Transpolarizing Trihedral Corner Reflector Characterization Using a GB-SAR System

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***Abstract*—The use of a low-profile, lightweight, and easy-to-fabricate transpolarizing surface placed on one side of a trihedral corner reflector (TCR) as a polarimetric calibrator is presented in this letter. The transpolarizing TCR presents a high backscattered cross-polar response contrary to standard TCRs. The performance of this device has been tested at the X-band using the Universitat Politecnica de Catalunya ground-based synthetic aperture radar.**

***Index Terms*—Polarimetric synthetic aperture radar (PolSAR) calibration, trihedral corner reflector (TCR), transpolarization, twist reflector.**

I. Introduction

POLARIMETRIC synthetic aperture radar (PolSAR) systems have caught the interest of the research community since they are able to provide much more information than conventional single polarization systems. This interest will gradually increase since several spaceborne PolSAR missions have been launched in the recent years: ALOS-PALSAR, RADARSAT-2, and TerraSAR-X. Thus, reliable polarimetric calibration procedures and techniques are mandatory.

PolSAR calibration is commonly performed by using dihedral corner reflectors tilted 45°, although they have a narrow beamwidth response in elevation. Trihedral corner reflectors (TCRs) are well-known SAR data calibrators, as they provide a high backscattering RCS response for a wide range of incident angles. Nevertheless, the TCRs lack a cross-polar response, making them limited for full polarimetric calibration, as stated from the scattering matrix of a TCR

$$\boldsymbol{S}_{\mathrm{TCR}} = \begin{bmatrix} S_{\mathrm{HH}} & S_{\mathrm{HV}} \\ S_{\mathrm{VH}} & S_{\mathrm{VV}} \end{bmatrix} = A \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{1}$$

where $A = S_0 e^{j\phi_0}$ is a constant and H and V stand for horizontal and vertical polarizations, respectively. Therefore, a TCR providing a cross-polar response, i.e., a transpolarizing TCR (TTCR), would be characterized by a scattering matrix (2) with antidiagonal nonzero values

$$\boldsymbol{S}_{\mathrm{TTCR}} = \begin{bmatrix} S_{\mathrm{HH}} & S_{\mathrm{HV}} \\ S_{\mathrm{VH}} & S_{\mathrm{VV}} \end{bmatrix} = A \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}. \tag{2}$$

Different solutions appeared in the 90s to realize such TTCRs, taking advantage of transpolarizing surfaces composed of grids, fins, or corrugations [1]–[4]. TTCRs are passive devices, but they are frequency dependent due to the design of the periodic inclusions. Moreover, a TTCR could even have non-cross-polarizing applications, like a gridded TCR used as a polarization selective calibrator in order to produce scattering matrices with only horizontal (S_{HH}) or vertical (S_{VV}) channels by properly choosing the azimuth angle of incidence [5]. The transpolarizing surfaces, also referred to as twist or depolarizing reflectors, are well-known polarization conversion surfaces [6]–[8], and they are characterized by a 90° rotation in reflection of the incident electric field polarization. They are also applied as transreflectors to reduce the secondary reflector blockage in Cassegrain antenna designs [9]–[11]. Such transpolarizing surfaces are placed on the bottom side of the TCR, with the fins or corrugations aligned at 45° with respect to the incident electric field polarization, thus producing a TCR with a cross-polarization response. All these TTCR designs present some fabrication issues, like the accuracy of the grid array above the absorbing material or the heavy and bulky piece of metal required to produce the $\lambda/4$ corrugations. A low-profile and lightweight transpolarizing surface composed of a periodic arrangement of metallic square patches with diagonal slots over a metal ground plane was presented in [12]. The advantages of this transpolarizing surface applied as a PolSAR calibrator were discussed in [13].

In this letter, the performance of a TTCR realized with the proposed transpolarizing surface is experimentally assessed for PolSAR calibration purposes. A measurement campaign has been carried out at the Campus Nord of the Universitat Politècnica de Catalunya (UPC) (Barcelona, Spain) using a ground-based SAR (GB-SAR) system, the so-called UPC X-band GB-SAR [14], [15].

II. Transpolarizing Surface Design

A transpolarizing surface has been designed and fabricated to operate around 9.65 GHz (X-band), according to the design

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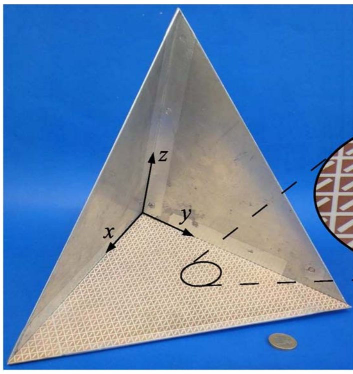

Fig. 1. Fabricated TTCR, with a detail of the transpolarizing surface placed on the bottom side of the TCR.

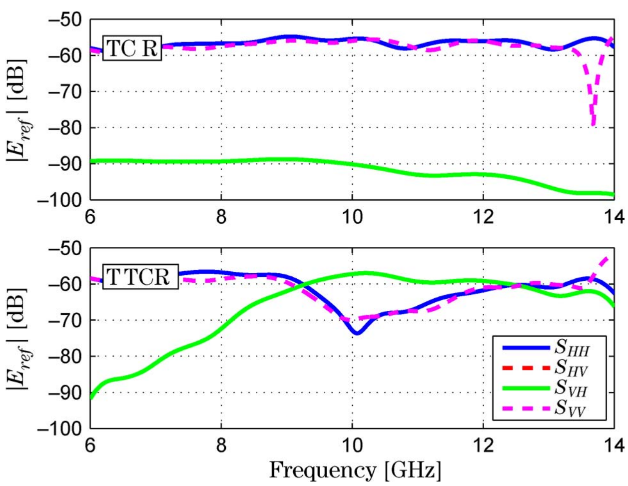

Fig. 2. Measured reflection response of the TCR and TTCR in the anechoic chamber for $\tau = 0°$.

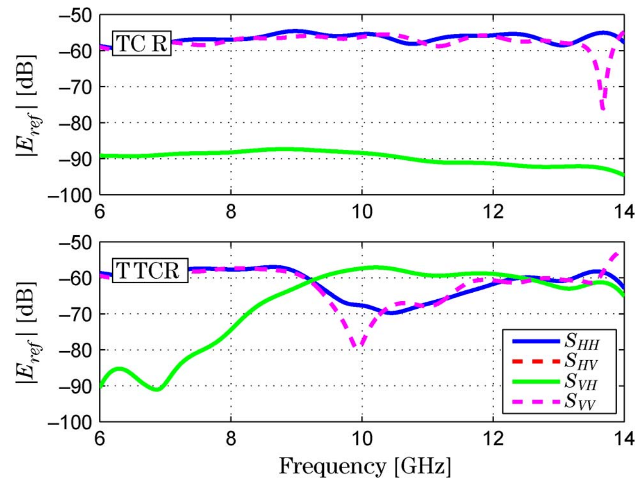

Fig. 3. Measured reflection response of the TCR and TTCR in the anechoic chamber for $\tau = 90°$.

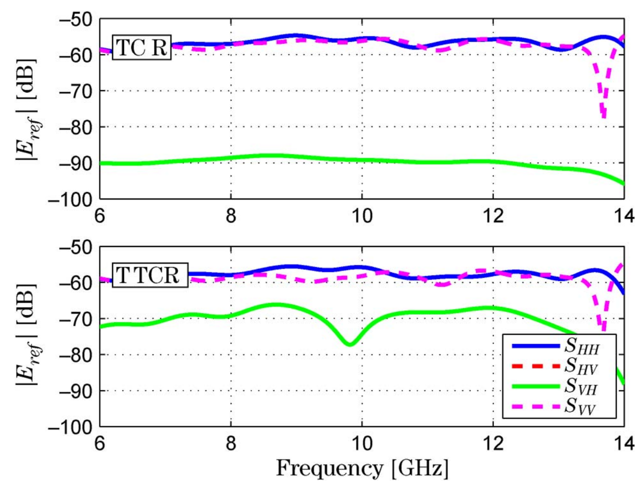

Fig. 4. Measured reflection response of the TCR and TTCR in the anechoic chamber for $\tau = 45°$.

guidelines presented in [16]. The transpolarizing surface is basically composed of square patches with inner diagonal slots etched on a grounded dielectric substrate. The square patches have a width of 4.8 mm, with a gap of 1 mm between adjacent patches. The overall size of the unit cell is then 5.8 mm, which corresponds to $\lambda/5.4$. The diagonal slot has a length of 4.8 mm and a width of 1.4 mm. The prototype has been fabricated using standard photoetching techniques applied on a 1.52-mm-thick Rogers RO4003C ($\varepsilon_r = 3.38$ and $\tan\delta = 0.0027$) dielectric substrate. The overall thickness of the transpolarizing surface is 1.52 mm, i.e., $\lambda/20$, which is much smaller than the $\lambda/4$ thickness required for the fabrication of the corrugations [4]. The fabricated triangular-shaped transpolarizing surface is then placed on the bottom side of a TCR forming a TTCR, as shown in Fig. 1.

The standard TCR and the TTCR have been measured in the UPC anechoic chamber using two broadband ridged horn antennas placed in a bistatic configuration. The TCR is oriented at boresight, with a roll angle τ of 0°, an azimuth angle ϕ of 45°, and an elevation angle θ of 54.74° [4] for which the maximum response of a TCR/TTCR is expected, as also confirmed in [17] and [18] using different numerical methods. Measured copolar ($S_{\rm HH}$ and $S_{\rm VV}$) and cross-polar ($S_{\rm HV}$ and $S_{\rm VH}$) responses are shown in Fig. 2. Note that the cross-polar channels are equal ($S_{\rm HV} = S_{\rm VH}$) for reciprocity of the measuring antenna system. The measured results show that the standard TCR presents a broadband response with a copolar-to-cross-polar ratio of about 30 dB. On the other hand, the TTCR produces a high cross-polar response around 10 GHz with a cross-polar ratio of more than 14 dB, whereas the cross-polar ratio around 9.65 GHz is about 8 dB, which is not maximum due to a slight frequency shift of the transpolarizing surface when placed inside the TCR.

Moreover, the TTCR presents an angular τ dependence around its axis due to the geometry of the transpolarizing surface. The same performance is obtained at every 90° rotation, which is contrary to the roll invariance of a TCR. This fact is shown in Fig. 3 for an angular τ rotation of 90°.

Another consequence of the angular dependence is that the TTCR behaves almost like a standard TCR for τ equal to 45° but with higher cross-polar responses, as shown in Fig. 4.

The scattering matrices (1) and (2) have been extracted for the TCR and TTCR, considering an orientation $\tau = 0°$. The results show the expected behavior for the TCR, whereas the TTCR presents higher copolar components that may be

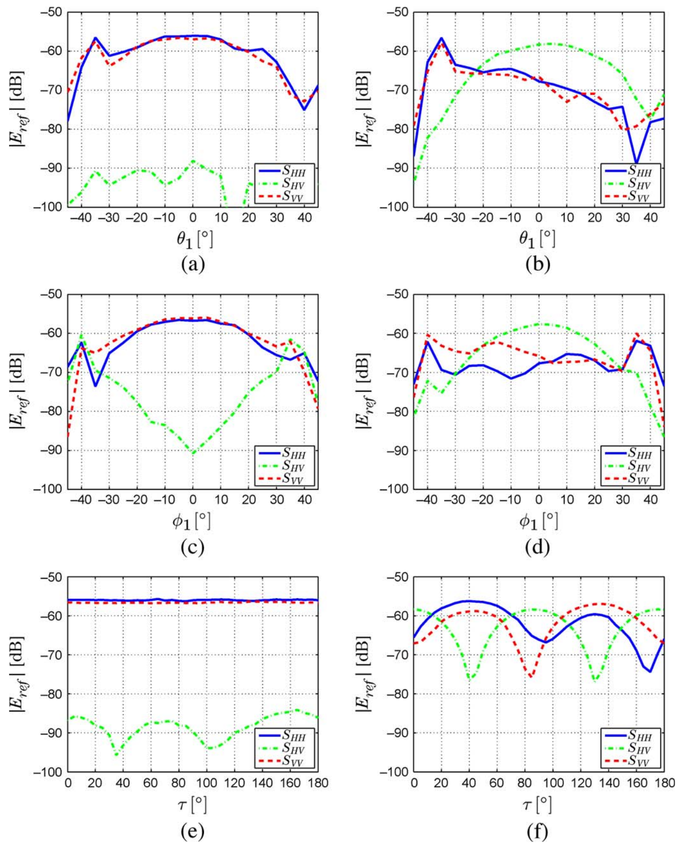

Fig. 5. Measured angular response for the TCR/TTCR at 9.65 GHz. (a) TCR θ_1. (b) TTCR θ_1. (c) TCR ϕ_1. (d) TTCR ϕ_1. (e) TCR τ. (f) TTCR τ.

produced by the suboptimal response found at 9.65 GHz. Note that no external calibration has been applied to these results

$$\boldsymbol{S}_{\mathrm{TCR}}^{\mathrm{meas}} = A\begin{bmatrix} 1.00_{\angle 0^\circ} & 0.02_{\angle 30^\circ} \\ 0.02_{\angle 30^\circ} & 0.93_{\angle 13^\circ} \end{bmatrix}$$

$$\boldsymbol{S}_{\mathrm{TTCR}}^{\mathrm{meas}} = A\begin{bmatrix} 0.43_{\angle -22^\circ} & 1.00_{\angle 0^\circ} \\ 1.00_{\angle 0^\circ} & 0.36_{\angle -77^\circ} \end{bmatrix}. \qquad (3)$$

The angular response around boresight of the TCR/TTCR has been also studied. In particular, measurements have been carried out at 9.65 GHz for different angles $-45^\circ \leq \theta_1 \leq 45^\circ$, $-45^\circ \leq \phi_1 \leq 45^\circ$, and $0^\circ \leq \tau \leq 180^\circ$, as shown in Fig. 5, where $\theta_1 = 54.75^\circ$ and $\phi_1 = 45^\circ$. The angular response of the TCR shows that its maximum response is found at boresight. However, the TTCR slightly improves its response at boresight when $0^\circ \leq \theta_1 \leq 30^\circ$ because the transpolarizing surface placed inside the TTCR is illuminated with a higher grazing angle, thus enhancing the transpolarization effect.

III. Field Measurement Results

Full polarimetric field measurements at 9.65 GHz (X-band) have been carried out with a GB-SAR system to assess the performance of the designed TTCR.

A. Measurement Setup

The GB-SAR is mounted on the top of a terrace at the Campus Nord UPC facing toward a flat square with some small trees, as shown in Fig. 6. The trihedral under test (TUT) has been placed in the middle of the measurement scenario, which is also complemented with different reference point scatters: four conventional TCRs (T1–T4), which provide a pure copolar response; one Bruderhedral (B) [19], tilted 45°, which provides a passive pure cross-polar response; and a polarimetric active radar calibrator (PARC) [20], tilted 45°, thus producing copolar and cross-polar responses, making its signature to be present in the results for the four terms of the measured scattering matrix. The measurement parameters of the UPC GB-SAR system can be found in [15, Table I].

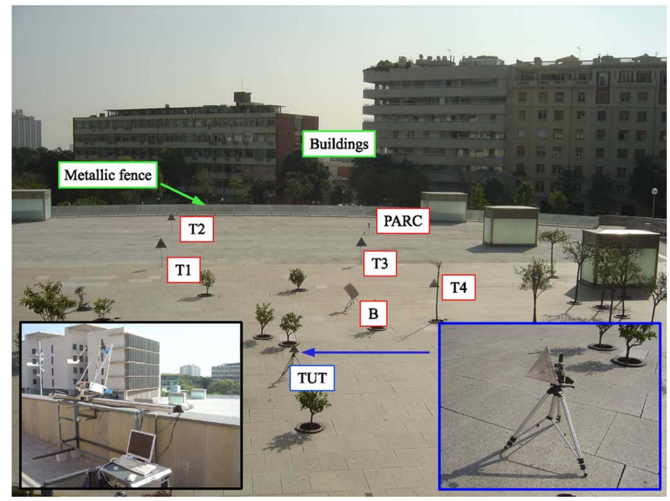

Fig. 6. Measurement scenario at the Campus Nord UPC. The TUT and the GB-SAR system are shown in the inset.

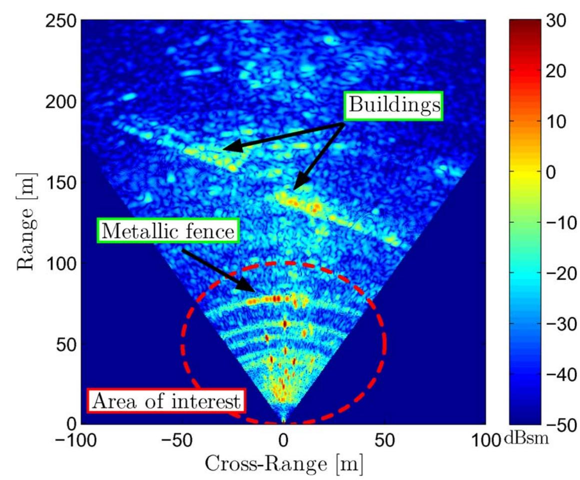

Fig. 7. Measured $|S_{\mathrm{HH}}|$ channel of the scenario at full range.

B. Measured Results

The measured $|S_{\mathrm{HH}}|$ channel of the scenario at full range is shown in Fig. 7. The maximum range in the measurements is about 250 m, including the metallic fence and the buildings, although the TUT and the reference scatters are located at a range below 70 m.

The measured results for the case of a conventional TCR as TUT for copolar ($|S_{\mathrm{HH}}|$ and $|S_{\mathrm{VV}}|$) and cross-polar ($|S_{\mathrm{HV}}|$ and $|S_{\mathrm{VH}}|$) channels are shown in Fig. 8, considering a maximum range of 80 m, i.e., zooming in the area of interest. It is seen that the TUT presents a high backscattered level in the

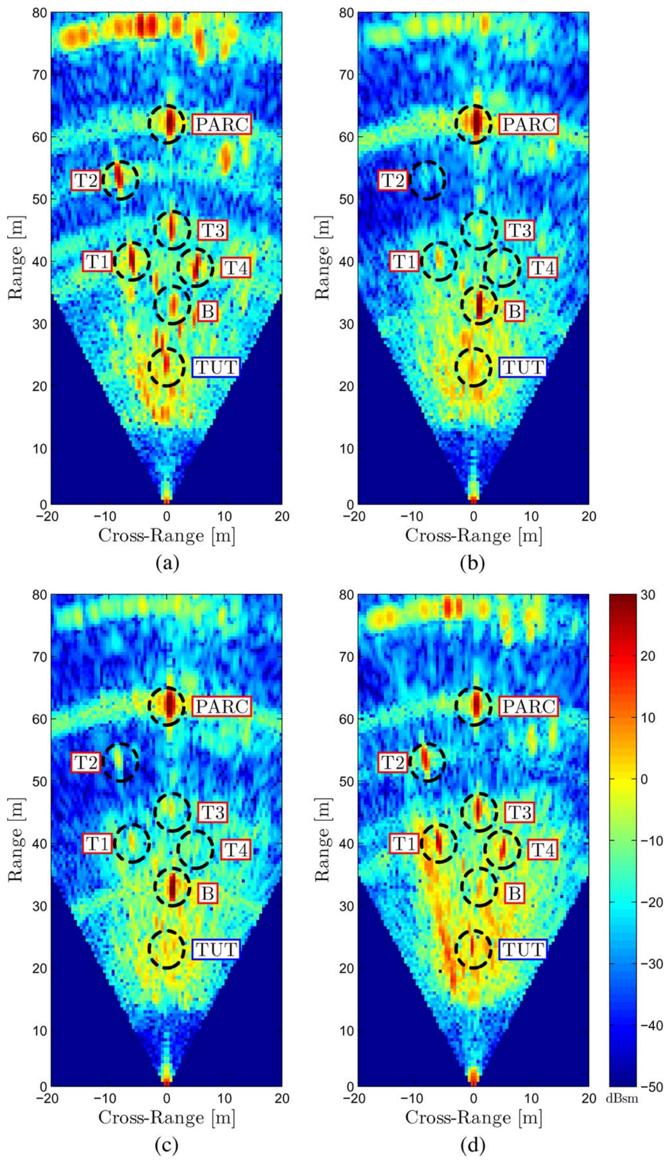

Fig. 8. Measured $|S_{\mathrm{HH}}|$, $|S_{\mathrm{HV}}|$, $|S_{\mathrm{VH}}|$, and $|S_{\mathrm{VV}}|$ channels for the TCR. (a) TCR $|S_{\mathrm{HH}}|$. (b) TCR $|S_{\mathrm{HV}}|$. (c) TCR $|S_{\mathrm{VH}}|$. (d) TCR $|S_{\mathrm{VV}}|$.

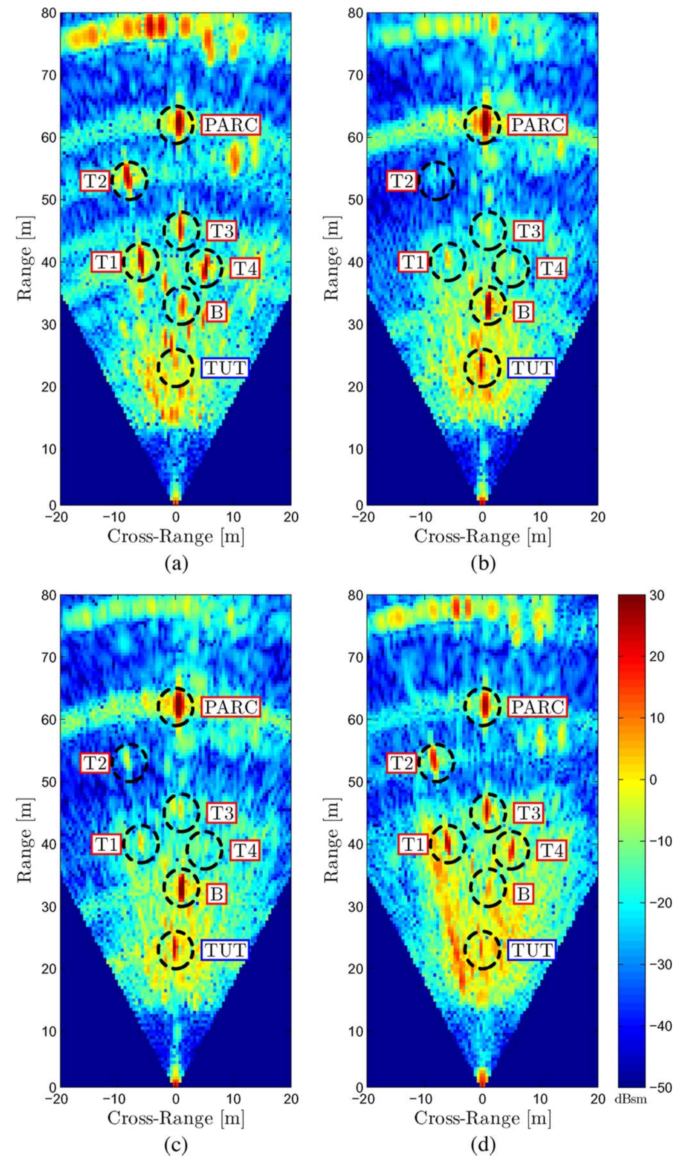

Fig. 9. Measured $|S_{\mathrm{HH}}|$, $|S_{\mathrm{HV}}|$, $|S_{\mathrm{VH}}|$, and $|S_{\mathrm{VV}}|$ channels for the TTCR. (a) TTCR $|S_{\mathrm{HH}}|$. (b) TTCR $|S_{\mathrm{HV}}|$. (c) TTCR $|S_{\mathrm{VH}}|$. (d) TTCR $|S_{\mathrm{VV}}|$.

copolar channels, while its level is reduced in the cross-polar ones, as expected for a conventional TCR. This is confirmed as well with the backscattered signal of the reference TCRs (T1–T4). Note that the Bruderhedral (B) is only present in the cross-polar channels, as expected from a cross-polarizing device. This is not the case of the PARC, which is clearly identified in all polarizations, due to its 45° tilt. It is worth noting that the amplification in the near range of our measurement scenario, mainly due to the proximity to the GB-SAR system, increases the floor level in the surroundings of the TUT, while slightly masking its polarimetric signature.

The same measurements have been carried out for the case of a TTCR as TUT. The magnitudes of the copolar ($|S_{HH}|$ and $|S_{VV}|$) and cross-polar ($|S_{HV}|$ and $|S_{VH}|$) channels are shown in Fig. 9. The reference TCRs are clearly identified in the copolar results, as expected. However, it can be seen that the TTCR presents a high cross-polar response, as well as the Bruderhedral and the PARC system, which is contrary to the case of a standard TCR as TUT. Moreover, although not completely vanished, the TTCR presents a low backscattered level in the copolar results, which is comparable to the cross-polar level found at the reference TCR positions.

The measured backscattered cross-range cuts for the four polarimetric channels at the TUT position are shown in Fig. 10. The maximum backscattered results are well identified in the center of the cross-range cuts. The TCR has high copolar and low cross-polar responses, whereas the TTCR produces a reverse result to that of a TCR, and hence, the cross-polar enhancement of the TTCR is proved. The TTCR presents a cross-polarization ratio of 12 dB at 9.65 GHz, outperforming the result obtained in the anechoic chamber.

The scattering matrices (1) and (2) have been also extracted from the GB-SAR measurements at 9.65 GHz. Despite some small disagreements, the scattering matrices are similar to those extracted from the anechoic chamber measurements (3). The TTCR presents an almost antidiagonal matrix with a phase difference smaller than 20° between cross-polar components.

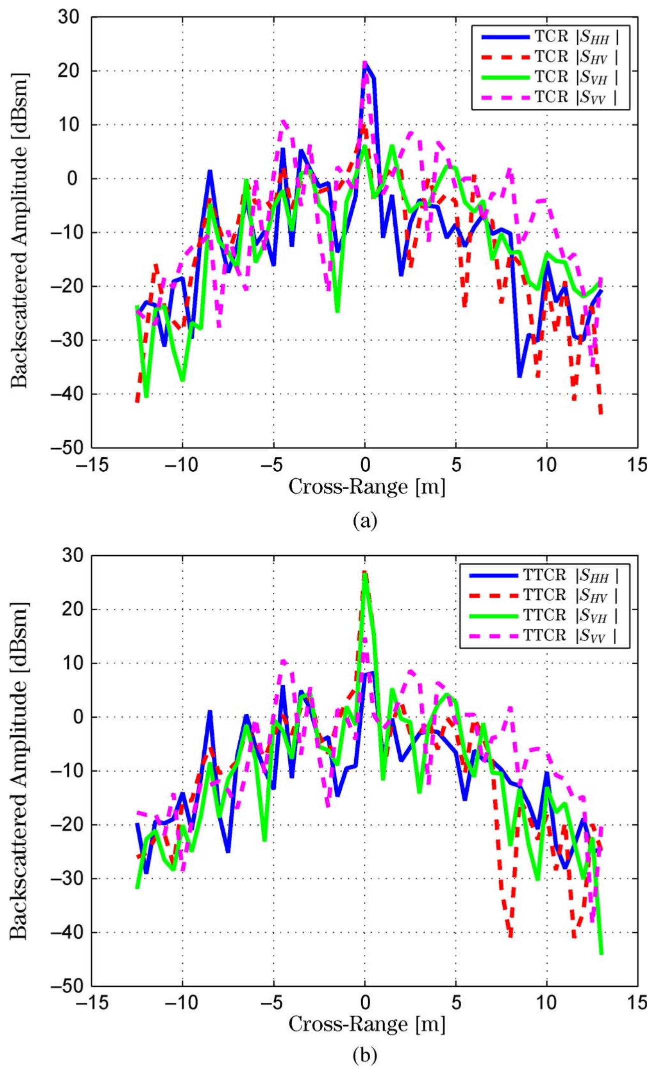

Fig. 10. Measured cross-range cuts for the TCR and TTCR at the TUT position. (a) Cross-range cut for TCR. (b) Cross-range cut for TTCR.

Therefore, the GB-SAR measurement results prove the feasibility of the proposed TTCR as a PolSAR calibrator

$$\boldsymbol{S}_{\mathrm{TCR}}^{\mathrm{meas}} = A \begin{bmatrix} 0.96_{\angle 10^\circ} & 0.27_{\angle 81^\circ} \\ 0.16_{\angle 40^\circ} & 1.00_{\angle 0^\circ} \end{bmatrix}$$

$$\boldsymbol{S}_{\mathrm{TTCR}}^{\mathrm{meas}} = A \begin{bmatrix} 0.09_{\angle -117^\circ} & 1.00_{\angle 0^\circ} \\ 0.88_{\angle -19^\circ} & 0.22_{\angle 135^\circ} \end{bmatrix}. \quad (4)$$

IV. Conclusion

In this letter, the performance of a TTCR for PolSAR calibration purposes has been assessed with a GB-SAR system operating at 9.65 GHz (X-band). The TTCR presents a cross-polarization ratio of 12 dB and a phase difference of 19° between cross-polar components. These results could be improved by slightly retuning the transpolarizing surface design in order to enhance the transpolarization performance of the TTCR at 9.65 GHz. In addition, these measurements are affected by the amplification that is present in the near range of the GB-SAR system, which increases the noise level; this fact may be overcome by using a bigger TTCR placed in a farther and cleaner region in the measurement scenario. The TTCR design is characterized by its low-profile and lightweight transpolarizing surface, which can be easily fabricated by applying standard photoetching techniques, while overcoming some practical fabrication aspects of previous TTCR designs (gridded and corrugated TCRs). Finally, the proposed TTCR design could also be applied to other frequency bands (e.g., L-band or C-band) by scaling, in terms of wavelength, the dimensions of the elements (square patches with slots) of the transpolarizing surface to the corresponding frequency of operation.

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