Indoor C-Band Polarimetric Interferometry Observations of a Mature Wheat Canopy

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Abstract—We present results from experiments carried out in the GB-SAR facility at the University of Sheffield to ascertain the role of polarimetric interferometry in crop height retrieval. To this end, a mature wheat canopy, grown in outdoor conditions, was re-assembled inside the GB-SAR chamber and imaged at C-band using a two-dimensional scan. This allowed fully polarimetric tomography and interferometry. Interferometry using the VV, HH and VH polarization states shows that the HH and VH interferograms retrieve a height close to the top of the soil layer for all angles of incidence considered, whereas the height retrieved from the VV interferogram increases with angle of incidence. The use of a Pauli basis gives poor results, due to the different location of the scattering phase centres in the VV and HH channels. The use of arbitrary polarization states shows that the top of the soil can be very accurately estimated using left circular polarization (L.L.), whereas, for angles of incidence close to 45 degrees, a polarization state similar to VV can be used to retrieve the top of the canopy; hence crop height can be recovered as the difference of these two interferometric heights. Polarimetric coherence optimisation techniques are also studied. Unconstrained coherence optimisation gives very unstable results, due to the small number of available samples. Constrained optimisation results in stable retrieved heights, and the retrieved polarization states agree well with the polarization synthesis results.

Index Terms—Vegetation monitoring, coherence optimization, indoor synthetic aperture radar.

I. INTRODUCTION

In recent years, there has been great interest in using airborne and spaceborne SAR systems to study agricultural crops. Multi-channel SAR techniques, such as polarimetry or interferometry, show potential for crop parameter retrieval (see [1] for a review). Critical to this objective is to understand the properties of microwave scattering in vegetation canopies. Up to now, this has mainly been studied using electromagnetic models, due to the lack of experimental facilities capable of probing the scattering in detail [2-5]. In contrast, here we adopt a predominantly measurement-based approach, taking advantage of a ground-based facility that allows fully polarimetric three-dimensional imaging, using a technique often referred to as tomography [6-10]. This permits detailed study of the scattering within a crop canopy, providing direct insight into the scattering, and helping to refine models and improve our understanding of the underlying physics.

Tomographic data acquired from wheat canopies in the GB-SAR facility at the University of Sheffield clearly show stratification of the backscatter at both C and X band [6]. There are also clear differences in the vertical structure of the backscatter at different polarizations. This strongly suggests that significant information about these canopies can be gained by the combined use of polarimetry and interferometry.

Polarimetry is sensitive to the properties of the dominant scatterers in the scene (such as dielectric, orientation and shape). Hence different polarization states may be associated with different parts of a canopy [5, 11]; for example, the direct interaction between the incoming field and the soil or canopy consists of single bounce scattering, a double bounce mechanism will typically describe the soil-stem interaction in a crop, and volume scattering will occur in canopies made up of branches, leaves, etc. In interferometric SAR (InSAR), the same scene is imaged from slightly different positions, and information on the height of scatterers can be inferred from the associated phase difference. By acquiring polarimetric data in an interferometric geometry, interferograms can be calculated for different polarizations. This allows information to be gained about the positions of different types of scatterers within a given pixel [11-15]. For example, using polarimetric interferometry, two different polarization states could be used to retrieve the positions of the soil and the upper canopy, and the difference between the two interferograms would yield vegetation height. This has been demonstrated for both forests [5, 10, 11, 15-17] and crops [17, 18].

For distributed targets, the magnitude of the complex correlation coefficient, usually called the coherence, controls the uncertainty with which vertical position can be estimated (assuming Gaussian data, see [19]). This leads naturally to the
idea of maximising the coherence by selecting particular polarization states. These states may also provide significant insight into the dominant scattering mechanisms, as has been demonstrated both for airborne SAR [14-16] and with the indoor European Microwave Scattering Laboratory (EMSL) in an experiment using maize and rice plants [18]. Such interpretations are aided by recent advances in the use of simple models (such as a random [16] or oriented [5] volume model) to infer whether stem-soil interactions contribute significantly to the magnitude and phase of the co-polar correlation coefficient to tomographic data introduced in [6]. In particular, we use the results from analysing a subset of the three-dimensional polarimetric reconstructions by using a two-dimensional synthetic aperture that provides height resolution, the range resolution depends on both range and angle of incidence, but values around 3-4 wavelengths can be regarded as typical at 45° incidence angle.

Due to the geometry of the GB-SAR chamber, the angle of incidence varies with range and also within the resolution cell. Change of incidence angle with range are common for airborne sensors, but negligible for spaceborne sensors. In the case of GB-SAR, the variation over the target region limits the number of samples available for multi-look processing. This is of great importance, since coherence optimization techniques need estimates of the polarimetric coherence and covariance matrices [19, 21, 23]. It is thus desirable to use techniques that are robust in the presence of estimation uncertainties.

The variation of angle of incidence within a single range resolution cell is also a function of range. A diagram depicting this is shown in Fig. 3. In the recorded data, the variation between the angle of incidence at soil level and at the top of the canopy was as high as 10°. This means that, within a range resolution cell, scatterers located at different heights will be imaged with different angles of incidence. In airborne or spaceborne sensors, this variation is negligible, so care must be exercised in interpreting the GB-SAR results in terms of more conventional SAR sensors.

When using an interferometric set-up, each reconstructed image transduces a different band of the scene’s reflectivity spectrum. If the baseline is less than some critical value, $B_c$, the bands for each image will overlap [24, 25]. Wavenumber-shift filtering [26] can be used to ensure that only the overlapping regions of the spectra are present in the final interferograms. For surface scattering, this results in an enhancement of the coherence over unfiltered images [18, 20, 26].

After multi-looking (see Section II-D), height estimation is derived from the phase difference, $\Delta \varphi$, between the two SAR images, taking into account the imaging geometry and radar frequency [24, 25]:

$$h = -\frac{r \tan \theta}{2kB} \Delta \varphi,$$  

(1)
Here $r$ is the slant range, $k$ is the wave number, $B$ the horizontal baseline, and $\theta$ is the angle of incidence at soil level. In this paper, the top of the soil is taken as the reference plane; positive and negative heights indicate height above and below the soil, respectively. For the anechoic chamber, the associated ground phase is well known through calibration. This is quite different from the spaceborne or airborne case, where determining the ground phase in order to correct for topography presents a major problem.

\subsection*{B. The Effect of GB-SAR Geometry on the Resolution Cell}

Some remarks are needed in order to appreciate how the GB-SAR geometry affects the InSAR results presented in this paper. As noted in Section II-A, the angle of incidence changes within the resolution cell. This happens because, for a SAR, the resolution cell is delimited by two wavefronts, centred at the antenna phase centre, whose separation in the range direction is a function of the bandwidth, whereas in the azimuth direction, the cell size is governed by the size of the synthetic aperture. The value recorded by GB-SAR in a given range bin is an integration of the contributions from all scatterers within the volume of the resolution cell. The interferometric phase from this bin is converted into the height of a scattering effective phase centre, which depends on the distribution of backscattered power. In GB-SAR, the change in angle of incidence is controlled by the depth of the target and by the angle of incidence at soil level (it decreases with increasing angle of incidence). A target canopy with depth 0.5 m and a ground angle of incidence of 45°, imaged with antennas located 2.1 m above the soil level (a typical value for GB-SAR), results in a difference in angle of incidence of 11° between the soil and the top of the canopy.

\subsection*{C. Imaging Set-Up}

The canopy described in Sect. IV was imaged at C-band to produce three-dimensional reconstructions, under the imaging geometry shown in Fig. 1. The canopy, whose mean height was 0.58 m, was grown in 0.25 m of soil, and was located on top of a trolley for transport into the GB-SAR chamber. The bottom of the trolley was located 0.55 m above the floor of the chamber. The two-dimensional aperture measured 0.78 (azimuth) by 1.76 (range) m and was situated in a plane 3.20 m above the chamber floor. The vertical distance from the antenna cluster phase centre to the top of the soil was 2.13 m.

The two-dimensional aperture was sampled every 0.02 m. Three-dimensional backscattering reconstructions result from processing the two-dimensional aperture (details of the processing can be found in [27]), while InSAR processing can be carried out by treating any two azimuth scans as an interferometric pair. For InSAR analysis, the azimuth scans furthest from the target region are of greatest use, as the angle of incidence will be larger, resulting in a smaller variation of angle of incidence within the resolution cell.

The data were recorded over a 1.43 GHz bandwidth centred at 5.44 GHz, with an aperture measuring 0.78 m, giving a theoretical range resolution varying between 0.19 m (near range) and 0.13 m (far range), and a theoretical azimuth resolution varying between 0.10 m (near range) and 0.13 m (far range). The complete data were used to produce the three dimensional reconstructions, and two azimuth scans were used for interferometry.

\subsection*{D. Interferometric processing}

Scan-lines 4 and 5 from the dataset described in Section II-C were used (where scan 1 is the scan farthest from the target) because the scans further out showed glitches in the reconstructed images. These two scans subtend a 0.02 m horizontal baseline, providing an unambiguous height range of ±2 m, which is suitable for the wheat canopy. The angle of incidence over the region of interest varied from 33° to 55° for the two scans. The images were wavenumber-shift filtered [20, 26]. Taking the minimum angle of incidence to be 30° resulted in a discarded bandwidth of 67.8 MHz. The data were windowed in both range and azimuth with a raised cosine (or Hanning) window, which broadens the point spread function by a factor of about two.

The relatively small size of the canopy, and the large change in angle of incidence over the target region and within the resolution cell, result in different regions of the image containing very different contributions from the canopy. Three regions can be identified (see Fig. 3):

**Region 1:** The contribution from the soil suffers little or no attenuation, as it does not traverse a full canopy. The angle of incidence at the top of the canopy is around 50°, and around 35° at ground level.

**Region 2:** The signal from the soil traverses the canopy and is thus attenuated. The angle of incidence at the top of the canopy is larger than 55°. At ground level, the angle of incidence goes up to 46°.

**Region 3:** The returned signal only contains attenuated returns from soil level, and no returns from the top of the canopy, as the resolution cell no longer includes this part of the target. This region starts at around 47° incidence angle at ground level.

The images were initially processed to achieve a pixel size of 0.02 by 0.02 m, and were subsequently subsampled by a factor of 8, resulting in the range and azimuth autocorrelation functions dropping to around 0.2-0.3 in the first lag, so that adjacent pixels could be used for multilook processing. Due to the change in look angle between consecutive range bins (around 3° at near range and 1° at far range), multilooking was performed using a rectangular 3 by 13 (range, azimuth) mask, which resulted in an ENL of between 31 and 34 (depending
on the polarization). Note that at the high resolution of the system, there may not be a large number of scatterers per resolution cell, and this number will fluctuate between cells. However, Fig. 2 indicates that, at the macroscale, the canopy can be treated as homogeneous, except near the edges, and the geometry of the resolution cell (Fig. 3) tends to homogenise the distribution of scatterers. Tests also confirmed that the observed statistics of the data were approximately Gaussian. Hence the averaging procedures should yield representative overall behaviour.

For SAR systems, a number of factors affect the coherence: thermal noise, different look directions, temporal changes between acquisitions, and the vertical spread of the scatterers [25]. However, GB-SAR is a high SNR system, so the effect of thermal noise on coherence is negligible. Decorrelation due to spectral mismatch is minimised by wavenumber-shift filtering, as mentioned above. The use of an indoor system means that the canopy hardly changes at all between scans. Hence the only source of decorrelation is volume decorrelation. This allows low coherence to be interpreted as evidence of significant volume scattering, while high coherence indicates that volume scattering has little effect.

The interferometry results are displayed as a function of angle of incidence angle at soil level. The angle of incidence is calculated from the scans used to produce the interferogram; this results in different values from those depicted in Figs. 4 and 5, where the angle of incidence is calculated from the centre point of the 2D array. To reduce contributions from non-canopy regions and inhomogeneous areas near the edges of the canopy, 13 multi-looked azimuth samples are combined at each range position to produce a single mean height in each range bin.

III. POLARIMETRIC COHERENCE SYNTHESIS AND OPTIMISATION

The acquisition of fully polarimetric data in an interferometric set-up allows interferograms to be produced with different polarizations. An arbitrary polarization state can be synthesised for each image using a change of basis transformation [13, 23]. For InSAR processing, it is useful to use a vector expression of the interferometric coherence to demonstrate this. As a function of the polarization states of the two images in the interferometric pair, \( \gamma(u, v) \), the coherence is given by [13]

\[
\gamma(u, v) = \frac{\langle uQv^* \rangle}{\sqrt{\langle uTv^* \rangle \langle uPv^* \rangle}}, \quad (2)
\]

where the angle brackets stand for expected value, \( ^* \) denotes conjugate transpose, \( T \) and \( P \) are the covariance matrices for the two images in the interferometric pair, \( Q \) is the cross-covariance matrix, which contains information about the interferometric phase, and \( u \) and \( v \) are unitary vectors that represent the polarization states of the two images in the interferometric pair [13]. By manipulating (2), the coherence can be written in terms of the orientation \( (\phi) \) and ellipticity \( (\psi) \) angles that define the polarization [18, 28], by defining a polarimetric coherence matrix \( \Gamma(\psi, \phi) \):

\[
\Gamma(\psi, \phi) = \frac{\langle UQU^T \rangle \langle UTU^T \rangle}{\sqrt{\langle UQU^T \rangle \langle UTU^T \rangle}}, \quad (3)
\]

where \( U \) is a transformation matrix (a function of ellipticity and orientation). The definition of the matrix \( U \) is given in [18]. In (3) we have also assumed that the transformation matrix is identical for both images \( U \) in the interferometric pair, which is expected when the polarimetric properties of the target are invariant between acquisitions [18]. The polarimetric coherence matrix describes the interferometric coherence in an arbitrary polarization state. In practice, one is interested in the first two terms along the main diagonal of \( \Gamma(\psi, \phi) \) (the co- and cross-polar terms, respectively).

Eq. (2) can be used as the basis for coherence optimisation, which consists in finding the polarization states \( u \) and \( v \) that maximise the coherence. A derivation of an optimisation algorithm, based on the Lagrange multiplier, is given in [13]. This procedure results in two coupled matrix equations with identical eigenvalues, \( \lambda \):

\[
\begin{align*}
[T^*Q][P^*Q^T]u &= \lambda u \\
[P^*Q^T][T^*Q]v &= \lambda v
\end{align*}
\]

(4)

Solving (4) results in three pairs of eigenvectors, with their associated eigenvalues. The eigenvectors will normally be different for the two images, and the eigenvalues can be shown to be the square of the coherence obtained using associated eigenvectors for projecting the data.

It is possible to constrain the coherence optimisation algorithm to use the same polarization state for both images. This leads to a single matrix equation:

\[
[T + P]^{-1}[Q + Q^T]u = \lambda u \quad (5)
\]

In this case, each eigenvalue is equal to the real part of the complex correlation coefficient associated with the corresponding eigenvector \( u \) (see [20] for example), and the coherence needs to be calculated by inserting the eigenvectors of (5) into (2). Hence the interferometric phase affects the algorithm, leading to potential instabilities if the real part of \( \gamma \) is close to zero. In this particular experiment, due to the location of the phase centres of the soil and canopy, it is not an issue, but may need to be taken into account in other situations.
IV. THE WHEAT CANOPY

In this work, we report on polarimetric and interferometric measurements on a spring wheat (Triticum aestivum, “Chablis” variety) canopy, described in more detail in [6], consisting of wheat hand-sown in containers in March 1999, and grown under normal field conditions. Batches of containers were delivered at different growth stages to the University of Sheffield, where they were assembled to reconstruct a canopy. This was achieved by packing the contents of the containers in a trolley, which acted as a support for the soil and the reconstructed canopy. Any empty spaces were covered with spare soil, so as not to leave any gaps. The canopy size was 1.56x1.74 m (azimuth x range). The soil was Kettering loam (41% sand, 37% silt and 22% clay) with a depth of 0.25 m and rms height of around 0.01 m, while soil moisture was less than 10%.

This paper deals with the wheat canopy shown in Fig. 2, which was imaged on June 18, 1999, when the ears were just emerging. The crop was green, with gravimetric moisture between 71 and 80%. The mean height of the crop was 0.58 m (with a standard deviation of 0.09 m) and the shoot density was 441 shoots m$^{-2}$. The Green Area Index was around 2.9 [6].

V. TOMIC GRAPHIC IMAGING

An analysis of the backscatter from the canopy used in this work has been presented in [6], but here we examine the magnitude and phase of the co-polar correlation coefficient to investigate the nature of the scattering within the canopy. The phase of the co-polar correlation coefficient can be symtomatic of single bounce scattering (phase values close to 0°) or double bounce (phase values close to 180°).

The phase difference needs to be estimated from the data, and its statistical properties are governed by the magnitude of the co-polar correlation coefficient [19]. A magnitude close to unity will be associated with narrow phase distributions, whereas low magnitudes will be associated with broad distributions, in the same way as the interferometric coherence controls InSAR phase spread.

In order to investigate the prevalence of either type of scattering mechanism, the co-polar correlation coefficient was calculated as:

$$\rho = \frac{\langle S_{vv}S_{hh}^* \rangle}{\sqrt{\langle S_{vv}S_{vv} \rangle \langle S_{hh}S_{hh}^* \rangle}}.$$

The expected values shown in Eq. (6) were estimated by averaging pixels in the cross-range direction. The number of pixels averaged varied with position within the canopy, as the resolution cell changes with angle of incidence, but it was always larger than 15. The results are shown in Fig. 4 and 5. In these plots, the horizontal direction is the angle of incidence at soil level, referred to the location of the phase center of the synthetic aperture, and the vertical direction indicates height above the ground. (Note that the incidence angle changes with height for a given range-azimuth position, so that the image is not rectangular.) The colour scale represents the value of the phase or magnitude of the co-polar correlation coefficient obtained from azimuthal averaging. The phase difference is small for small angles of incidence at the front of the canopy (where the scattering will mainly consist of an unattenuated soil contribution), and for large angles of incidence (at flag-leaf level). At soil level, the phase difference increases for angles of incidence exceeding 30°. The magnitude of the correlation is very low, so there is a large spread around this region, and no conclusive evidence for the existence of double scattering can be extracted from these plots. However, the tendency in this region is for the phase difference to be large, suggesting the relative importance of canopy-soil interaction.

VI. INTERFEROMETRY RESULTS

A. InSAR Results Using the V-H Basis.

Coherence and retrieved height (defined in (1)) as a function of angle of incidence for interferograms constructed for the VV, HH and VH polarizations are shown in Fig. 6. For both plots, the VV channel has a distinctly different trend than the HH and VH channels. The VV-VV interferogram shows a marked dependence on angle of incidence. The measured effective height is close to soil level at the front of the canopy; this occurs in an area where there is little canopy attenuation, and the soil return is very strong. As the angle of incidence increases, the ground return suffers larger attenuation due to the coupling between the incident field and stems, while the return from the flag leaves becomes stronger. The combined effect is to raise the effective height, to a maximum of 0.43 m occurring at an incidence angle of around 46°. As incidence angle increases further, the effective height rapidly drops back to soil level. This is because the resolution cell only contains returns from the soil level, and not from the top of the canopy, as illustrated in Figure 3. The coherence is slightly lower than that of the HH-HH and VH-VH interferograms because of the strong attenuation of the VV signal. This lower signal level results in a reduced SNR, and thus lower coherence.

The HH-HH and VH-VH interferograms are similar, giving an effective height around -0.07 m at near range and rising to around 0 m throughout most of the target, with small fluctuations. The HH behaviour suggests that there is very little interaction between the HH signal and the canopy, in line with what is observed in the 3-D reconstructions [6]. Even for large angles of incidence, where there is a significant return from the flag leaf level in the 3-D reconstruction of the HH
channel [6], the retrieved height is still close to the ground, as this increased contribution is dominated by the strong ground return. The scattering also seems to be coming from the soil level for the VH polarization. The origin of this signal is unclear. It could arise from direct soil scattering, but the soil was fairly smooth and would be expected to behave like a Bragg surface, with minimal cross-polar return. The signal could also arise from second order interactions within the canopy, resulting in a total path length similar to that of the direct soil return.

The coherence of the HH-HH and VH-VH interferograms shows little variation with angle of incidence, and is very high, typically above 0.9. The coherence of the VV-VV interferogram is initially slightly lower than that of the other two interferograms, and after $46^\circ$ drops sharply, due to the recorded signal consisting only of very attenuated soil returns (this region is referred to as region 3 in Fig. 3).

### B. Pauli Basis Interferometry

Fully polarimetric data can be used to produce interferograms using other polarization combinations. The Pauli basis (see e.g. [29]) is often considered useful for data analysis, as the polarizations that make up the basis represent idealised odd and even bounce and diffuse scattering mechanisms. The new polarizations are obtained as combinations of the elements of the recorded scattering matrix: $S_{vv} + S_{hh}$ (odd bounce), $S_{vv} - S_{hh}$ (even bounce) and $S_{hh}$ (diffuse scattering).

In terms of a wheat canopy, the odd-bounce contribution would be expected to be made up of the direct returns from the canopy and the soil, while the even-bounce contribution would include some second order interactions, such as stem-ground (located near soil level). The diffuse scattering contribution would characterize crop elements such as leaves and emerging ears and second order canopy interactions (located above the soil level for interactions happening towards the top of the canopy, and below soil level for interactions occurring close to the soil level due to the long path lengths).

The results for the Pauli basis are shown in Fig. 7. The odd and even bounce contributions only make sense for small angles of incidence, where the backscatter recorded by the VV and HH channels is located at similar vertical locations. At larger angles of incidence, the strong attenuation of the vertical polarization results in the scattering centres being located at different heights, so no useful information will be found by using the sum or difference of these two channels, which are essentially imaging different targets. The diffuse scattering results are of course identical to the VH-VH interferogram presented in Sect. VI-A.

### C. Interferometric Polarization Synthesis

The coherence and retrieved height for all polarization states was calculated for a sample at $43.6^\circ$ incidence angle (this is in the middle of the target area where full attenuation effects occur). The results are shown in Fig. 8, plotted as a function of the ellipticity ($\psi$) and orientation ($\phi$) angles of the polarization state. It can be seen that the maximum height is located towards the centre of the co-polar plot, not far from the VV-VV configuration (which is located exactly at the centre). The minimum height is located close to the RR-RR configuration (the top left corner of the plot), whereas the maximum coherence is close to the LL-LL interferogram (i.e., the top right corner). The lowest coherence is found close to the centre of the plot.

The polarimetric variation of coherence and retrieved height suggests that, at around $45^\circ$ incidence angle, an interferogram with approximately VV polarization locates the upper layer of the canopy, while RR-RR (or LL-LL) retrieves the soil layer. The reasons why the circular polarizations are preferred for locating the soil are not clear. The predominantly vertical structure of the canopy means that vertically polarised waves should be much more strongly attenuated than horizontal waves [4, 30]. Hence one might expect HH rather than circular interferograms to be best for locating the soil. A tentative explanation could be that the anisotropic dielectric in the canopy gives rise to slight phase differences between the two scans in the interferometric pair for the linear polarizations, while the circular polarizations are unaffected (an effect akin to Faraday rotation). This clearly needs further investigation.

The above results for an angle of incidence of $43.6^\circ$ are broadly reproduced in the middle range of incidence angles, though with some variation, as summarized in Table 1. This table shows the maximum height for all samples with the same angle of incidence, as well as the associated coherence, ellipticity and orientation angles. The values differ from the retrieved height vs. angle of incidence plots (Figs. 6 and 7), which show mean retrieved height. The table shows that the maximum heights rise from 0.34 to 0.53 m as incidence angle increases from 39° to 46°, with associated coherence values decreasing from 0.9 to 0.72. These maximum heights occur for small values of ellipticity and orientation values around 70°, i.e., for nearly linear polarization states, equivalent to a vertical dipole rotated by about 20°. The retrieved height is located within the flag leaves and emerging ears, and is lower in the canopy than the tips of the flag leaves, from which the mean crop height of 0.58 m is measured.

The maximum coherence is typically found at the top and bottom corners of the polarization space, in the RR-RR ($\psi = -45^\circ$) and LL-LL ($\psi = 45^\circ$) regions. The value of coherence is slightly higher in the LL-LL region, where the
retrieved height is within 0.03 m of the soil level, but the RR-RR results are very similar.

These findings suggest that an estimate of the crop height can be found by using the height difference between the LL-LL interferogram and an interferogram using the polarization state characterised by $\psi = 0^\circ$, $\phi = 70^\circ$. The best crop height estimate would be obtained at around $45^\circ$ incidence, where the second polarization state indicates an important contribution from the top of the canopy, and the estimated height would be within a standard deviation of the mean crop height. The crop height would be underestimated for smaller angles of incidence, due to the weaker contribution from the top of the canopy and the strong soil return. These findings are supported by the tomographic data analysed in [6], where it was apparent that the contribution from the top of the canopy is significant at around $45^\circ$ incidence angle, and that horizontal polarizations have a strong ground return for all angles of incidence.

VII. POLARIMETRIC COHERENCE OPTIMISATION

The results and conclusions about optimal polarizations in Section VI arise from exhaustive searching over a limited portion of the full polarization space. However, more formal methods to locate optimal polarizations are available, as discussed in Section III. Here we evaluate approaches based on unconstrained [13] and constrained [20, 21] coherence optimisation, and compare their results with those of Section VI.

A. Unconstrained Optimisation

The results from unconstrained coherence optimisation in Fig. 9 show that the height retrieved using the polarization state corresponding to the maximum eigenvalue is usually located slightly below ground level, due to the coherence matrices being estimated over a region made up of a mixture of canopy and the front of the trolley (located slightly below the top of the soil). The second eigenvector gives heights rising to around 0.1 m for incidence angles between $38^\circ$ and $44^\circ$, and then drops back to below soil level at larger angles of incidence. The height from the third eigenvector lies close to the soil surface up to an incidence angle of $44^\circ$, then shows an upward trend. At the end of Region 2 (where the angle of incidence is around $45^\circ$), the mean height reaches 0.17m, with an associated standard deviation of 0.12m.

The coherence derived from the maximum eigenvalue is very close to unity and varies little over all angles of incidence, whereas the second eigenvalue, while exceeding 0.9 for all points except that at $49^\circ$, shows a slight variation with angle of incidence. The minimum coherence is very similar to that of the VV-VV interferogram, shown in Fig. 6.

The corresponding polarization states change substantially with azimuth for the same range bin. These uncertainties result in samples at the same range distance being weighted differently, which translates into a large variation in the retrieved height. The first eigenvector has a strong contribution from the HH channel for all angles of incidence, even though its composition changes from sample to sample. At the front of the canopy, there are contributions from the VV and VH channels. As range increases, the contributions from the VV channel diminish, whereas those from the VH channel increase. The second eigenvector is nearly identical to the VH channel, whereas the third is a mixture of a strong VV component and smaller VH contributions. In all three cases, there is a substantial difference in the optimal polarization states for the two images, even though the small baseline (0.02 m) and the almost complete stability of the target imply that these should be identical if they correspond to real physical scattering properties of the target. The fact that different polarizations are found, and that the retrieved polarization states vary greatly within samples at similar incidence angle, is probably due to inadequate estimation of the covariance matrices caused by the small number of independent samples used in the averaging.

The first eigenvector pair yields an effective height close to the soil level, which is obtained either by a very strong contribution from the HH channel at near range, or by a combination of the HH and VH channels at far range. The second pair of eigenvectors are close to the VH channel, so that the height retrieved is similar to that shown in Fig. 6. The third pair of eigenvectors is made up of a significant VV contribution. In all three cases, we found that the two eigenvectors that related to the same eigenvalue were different.

B. Constrained Optimisation

Constrained optimisation is a sub-optimal approach, in that it does not find the maximum possible coherence under independent polarization states for the interferometric pair, but instead uses identical polarization states for both InSAR acquisitions. When the polarimetric properties of the scene do not change between acquisitions, and the estimates of the covariance and cross-covariance matrices are perfect, the results from unconstrained and constrained optimisation would be identical, as the covariance matrices for the two acquisitions and over different samples would be identical [20]. This forces the two eigenvectors associated with each eigenvector in unconstrained optimisation to be identical (hence to obey the constraint used in constrained optimisation).

When estimation errors are present, constrained optimisation should result in more stable retrieved heights. The plots of coherence and height derived from this approach are shown in Fig. 10. The coherence plots are similar to those in Fig. 9,
though with slightly lower values, due to the loss of a degree of freedom in the optimisation procedure [20, 21]. However, the associated height retrievals are more satisfactory, not simply because they produce values nearer the true heights, but because of their far greater stability.

The effective height for the largest coherence value is close to ground level for all angles of incidence, as in the unconstrained optimisation case, but exhibits less height variation over all angles of incidence than the unconstrained case. The heights from the second eigenvalue are again similar to those from unconstrained optimisation, being very close to soil level. In the constrained case, the effective height remains closer to the soil level than in the unconstrained case. Finally, the third eigenvalue yields heights very similar to the VV-VV interferogram. The retrieved maximum height occurs at around 45°, with a value of 0.48 m, closer to the mean crop height than the largest retrieved height from the VV-VV interferogram.

In this situation, where the number of independent samples available to carry out multi-look processing is limited, the retrieved polarization states are more stable than in the unconstrained case, as can be seen by the smaller standard deviation of the azimuth-averaged retrieved heights (see also [20]). In addition, adjacent samples in cross-range have nearly identical retrieved polarization states and effective heights. Hence the constrained procedure is both more robust and conceptually more satisfying, as discussed in Section VIII.

The results described in this Section compare well with those from polarimetric coherence synthesis shown in Section VI. The largest effective height occurs at around 45° with the third solution, where the difference between the first and third solutions is 0.53 ± 0.07 m. This is close to the average crop height of 0.58 ± 0.09 m.

VIII. DISCUSSION

It is important to interpret the results presented in this paper in the light of our theoretical understanding of scattering in wheat canopies. Hence, in this Section, we compare our findings with models of wheat canopies.

The height retrieved from the VV-VV interferogram is consistent with the VV channel being dominated by scattering from the flag leaf layer at the top of the canopy for large angles of incidence. This agrees with analyses using electromagnetic models [3, 4], where it is shown that the VV signal consists of a significant contribution from the flag leaves and a highly attenuated ground return, due to the vertical orientation of the stems. According to these two models, the HH-HH signal mostly consists of a significant ground return and a stem-ground component. These contributions suffer little attenuation in traversing the canopy, as there is little interaction with the stems. The model results of Marliani et al. [2] do not agree with the experimental data presented here. They predict an equivalent height close to the soil for all the single polarization interferograms, whereas we find this is not true for the VV-VV interferogram. This discrepancy arises from the assumption in [2] that the main scattering mechanism in a wheat canopy will be a stem-ground interaction (irrespective of polarization). Both the single polarization tomographic data analysis in [6] and the results in this paper show that this assumption is not justified in the canopy studied.

The interferometric analysis of the location of scattering heights confirms some of the results obtained in [6]:

- The horizontal polarization suffers little attenuation in traversing the canopy, irrespective of angle of incidence.
- The vertical polarization is strongly attenuated. This arises from the alignment of the field with vertical stems. The attenuation increases with angle of incidence, and at larger incidence angles the soil is sufficiently shielded for the VV backscatter to be dominated by the upper portions of the canopy. In this case, the retrieved height occurs in the flag leaf and ear layer, and is slightly below the tip of the flag leaves from which the crop height is derived by ground measurements.
- The cross-polar return presents problems in its interpretation. The retrieved height is close to the soil level, but this is unlikely to be due to direct scatter, as this mechanism is very weak in cross-polarisation. Stem-ground double bounce or second order canopy interactions may be occurring; the former seems more likely as it yields heights near soil level, while the latter would give a smeared height response.

An important aspect of this study concerns the physical meaning of the eigenvectors recovered by coherence optimisation methods. Unconstrained optimisation yields the maximum possible coherence given a pair of polarimetric images, by allowing independent polarization states for the interferometric pair. These polarization states are often discussed in the literature as corresponding to scattering mechanisms describing what actually occurs in the canopy. This raises a conceptual problem, since allowing different polarizations in the two images implies that the physical properties of the canopy have changed between the two acquisitions. For vegetation canopies, there seems little reason to believe this would occur. Constrained optimisation disallows such a change in the canopy, and is likely to be closer to reality. (Nonetheless, one has to treat the physical interpretation of the retrieved eigenvectors carefully. We have shown that in the simple layered system of a wheat canopy, the eigenvectors are broadly consistent with the expected
physical scattering mechanisms, but this may not apply in more complex scattering scenarios). For the dataset described in this paper, it also leads to much more stable eigenvectors and height recovery. Hence on both conceptual and algorithmic grounds, it is the preferred approach.

IX. CONCLUSIONS

The experimental results presented in this paper demonstrate that C-band interferometry is a useful tool for crop height retrieval of mature wheat canopies, provided that fully polarimetric data are available and that these have been gathered at large angles of incidence. If so, the height difference between an interferogram produced using a linear polarization state close to VV and one using a left hand circular polarization state is likely to be close to the crop height. These findings are important in the design of any future C-band satellite sensors intended for agricultural applications.

The data have been examined using different polarimetric and interferometric techniques, including tomographic polarimetry, polarimetric coherence synthesis and both constrained and unconstrained coherence optimisation. We show that these techniques help in understanding the fundamental physical processes that underpin polarimetric interferometry. Constraining the optimisation so that the two images in the interferometric pair share the same polarization state stabilises an otherwise unstable algorithm, and produces physically meaningful polarization states that result in realistic, stable height measurements.

The results presented in this paper also illustrate the usefulness of experimental facilities for target characterization. It would be of great interest to perform similar experiments and exploit the exemplified analysis techniques both to understand the crop scattering throughout the growing season and to study its properties at other frequencies (at X band, in particular, tomographic analysis also suggests a layered structure [6]) and for other crops. Indeed, the results derived here are for a wheat crop at a particular growth stage, and further studies are needed to establish how far they can be generalized.

The role of circular polarizations in estimating the properties of soil underneath a canopy also deserves further experimental and theoretical investigation.

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REFERENCES


José L. Gómez-Dans was born in A Coruña (Galicia), Spain in 1976. He studied Electronic Engineering at the University of Sheffield (UK), where he obtained a MEng in 1998. During this time, he spent a year at the Ruhr-Universität-Bochum (Germany). He received the PhD degree from the University of Sheffield (UK) in Electronic Engineering in 2004. From 2004 to 2005 he was a Research Assistant at the Centre for Polar Observation and Modelling (CPOM), based at the University of Bristol (UK), working on surface topography of ice sheets. He is currently employed by the Empresa Pública de Desarrollo Agrario y Pesquero, S.A. in Sevilla (Spain), where he works on assimilating remote sensing data for agricultural monitoring. His current research interests include the use of remote sensing for the extraction of biophysical and geophysical parameters, applied to agricultural and environmental monitoring.

Shaun Quegan received the B.A. (1970) and M.Sc. (1972) degrees in mathematics from the University of Warwick. His Ph.D., awarded by the University of Sheffield in 1982, was concerned with atmospheric modelling. Between 1982 and 1986 he was a Research Scientist at Marconi Research Centre, and led the Remote Sensing Applications Group from 1984-86. He established the SAR Research Group at the University of Sheffield in 1986, whose success led to his Professorship awarded in 1993. In the same year he helped to inaugurate the Sheffield Centre for Earth Observation Science, of which he remains the Director. In 2001 he became the Director of the UK National Environmental Research Council Centre for Terrestrial Carbon Dynamics (CTCD), which is concerned with assimilating Earth Observation and other data into process models of the land component of the carbon cycle. He is a member of the ESA Earth Science Advisory Committee, and until recently was Chairman of the Terrestrial Carbon Observations (TCO) Panel, which forms part of the Global Terrestrial Observing System initiative. His broad interests in the physics, systems and data analysis aspects of radar remote sensing are now subsumed in the more general aim of exploiting EO technology to meet the needs of the CTCD.
### Table 1: Maximum height as a function of polarization

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<tr>
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<tr>
<td>36</td>
<td>0.067</td>
<td>-19, 90</td>
<td>0.80</td>
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<tr>
<td>38.7</td>
<td>0.341</td>
<td>-17, 79</td>
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<td>0.89</td>
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<td>0.450</td>
<td>0, 71</td>
<td>0.88</td>
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<tr>
<td>45.8</td>
<td>0.526</td>
<td>5, 69</td>
<td>0.72</td>
</tr>
<tr>
<td>47.8</td>
<td>0.125</td>
<td>-22, 98</td>
<td>0.68</td>
</tr>
</tbody>
</table>
Figure 1 Imaging geometry. Canopy dimensions were 1.56 x 1.74 m (azimuth, range), with a mean height of 0.58 m.
Figure 2: Photograph of the imaged wheat canopy inside the GB-SAR chamber.
Figure 3: Diagram showing the angle of incidence variation in a resolution cell along the range direction over the target region.
Figure 4: Magnitude of the co-polar correlation coefficient. The top of the soil was located at 0 m, and the mean canopy height was 0.58 m.
Figure 5: Phase of the co-polar correlation coefficient.
Figure 6: Mean coherence (top), mean retrieved height (middle) and standard deviation of the retrieved height (bottom) using the linear V-H basis. These values have been averaged in cross-range.
Figure 7: Coherence (top) and retrieved height (bottom) using the Pauli basis.
Figure 8: Coherence (colour map) and retrieved height (contour lines) from co-polar polarimetric synthesis.
Figure 9: Mean coherence (top), mean retrieved height (middle) and standard deviation of the retrieved height (bottom) using unconstrained polarimetric coherence optimisation.
Figure 10: Mean coherence (top), mean retrieved height (middle) and standard deviation of the retrieved height (bottom) using constrained coherence optimisation.