \), the radar wavelength \( \lambda \), and the local incidence angle \( \theta \)

\[
\omega = \frac{4\pi B_n}{\lambda R \sin \theta}.
\]

(3)

B. Validity of the IWCM

The IWCM includes only the direct scattering components, and, therefore, it can be questioned whether it is correct to neglect ground–trunk and multiple-scattering components. At C-band, double-bounce and multiple-scattering effects can be neglected because of the strong attenuation within the first meters of the tree canopy and the often-rough surface [28]. For maize, they might be of importance because of the shorter canopy height and the smoother surface. Nonetheless, if we restrict to the ERS configuration (VV-polarization, 23° incidence angle, and frequency of 5.3 GHz), a number of experiments on scattering properties of maize and modeling results let us infer that, for this configuration, the volume scattering is dominant. In [29], scatterometer measurements of 2.7-m-tall maize plants showed that, for look angles between 30° and 50°, the maximum backscatter was measured at 2.0 m above the soil, which corresponded to the volume of the canopy with the largest leaf area. The soil contribution was very small. It was concluded that
the majority of scattering occurred in the top first meter of the canopy. The soil contribution was, instead, dominant for a look angle of 10°. For the ERS geometry, it can be inferred that the volume component is relevant and that there is a non-negligible soil component. Measurements from a controlled experiment in an anechoic chamber with 1.8-m-tall maize plants showed that the trunk–ground term may be of importance at lower frequencies, e.g., L-band, whereas, for higher frequencies (e.g., C- and X-band), the dominant scattering comes from the volume, in particular, at VV-polarization [30]. The strong extinction at VV-polarization due to the predominantly vertically oriented structure of the scattering elements reported in [31] and [32] also let us infer that multiple-scattering components can be considered negligible. In [33], the backscattering coefficient for maize simulated using the “Tor Vergata” radiative transfer model confirms the general properties of backscattering studies based on a more simple “water cloud” model [34], where two vegetation layers were assumed, an upper dominated by leaves and a lower one by stalks. It is concluded in [34] that the stalk and the soil terms are important only if the leaf area index (LAI) is < 0.5. Our conclusion then is that the IWCM in its original form can be applied; however, some restrictions on its validity shall be considered, for example, when the LAI is small.

The expression for the decorrelation of the vegetation, i.e., the last term in (1), includes the backscattering coefficient of the canopy $\sigma^0_{\text{veg}}$, the temporal coherence of the canopy $\gamma_{\text{veg}}$, and the transmissivity of the radar wave through the vegetation layer $T$. For simplicity, the number of scatterers is assumed to be constant with height, and only the variation due to extinction is included. From indoor observations, the vertical scattering profile of a sample of corn plants has been demonstrated using polarimetric InSAR (PolInSAR) [30]. Compared to an assumption of constant scattering with height, the effective height of the vegetation was 5%–10% lower [35]. For outdoor conditions, temporal decorrelation, which is increasing with height, also has to be taken into account, and we expect the effective height to be further decreased. However, if the wind speed is low, this effect will be small.

C. IWCM Parameter Values

In order to simulate the coherence and the InSAR height using the IWCM, a number of parameters have to be determined since they are unknown a priori ($\gamma_{\text{gr}}, \gamma_{\text{veg}}, \sigma^0_{\text{gr}}, \sigma^0_{\text{veg}}, \eta$, and $\alpha$). All of these parameters have a physical meaning which has to be made plausible for the maize case. The parameters can be constrained by direct observations or by observations from similar conditions. Although we had information on crop height on the day of the image acquisition, the limited number of reference fields and the lack of more detailed in situ data prevented from proceeding with a full validation of the model. The information that is available on the maize fields under investigation only allowed analyzing the model performance by selecting for each parameter a specific value, when possible, or a range of values.

The ground temporal coherence $\gamma_{\text{gr}}$ could be reasonably assumed to coincide with the coherence of bare fields since, over 28 min, there should not be substantial differences in the decorrelation mechanism from a bare soil and a soil covered with vegetation (e.g., geometric variations due to moisture variations). Since the range of coherence measurements for the bare fields in our case was small, this parameter was set equal to the mean coherence of the bare fields. Table I shows that the coherence of the bare fields was between 0.71 and 0.78; hence, $\gamma_{\text{gr}}$ was set equal to 0.75. The same reasoning was applied to the backscatter coefficients for the ground $\sigma^0_{\text{gr}}$ and for the vegetation $\sigma^0_{\text{veg}}$. The parameter $\sigma^0_{\text{veg}}$ was set equal to an average value of the backscattering coefficient over the bare fields described in Table I. The average backscattering coefficient for the bare fields was $-9$ dB. The parameter $\sigma^0_{\text{veg}}$ was set equal to the average value of the backscattering coefficient over the five maize fields since it could be reasonably assumed that the total backscatter from these fields corresponds to the backscatter from the canopy. The average value was $-10.5$ dB. Compared to the backscattering coefficient from the bare fields, this value is lower because of the roughness of the bare surface. The dry conditions on several days prior to the image acquisition and on the day of the image acquisition let us conclude that the soil moisture effects on the backscatter were of lesser importance.

It has to be remarked that, in the IWCM, the ground and vegetation components of the coherence are related to the ratio of the corresponding component of the backscatter with respect to the total backscatter. At C-band, the difference between the ground and vegetation backscatter is rather small (in this case, 1.5 dB) so that the backscatter terms in (1) play a minor role in determining the total coherence. For this reason, it is reasonable to use one value each for $\sigma^0_{\text{gr}}$ and $\sigma^0_{\text{veg}}$.

An estimate of the temporal coherence of the vegetation $\gamma_{\text{veg}}$ was obtained by considering the expression relating temporal coherence to the rms motion of scatterers along the line of sight $\delta_{\text{rms}}$ [36]

$$\gamma_{\text{temporal}} = e^{-\left(\frac{\pi \delta_{\text{rms}}}{\lambda}\right)^2/2}.$$  

(4)

As discussed in Section I, for stable weather conditions between the acquisition, the decorrelation in vegetated areas can primarily be related to the wind-induced motion of the canopy. The rms motion of fully grown maize plants was derived from the measurements of horizontal displacements of maize stalks under wind loading reported in [37]. Assuming a linear relationship between wind speed and displacement, we computed the component along with the rms motion corresponding to the recorded wind speed of 0.5–1 m/s (see Section II) to be approximately 1–2 mm along the line of sight (23° incidence angle). With such rms displacements, temporal coherence values that are greater than 0.9 were obtained from (4). It should be remarked that this result is valid for the stalks. Considering that the maize plant includes leaves and the maize tassel, which are presumably more sensitive to wind effects, the temporal coherence should be somewhat lower. The lack of more detailed information on the motion of these plant components did not allow us to further quantify this decrease and, thus, to define a specific value for $\gamma_{\text{veg}}$. For this reason, the value will be handled as highly uncertain.

To obtain an idea of the interval for the two-way attenuation coefficient $\alpha$ that is feasible for the maize, we considered
published values on wave extinction in maize canopies. The best information on the wave extinction in maize seems to be scatterometer experiments reported in [32]. For 2.7-m-tall plants under full-canopy conditions, the extinction for vertically polarized C-band (4.75 GHz) waves at 20° look angle had a mean value that is slightly above 2 dB/m, with error bars extending from approximately 1 to 3.5 dB/m. Model-based estimates of extinction were reported in [35] based on PolInSAR measurements of 1.8-m-tall maize plants and an oriented-volume-over-ground modeling approach. At C-band, the extinction was estimated in the range 0.5–2 dB/m and 1.5–2.5 dB/m depending on the inversion approach used. As an outcome of these investigations, a realistic range of values for the extinction is between 0.5 and 3.5 dB/m. The relationship between the extinction in dB/m $\kappa$ and the two-way attenuation coefficient $\alpha$ is

$$\exp(\alpha) = \exp(2\kappa / \cos \theta)$$  \hspace{1cm} (5)

so that the realistic two-way attenuation values for maize are between 1 and 7 dB/m.

The model in (1) includes both the horizontal and vertical properties of the canopy, which are described by the canopy cover and the height, respectively. To reduce the number of unknowns in the model, canopy cover was related to height. Unfortunately, we could not find in the literature an expression that is specific for (European) maize relating canopy cover to height. For this, we had to develop an empirical relationship based on measurements reported in literature and models linking other vegetation parameters. We started from the well-documented relationship between LAI and fraction of photosynthetically active radiation (fPAR) intercepted by the canopy, which is also a measure of the canopy cover [38]

$$c = a(1 - e^{-k_{LAI}}).$$  \hspace{1cm} (6)

In (6), $c$ represents the canopy cover (for a given angle from zenith), $a$ represents the canopy cover for a fully developed field, and $k$ is related to the projection of the unit leaf for the given zenith angle. Although several authors have remarked the necessity of including in this kind of relationship architectural information such as planting distance, e.g., [39]–[41], (6) can be considered sufficient as a first approximation, also considering the lack of information about the architectural properties of the fields under investigation in this paper.

Information on maize grown under European conditions is found in [24], [33], and [42] with ground data collected over a field at the Central Plain in 1988 and the Loamy Region in Belgium in 2003. The data include crop height, LAI, and canopy cover in two cases for the loamy site. The observations result in $a = 1$ and $k = 0.36$. These values are within the range reported in [39] and [43] for various climate zones ranging from 1 to 0.83 for $a$ and from 0.35 to 0.65 for $k$ depending on maize hybrid, row spacing, water regime, etc. By plotting the measurements of crop height versus the corresponding canopy cover from (6), we could obtain a relationship between these two parameters in the same form as (6)

$$\eta = b \cdot \left[1 - e^{-k_{h_{c}}(h-h_{0})}\right]$$  \hspace{1cm} (7)

with $b = 0.85$, $k_{h_{c}} = 1.8$, and $h_{0} = 0.08$. In (7), we preferred using the symbol $\eta$ instead of $c$ to comply with the expression of the IWCM in (1). Fig. 8 shows the measurements and the realization of (7). The curve is extended to include senescence at a crop height of 2.7 m for the Loamy Region site. During the growth period, soil moisture may influence the relationship. After senescence, some leaves start wilting, and LAI decreases, while the height is unchanged so that the canopy cover can no longer be expressed by means of crop height with (7).

In the following, we will use (7) assuming that the formulation reported here is general enough for its application to the maize fields in the Seeland area. Visual observations of the maize growth in previous studies dealing with the behavior of active and passive microwave signatures throughout the growth period [22] agree with the trend illustrated in Fig. 8. The canopy cover first increases rapidly with height and then reaches saturation already at an early growth stage when the canopy almost entirely covers the ground.

V. MODEL SIMULATIONS

Having assessed the possible ranges of values for each of the unknown IWCM parameters, the coherence and InSAR height were simulated as a function of height for the different combination of the parameters values. In Fig. 9, we show a realization of the modeled coherence and InSAR height for a given set of values. The curves in Fig. 9 were obtained using a specific set of plausible model parameter values ($\gamma_{gr} = 0.75$, $\gamma_{veg} = 0.7$, $\sigma_{gr} = -9$ dB, $\sigma_{veg} = -10.5$ dB, and $\alpha = 3$ dB/m corresponding to an extinction of approximately 1.5 dB/m). The coherence and InSAR height measurements have also been reported on the vertical axis to allow a comparison with the model-based predictions.

The modeled coherence in Fig. 9 decreased for increasing height, with the curve being steeper for heights between 1

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{figure8.png}
\caption{Plot of the canopy cover as a function of height. (Solid line) Connecting values from (7) using height measurements from Central Plain [42] in points marked by ●; (dotted line) the same but with values from the Loamy Region [33]; × marks the canopy cover measurements from Central Plain [24] and ⋄ the measurements from the Loamy Region [33].}
\end{figure}
and 2.5 m. The modeled interferometric height in Fig. 9 increased for increasing height of the vegetation. The slope got steeper for increasing height. The increasing sensitivity of the interferometric observables to the height of the vegetation is related to the stronger effect of volume decorrelation for a thicker vegetation layer [see (2)]. The slope of the curve is also controlled by the temporal coherence of the vegetation \( \gamma_{\text{veg}} \) and the two-way attenuation per meter \( \alpha \). For a given interferometric geometry, the shape of the curve will therefore depend on \( \gamma_{\text{veg}} \) and \( \alpha \). This aspect will be considered further on in this section.

For the combination of parameter values used to obtain the curves shown in Fig. 9, the sensitivity of the coherence upon the height of the vegetation appeared particularly strong. According to the realization of (1) in the left plot in Fig. 9, the range of coherence measured at the five maize fields on interest (asterisks on the vertical axis) corresponded to vegetation with heights between 1.7 and 2.3 m, thus being slightly below the average height of 2.5 m reported by the local authorities managing the fields but close to the 2.2-m value reported in [22] and [23].

The interferometric height was well below the reported crop height. The sensitivity of the InSAR height increased with the vegetation height, which is minimal for short vegetation below 1 m. The right plot in Fig. 9 shows that the range of interferometric heights measured at the five maize fields (asterisks on the vertical axis) corresponded to a range of vegetation heights of 1.5–2.8 m. This result indicates that both the coherence and interferometric height observations at the six maize fields correspond to roughly the same range of heights. The uncertainty is, however, large, in particular, for what concerns the interferometric height.

To assess the sensitivity of the IWCM to the different model parameter and possibly define a range of model parameter values, we let one of the parameter vary, leaving the others unchanged. Changing once at a time \( \sigma_{\text{gr}} \), \( \sigma_{\text{gr}}^0 \), or \( \sigma_{\text{veg}}^0 \) within ranges of realistic values derived from the observations did not have any particular effect on the modeled complex coherence. Similarly, setting all parameters to a specific value and changing the \( k_h \) coefficient in (7) between 1.5 and 2 in order to take into account some different growth scenarios did not have any effect. This indicates that the specific realization of the model suggested in (7) is not crucial for the modeling of the complex coherence. The strongest sensitivity of the model was found indeed for \( \alpha \) and \( \gamma_{\text{veg}} \). For this reason, we report here a summary on the IWCM realizations obtained with all combinations of \( \alpha \) in the range of possible values, i.e., between 1 and 7 dB/m, and \( \gamma_{\text{veg}} \) between 0.3 and 0.8. Although, in this case, the temporal coherence of the vegetation should have been high, lower values were still included for completeness.

In the left plot in Fig. 10, the two solid lines illustrate the coplotted IWCM realizations of the coherence and InSAR height for a low \( \alpha \) value (1 dB/m) in the case of a low \( \gamma_{\text{veg}} \) value (0.4, lower curve) and a high \( \gamma_{\text{veg}} \) value (0.7, upper curve). Similarly, in the right plot in Fig. 10, the two solid lines represent the coplotted IWCM realizations of the coherence and InSAR height for a high \( \alpha \) value (5 dB/m) in the case of a low \( \gamma_{\text{veg}} \) value (0.4, lower curve) and a high \( \gamma_{\text{veg}} \) value (0.7, upper curve). The dashed lines represent the IWCM realization for the parameter values used in Fig. 9 (\( \alpha = 3 \) dB/m and \( \gamma_{\text{veg}} = 0.7 \)). For reference, the part of the coplotted modeled coherence and InSAR height corresponding to heights between 2.2 and 2.5 m has been thickened. The plots also include the observations of the coherence and InSAR height for the five maize fields. The bars represent the corresponding standard deviations of the coherence and InSAR height.

The left plot in Fig. 10 gives an indication for what happens if weak attenuation is assumed, i.e., below 2 dB/m. The span of the modeled InSAR height was small, and the sensitivity of the IWCM to \( \gamma_{\text{veg}} \) was practically negligible. Furthermore, the modeled coherence was overestimated, whereas the InSAR height was underestimated. The thickened segments on the solid lines indicate that the modeled values are outside the range of the observations. The dashed line exemplifies a case with \( \alpha \) between 2 and 4 dB/m. Both the coherence and the InSAR height were then more sensitive to height as well as to different values of \( \gamma_{\text{veg}} \) (not illustrated here). The agreement with the
observations was best for such a case. The right plot in Fig. 10 illustrates what happens for strong attenuation (> 4 dB/m). The span of both the modeled coherence and InSAR height was large, with the coherence showing some saturation in the case of long vegetation. Compared to the behavior in the case of lower attenuations, here, both the coherence and the InSAR height appeared to be more sensitive to $\gamma_{\text{veg}}$. For heights ranging between 2.2 and 2.5 m, the coherence tended to be underestimated for low $\gamma_{\text{veg}}$ values (see lower curve). The InSAR height was, instead, in the range of the observations or slightly above, in particular, if large $\gamma_{\text{veg}}$ is assumed.

Plots of the kind reported in Fig. 10 give an indication on the range of feasible model parameter values for $\alpha$ and $\gamma_{\text{veg}}$. Further along this line, we tried to identify which combinations of $\alpha$ and $\gamma_{\text{veg}}$ could be more plausible with respect to the observations. In Fig. 11, the combinations of $\alpha$ and $\gamma_{\text{veg}}$ are plotted for which both the predicted coherence and the predicted InSAR height are within the range of values defined by the highest and lowest measured coherence and InSAR height, respectively, from the five maize fields (see Table II). For clarity reasons, the combinations of $\alpha$ and $\gamma_{\text{veg}}$ were plotted using a step of 0.5 for $\alpha$.

Fig. 11 shows the result for a vegetation height of 2.2 m. The distribution of the dashed bars indicates a wide range of plausible combinations primarily because of the large range of coherence and InSAR height observed. However, it is possible to note a tendency toward a two-way attenuation per meter between 2 and 4 dB/m and $\gamma_{\text{veg}}$ above 0.5. The plausible interval of two-way attenuations corresponds to a one-way attenuation between 1 and 2 dB/m, thus being at the lower end of what has been reported in previous studies. A simulation for a vegetation height of 2.5 m has also been considered. The only plausible value for $\alpha$ was 2 dB/m with $\gamma_{\text{veg}}$ above 0.5. The low attenuation estimated is probably due to the rather dry conditions of the plants at this stage of the growth cycle (harvest, just before senescence). The temporal coherence of the vegetation $\gamma_{\text{veg}}$ is expected between 0.6 and 0.8, a range of values which is strictly related to the specific weather conditions that occurred at the time of image acquisition.

VI. CONCLUSION

In this paper, we have investigated the signatures of ERS–Envisat interferometric coherence and phase for five maize fields and a sunflower field. Furthermore, it was analyzed whether a simple but still physically-based model linking the InSAR observables and crop parameters could explain the interferometric observations in the case of maize fields.

This investigation was triggered by the evidence that the interferogram formed by two images acquired on October 15, 2007, over the Seeland region, Switzerland, showed a number of agricultural fields with lower coherence and higher interferometric height with respect to neighboring fields. At this time of the year, most fields have already been harvested, thus being bare; nonetheless, some are still covered by mature plants. Information from local authorities confirmed that the fields showing lower coherence and higher interferometric height were vegetated at the time of image acquisition while the remaining fields were bare. For the six vegetated fields, the coherence was approximately 0.4–0.5, while the InSAR height presented an offset of up to 1 m with respect to the neighboring fields. Bare fields showed a coherence, on average, of 0.75.

The interferometric quantities were modeled as a function of height using the IWCM. Model simulations were in line with the observations and showed that both the coherence and the InSAR height are sensitive to crop height. A sensitivity analysis indicated plausible model realizations for two-way attenuation in the range 2–4 dB/m, corresponding to extinction of approximately 1–2 dB/m, and temporal coherence of the vegetation of 0.6–0.8. The low attenuation should be a consequence of the dry conditions of the plants since the images were acquired almost at the end of the growing season. The very high temporal coherence of the vegetation should be a consequence of the stable weather conditions and the low wind speed at image acquisition.

The strong sensitivity of both the coherence and the InSAR height to crop height indicates a certain potential for retrieving height of maize using both interferometric observables. This needs to be confirmed with a large data set of reference fields and more detailed in situ measurements. This, in turn, would also allow confirming the indications on the values of the IWCM parameters. The possibility of using both interferometric observables to retrieve crop height is a unique capability of ERS–Envisat interferometry with respect to other single-polarization interferometric systems, where either only the coherence (e.g., ERS-1 three-day mission and ERS-1/2 tandem mission) or the interferometric phase, as in the case of SRTM, has been proven to be useful for retrieval purposes. In the first case, the phase is generally too noisy to provide sufficiently accurate estimates of the biophysical parameters. In the latter case, the single-pass configuration has the consequence that the coherence is basically close to one regardless of the vegetation structure. In ERS–Envisat interferometry, the sensitivity of both interferometric observables to biophysical parameters is enhanced due to the short repeat-pass interval that decreases the risk of strong temporal decorrelation and the long baseline that introduces a strong volume decorrelation component.
With respect to single-polarization interferometry, the advantage of using PolInSAR techniques consists in the larger number of observables available, which allow obtaining more information about the scattering processes and thus developing more complete retrieval methods. In controlled experiments, it has been demonstrated that both the ground topography and the vegetation height can be determined by inverting full-polarimetric [35], [44], as well as dual-polarimetric, data sets [44] with high accuracy over a large range of frequencies. Nonetheless, these experiments are not affected by temporal decorrelation, which therefore limits the conclusions concerning the effective accuracy such methods would achieve in a repeat-pass scenario. Apart from the TanDEM-X mission, for all other spaceborne interferometric systems, including future missions, we have a repeat-pass configuration when wind effects may cause vegetation decorrelation even with a repeat cycle as short as a few seconds. For the TanDEM-X constellation (in single-pass mode), temporal decorrelation is introduced over vegetated areas for moderate to high wind speeds if the along-track separation between the two satellites is too long; the orbital configuration of the TanDEM-X mission is such that this issue is accounted for [45].

To further investigate the signatures of the interferometric coherence and phase in short vegetation such as crops, a new ERS–Envisat interferometric campaign to take place during an entire growing season is suggested. Future studies involving a multitemporal analysis should consolidate the indications provided in this initial investigation. The effect of different temporal decorrelation effects and residual uncompensated atmospheric artifacts could also be addressed. The impact of the DEM vertical accuracy is finally another factor to be considered. With one interferogram available as in this case, the InSAR height of the crops is determined by taking the difference of the differential interferometric phases between the vegetation and a ground reference. Not only this requires the availability of unvegetated bare areas with high coherence in the neighborhood of the fields but also errors in the DEM would propagate to the estimate of the phase difference, i.e., of the InSAR height of the vegetation. In this paper, we considered for each field of interest the mean elevation of the surrounding bare fields as reference. While this minimized the possibility that residual elevation due simply to ground topography would bias the estimates of the InSAR height, still, the rather coarse DEM used for this study (SRTM-3) could be a source of uncertainty in the observations. If a second interferogram acquired prior to the growth period is available, the InSAR height estimate could be refined by taking the difference between the InSAR elevations from the two interferograms. In this way, the impact of the DEM-induced errors would be minimized. In addition, the requirement for neighboring bare fields would drop since the InSAR height of a field would be estimated with respect to the surface elevation of the very same field.

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References
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