CSG QUAD-POLARISATION DATA ASSESSMENT FOR POLARIMETRIC CALIBRATION

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ABSTRACT: High-resolution quad-polarisation X-band data are currently available from COSMO-SkyMed Second Generation (CSG) satellites. This paper presents a preliminary assessment on the CSG quad-polarisation data for polarimetric calibration. Both trihedral and dihedral corner reflectors were deployed simultaneously during the CSG data acquisition over Singapore in April and May 2023. From the point target analysis, the phase difference between HH and VV was found to be deviated often from the theoretical value. On the other hand, the average values of crosstalk parameters were below −30 decibel (dB), indicating a good isolation of the CSG SSAR1 antenna. After applying the polarimetric calibration, the polarisation signatures of the trihedral corner reflectors were restored appearing close to the theoretical response.

1. INTRODUCTION

Fully polarimetric synthetic aperture radar (PolSAR) provides valuable opportunities in understanding and quantifying physical interaction behaviours between radar waves and the illuminated Earth's surface through its measured scattering matrix or polarimetric covariance matrix (Lee and Pottier, 2009; Cloude, 2010; Yamaguchi, 2020; Hajnsek and Desnos, 2021). With the recently launched Earth observation satellites such as NeuSAR, TeLEOS-2, and DS-SAR, the acquired spaceborne data open more doors of opportunity for further exploring and improving various PolSAR applications. The PolSAR imaging systems are, however, imperfect in reality. Apart from absolute radiometric calibration, relative amplitude and phase components between different polarisations are required to be calibrated in polarimetric radar measurements (Curlander and McDonough, 1991; van Zyl and Kim, 2011; Shimada, 2018). To date, there exist many different polarimetric calibration techniques in the literature. Among them are van Zyl (1990), Klein (1992), Quegan (1994), Ainsworth *et al*. (2006), Shimada (2011), Fore *et al*. (2015), etc.

COSMO-SkyMed Second Generation offers high-resolution quad-polarisation data through its two enhanced satellites, namely, CSG1 and CSG2. Being positioned separately at 180° on the same orbit, each CSG satellite has its revisit time of 16 days. For the CSG quad-polarisation stripmap imaging mode, both azimuth and range resolutions are about three meters (Agenzia Spaziale Italiana, 2021). Although the CSG quad-polarisation data are radiometrically calibrated, different polarisations of the same acquisition are often not co-registered with each other. This implies that the exact polarimetric calibration might not be applied to the CSG data. Hence, this paper is intended to examine the CSG quad-polarisation data for polarimetric calibration.

2. METHODOLOGY

The methodology of this study is composed of the following four main modules: 1) data acquisition, 2) co-registration, 3) corner reflector analysis, and 4) polarimetric calibration.

2.1 Data Acquisition

In April and May 2023, three sets of the CSG quad-polarisation data were acquired over Singapore. Table 1 summarises the X-band data collection in the ascending orbit. During the CSG data acquisition, two trihedral and one dihedral corner reflectors were deployed concurrently near the NUS football field and Defu Lane 10 for Singapore west and east, respectively. Figure 1 presents few photos of the deployed corner reflectors. Each corner reflector has its edge length of 50 cm and plate thickness of 2 mm. With the given parameters of the CSG imaging geometry, setting up all the corner reflectors for their azimuth angle and elevation angle followed closely the procedures as suggested by van Zyl *et al*. (1992) and Doerry (2014).

Table 1. Specifications of CSG test data

	Singapore west	Singapore east
Acquisition date	6th May 2023	15th April 2023
		17th May 2023
Wavelength	3.1228381 cm	
Polarisation	HH, VH, HV, VV	
Satellite ID	SSAR1	
Satellite altitude	625.518 km	625.531 km
		625.546 km
Beam number	QPS-006	QPS-017
Antenna direction	Right	
Product type	SCS_B	
Number of looks	1 (azimuth), 1 (range)	
Near incidence angle	27.07°	40.36°
		40.32°
Far incidence angle	28.44°	41.41°
		41.39°
Line spacing	2.049 m	2.149 m
Pixel spacing	1.071 m	1.499 m

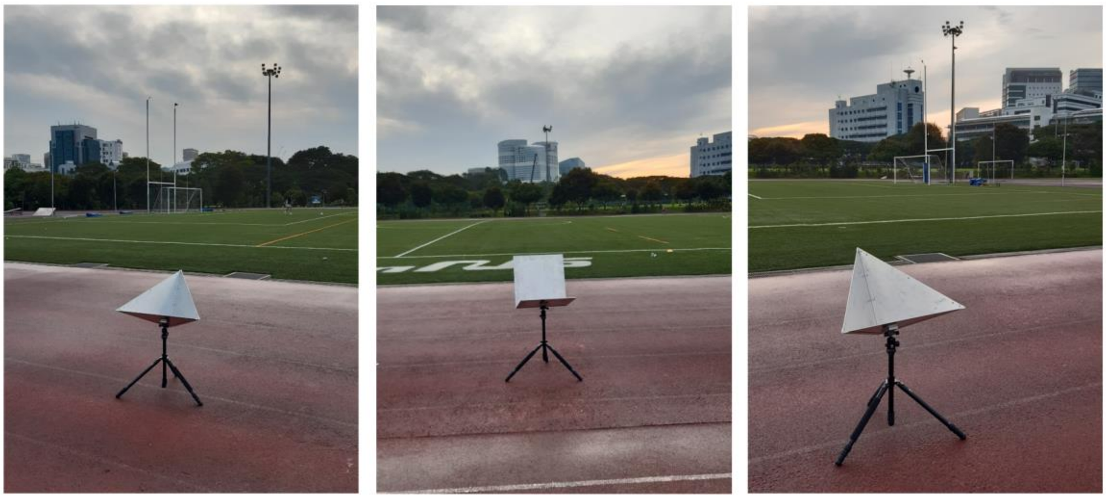

Figure 1. Deployment of corner reflectors on 6th May 2023, where two trihedral and one dihedral corner reflectors were set up on the running track next to the NUS football field.

2.2 Co-registration

The CSG quad-polarisation data are distributed in hierarchical data format (HDF), where different polarisations of the same acquisition might not be co-registered with each other. Prior to the response analysis of corner reflectors, the CSG data of different polarisations were co-registered based on slow-time (in azimuth direction) and fast-time (in slant range direction). To do this, one among the quad-polarisation channels was selected as master reference. The remaining three different polarisations were then resampled onto the same time grid accordingly by using nearest neighbour approach. The required parameters in the processing included 1) number of image columns and lines, 2) column and line time intervals, and 3) zero-Doppler azimuth and range first times. All the parameters can be obtained from the CSG HDF attributes (Agenzia Spaziale Italiana, 2021).

2.3 Corner Reflector Analysis

The integral method proposed by Gray *et al*. (1990, p. 377) was considered for corner reflector analysis. Its detailed implementation is available in van Zyl *et al*. (1992) and Freeman (1992, pp. 1115–1116). An odd-sized local window was used in the analysis, which is recommended to be centred at peak pixel of corner reflector. The peak refers to the maximum value of HH and VV intensity sum. Four response parameters of corner reflectors were computed, namely, 1) HH-VV phase difference, 2) VV/HH amplitude ratio, 3) crosstalk between VH and HH, and 4) crosstalk between HV and VV.

2.4 Polarimetric Calibration

To calibrate polarimetrically the CSG quad-polarisation data, the widely used Quegan's method was employed in this study. Without the assumption of radar system symmetry, it unifies both phase and crosstalk calibrations in a noniterative way. The polarimetric distortion matrix is given by

$$\mathbf{D} = Y \begin{bmatrix} \alpha & v+\alpha w & vw \\ \alpha u & \alpha & v \\ \alpha z & 1 & w \\ \alpha uz & u+\alpha z & 1 \end{bmatrix} \begin{bmatrix} k^2 & 0 & 0 \\ 0 & k & 0 \\ 0 & 0 & 1 \end{bmatrix}, \tag{1}$$

where Y denotes the overall system gain and k is the receive channel imbalance. The parameters u, v, w, z are the crosstalk ratios, while α represents the ratio of the receive and transmit channel imbalances. The crosstalk ratios and α can be estimated from the averaged 4×4 Hermitian covariance matrix of natural distributed target, for example, forest or grassland. Contrarily, the estimation of Y and k involves the use of calibration devices. The reader is referred to Quegan (1994) or van Zyl and Kim (2011, Chapter 4) for all the mathematical solutions.

By assuming that the crosstalk is negligible (Azcueta *et al*., 2022), the measured scattering vector takes the form of

$$\begin{bmatrix} M_{\mathrm{HH}} \\ M_{\mathrm{VH}} \\ M_{\mathrm{HV}} \\ M_{\mathrm{VV}} \end{bmatrix} = Y \begin{bmatrix} \alpha & 0 & 0 \\ 0 & \alpha & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} k^2 & 0 & 0 \\ 0 & k & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} S_{\mathrm{HH}} \\ S_{\mathrm{HV}} \\ S_{\mathrm{VV}} \end{bmatrix}, \tag{2}$$

where S_{rt} refers to the true scattering element of the received polarisation r and transmitted polarisation t. The solution for α is straightforward as follows:

$$\alpha = \frac{\langle M_{\mathrm{VH}} M_{\mathrm{HV}}^{*} \rangle}{\langle M_{\mathrm{HV}} M_{\mathrm{HV}}^{*} \rangle}. \tag{3}$$

The angular brackets represent the expectation or ensemble average. The complex conjugate is denoted by *. The estimation of α may make use of all image pixels in cross-polarised channels. After compensating for α by using the method of least squares, k is estimated from the response of trihedral corner reflector.

3. RESULTS AND DISCUSSION

In this study, only the CSG data of 15th April 2023 were co-registered for different polarisation channels. No co-registration was needed for the other two data sets. After the co-registration, the HH and VV peak values of the corner reflectors were found to be co-located at the same pixel. Figure 2 shows the polarimetric responses of the corner reflectors, which were installed near the NUS football field on 6th May 2023. As expected, a strong backscattering response from all the corner reflectors can be clearly seen in the HH and VV polarisations, but it is not the case for the HV and VH polarisations.

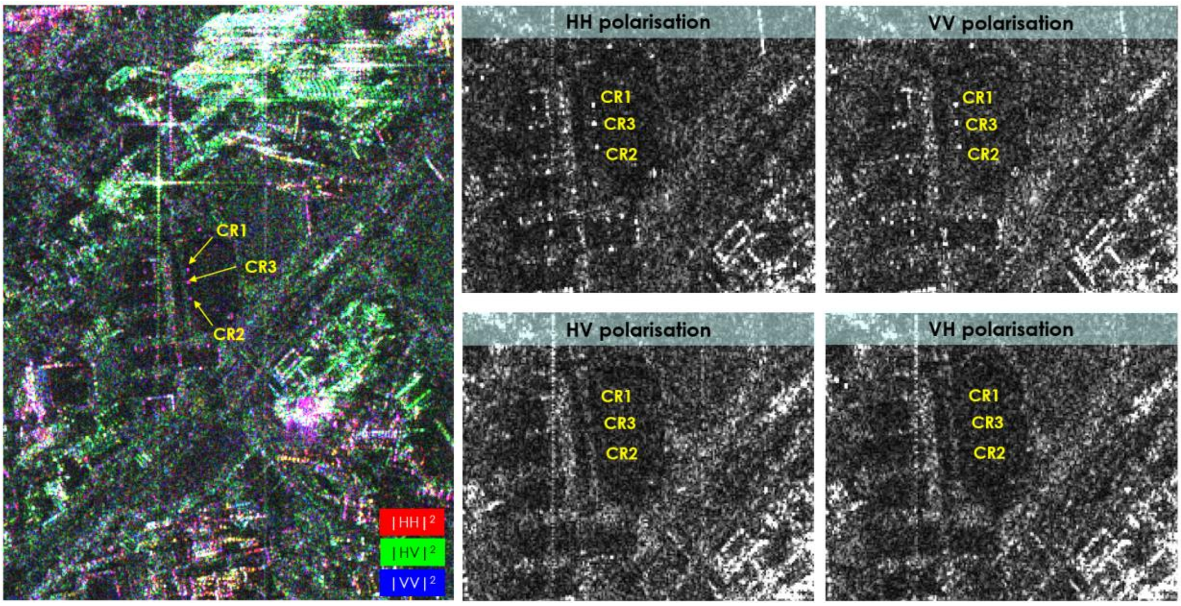

Figure 2. Polarimetric responses of corner reflectors in the CSG data of 6th May 2023. CR1 and CR2 are the deployed trihedral corner reflectors, while the dihedral corner reflector is labelled as CR3.

Table 2 tabulates the four response parameters computed from the deployed trihedral corner reflectors. Theoretically, a trihedral corner reflector should exhibit a null phase difference between HH and VV polarisations. An average of −69.78° and 76.36° in the HH-VV phase difference were observed for the beam no. QPS-017 and QPS-006, respectively. For the amplitude ratio of VV to HH, the values ranged from 0.867 to 1.048. Both the VH/HH and HV/VV crosstalk values were below −24 dB with their average of −30.13 dB and −30.46 dB, indicating a good isolation of the CSG SSAR1 antenna. Meanwhile, the estimated crosstalk ratios from selected grass fields were also low as listed in Table 3, i.e., below −35 dB.

Table 2. Parameters derived from corner reflector analysis

	HH-VV phase difference	VV/HH amplitude ratio	VH/HH (dB)	HV/VV (dB)
Singapore east (QPS-017, 15th April 2023)				
Trihedral CR1	−64.67°	0.938	−27.57	−24.73
Trihedral CR2	−69.15°	0.869	−35.82	−40.32
Singapore east (QPS-017, 17th May 2023)				
Trihedral CR1	−73.25°	1.048	−26.62	−32.27
Trihedral CR2	−72.05°	0.921	−30.38	−27.39
Singapore west (QPS-006, 6th May 2023)				
Trihedral CR1	76.85°	0.867	−33.23	−30.20
Trihedral CR2	75.87°	0.881	−27.16	−27.87

Table 3. Crosstalk ratios (in dB) estimated from natural distributed targets

	u	*v*	*w*	*z*
Singapore east (QPS-017, 15th April 2023)	−42.07	−52.51	−43.83	−40.57
Singapore east (QPS-017, 17th May 2023)	−35.51	−48.37	−48.96	−37.81
Singapore west (QPS-006, 6th May 2023)	−40.02	−39.77	−47.09	−44.58

Figure 3 and Figure 4 compare the co- and cross-polarisation signatures of trihedral corner reflector before and after the polarimetric calibration for different acquisition dates. After applying Quegan’s method, all the distorted polarisation signatures were recovered, where their shape is close to the theoretical plot. Figure 5 presents the polarisation signatures of trihedral corner reflector after the polarimetric calibration without crosstalk removal. Visually, the co- and cross-polarisation signatures in Figure 5 resemble closely those plots in Figure 3 and Figure 4.

4. CONCLUSIONS AND RECOMMENDATION

A preliminary evaluation on the CSG quad-polarisation data for polarimetric calibration was reported in this paper. Both the trihedral and dihedral corner reflectors were deployed concurrently during the CSG data acquisitions over Singapore. From the trihedral corner reflector response analysis, the presence of HH-VV phase offset was noticed causing the undesired distortion in the polarisation signature plots. On the other hand, the crosstalk parameters were below −30 dB on average, showing that the CSG SSAR1 antenna is reasonably well-isolated. Since this study focused only on calibrating the CSG SCS_B products for two particular beams, other CSG product (i.e., SCS_U) with different imaging beams can be considered for future investigation.

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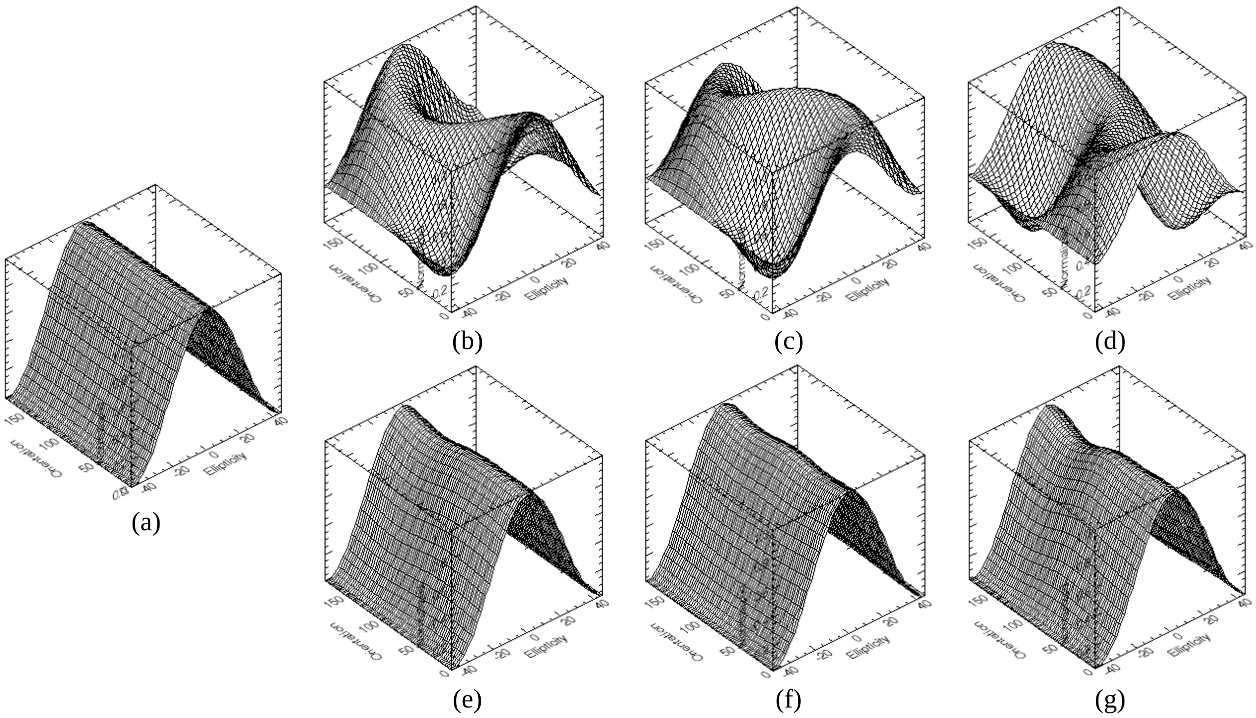

Figure 3. Co-polarisation signatures of trihedral corner reflector before (top row) and after (bottom row) polarimetric calibration. (a) theoretical plot, (b) and (e) Singapore east of 15th April 2023, (c) and (f) Singapore east of 17th May 2023, (d) and (g) Singapore west of 6th May 2023.

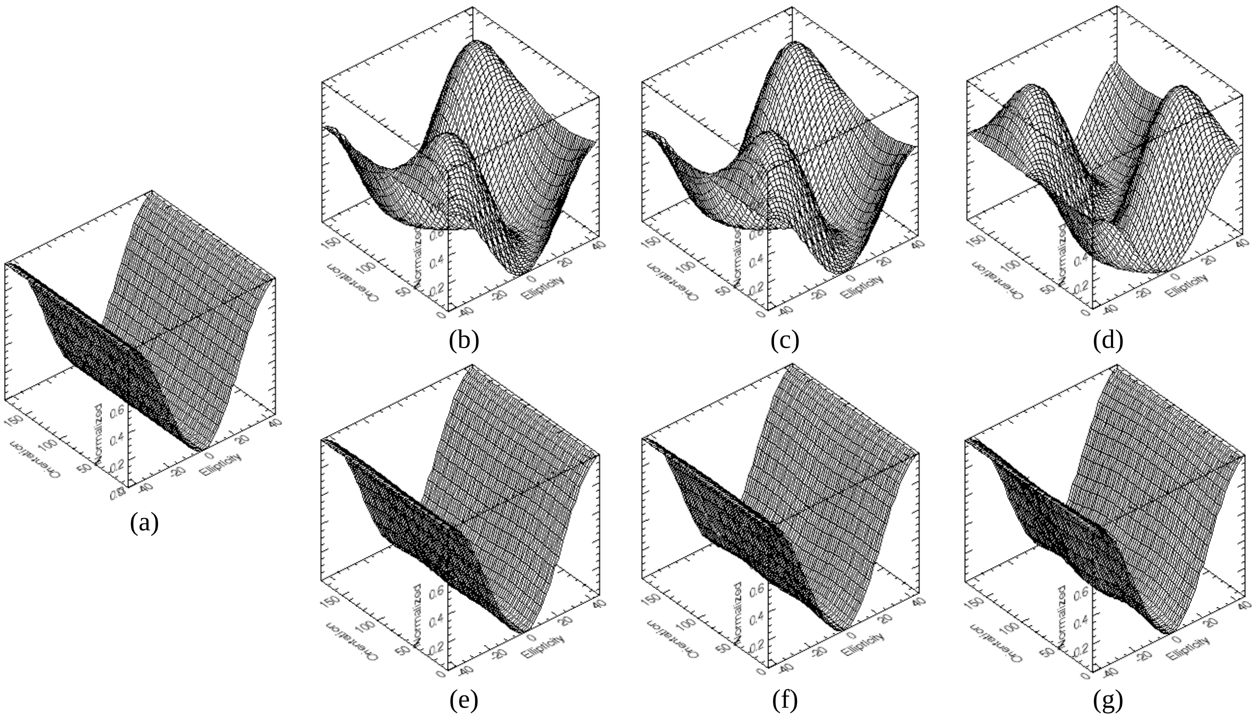

Figure 4. Cross-polarisation signatures of trihedral corner reflector before (top row) and after (bottom row) polarimetric calibration. (a) theoretical plot, (b) and (e) Singapore east of 15th April 2023, (c) and (f) Singapore east of 17th May 2023, (d) and (g) Singapore west of 6th May 2023.

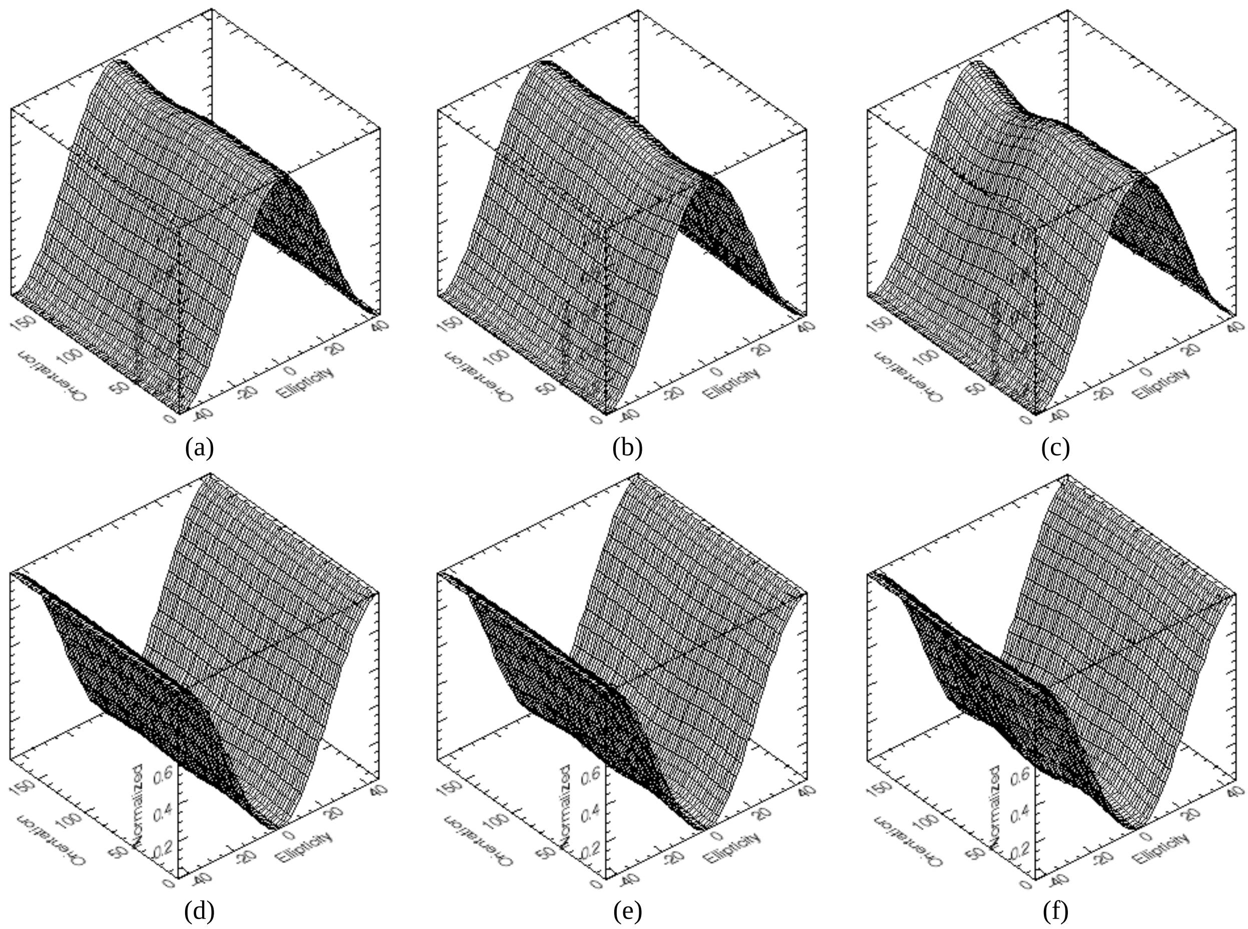

Figure 5. Polarisation signatures of trihedral corner reflector after polarimetric calibration without crosstalk removal. Co- and cross-polarisation signatures are shown separately in top and bottom rows. (a) and (d) Singapore east of 15th April 2023, (b) and (e) Singapore east of 17th May 2023, (c) and (f) Singapore west of 6th May 2023.

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