Fully Polarimetric High-Resolution 3-D Imaging With Circular SAR at L-Band

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Abstract—This paper presents the first fully polarimetric high-resolution circular synthetic aperture radar (CSAR) images at L-band (1.3 GHz). The circular data were acquired in 2008 by the Experimental SAR (E-SAR) airborne system of the German Aerospace Center (DLR) over the airport of Kaufbeuren, Germany. The obtained images resulting from the coherent integration of the whole circular flight are investigated and discussed in terms of two of the main CSAR properties, namely, the theoretical subwavelength resolution in the horizontal plane $(x,y)$ and the 3-D imaging capabilities. The 3-D imaging capabilities are of special interest due to the penetration of L-band in vegetated areas. These results were compared with images processed by the incoherent addition of the full synthetic aperture. The coherent approach showed a better performance since scatterers are focused at their maximum resolution. Due to the nonlinearity of the tracks and the high-computational burden, an efficient fast factorized back-projection (FFBP) has been developed. Unlike frequency-domain processors, it accommodates azimuthal variances and topography changes. Limits and considerations of the proposed algorithm are described and discussed. To further accelerate this process, the FFBP was also implemented in a graphics processing unit (GPU). Processing performance has been assessed with the direct BP (DBP) as a reference, obtaining speedup factors up to 1800. Residual motion errors have been estimated with a new frequency-based autofocus approach for CSAR configurations based on low signal-to-clutter ratio (SCR) isotropic scatterers. High-resolution images of man-made and distributed scatterers have been analyzed and compared with a stripmap SAR, both concerning anisotropic and isotropic-like scatterers. Results include a single-channel tomogram of a Luneburg lens and a fully polarimetric tomogram of a tree.

Index Terms—Autofocus, circular synthetic aperture radar (CSAR), fast factorized back-projection (FFBP), graphics processing unit (GPU), high-resolution SAR, polarimetry, synthetic aperture radar (SAR), tomography.

I. INTRODUCTION

Due to its intrinsic characteristics, circular synthetic aperture radar (CSAR) has lately become of particular interest to the SAR community. Unlike stripmap SAR mode, CSAR offers significant properties by changing the geometry to a circular flight. On one hand, it has the potential to provide resolution of $\sim (\lambda/4)$ when the information of a single pass is coherently added over the 360°. On the other hand, it has the potential to retrieve the power distribution of the scatterers in the height direction, i.e., tomographic imaging for lower bands, due to the aspect angle diversity inherent to the circular trajectory. Nevertheless, both potentials are linked to the backscattering persistence of the targets for long illumination angles, hence limiting the performance in real-world scenarios, where the targets tend to be anisotropic.

The impulse response function (IRF) of CSAR and its resolutions in the $(x,y,z)$ space, which is based on the isotropic behavior of the scatterers, have already been analyzed in several references [1]–[5]. The CSAR IRF has been compared with confocal imaging with simulated data in [2] and [6]. On the other hand, the 3-D resolution of the anisotropic scatterers as a function of their angular persistence has been discussed before in [6]. It shows that only scatterers having an angular persistence greater than 45° have a resolution in $z$ that is comparable with the system bandwidth.

In addition, CSAR has been an object of study with real data at X-band for 2-D and 3-D reconstructions of man-made (highly directive) targets in [1], [7], and [8], and at very high-frequency (VHF) band, L-band, and P-band for foliage penetration and target detection [9]–[11]. In [1], the SAR focusing has been performed at the highest resolution and at different heights using the direct back-projection (DBP) and a frequency-based focusing algorithm, assuming that the trajectory is a perfect circle (turntable acquisition). Although images were focused at different heights to show the 3-D CSAR capabilities, this paper has been done with interest on man-made targets (i.e., a tank) with angular persistence lower than 90°; therefore, subwavelength resolution has not been proven. In [7]–[12], focusing is based on the anisotropic behavior of the targets under investigation, i.e., vehicles. For this reason, this approach does not focus all targets at their maximum resolution since angular directivity and persistence for most of them is unknown. This paper further extends the investigations of previous work by analyzing the properties at L-band of both man-made and natural targets when processing the whole synthetic aperture. The maximum spatial resolutions, as well as the tomographic potential of vegetated areas, are addressed. In addition, the comparison with the noncoherent addition of the sub-apertures is discussed. In fact, coherent addition and incoherent addition have been compared before with simulated data of man-made targets at X-band and ultrahigh frequency (UHF) in [13].
Concerning the efficient processing of CSAR data, several aspects need to be taken into account. Most traditional algorithms for stripmap or spotlight SAR geometries cannot be used for image synthesis due to their inherent azimuth-invariant assumption. In [1], a computationally efficient frequency-domain processor based on the Fourier analysis of the Green’s function is presented. However, it has many restrictions imposed upon significant factors, such as the necessity of a well-shaped platform trajectory and the assumption of a flat surface. Therefore, this approach becomes invalid in the presence of non-ideal trajectories and topographic variations within the scene. Time-domain processing using the DBP algorithm, unlike Fourier analysis, can precisely accommodate the real track of the platform, thus achieving exact focusing [1]. Nevertheless, it leads to a huge computational burden. Fast BP techniques decrease the computational burden by means of factorizing the synthetic aperture into sub-apertures and using a more convenient geometry, i.e., polar grids, as well as efficient interpolation kernels [14]–[16]. Even so, these algorithms have been mainly used for linear flights. In this paper, we discuss an extension of the multiple-stage fast factorized BP (FFBP) algorithm for circular trajectories.

A further aspect related to the processing of the airborne CSAR data is the accurate estimation of the platform trajectory. The navigation data are usually affected by residual motion errors on the order of 1–5 cm because of the limited accuracy of the navigation system. Due to the larger integrated aperture when compared with stripmap, the requirements in terms of trajectory knowledge are much more demanding. The use of autofocus approaches is established in the literature in order to estimate these residual motion errors; among the most common approaches are the map-drift [17], [18] and the phase gradient autofocus (PGA) [19], [20]. Algorithms such as the PGA can be directly applied to the range-compressed data in order to estimate motion errors. However, one of the main requirements is the presence of point-like scatterers with a sufficient signal-to-clutter ratio (SCR) during the whole synthetic aperture, i.e., range compression must be applied before. These kinds of targets are not easy to find in a CSAR image since they must have an isotropic behavior [7]. Methods based on other metrics, e.g., contrast optimization or entropy [21], [22], are also possible but do not usually achieve the same performance as those based on strong and known targets since a much smaller angular persistence of the backscattering is needed. For these reasons, a frequency-based autofocus algorithm is proposed in this paper, which is based on the analysis of the IRF of a Luneburg lens in order to achieve the highest possible theoretical resolution of $\lambda/4$, hence demonstrating for the first time the maximum possible resolution with CSAR using real airborne data [23].

As aforementioned, CSAR has the potential to retrieve tomographic information. SAR tomography with linear tracks is already a well-established topic that has been discussed before at L-band [24]–[26]. This frequency band offers foliage penetration and, hence, the potential of volume information retrieval. In these references, SAR tomography is achieved by the formation of a synthetic aperture in elevation using repeated stripmap SAR acquisitions. The same idea was exploited in [8] using circular tracks, where eight circular flights at different altitudes were acquired. The processing was applied in small angular sub-apertures, so that the principle to retrieve the third dimension does not differ from the conventional one. This paper shows the first demonstration of CSAR 3-D fully polarimetric imaging with real data at the L-band using a single circular flight, as well as high-resolution imaging in the $(x, y)$ plane close to the theoretical value of $\sqrt{\lambda/4}$. Among others, some of the future applications of this mode could be the estimation of biomass and 3-D profile of forests, the 3-D ice profile, and 3-D mapping of the Earth (e.g., volcanoes and cities) at very high resolution.

This paper is organized as follows. Section II presents theoretical considerations when processing CSAR data. The analytical expression of the CSAR IRF of a target in the center is analyzed. The behavior of the peak-to-sidelobe ratio (PSLR) as a function of the system bandwidth is discussed. Moreover, expressions of resolutions in $(x, y, z)$ directions are given. Section III-A describes an implementation of a robust FFBP algorithm for circular trajectories. The goal of this method is to generate high-resolution images considering the topography, keeping high accuracy in amplitude and phase, while decreasing the computational burden with respect to the DBP. The experimental setup, limitations, and results of this algorithm are studied in terms of the speedup factor and accuracy. The FFBP was also implemented in a graphics processing unit (GPU), in order to further accelerate its processing. Next, Section III-B presents an autofocus approach to estimate residual motion errors of the platform based on the IRF analysis in the frequency domain. The advantage of the proposed approach is that the target does not need to have a large SCR in the range-compressed domain as it is usually required with techniques based on point-like targets. The proposed approaches are validated with simulated and real circular data. Real data were acquired by the E-SAR system of the German Aerospace Center (DLR) in 2008 in a fully polarimetric mode. Section IV shows and discusses experimental results of the campaign. Images focused by the coherent and incoherent integration of the full synthetic aperture are analyzed. The obtained images are also compared with the conventional stripmap mode. Moreover, both potentials, the theoretical sub-wavelength resolution in the horizontal plane $(x, y)$ and the 3-D imaging capabilities with anisotropic- and isotropic-like scatterers of man-made and natural targets, are identified and discussed. Furthermore, the first 3-D circular reconstructions of a Luneburg lens and a tree are shown. Finally, Section V presents the conclusions and provides suggestions for future research work.

II. THEORETICAL CONSIDERATIONS

A. IRF

The following system model is considered to analyze the IRF. This analysis is based on [1]–[5]. The radar platform moves along a circular trajectory over a spotlighted region with coordinates $\hat{R}(\phi) = (R_{xy} \cdot \cos(\phi), R_{xy} \cdot \sin(\phi), R_z)$, where $R_{xy}$ is the radius of the track, and $\phi \in [0, 2\pi]$ is the azimuth angular variation (corresponding to the slow time in stripmap SAR.
mode). The collected data are described in the spatial-frequency domain as

\[ s(\vec{k}, \phi) = P_\omega(\omega) \int f(\vec{r}_{\text{grid}}) \cdot e^{-j2k|\vec{r}_{\text{grid}}-\vec{R}(\phi)|} d\vec{r} \]  
(1)

where \( P_\omega(\omega) \) is the transmitted pulse in the spatial-frequency domain, \( f(\vec{r}_{\text{grid}}) \) is the complex reflectivity of the imaging grid defined by \( \vec{r}_{\text{grid}} = (r_x, r_y, r_z) \), and \( k = |\vec{k}| = (2\pi/\lambda(\omega)) \) is the wavenumber with \( \lambda \) as the range (fast-time) angular frequency.

The components of \( \vec{k} \) in the \((x, y, z)\) directions are

\[ k_x = k_r \cdot \cos (\phi) \]  
(2)
\[ k_y = k_r \cdot \sin (\phi) \]  
(3)
\[ k_z = 2k \cdot \cos (\theta_{el}) \]  
(4)

respectively, where \( \theta_{el} \) is the elevation angle, and

\[ k_r = 2k \cdot \sin (\theta_{el}) = \sqrt{k_x^2 + k_y^2} \]  
(5)

is the ground projection of \( \vec{k} \).

The complex reflectivity of the targets or scene \( f(\vec{p}) \) with coordinates \( \vec{p} = (p_x, p_y, p_z) \) is a 3-D Dirac delta function for simplification. This means that \( f(\vec{r}_{\text{grid}}) = f(\vec{p}) = 1 \) and 0, otherwise. Thus, the unknown \( f(\vec{r}_{\text{grid}}) \) can be defined as

\[ f(\vec{r}_{\text{grid}}) = \int s(\vec{k}, \phi) \cdot e^{-j2k|\vec{r}_{\text{grid}}-\vec{R}(\phi)|} d\vec{k} \]  
(6)

with \( s(\vec{k}, \phi) = e^{-j2k|\vec{p}-\vec{R}(\phi)|} \).

Subsequently, by knowing that the trajectory of the radar follows a circular geometry at a given height \( R_z \), then we have

\[ f(\vec{r}_{\text{grid}}) = \int_{\vec{k}} k \cdot e^{-j2k|\vec{p}-\vec{R}(\phi)|} \cdot e^{j2k|\vec{r}_{\text{grid}}-\vec{R}(\phi)|} d\phi dk \]  
(7)

Considering the Fourier analysis of the free-space Green’s function \( g_\phi = e^{j2k|\vec{r}_{\text{grid}}-\vec{R}(\phi)|} \), \( f(\vec{r}_{\text{grid}}) \) can be represented as

\[ f(\vec{r}_{\text{grid}}) = \int_{\vec{k}} k \cdot e^{-j2k_s(p_z-r_z)} \cdot e^{-jkr}(\vec{p}_s-\vec{R}(\phi)) \cdot e^{jk_r(|\vec{r}_{\text{xy}}-\vec{R}(\phi)|)} d\phi dk. \]  
(8)

If the target is in the center \( \vec{p} = (0, 0, 0) \), then (8) becomes

\[ f(\vec{r}_{\text{grid}}) = \int_{\vec{k}} k \cdot e^{jkr}(p_z-r_z) \cdot e^{-jkr}(\vec{p}_s-\vec{R}(\phi)) \cdot e^{jk_r(|\vec{r}_{\text{xy}}-\vec{R}(\phi)|)} d\phi dk. \]  
(9)

Moreover, by solving the integral with respect to \( \phi \) and knowing that \( k_z = k_r \cdot \cot (\theta_{el}) \), then we have

\[ f(\vec{r}_{\text{grid}}) = 2\pi \int_{k_r} k_r \cdot e^{jkr \cdot \cot (\theta_{el})} \cdot J_0(k_r \cdot r_{xy}) dk_r. \]  
(10)

where \( J_0(\cdot) \) is the Bessel function of the first kind and the zeroth order. If the target is focused at height \( r_z = 0 \), then 2-D IRF is

\[ f(\vec{r}_{\text{grid,xy}}) = 2\pi \int_{k_r} k_r \cdot J_0(k_r \cdot r_{xy}) dk_r \]  
(11)

where the integral of (11) is

\[ f(\vec{r}_{\text{grid,xy}}) = 2\pi \cdot k_r \cdot J_0(k_r \cdot r_{xy}) \]  
(12)

Fig. 1. (a) Simulated IRF of CSAR based on (13) for a target located at \( \vec{p} = (0, 0, 0) \) with an incidence angle of \( 45^\circ \), a wavelength of \( \lambda = 0.24 \text{ m} \), and a bandwidth of \( 100 \text{ MHz} \). Note that the power of the side lobes is at \(-8 \text{ dB}\) for this configuration. (b) PSLR as a function of the bandwidth of the IRF. Note that the power of the side lobes decreases when bandwidth increases.

for \( k_{r2} \approx k_{r1} \), which means narrow bandwidth, and

\[ f(\vec{r}_{\text{grid,xy}}) = \frac{2\pi}{r_{\text{grid,xy}}} \left[ k_{r2} \cdot J_1(k_{r2} \cdot r_{\text{grid,xy}}) - k_{r1} \cdot J_1(k_{r1} \cdot r_{\text{grid,xy}}) \right] \]  
(13)

for \( k_{r2} > k_{r1} \) for wide bandwidth.

B. Resolution

In addition to the PSLR, another metric to measure the system performance is the resolution. The theoretical resolutions \( \Delta x, \Delta y, \) and \( \Delta z \) can be calculated by analyzing the spectrum of the compressed data in the scatterer orientation \( \phi_n \) and its perpendicular axis in the following manner [1] (see Fig. 2):

\[ \Delta x = \frac{\pi}{\sin (\theta_{el}) \cdot (k_{\text{max}} - k_{\text{min}} \cos (\phi_0))} \]  
(14)

with \( \phi_0 \epsilon [0, \pi] \) for an angular persistence of \( [\phi_n - \phi_0, \phi_n + \phi_0] \) with \( \phi_n \) defining the scatterer orientation. In this case,
it is assumed that the target is at \( \phi_0 = 0 \) for simplicity, \( k_{\text{max}} = (2\pi \cdot (f_c + \text{BW}/2)/c_0) \), and \( k_{\text{min}} = (2\pi \cdot (f_c + \nu \cdot \text{BW}/2)/c_0) \), where \( f_c \) is the central frequency, \( \text{BW} \) is the transmitted bandwidth, \( c_0 \) is the speed of the light, and

\[
\nu = \begin{cases} 
-1, & 0 < \phi_0 \leq \pi/2 \\
1, & \pi/2 < \phi_0 \leq \pi.
\end{cases}
\]

The resolution in \( y \) is determined as \[1\]

\[
\Delta y = \frac{\pi}{2 \cdot k_{\text{max}} \cdot \gamma \cdot \sin(\theta_{el})}
\]

where

\[
\gamma = \begin{cases} 
\sin(\phi_0), & 0 < \phi_0 \leq \pi/2 \\
1, & \phi_0 > \pi/2.
\end{cases}
\]

Note that both (14) and (15) depend on the aperture angle \( \phi_0 \). In fact, only scatterers holding an angular persistence \( \phi_0 \) greater than \( \pi/8 \) rad in the plane \((x,y)\) have a resolution in the \( z \) direction comparable with the range resolution \[2\], \[6\], i.e.,

\[
\Delta z = \frac{2}{\sqrt{\pi} \cdot \cos(\theta_{el})} \cdot \frac{c_0}{\text{BW}}.
\]

Moreover, isotropic targets seen over 360° own the maximum resolution in the plane \((x,y)\), resulting in \( \Delta x = \Delta y = (\lambda/(4 \cdot \sin(\theta_{el}))) \) with \( \phi_0 = \pi \) and assuming that the bandwidth of the system can be neglected because \( f_c \gg (\text{BW}/2) \). This resolution would be 0.08485 m for \( \lambda = 0.24 \) m (L-band) and \( \theta_{el} = 45^\circ \) at ~3 dB (see Fig. 1).

### C. Topography Impact

Additionally, if the true height of targets is unknown when forming the SAR images, circular patterns appear due to the sidelobes in the direction perpendicular to the line of sight (LOS). This implies degradation in the image when the topography is not precisely known. However, this fact can be overcome, knowing their diameter \( D \) and considering the elevation angle \( \theta_{el}(\phi) \) at a given azimuth angular moment \( \phi \), i.e.,

\[
\Delta h = \frac{D}{2 \cdot \cot(\theta_{el}(\phi))}
\]

where \( \Delta h \) is the mismatched height \[6\], \[7\], \[27\]. Nevertheless, this occurs for point-like targets with a long angular integration time \( \phi_0 \) and high SCR.

Another approach to estimate the 3-D structure of the observed objects is given in \[28\]. Assuming two scatterers at the same \((x,y)\) coordinate but different heights, when focusing at the height of the first one, the second will be separated a distance \( l \) that can be measured, and from this distance and the elevation angle \( \theta_{el} \), its real altitude can be derived with

\[
h = \frac{l}{\cot(\theta_{el})}.
\]

This approach can be used with directive point-like scatterers, e.g., the different elements forming a vehicle, as shown in \[28\].

### III. EFFICIENT PROCESSING OF CSAR DATA

In this section, an efficient implementation of the FFBP considering the circular geometry of CSAR is described. The proposed method can accommodate non-ideal circular trajectories and topographic information, while reducing considerably the number of operations. In addition, the second part of this
Fig. 4. CSAR geometry in 3-D and 2-D views to perform the FFBP. (a) Three-dimensional view: The FFBP considers the real trajectory of the platform and the topography of the scene, where \( r_{\text{track}} \) is the radius of the circular flight, \( h_{\Theta} \) is the height of the scatterer \( \Theta \), and \( \vec{q}_i \) is the center of the \( i \)th sub-aperture. (b) Top view: The polar coordinate systems are translated to the sub-aperture center \( \vec{q}_i \) and rotated \( \beta \) degrees with respect to the global Cartesian coordinate system. \( \Delta \) is half of the size of the biggest sub-aperture \( L_{\text{max}} \) in meters. (c) Zoom-in image of the top view: considered geometry to perform P2P interpolations, in this case, from a small sub-aperture to a bigger sub-aperture at the \( k \) and \( k-1 \) stages, respectively (see Fig. 5). (d) Transition of two contiguous images through P2P interpolations. The information of both sub-apertures at the processing stage \( k \) are merged to form the image of the sub-aperture at the \( k-1 \) stage (see Fig. 5).

section describes an autofocus approach that uses the phase information of targets with a low SCR in the range-compressed domain by exploiting their response in the frequency domain.

A. FFBP for CSAR

The FFBP algorithm described in [14] speeds up the processing time by dividing the full synthetic aperture of dimension \( L = L_{\text{full}} \) by \( k \) times in a recursive way until \( L_i = L_{\text{min}} \), where \( L_i \) is the number of pulses of each sub-aperture at the \( i \)th stage with \( i = 1, 2, \ldots k \), and \( L_{\text{min}} \) is the minimum sub-aperture size.

In order to use this method with circular trajectories, two main issues have to be considered. First, a linear-like flight track in the cross-range direction can no longer be assumed. Second, the higher spatial resolution in CSAR than in stripmap increases the computational burden of DBP when compared with FFBP.

As depicted in Fig. 3, DBP back-projects each echo to the output Cartesian grids \( \vec{r}_{\text{Stripmap}}(x,r) \) and \( \vec{r}_{\text{CSAR}}(x,y,z) \) for stripmap and CSAR, respectively. \( \vec{r}_{\text{Stripmap}}(x,r) \) has a much coarse resolution than that in the CSAR case. Therefore, since the computational burden of DBP increases exponentially with the number of output samples, whereas FFBP only in a logarithmic fashion, FFBP is more efficient when applied to CSAR data than with stripmap data.

1) Geometry: The geometry of CSAR for FFBP is able to consider a non-ideal circular trajectory illuminating the same spot region over 360° and taking also into account the topographic information of the individual targets, as depicted in Fig. 4(a). Let us define a global Cartesian coordinate system \( \vec{r}_{\text{CSAR}}(x,y,z) \) with origin at \((0,0,0)\) that will be used as reference to obtain the final image. In the CSAR mode, for each sub-aperture, a polar coordinate system \( \Theta(\alpha,r) \), which is tangent to the circumference, is translated to the center of each sub-aperture and rotated \( \beta = \tan^{-1}(x/(-y)) \) degrees with respect to \( \vec{r}_{\text{CSAR}}(x,y,z) \). Consequently, the circumference can be seen as a polygon of \( L_{\text{full}}/L_{\text{max}} \) equal sides, with \( L_{\text{max}} \) as the length of the biggest sub-aperture where the polar grids are defined [see Fig. 4(b)].

2) Methodology: The process is divided into four parts: factorization of the full synthetic aperture, performance of the BP in polar coordinates, and polar-to-polar (P2P) and...
The coherent addition of interpolated images from polar to a global direction is achieved by recursively interpolating every two-by-two contiguous images through a P2P interpolation performed for the smallest sub-apertures. This step is followed by the merging of raw data as the input of the system, which is divided into sub-apertures by the polar BP for every stage. The last step is the coherent addition of interpolated images from polar to a global Cartesian grid (P2C). The number of pixels in angular and range directions is determined by the sub-aperture size.

Fig. 5. Block diagram of the FFBP for CSAR for \( n = 2 \). It starts with the raw data as the input of the system, which is divided into sub-apertures by recursively \( k \) stages until \( L_i = L_{\text{min}} \). Then, the BP in polar coordinates is performed for the smallest sub-apertures. It is followed by the merging of every two-by-two contiguous images through a P2P interpolation \( k \) stages. The last step is the coherent addition of interpolated images from polar to a global Cartesian grid (P2C). \( N \) and \( M \) are the number of pixels in angular and range directions.

P2P interpolations using the new coordinates \( \tilde{\Theta}_{k-1}(\alpha, r) \), in order to get \( N \cdot M \)-sized grids. At this point, it must be mentioned that the law of cosines cannot be used as proposed in [14] as a result of the curved track. \( \tilde{\Theta}_{k-1}(\alpha, r) \) is defined with respect to the tangent of the center \( \bar{q}_{k-1} \) and not with respect to the vector \( \Delta \bar{d}(r, \bar{v}) \) [see Fig. 4(c) and (d)]. Subsequently, using (19), \( \tilde{\Theta}_{k-1}(x, y, z) \) is deduced and can be expressed with respect to \( \Theta_k(\alpha, r) \) using the dot product \( (\vec{A} \cdot \vec{B}) = |AB| \cdot \cos(\alpha) \). This method is shown for one sub-aperture for simplicity, but it has to be implemented for every second sub-aperture in the same way.

The unitary vector respective to the \( k \)th tangent can be expressed as \( \tilde{s}_k(\cos(\beta), \sin(\beta)) \). The second vector can be represented by \( r_k = |\tilde{\Theta}_{k-1} - \tilde{q}_k| \). With these two inputs it is possible to get \( \alpha_{k-1} \) in terms of \( \alpha_k \), i.e.,

\[
\alpha_k = \cos^{-1}\left( \frac{(\tilde{\Theta}_{k-1} - \tilde{q}_k) \cdot \tilde{s}_k}{|\tilde{\Theta}_{k-1} - \tilde{q}_k|} \right).
\]

Thus, having the coordinates \( \tilde{\Theta}_{k-1}(\alpha, r, k) \) to interpolate an image of \( (N/2^{k-1}) \cdot M \). Afterward, the interpolated images have to be integrated coherently to enhance the resolution in the flight direction and proceed with the next stage. P2C interpolations are implemented in the same way as P2P, but instead of using \( \tilde{\Theta}_{k-1}(x, y, z) \), the final grid \( \tilde{\Gamma}_{\text{CSAR}}(x, y, z) \) of \( P \) by \( P \) pixels and regular in Cartesian coordinates is used.

3) Sampling Requirements: The derivation of the sampling rates is done in a similar way, as in [14] and [29]. To meet the Nyquist requirements for the angular axis, the worst case has to be considered. If we denote two consecutive samples of the image in the angular direction and the difference of both distances to the radar as

\[
\Delta r = R(\alpha + \Delta \alpha) - R(\alpha)
\]

then this difference does not have to be higher than the radial requirements. \( \Delta r \leq \pi (|k_{\text{max}} - k_{\text{min}} \cdot \cos(\Delta r/|\text{track}|)) \) with \( r_{\text{track}} \) as the radius of the track and \( \Delta r \) as the size of the arc in meters from the center of the sub-aperture to one of its ends since it is considered the worst case; otherwise, it will cause aliasing. Thus, the angular resolution in terms of \( \cos(\alpha) \) deduced by (21) is defined as

\[
\Delta \cos(\alpha) \leq \Delta r \cdot \left( \frac{R(\alpha)}{r_i \cdot \Delta r} \right)
\]

where \( R(\alpha) = \sqrt{r_i^2 + \Delta \alpha^2} - 2 \cdot r_i \cdot \Delta \alpha \cdot \cos(\alpha_{\text{min}}) \), with \( r_i \) and \( \alpha_{\text{min}} \) being the minimum range and the minimum \( \alpha \) of the polar grid \( \tilde{\Theta}(\alpha, r) \) for every stage. This approximation considers the curvature of the sub-aperture. This means that, at a certain point, the spectrum of the image starts to curve, thus causing an increment in the sampling requirements in both directions. Therefore, it is not worth to keep interpolating polar grids and the step to Cartesian coordinates should be performed at \( L_{\text{max}} \) before \( L_{\text{full}} \) is reached since the total number of pixels in the polar grid \( \tilde{\Theta}(\alpha, r) \) will be on the same order of magnitude as the final Cartesian grid \( \tilde{\Gamma}_{\text{CSAR}}(x, y, z) \). This fact only implies a linear decrease in the computational efficiency...
Fig. 6. Analytical performance of FFBP adapted to circular flights and compared with the DBP. The number of pixels considers different sizes of \( \Gamma_{\text{CSAR}}(x, y, z) \), \( k \) is the number of stages of the FFBP.

because images of large dimensions (in meters) can be processed. The selection of \( L_{\text{max}} \) depends on the configuration of every experiment, i.e., the number of total pulses \( L_{\text{full}} \), on the range (21) and angular (22) resolutions, oversampling factors, and interpolation kernels, so that a numerical evaluation of the number of operations should give the most appropriate value. In the results shown in Section IV, an \( L_{\text{max}} \) value corresponding to an aperture of 45° has been selected as a good compromise.

4) Computational Burden: The estimation of the computational burden in CSAR, unlike stripmap SAR in [14], takes into account the Cartesian output grid of \( P \) by \( P \) at a resolution of \( \Delta L \phi, \Delta \omega \) [see (15)], as well as the interpolations to estimate polar grids [i.e., digital elevation model (DEM)]. The number of operations necessary to focus a CSAR image at full resolution can be defined as

\[
O(\text{DBP}) \approx L_{\text{full}} \cdot P^2
\]

\[
O(\text{FFBP}) \approx O(\text{BP}) + O(\text{P2P}) + O(\text{P2C}) + O(\text{grid})
\]

for the DBP and the FFBP, respectively, where

\[
O(\text{BP}) \approx \frac{L_{\text{max}}}{2^k} \cdot \frac{N}{2^k} \cdot M \cdot 2^k \cdot \frac{L_{\text{full}}}{L_{\text{max}}}
\]

\[
O(\text{P2P}) \approx \left( 2 \cdot \frac{N}{2^{k-1}} \cdot M \cdot 2^k \right) \cdot (k - 1) \cdot \frac{L_{\text{full}}}{L_{\text{max}}}
\]

\[
O(\text{P2C}) \approx P^2 \cdot \frac{L_{\text{full}}}{L_{\text{max}}}
\]

\[
O(\text{grid}) \approx \left( \frac{N}{2^k} \cdot M \cdot 2^k \right) \cdot k \cdot \frac{L_{\text{full}}}{L_{\text{max}}}
\]

\[
N \text{ and } M \text{ as the number of pixels in angular and range directions, and } k = \log_2 \left( \frac{L_{\text{max}}}{L_{\text{min}}} \right). \text{ Simplifying (23) and (24), the speedup factor can be described as}
\]

\[
O(\text{DBP}) \approx \frac{L_{\text{full}} \cdot P^2}{N \cdot M \cdot \left( \frac{L_{\text{max}}}{2^k} \cdot \frac{L_{\text{full}}}{L_{\text{max}}} + P^2 \cdot \frac{L_{\text{full}}}{L_{\text{max}}} \right)}
\]

\[
(29)
\]

Thus, since the denominator is split in two additions, i.e., \( P^2 > (N \cdot M \cdot (\cdot)) \) and \( L_{\text{full}} > (L_{\text{full}}/L_{\text{max}}) \), the performance of the FFBP for CSAR increases much more than using stripmap SAR mode. Nearest neighbor interpolations were considered in this analysis for simplicity.

Fig. 6 shows the distribution of (29) in a logarithmic scale. It considers the ratio \( (P/M) = (\Delta x/\Delta y) \) and \( N = L_{\text{max}} \), with \( \Delta y \) defined for the maximum theoretical resolution [see (15)].

It can be inferred that, as the number of stages increases, a logarithmic curve is formed, showing the improvement of the speedup factor as the matrix size increases. There is a tradeoff for a better speedup factor between the number of stages \( k \) and the size of the matrix \( \Gamma_{\text{CSAR}}(x, y, z) \) of \( P^2 \) pixels since it is not always worthy to increase the size of \( L_{\text{max}} \).

In this subsection, the differences of the FFBP with the FFBP for linear tracks, as well as the performance and limitations of the FFBP, were discussed. To summarize, the following aspects have to be taken into account: 1) The theoretical resolution and the sampling criteria to define the final grid \( \Gamma_{\text{CSAR}}(x, y, z) \) in Cartesian coordinates at the highest resolution makes the speedup factor higher than that in the stripmap SAR case; 2) \( L_{\text{full}} \) and \( L_{\text{max}} \) have to be defined and considered for the processing since P2P interpolations are not performed for the full circle; 3) in order to perform the interpolations of the polar BP, P2P, and P2C, the curvature of the circular track has to be taken into account as described in Section III-A2; and 4) the curvature of the circular track has to be also considered in the definition of the sampling criteria, as defined in Section III-A3. Moreover, as defined in [14], oversampling, interpolator kernels, and the used hardware are key factors for the performance (accuracy and speedup factor) of the FFBP, in this case of the FFBP for CSAR.

B. Frequency-Domain Autofocus

Existing autofocus techniques based on point-like scatterers, such as PGA, assume that the point targets have a sufficient SCR in the range-compressed domain. This is usually the case with stripmap configurations. However, isotropic targets with a sufficient SCR after having been compressed only in the range dimension are not easy to find. For the experimental results shown in Section IV, a Luneburg lens was deployed because of its properties to keep a constant RCS for all 360°. Due to its limited size of about 60 cm of diameter, the power of the range-compressed signal is well below the clutter level. For this reason, the frequency-domain autofocus approach is proposed in the following works with the fully compressed data so that the integration gain due to the azimuth compression increases the SCR.

The frequency-domain autofocus exploits the well-known angle (time)–frequency relation in SAR, namely, that each angle in the space domain is mapped into an angle in the 2-D frequency domain. Hence, it is possible to retrieve the phase error in the IRF from the phase of the 2-D spectrum (see Fig. 2) and then map this phase into the time domain. The residual phase error can be described as a function of the aspect angle \( \phi \) and the elevation angle \( \theta_{el} \) at a given range (fast-time) angular frequency \( \omega \), i.e.,

\[
\psi(\phi, \theta_{el}, \omega) = \rho(\omega) \cdot \frac{\Delta \psi \text{err}}{\cos \left( \frac{\pi}{2} - \theta_{el} \right)}
\]

(30)

given

\[
\phi = \tan^{-1} \left( \frac{y}{x} \right) = \tan^{-1} \left( \frac{k_y}{k_x} \right)
\]

(31)

\[
\rho(\omega) = \frac{4\pi}{\lambda(\omega)} = \sqrt{k_x^2 + k_y^2}
\]

(32)
TABLE I
PARAMETERS FOR CSAR FLIGHTS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>simlated</th>
<th>real</th>
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<td>Pulse Repetition Frequency [Hz]</td>
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<td>Wavelength [m]</td>
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<td>DEM*</td>
</tr>
<tr>
<td>Radar speed [m/s]</td>
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<td>~90</td>
</tr>
<tr>
<td>Polarisation</td>
<td>n/a</td>
<td>fully</td>
</tr>
</tbody>
</table>

*Digital Elevation Model

where it can be seen how the error at a given time instant is mapped onto a certain spectral component \((k_x, k_y)\). In light of that, the autofocus approach can be summarized as follows. First, a high-resolution CSAR image of an isotropic target is focused. Then, its 2-D spectrum is computed after shifting the target to the origin in order to remove undesired phase ramps. Afterward, the LOS phase error is estimated in the frequency domain and mapped (interpolated) to the time domain, as described in the previous equations. Note that, usually, a certain bandwidth is available, so that the information of several bins located at the same angular frequency can be averaged to reduce phase noise. Finally, the error is mapped to Cartesian coordinates in order to correct the navigation data. The approach can be applied iteratively to improve the performance.

IV. EXPERIMENTAL RESULTS

A fully polarimetric CSAR data set was acquired in 2008, consisting of one complete circular-like pass acquired at L-band, as shown in Fig. 7. The main system and processing parameters can be found in Table I. The goal of this campaign was to obtain fully polarimetric high-resolution images of man-made targets (i.e., buildings, light poles, hangars, shelters, and fences) and, in particular, of natural scatterers (i.e., trees, forest, fields, and ground) by foliage penetration, and to investigate tomographic imaging. The data set illuminates a spotlighted region of \(1.5 \text{ km} \times 1.5 \text{ km}\) over the airport region of Kaufbeuren, Germany (see Fig. 8). A Luneburg lens with a radius of 60 cm was located in the illuminated area to analyze its potential reflectivity distribution in height, as simulated in [2] with an isotropic target. The stripmap SAR results shown in this section, for comparison purposes, were acquired with a linear flight using the same sensor at the same altitude.
It is important to remark that the results concerning accuracy and processing time depend directly on the interpolation methods (linear, zero padding and cubic, truncated sinc, or Knab pulse), upsampling factor (in azimuth and range), and the used hardware (CPU and/or GPU) [15]. All data were interpolated as follows: 1-D complex interpolation with 1-D fast Fourier transforms, zero padding (factor of 8), and cubic (four points) at the first stage of the FFBP processing; 2-D complex interpolation for P2P and P2C with a truncated Knab pulse of 21 points because of its adaptability to band-limited signals, the high accuracy that it provides, and its efficiency in terms of computational cost; and 2-D double-precision quadratic polynomial interpolation to compute the grids [30]. An eight-core Intel(R) Xeon(R) CPU of 2.4 GHz with 24-GB random access memory and Linux operating software was used. Parallelization was done using a GPU Tesla C2070 of 1.15 GHz, 2.0 capability, 6-GB global memory, and 448 cores [31], [32].

Real and simulated data were focused with the FFBP using the next parameters:

\[ L_{\text{min}} = 256 = 2^8, \quad L_{\text{max}} = 16384 = 2^{14}, \]
\[ L_{\text{full}} = 131072 = 2^{17}. \]

A. Simulated Data

The DBP was taken as a reference to assess the accuracy and the speed of the FFBP. Fig. 9(a) depicts the comparison between the IRF of CSAR focused with DBP (black solid lines) and FFBP (red dotted lines), and Fig. 9(b) depicts its 2-D IRF. The parameters used to simulate these data are listed in Table I. Moreover, the focused IRF has a resolution of \( \approx 0.084 \) m and a PSLR on the order of \( -8 \) dB, which is in accordance with the theoretical investigations shown in Section II-A.

Although the circular flight was nonideal, the FFBP achieved the expected performance both in terms of resolution and PSLR.

B. Fully Polarimetric High-Resolution Imaging

Every polarimetric channel (HH, VV, and HV) of the real data acquired with the E-SAR System was focused with the FFBP and used a DEM. Coherent and incoherent (sub-apertures every \( 10^\circ \)) addition of the full synthetic aperture was performed in the shown results.

1) FFBP Assessment: The whole circular aperture was taken as input, but only an output region of size \( P \) by \( P \) pixels was processed at the maximum resolution, with \( P = 400, 800, 1200, 1600, 2000, 4000, 6000, 12000, \) and \( 25000 \). Fig. 10 shows the computational performance of the FFBP compared with the direct DBP in a logarithmic scale. It is noticeable that the speedup factor of the circular FFBP (CPU) improves as the output matrix size increases, obtaining up to \( \approx 500 \) times faster than the DBP. Additionally, this algorithm and the DBP were parallelized on the GPU, remaining the same theoretical speedup factor BP/FFBP but further accelerating the process and considering also the constraint of the 6-GB global memory. The computational time of the FFBP (GPU) was improved up to \( \approx 1800 \) times, whereas the DBP (GPU) improved only \( \approx 100 \) times. The performance of the GPU was limited by its available RAM and by the data throughput because images with a large number of pixels have to be divided and processed into smaller blocks. Moreover, the enhancement of the speedup factor is noticeable mainly in the BP using polar coordinates and the 2-D interpolation phases, which are the main bottlenecks of the FFBP. The coherence between the focused images with the FFBP and the DBP indicated a good focusing quality with a mean coherence of 0.99991, a standard deviation of the coherence of 0.0004521, and a phase standard deviation of 4.7°.

Given the maximum \( P \) value, the processing times for each polarimetric channel (HH–VV–HV) with the FFBP on CPU...
and GPU were \(\sim 11.2 \) h (\(\sim 0.5 \) days) and \(\sim 3.1 \) h (\(\sim 0.1 \) days), respectively, whereas the direct BP on CPU and GPU would have been \(\sim 5734 \) h (\(\sim 238 \) days) and \(\sim 63 \) h (\(\sim 3 \) days), respectively.

2) Real Data Assessment: Fig. 11(a) shows a fully-polarimetric high-resolution image in the Pauli basis. It covers an area of 1500 m \(\times\) 1500 m, which is the maximum size of the spotlighted region in this campaign. Its sampling criteria is 0.06 m by 0.06 m (25,000 \(\times\) 25,000 pixels) in order to accommodate the theoretical resolution of \(\Delta x = \Delta y = 0.084 \) m when performing coherent integration of the full synthetic aperture [see (15)]. Due to the integrated reflectivity of the full circular aperture, targets are focused at their maximum resolution. The multiple-aspect measurements provide a better physical interpretation of the objects when compared with stripmap SAR. This is the result of the anisotropic behavior; indeed, the anisotropic behavior of scatterers has already been a topic of research also for stripmap and smaller synthetic apertures [33]. In this paper, we assume that the strongest signatures will persist. The basic scattering mechanisms can be clearly observed: double bounces (red), such as fences and walls of buildings; single bounces (blue), such as the ground; and volume or distributed scatterers (green), particularly trees, forests, and bushes. Since a DEM was used for this image, targets that are not located at the height given by this DEM are not correctly focused.

Fig. 11(b) was processed by adding incoherently sub-apertures every 10°. Most of the scatterers are not focused at their maximum resolution; therefore Fig. 11(a) shows an enhancement in their polarimetric signatures. The images in Fig. 12 illustrate smaller regions around the middle of Fig. 11. In the first two rows, it is possible to see that some objects are lost in the resulting incoherent images, whereas in the left column, they are kept, and the SCR of the objects improves. Although the ground in the third row looks similar, the signature of the figure processed coherently is sharper. Finally, the last row shows a building, where the improvement is evident for the coherent case since building signatures such as walls, roofs, and fences can be better observed.

On the other hand, Fig. 13 shows a comparison between CSAR and stripmap SAR modes. All stripmap SAR images shown in this paper have an integration interval of 10°. The region was selected around the middle of Fig. 11 to discuss and analyze the main differences and advantages of using a circular trajectory when focusing isotropic-like targets coherently. First, due to the very high spatial resolution, the so-called speckle noise is considerably mitigated or even absent since there are much less elemental scatterers within the resolution cell [34], [35]. Note in any case that speckle is also reduced through the incoherent addition of the sub-apertures since it can be seen as doing multilooking (see Fig. 12). In fact, speckle has been a real challenge for scientists working with polarimetric SAR and polarimetric SAR interferometry (PolInSAR) because it leads to bias in statistical analysis [36], [37]. However, the statistical analysis of this kind of images will be subjected to future research activities. Second, unlike stripmap SAR, a few objects with a size smaller than the wavelength (\(\lambda = 0.24 \) m) and an isotropic behavior can be clearly seen. For example, the lights along the runway indicated with red circles with a size of only 0.16 m \(\times\) 0.2 m can be clearly seen [see Fig. 13(c)]. In fact, due to the vertical orientation of these lights, HH polarization receives more power than VV. Furthermore, the improvement in the resolution of the ground can be explained by what could be an almost isotropic-like behavior. This proves its isotropic-like behavior. Finally, due to the multian-gular diversity, many more features and details of anisotropic
Fig. 13. Comparison between (a) CSAR and (b) stripmap SAR modes using the same E-SAR system of DLR at L-band, with an image size of 500 m × 500 m image size. (a) Sampling of 0.06 m × 0.06 m. Red circles indicate focused lights with a size of 0.16 m by 0.2 m and smaller than $\lambda$. Note that a much larger amount of information is available with the CSAR image compared with that of stripmap SAR image. (b) Sampling of 1 m × 1.8 m. The red arrow indicates the direction of the radar illumination for stripmap. (c) Runway lights seen in (a).

Fig. 14. Comparison between stripmap SAR (a) (1 m × 1.8 m sampling) and CSAR (b) (0.06 m × 0.06 m sampling) imaging modes using the same E-SAR system of DLR at L-band and their optical representation with an image size of 160 m × 160 m. First row: Hangar with a gable roof. Second row: Hangar with an arched roof. Third row: Shelter covered with bushes. Fourth row: Trees and man-made targets. (c) Optics.
Fig. 15. Phenomenon of layover for 3-D reconstruction of man-made targets (building). (a) Ray Tracing. Red: double bounces. Blue: single bounces. (b) Optical image. (c) Two-dimensional amplitude image in the Pauli basis (blue: H+V; red: H−V; green: 2 HV), with image size of 140 m × 140 m and sampling of 0.06 m × 0.06 m.

Fig. 16. Experimental results of the proposed autofocusing approach in frequency domain using the IRF of an isotropic target: Luneburg lens. The results indicate high accuracy for the estimation of residual motion errors, thus having the potential to achieve theoretical resolutions. The image size corresponds to 2 m × 2 m. (a) Two-dimensional IRF phase spectrum before autofocusing. (b) Two-dimensional IRF phase spectrum before autofocusing. (c) Two-dimensional IRF amplitude after autofocusing. In addition to motion errors, constant errors (due to possible mismatch in the lever arm) are also corrected. (d) Normalized amplitude of the one-dimensional IRF, note that the PSLR is around −8 dB, and the resolution is 0.085 m.

Fig. 17. (a) First experimental results of the 3-D IRF of an isotropic target: Luneburg lens. (b) Two-dimensional IRF at 4 m wrong height. (note the ring-shaped sidelobes). (c) (x,z) slice, in this plane, the correct height of the Luneburg lens can be determined with a resolution similar to the bandwidth of the system Δz = 1.6 m at −3 dB, as defined in (16) and shown in (d). Cone-shaped sidelobes can be seen. (d) Height profile of the IRF along the z direction.

structures can be identified, e.g., in the runway or objects on the ground.

Fig. 14 shows a close-up image of the small regions of Fig. 11(a), including again the comparison with stripmap, as well as an optical image to be used as reference. First, man-made structures such as buildings, hangars, shelters, and fences (highly directive), cannot be well identified by the stripmap SAR images. This kind of targets has a high directivity and can be only recognized under certain aspect angles. The coherent processing of the full circular aperture allows a better distinction of the real shape of these targets and their polarimetric signatures [13]. Moreover, in the last row of this set, a group of trees is shown. Tree trunks are identified as double-bounces and isotropic-like targets, having a similar response as the light poles at the lower left corner. Since a DEM was used, canopies owning a volumetric response are slightly defocused. Although their response is similar to isotropic-like scatterers due to the ring-shaped sidelobes or circles of confusion, they have an anisotropic-like behavior, as seen in the following. A fence in V-form surrounding the building is seen as double bounces in the middle of the trees, showing a clear foliage penetration, as expected at L-band.

C. CSAR Tomography

An estimation of the 3-D reconstruction of man-made targets can be performed by means of layover in 2-D images, as shown in [28]. This phenomenon is shown in Fig. 15 with a building
close to the center of the scene. The image has been focused at the highest resolution using a DEM. Upper corners of the building are seen as single bounces (blue) in layover and walls as double bounces (red). Measuring the distance between these two mechanisms, and knowing the elevation angle to the edge at the roof of the building, an estimation of the height and the 3-D shape can be performed.

On the other hand, 3-D CSAR capabilities have been compared with confocal imaging in [2]. Using a single circular acquisition, 3-D imaging can be performed because the collected data are the 2-D mapping of the 3-D scene from all over 360°, and it contains information of the targets as a whole, similar to holographic data collection techniques [38]. However, low resolution in the direction perpendicular to the LOS results in cone-shaped sidelobes when a single circular track is used.

During this campaign, a Luneburg lens was placed in the spotlighted area. It was focused in a 3-D cube, aiming the achievement of the highest resolution in the plane \((x, y)\), as well as the energy retrieval in the vertical direction with real data. Since it was desired to integrate coherently the energy of the full circular track and knowing that the accuracy of the differential GPS (used in this campaign) is around \(\pm 0.1\) m in \((x, y, z)\), the autofocus method described in Section III-B was used. The available lens had a diameter in 0.6 m, resulting in some limitations. First, since it was small for L-band, it had a low SCR, and for this reason, the frequency-domain autofocus explained in Section III-B was used. Second, having only one lens, knowing by definition that the solution of the system is range dependent, and considering that its phase center changes as a function of the elevation angle, the correction cannot be applied to the whole image [23]. Nevertheless, it was used to analyze the response of an ideal isotropic target with real data, as shown in the following. Results using this method are depicted as 2-D images before and after motion corrections in Fig. 16. Inaccuracies in the navigation data defocus the IRF at high frequencies, whereas errors in the lever arm (also estimated) are reflected as constant shifts in \(x\) and \(y\) directions. These errors are depicted as fringes in the 2-D phase spectrum shown in Fig. 16(a). The measured resolution in the \((x, y)\) plane after the second iteration of the process was about 0.085 m similar to the expected theoretical one, and the PSLR was \(-8\) dB, as described in the theoretical IRF (see Section II-A). The volumetric reconstruction of the Luneburg lens showing the 3-D IRF of the CSAR mode is depicted in Fig. 17. Cone-shaped sidelobes in the image are caused by the low resolution in the plane perpendicular to the LOS. The 2-D image in the \((x, z)\) plane and the 1-D profile show the impulse response in elevation, where again the expected resolution of 1.6 m is achieved.

Similar as with the Luneburg lens, a cube with dimensions of 20 m by 20 m by 15 m in \((x, y, z)\) around a tree was processed, as shown in Fig. 18. Two-dimensional polarimetric slices in the \((x, y)\) plane of the tomogram were focused by the coherent integration of the full synthetic aperture [see Fig. 18(c)].

![Fig. 18. First 3-D reconstruction of a tree using a single circular pass at L-band, Pauli basis (blue: H+V, red: H−V, green: 2HV), with an image size of 20 m × 20 m and sampling of 0.06 m × 0.06 m. (a) Ray Tracing. Red: double bounces. Black: volume. (b) Optical image. (c) Slices of the tomogram. (d) Height profile, coherent, 5 × 5 × 1 multilook. (e) Height profile, incoherent addition with 36 sub-apertures of 10°.](Image)

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.
Fig. 19. Comparison of 2-D \((x,y)\) slices of a fully polarimetric CSAR tomogram in the Pauli basis (blue: H+V; red: H−V; green: 2HV) of a tree by coherent and incoherent (sub-apertures of \(10^\circ\)) additions of the circular aperture, with an image size of 20 m \(\times\) 20 m. (a) Incoherent, sampling of 0.5 m \(\times\) 0.5. (b)–(d) Sampling of 0.06 m \(\times\) 0.06 m. (b) Coherent, no multilook. (c) Coherent, 3 \(\times\) 3 multilook. (d) Coherent, 11 \(\times\) 11 multilook. First row to fourth row: \(z_1 = 757.5\), \(z_2 = 762\), \(z_3 = 766.6\), and \(z_4 = 771.1\) m. Note that the tree canopy shows an anisotropic behavior; nevertheless, if it is added coherently during the full synthetic aperture, it is focused with much higher resolution. The red line crossing the image results from the double bounce of a metal grid fence.

Fig. 20. Fully polarimetric CSAR tomography in the Pauli basis (blue: H+V; red: H−V; green: 2HV) using a single pass, with an image size of 400 m \(\times\) 400 m and sampling of 0.06 m \(\times\) 0.06 m, and using as a reference (a) and with different height offsets (b)–(d). (a) DEM + 0 m. (b) DEM + 2 m. (c) DEM + 3 m. (d) DEM + 4 m. Upper row: man-made targets such as metal grid fences, a Luneburg lens or runway lights, and natural targets such as ground and a part of forest. Lower row: man-made targets such as buildings, light-poles and metal grid fences, and distributed targets such as trees.
Moreover, the same region was also processed incoherently, resulting in a smoother 3-D profile with worse SCR and resolution [see Fig. 18(e)]. Fig. 19 shows 2-D slices of the tree focused in Fig. 18 focused coherent and incoherently. Although the signature of tree canopies at the wrong height depicts arc sidelobes, phase centers change randomly even with a very small movement in the angular direction (e.g., aperture smaller than stripmap SAR); again, this shows its anisotropic behavior. However, the coherent addition of this energy results in both the possibility of every scatterer to reach its maximum resolution and to suppress the 3-D signature of a light pole. Despite being composed of anisotropic scatterers, tree canopies focused at the wrong height depict a signature similar to an isotropic-like target with circles of confusion since they are physically concentrated around the same \((x, y)\) coordinates but are shifted into different directions when focused at the wrong height. The results show that, if trees are added coherently, then their 3-D signature improves.

Finally, the paper has included the first demonstration of CSAR tomography of an isotropic target, i.e., the Luneburg lens, using a single circular pass with an airborne sensor. Furthermore, the first demonstration of a one-pass CSAR tomoscan over a tree has been shown, obtaining as a result its polarimetric backscattering profile. Consequently, the 3-D imaging demonstration of semitransparent media with one single circular pass has been proven, hence opening new possibilities for the monitoring of vegetated areas in the biosphere research. These tomograms can further help to reduce uncertainties, particularly the assumption of axisymmetry in tree structures. The exploitation of this information is currently being further investigated.

A problem still to be solved is the reduction of high sidelobes appearing in the IRF, which turn into cone-shaped artifacts when performing the tomographic reconstruction. This might be overcome by estimating the true height of point-like targets with interferometric techniques (multiple-pass CSAR) or reducing sidelobes in 2-D and 3-D with nonlinear approaches [41].


Marc Rodriguez-Cassola was born in Barcelona, Spain, in 1977. He received the Engineer's degree in telecommunication engineering from the Public University of Navarra, Pamplona, Spain, in 2000 and the Ph.D. degree in electrical engineering from the Karlsruhe Institute of Technology, Karlsruhe, Germany, in 2012. From 2000 to 2010, he was with OrbiSat, working on the development of calibration algorithms for airborne SAR interferometry. Her research interests include signal and image processing, SAR interferometry, and high-resolution generation of digital elevation models.

Rolf Scheiber received the Diploma in electrical engineering from the Technical University of Munich, Munich, Germany, in 1994 and the Ph.D. degree in electrical engineering from the University of Karlsruhe, Karlsruhe, Germany, in 2003, with a thesis on airborne SAR interferometry. Since 1994, he has been with the Microwaves and Radar Institute, German Aerospace Center (DLR), where he developed the operational high-precision interferometric SAR processor for its experimental SAR airborne sensor. Since 2001, he has been the Head of the SAR Signal Processing Group with the Department of SAR Technology, Microwaves and Radar Institute, DLR. His research interests include algorithm development for high-resolution airborne and spaceborne SAR focusing, SAR interferometry, differential SAR interferometry, and SAR tomography, as well as radio sounding algorithms and applications. Dr. Scheiber was a corecipient of the Geoscience and Remote Sensing Society Transactions Prize Paper Award in 1996 for the contribution Extended Chirp Scaling Algorithm for Air and Spaceborne SAR Data Processing in Stripmap and ScanSAR Imaging Modes.

Andreas Reigber (M’02–SM’10) was born in Munich, Germany, in 1970. He received the Diploma in physics from the University of Konstanz, Konstanz, Germany, in 1997; the Ph.D. degree from the University of Stuttgart, Stuttgart, Germany, in 2001; and the Habilitation from the Berlin University of Technology, Berlin, Germany, in 2008.

From 1996 to 2000, he was with the Microwave and Radar Institute, German Aerospace Center (DLR), Wessling, Germany, working in the field of polarimetric SAR processing. In 2001, he joined the DLR airborne SAR system has been upgraded to operate in innovative Stripmap and ScanSAR imaging modes. He is a Member of the Radar and Antenna Group within the Department of Synthetic-Aperture-Radar Technology, German Aerospace Center (DLR), Wessling, Germany. Under his leadership, the DLR airborne SAR system has been upgraded to operate in innovative imaging modes such as polarimetric SAR interferometry and polarimetric SAR tomography. Since 2001, he has been the Director of the Microwaves and Radar Institute, DLR. The Institute contributes to several scientific programs and space projects for actual and future airborne and spaceborne SAR missions such as TerraSAR-X, TanDEM-X, SAR-Lupe, Sentinel-1, BIOMASS, and Tandem-L. The mission TanDEM-X, which is led by his institute, has successfully started the operational phase in December 2010. He is the Initiator and Principal Investigator for this mission. Since 2003, he has been a Full Professor with the Karlsruhe Institute of Technology, Germany, in the field of microwave remote sensing. He is the author of 330 papers in international conferences and journals, six book chapter contributions. He is the holder of 15 patents in the radar and antenna fields. His research interests include radar end-to-end system design and analysis, innovative microwave techniques and system concepts, signal processing, and remote sensing applications. Dr. Moreira is a member of the IEEE Geoscience and Remote Sensing Society (GRSS) Administrative Committee (1999–2001, 2004–2013, 2010 as President, and 2011–2013 as Past President). He was the Founder and Chair of the GRSS German Chapter (2003–2008). He was an Associate Editor for the IEEE GEOSCIENCE AND REMOTE SENSING LETTERS (2003–2007) and for the IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING (2005–2013). He and his colleagues received the GRSS Transactions Prize Paper Awards in 1997, 2001, and 2007 and the IEEE W.R.G. Baker Award in 2012. He was also the recipient of the DLR Science Award in 1996 for the contribution Extended Chirp Scaling Algorithm for Air and Spaceborne SAR Data Processing in Stripmap and ScanSAR Imaging Modes.