First Demonstration of Agriculture Height Retrieval with PolInSAR Airborne Data

Juan M. Lopez-Sanchez, *Senior Member, IEEE*, Irena Hajnsek, *Senior Member, IEEE*, and J. David Ballester-Berman

Abstract—**A set of three quad-pol images acquired at L-band in interferometric repeat-pass mode by DLR with the E-SAR system, in parallel with the AgriSAR2006 campaign, have been used to provide for the first time with airborne data a demonstration of the retrieval of vegetation height from agricultural crops by means of PolInSAR-based techniques. Despite the low frequency of the data, hence providing a weak response from the vegetation volume in contrast to the ground, accurate estimates of vegetation height at field level have been obtained over winter rape and maize fields. The same procedure does not yield valid estimates for wheat, barley and sugar beet fields, due to a mismatch with the physical model employed in the inversion and to the specific crop condition at the date of acquisition. These results show the value of the information provided by both interferometry and polarimetry for some agriculture monitoring practices.**

Keywords—**Polarimetric SAR interferometry, vegetation, parameter retrieval, agriculture, airborne sensors.**

I. Introduction

For many cereals and other crop types, vegetation height is an indicator of the current phenological stage, especially during the vegetative phase when plants grow and develop all stems, tillers, branches, etc. Hence, its retrieval by remote sensing would contribute to different agriculture applications, especially those related to phenology tracking, crop condition monitoring and other activities dedicated to precision farming [1]. Retrieval of crop height is useful provided that a direct relationship between height and phenology exists for a monitored crop at the stages of interest for a particular application. In other cases, however, height is not necessarily indicative of growth stage or crop condition (particularly for some crop types or at advanced phenological stages). Therefore, this limitation has to be considered when applying the approach employed in this letter to different scenarios.

To date, polarimetric SAR interferometry (PolInSAR) [2] has been successfully used for the estimation of height and other structural information of forests. Data provided by airborne sensors, such as DLR's E-SAR, and acquired at P-, L- and X-band have been exploited for that purpose [3], [4], [5], [6].

In contrast, and despite the working principle of this technique is the same for both agriculture and forests, so far there has not been any demonstration of this approach for agriculture with airborne data. The only examples of agriculture data analyzed with PolInSAR correspond to indoor experiments carried out at the European Microwave Signature Laboratory (EMSL) at JRC-Ispra, Italy. Ground topography and vegetation height were retrieved from samples of maize and rice at S-, C- and X-band [7]. Therefore, the objective of this work is to provide a first experimental demonstration of the retrieval of vegetation height in agriculture scenarios with airborne data. This letter is not aimed at exploring the complete potentials of PolInSAR and all available models, but just at showing its general behavior with the most simple algorithms. Furthermore, the final scenario of this agriculture application would consist of a satellite interferometric system providing a wide coverage with short revisit time, not an airborne system which would result too expensive for such purpose. Accordingly, the experiment described here constitutes an intermediate step between the early tests with indoor data and the future potential conception of such spaceborne remote sensing system.

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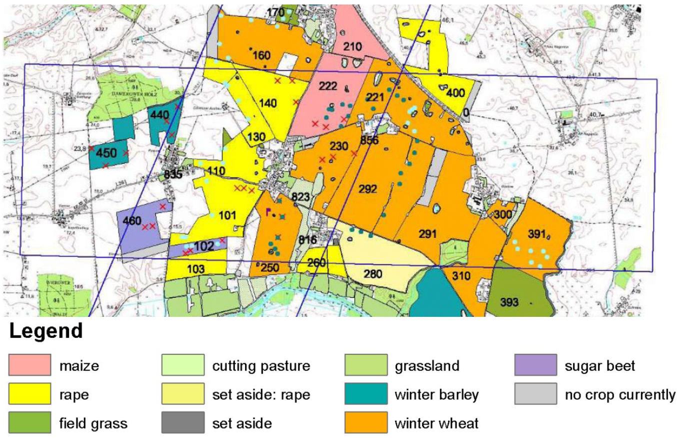


Fig. 1. Land cover map with location of the fields and the ground measurement points. Azimuth goes from right to left. Range goes from top to bottom

II. Ground campaign and interferometric data

The interferometric data employed in this work were acquired during the ESA supported AgriSAR2006 campaign [8], [9], so the ground measurements gathered in the framework of that campaign are employed here for validation purposes.

Figure 1 shows the area covered by the images. The test site is located in Demmin, Germany. Vegetation height values were measured *in situ* at the positions marked with red crosses (X) in Fig. 1. In this study we will concentrate on the following fields:

- Winter rape: fields 101, 110, 130 and 140[1].

[1]Note that intensive ground measurements were not acquired over rape fields 110 and 130, as indicated by the missing crosses (X) in Fig. 1.

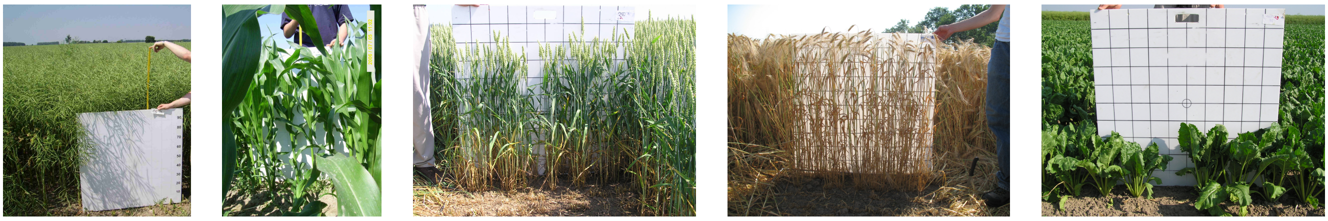


Fig. 2. Photographs of the five crop types at the date of acquisition

- Maize: field 222.
- Winter wheat: fields 230 and 250.
- Winter barley: fields 440 and 450.
- Sugar beet: fields 102 and 460.

Photographs of all crop types at the time of the radar acquisitions are shown in Fig. 2.

Radar data consist of three images acquired in interferometric repeat-pass mode by the DLR E-SAR system at L-band in fully polarimetric mode on July 5, 2006. Flights were separated by an interval of 7.5 minutes between passes. By combining these images, we have access to 3 different horizontal baselines: 30, 60 and 90 m.

Among all system parameters related to this application, two key aspects are frequency band and baseline. In this sense, the selection of L-band is clearly not optimum for agriculture purposes, since low microwave frequencies provide much penetration through the vegetation volume, which is very short in crops. Consequently, the radar echoes are mostly dominated by the ground response. This dominance depends on the actual vegetation height and the plant density and physical structure, which differ as a function of crop type and phenological stage. In principle C- and X-band would provide a better compromise between penetration and response from the above ground vegetation. However, also larger wavelengths as L-band can be used by optimizing the phase to height sensitivity using baseline variations, as described in Section III. In general, a sensitivity analysis can be performed in terms of the so-called *ground-to-volume ratio*, which is roughly defined as the ratio of the ground backscatter over the volume backscatter. A large variation of this ratio as a function of the polarimetric channel is required to provide accurate height estimates.

Regarding the baseline, in order to invert vegetation parameters from a PolInSAR data set, a right value of the vertical wavenumber (k_z) has to be provided by the system configuration and acquisition geometry. As a general rule, we can inspect the value of parameter k_v, which is defined as $k_v = k_z h_v/2$, where h_v is the vegetation height. This parameter appears as the argument of all functions obtained in a Fourier-Legendre series expansion of coherence [10], including the well-known first term, $\sin(k_v)/k_v$, for the volume decorrelation of a uniform vegetation profile. k_v should be in the range 1–1.5 for simultaneously ensuring enough sensitivity to the vertical profile of the scene and not producing excessive decorrelation [10]. Therefore, baselines that have to be employed for agricultural crops (with heights up to 2 m or 2.5 m) are quite larger than those adapted to forests (with 20 or 30 m tall trees). As a rule of thumb, baselines have to be larger by a factor of 10.

The vertical wavenumber provided by the three available baselines is shown in Fig. 3 as a function of range. Values at near range are larger than at far range as a consequence of the airborne geometry. If one takes into account the aforementioned criterion, a 1 m tall crop could be monitored properly with a k_z between 2 and 3, so only with the 90 m baseline at near range we fall within the ideal range of operation. Taller crops enjoy a wider range of range positions within the mentioned interval of operation. In general, however, the 30 and 60 m baselines are not large enough for applying PolInSAR in this scenario.

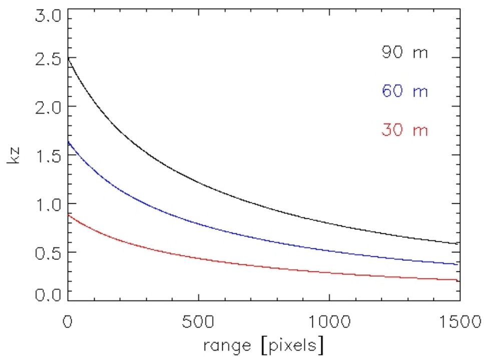
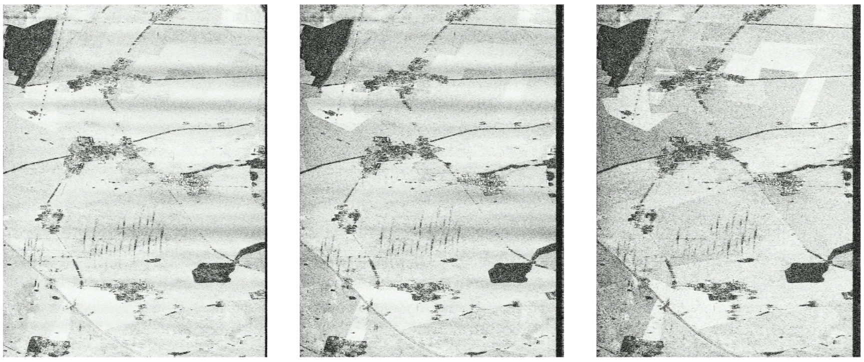


Fig. 3. Vertical wavenumber (k_z) as a function of range for 3 available baselines

For illustration purposes, the coherence maps obtained at the HH channel for the three available baselines are shown in Fig. 4. A common band filtering designed for the worst case (near range) was applied to the whole scene for removing the well-known baseline or geometrical decorrelation. As expected, coherences are generally lower at larger baselines, but they are high enough over the agricultural fields. Note that a total decorrelation (zero coherence) is observed over two forested areas present in the scene. The interferograms formed at 30 and 60 m baselines exhibit several horizontal stripes which are likely due to inaccuracies in the motion compensation applied when focusing the images, due to an excessive separation of the flight track with respect to its nominal one. Since the two interferograms affected have the 2nd flight in common, this seems to be the cause of such coherence degradation. Fortunately, the interferogram with the larger baseline (formed with the images acquired in 1st and 3rd flights) is not affected by such a problem and will be employed in the rest of this study.

III. Results

The capability of PolInSAR for retrieving structural parameters from a vegetated scene relies on variation of the observables (complex interferometric coherences) as a function of the polarimetric channel. Hence, good results are expected when



B_h = 30 m B_h = 60 m B_h = 90 m

Fig. 4. Coherences maps at HH channel for the 3 available baselines. Azimuth goes from bottom to top. Range goes from left to right

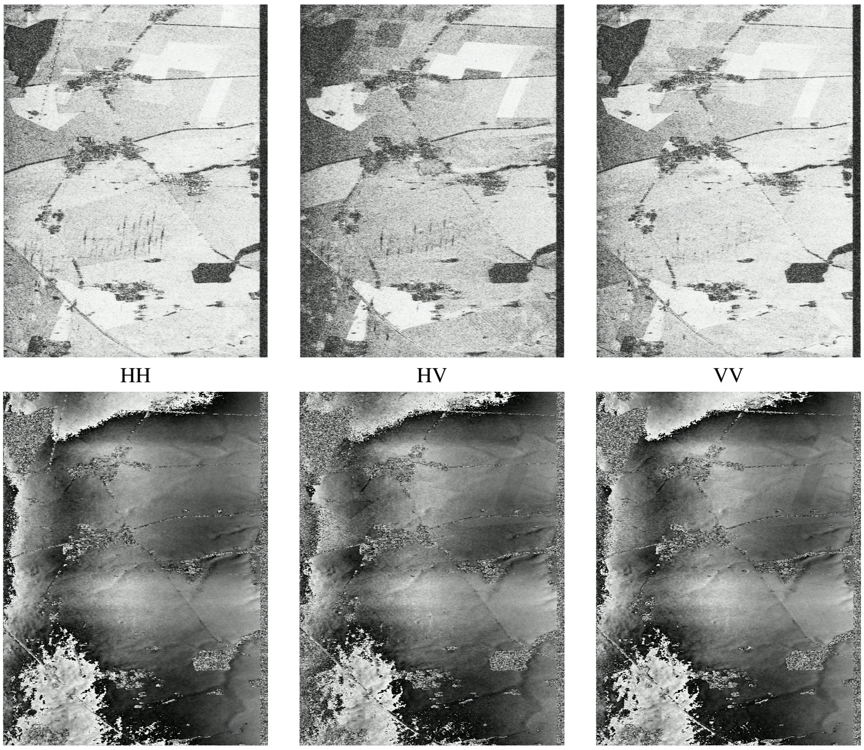


Fig. 5. Coherence (top) and interferometric phase (bottom) maps at all linear channels for the 90 m baseline. Topographic term has been approximately removed by using an auxiliary DEM generated by the E-SAR system at X-band at the beginning of the campaign (April 18, 2006).

both interferometric coherences and phases from the same area change when different polarimetric channels are chosen. Figure 5 presents both parameters for the three channels in the linear basis: HH, HV and VV. We can appreciate that coherences change at different fields from channel to channel, being more pronounced the difference between the cross-polar channel and the copolar ones. There are also fields with similar values at the VV and HV channels, and different from the HH one. Consequently, this first inspection on the polarization diversity of the observables is positive.

PolInSAR data can be employed to retrieve a set of scene parameters (e.g. underlying ground topography, vegetation height, extinction, etc.) by inverting a forward model of the scene. The most used model in this context is the so called random volume over ground (RVoG), which assumes a scene composed by a homogeneous layer of randomly oriented particles (a volume) over a ground surface. In the case of agriculture, when crops exhibit a preferred orientation in the volume (usually vertical due to the stems), a modification of the model (oriented volume over ground, OVoG) has been also used for retrieval purposes.

The first step of the inversion procedure starts with a line fit to the coherences on the complex plane, with yields the estimation of the underlying topographic phase (ϕ_0). Two options have been proposed in the literature for this fit:

- A fit to a selected set of coherences. The most employed set is formed by the coherences in the linear basis, the Pauli basis and the optimum ones, as described in [4].
- A fit to the data provided by a Maximum Likelihood (ML) estimator and ensuring the equal scattering mechanisms (ESM) condition, as proposed in [11].

After the ground topography estimation, the rest of model parameters are retrieved by fitting the data to the model, by means of either geometrical or numerical approaches. A practical expression for providing an estimate of the vegetation height is the

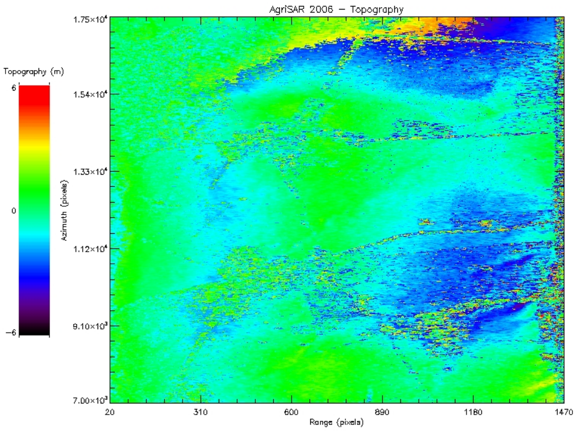


Fig. 6. Topography retrieved over the main study area

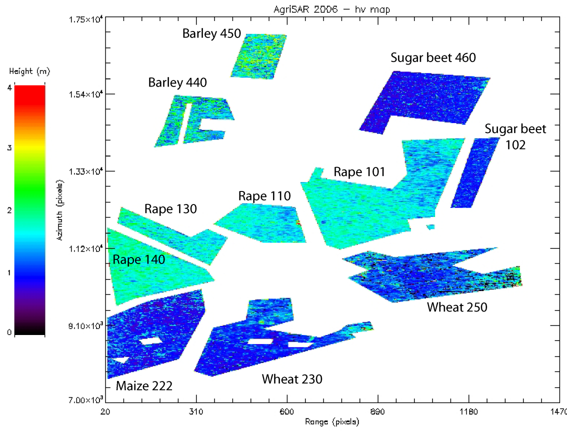


Fig. 7. Height retrieved over the studied fields

following [10, Eq.8.38]:

$$h_v = \left[\arg(\gamma_v e^{-j\phi_0}) + \eta(\pi - 2\arcsin(|\gamma_v|^{0.8}))\right]/k_z \qquad (1)$$

where η = 0.8, and γ_v corresponds to the coherence at a channel without any ground contribution. In general, and especially with crops at L-band, all polarimetric channels include a ground contribution, so γ_v is chosen as the coherence most separated along the line from the topographic point on the complex plane.

Figure 6 shows the estimates of ground topography over the whole central region in the images (where the studied fields are located), whereas Fig. 7 presents a map with the heights retrieved over the studied fields. The two options for line fit mentioned above produce similar results, but the ML algorithm is more efficient from the computational viewpoint, since it provides an analytical expression of the fitted line, and hence it is preferred when a large image has to be processed. Results are generated by using a boxcar filter of 15x15 pixels for multilooking and estimation. A system coherence term γ_{sys} = 0.95 has been applied to account for unknown extra decorrelation factors [12]. Finally, the location on the complex plane of the measured coherences for a pixel of each crop type (one field per crop type) is shown in Fig. 8.

The derived ground topography, relative to the auxiliary DEM employed in the processing, is rather smooth over all fields (Fig. 6). This is clearly a result of the low frequency band which ensures a dominant ground contribution, and hence the topography estimation is quite robust despite the type of crop, provided that enough sensitivity is guaranteed by a right vertical wavenumber value. In fact, the rapid decrease in k_z at near range has an impact on the estimates. For instance, when comparing the retrieved topography over fields 140 (rape) and 222 (maize), whose location is indicated in Fig. 7, we can notice that up to pixel 150-200 in range the values are quite similar for both fields, but they are progressively different from that range position. Finally, it must be noticed that topography is an intermediate by-product in this application, despite it would constitute a final product in other ones.

Regarding the height estimates in Fig. 7, they seem quite homogeneous over the rape, maize and sugar beet fields, but they are noisier for wheat and barley. In order to assess quantitatively the results obtained with this approach, we present in Table I the mean and standard deviation of the estimates over each field,

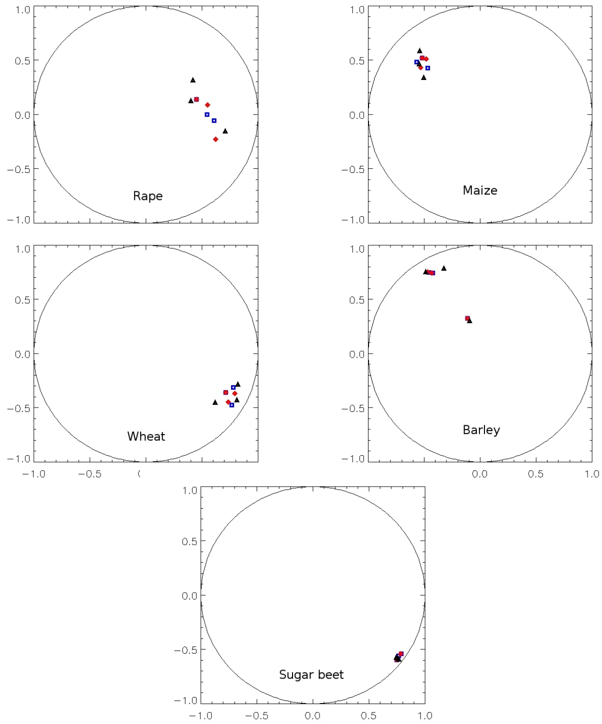


Fig. 8. Typical coherence sets for the five crop types at the date of acquisition. Linear basis: squares. Pauli basis: diamonds. Optimum: triangles

together with the data available from the ground campaign. Histograms of the estimates at every field have been computed, but are not shown here due to space constraints. From the application viewpoint, in principle farmers are interested in knowing the phenological stage of the monitored crops at field level (i.e. one value per field), so the comparison against the ground data will consider only the average retrieved height at each field.

At the rape fields the estimates are quite homogeneous and follow clear normal distributions. Morphology of rape plants (see Fig. 2) is well represented by a RVoG model (see the linear arrangement of coherences in Fig. 8), so this crop should produce the best estimates according to the employed model-based inversion. When comparing the average heights against the ground measurements, at near range (field 140) there is a slight overestimation, whereas at far range (field 101) values are slightly underestimated. The dependence of the estimates on

TABLE I
COMPARISON BETWEEN VEGETATION HEIGHT ESTIMATES h_v AT FIELD LEVEL AND GROUND MEASUREMENTS

Field	Mean (m)	Std.dev. (m)	Ground data (m)
Rape 101	1.61	0.22	1.70, 1.72, 1.75
Rape 110	1.60	0.24	N.A.
Rape 130	1.67	0.25	N.A.
Rape 140	1.76	0.20	1.45, 1.50, 1.55
Maize 222	0.98	0.31	0.90, 1.05, 1.10
Wheat 230	1.06	0.33	0.77, 0.79, 0.82
Wheat 250	1.31	0.47	0.78, 0.80, 0.87
Barley 440	1.61	0.47	0.96, 0.97, 1.10
Barley 450	1.89	0.61	0.91, 0.95, 0.98
Sugar beet 102	1.02	0.25	0.40, 0.50, 0.50
Sugar beet 460	0.93	0.31	0.13, 0.20, 0.25

range may originate from the different incidence angles, which provide different ground-to-volume ratios and, as a result, different sensitivities. The influence of vertical wavenumber (at far range is less than half that available at near range) has to be taken into account too.

Regarding maize, the average estimated height in the monitored field is in agreement with the available ground data. For this particular field, very different height estimates were recorded in the ground campaign, which were even more pronounced towards the end of the growth cycle (e.g. heights from 1.7 to 2.7 m were present here at the last dates before harvest), so this field should not be regarded as strictly homogeneous.

It should be mentioned that, in general (not only for maize), crop height can vary quite significantly within a field due to local variations in soil properties and topography. Even along one crop row, height can vary from one plant to another. Consequently, the available three measurements per field are not sufficient to capture this variability, and hence the conclusions about this validation with ground measurements are limited. Ground measurements are assumed as representative of the average field, but the locations of the ground measurement points are rather constrained to a small area of the fields (see Fig. 1), so this uncertainty has to be considered when deriving conclusions from this study.

Heights retrieved at the wheat fields are clearly overestimated and show larger variances than for maize and rape. This is expected from the physical structure of wheat and its mismatch with respect to the RVoG model, i.e. with high plantation density and an evident preferred vertical orientation of the plants elements (a line cannot be identified in Fig. 8), which suggest that the OVoG model would suit better. In addition, previous studies have shown multiple scattering effects in such a crop [13].

Results obtained at barley fields are completely wrong, since they are very noisy and largely overestimated. Plant structure at the time of the radar acquisition was extremely dry (see Fig. 2), as it was to be harvested 10 days after. With such a dry vegetation layer, the radar signal comes mostly from the ground surface and, what is also important here, the cross-polar return is very weak. This last aspect has an impact on the PolInSAR performance because the coherence for the HV channel is very low at the barley fields (they can be easily identified in Fig. 5) as a result of a poor SNR. Therefore, the HV coherence departs from the expected line towards the origin (Fig. 8) and the whole retrieval procedure is not consistent anymore.

Finally, results for the sugar beet exhibit a clear overestimation too, despite they are quite homogeneous. In this case the error source is the short vegetation layer (13–50 cm) and the subsequent lack of sensitivity of the interferometer, since the available baseline is not large enough to ensure a good k_v value. The situation is even worse than for other crops because both sugar beet fields are in the far range region. This leads to a concentration of the coherences on the complex plane over a small cluster close to the unit circle (Fig. 8), hence having access only to a short visible line length in the model inversion.

IV. CONCLUSIONS AND FUTURE WORK

Results presented in this study constitute the first demonstration with real airborne data of the feasibility of PolInSAR to retrieve vegetation height from agricultural crops. Notwithstanding the employed frequency band is not optimum for such a scene, average estimates at field level with a 10% accuracy have been obtained for two crop types: rape and maize. Therefore, the volume information provided by interferometry is still present and enables the application of PolInSAR-based retrieval approaches, despite it is not general for all crop types and for all phenological phases.

This study will be complemented by assessing the influence of baseline and incidence angle at local level, together with a study about the sensitivity provided by the dynamic range of ground-to-volume ratios available. Moreover, more adapted models, like the OVoG, will be tested with these data, since they are expected to provide better estimates in some cases.

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