Polarimetric Calibration of Space SAR Data Subject to Faraday Rotation –A Three-Target Approach–

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***Abstract*- Polarimetric calibration method is proposed for space SAR data subject to Faraday rotation. It makes use of three reference targets, i.e. dihedral, trihedral and polarimetric active radar calibrator, and needs no assumptions on background scene. Validation is carried out using numerical calculations**.

INTRODUCTION

Spaceborne polarimetric synthetic aperture radar (SAR) provides us with valuable image data over the earth. Because polarimetric SAR's are usually operating on linear polarization basis, polarization directions of the radar waves rotate during propagation through the ionoshere. This effect is known as Faraday rotation, which is more pronounced at low frequencies. L-band polarimetric SAR (PALSAR) will be launched in a near future onboard Advanced Land Observing Satellite (ALOS) at the altitude of 692 km. This satellite altitude is high enough as compared to that of the ionosphere, so we need to compensate for the influence of Faraday rotation to be included in the PALSAR data. Several approaches were proposed to correct the Faraday rotation effect [1]-[3] that relied on statistical characteristics of background surfaces. Although their approach must be useful for practical applications, we still need the method that does not need assumptions and not rely on the surface conditions for validation of their results.

This paper proposes a polarimetric calibration method of space SAR data subject to Faraday rotation using three artificial targets.

THEORY

Measurement model of a space SAR subject to Faraday rotation is given as follows [1]:

$$\boldsymbol{M} = a\boldsymbol{R}^T \boldsymbol{FSFT} + \boldsymbol{N} \tag{1}$$

where $\boldsymbol{M}$ and $\boldsymbol{S}$ are measured and actual scattering matrices, respectively. T shows a matrix transpose, and a is a complex number that gives the amplitude and phase of the radar return. $\boldsymbol{R}$ and $\boldsymbol{T}$ are polarization transfer matrices on receive and transmit, respectively, and $\boldsymbol{N}$ is a noise matrix. By introducing the notation of $\boldsymbol{R}$ and $\boldsymbol{T}$ matrices after [4] that are normalized by their HH elements, normalizing with a and neglecting $\boldsymbol{N}$, we obtain the following measurement equation.

$$\begin{pmatrix} m_{hh} & m_{hv} \\ m_{vh} & m_{vv} \end{pmatrix} = \begin{pmatrix} 1 & C_1 \\ C_2F_R & F_R \end{pmatrix} \begin{pmatrix} \cos\Omega & \sin\Omega \\ -\sin\Omega & \cos\Omega \end{pmatrix} \begin{pmatrix} s_{hh} & s_{hv} \\ s_{vh} & s_{vv} \end{pmatrix} \times \begin{pmatrix} \cos\Omega & \sin\Omega \\ -\sin\Omega & \cos\Omega \end{pmatrix} \begin{pmatrix} 1 & C_2F_T \\ C_1 & F_T \end{pmatrix} \tag{2}$$

where C_1 or C_2 is the cross-talk from horizontal to vertical polarization or vertical to horizontal polarization, and F_R or F_T is the channel imbalance on receive or transmit. Ω is the Faraday rotation angle.

In the previous approach [5], we assumed to use the three reference targets, i.e., a polarization-preserving reflector, horizontal-polarization-selective reflector and polarization-rotating reflector. However, it had a weak point that the response of a polarization selective reflector might be affected by co-polarized background clutter. In the present approach, we will use a polarization-preserving reflector (trihedral), 45°-rotated polarimetric active radar calibrator (PARC) and dihedral. They have strong co-polarized backscattering, so co-polarized background clutter does not influence their responses seriously. Their scattering matrices are given as follows:

Polarization-preserving reflector (tri): $\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$

45°-rotated PARC (p): $\begin{pmatrix} 1 & 1 \\ -1 & -1 \end{pmatrix}$ (4)

Dihedral (di): $\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

The measurement matrices for the polarization-preserving reflector, 45°-rotated PARC and dihedral reflector are obtained by direct calculation. Then, the results are normalized with each hh term and the second order terms of C_1 and C_2 are ignored as shown below.

$$\begin{pmatrix} 1 & m_{hv}^{tri} / m_{hh}^{tri} \\ m_{vh}^{tri} / m_{hh}^{tri} & m_{vv}^{tri} / m_{hh}^{tri} \end{pmatrix} = \begin{pmatrix} 1 & F_T(C_1 + C_2 + \tan 2\Omega) \\ F_R(C_1 + C_2 - \tan 2\Omega) & F_RF_T \end{pmatrix} \tag{5}$$

$$\begin{pmatrix} 1 & m_{hv}^{p}/m_{hh}^{p} \\ m_{vh}^{p}/m_{hh}^{p} & m_{vv}^{p}/m_{hh}^{p} \end{pmatrix} = \begin{pmatrix} 1 & \dfrac{F_T(C_1 - C_2 - \cos 2\Omega + (C_1 + C_2)\sin 2\Omega)}{\sin 2\Omega - 1} \\ \dfrac{F_R(C_1 - C_2 + \cos 2\Omega + (C_1 + C_2)\sin 2\Omega)}{\sin 2\Omega - 1} & \dfrac{F_R F_T(1 + \sin 2\Omega)}{\sin 2\Omega - 1} \end{pmatrix} \tag{6}$$

$$\begin{pmatrix} 1 & m_{hv}^{di}/m_{hh}^{di} \\ m_{vh}^{di}/m_{hh}^{di} & m_{vv}^{di}/m_{hh}^{di} \end{pmatrix} = \begin{pmatrix} 1 & F_T(-C_1 + C_2) \\ F_R(-C_1 + C_2) & -F_R F_T \end{pmatrix} \tag{7}$$

From the trihedral response (5) (or dihedral response (7)) and the PARC response (6), we can obtain the expression for the Faraday rotation angle as follows:

$$\frac{1 + \sin 2\Omega}{\sin 2\Omega - 1} = \frac{m_{vv}^{p}/m_{hh}^{p}}{m_{vv}^{tri}/m_{hh}^{tri}} \quad \text{or} \quad -\frac{m_{vv}^{di}/m_{hh}^{di}}{m_{vv}^{tri}/m_{hh}^{tri}} \tag{8}$$

Then, by solving (8) with respect to Ω, the Faraday rotation angle is calculated as,

$$\Omega = \frac{1}{2}\sin^{-1}\frac{\dfrac{m_{vv}^{p}/m_{hh}^{p}}{m_{vv}^{tri}/m_{hh}^{tri}} + 1}{\dfrac{m_{vv}^{p}/m_{hh}^{p}}{m_{vv}^{tri}/m_{hh}^{tri}} - 1} \quad \text{or} \quad \frac{1}{2}\sin^{-1}\frac{-\dfrac{m_{vv}^{di}/m_{hh}^{di}}{m_{vv}^{tri}/m_{hh}^{tri}} + 1}{-\dfrac{m_{vv}^{di}/m_{hh}^{di}}{m_{vv}^{tri}/m_{hh}^{tri}} - 1} \tag{9}$$

The ratio of F_T and F_R is obtained from the dihedral response (7) as,

$$\frac{F_T}{F_R} = \frac{m_{hv}^{di}/m_{hh}^{di}}{m_{vh}^{di}/m_{hh}^{di}} \tag{10}$$

Thus, using (10) together with (5) or (7), we can calculate F_T and F_R as shown below.

$$F_T = \pm\sqrt{\frac{m_{vv}^{tri}}{m_{hh}^{tri}} \cdot \frac{m_{hv}^{di}/m_{hh}^{di}}{m_{vh}^{di}/m_{hh}^{di}}} \quad \text{or} \quad \pm\sqrt{-\frac{m_{vv}^{di}}{m_{hh}^{di}} \cdot \frac{m_{hv}^{di}/m_{hh}^{di}}{m_{vh}^{di}/m_{hh}^{di}}} \tag{11}$$

$$F_R = \pm\sqrt{\frac{m_{vv}^{tri}}{m_{hh}^{tri}} \cdot \frac{m_{vh}^{di}/m_{hh}^{di}}{m_{hv}^{di}/m_{hh}^{di}}} \quad \text{or} \quad \pm\sqrt{-\frac{m_{vv}^{di}}{m_{hh}^{di}} \cdot \frac{m_{vh}^{di}/m_{hh}^{di}}{m_{hv}^{di}/m_{hh}^{di}}} \tag{12}$$

Here, appropriate sign should be chosen for further processing. Once, we obtain the values of Ω, F_T and F_R, the cross talk terms C_1 and C_2 can be calculated in a straightforward manner as,

$$C_1 = \frac{1}{2F_T}\left(\frac{m_{hv}^{tri}}{m_{hh}^{tri}} - \frac{m_{hv}^{di}}{m_{hh}^{di}}\right) - \frac{\tan 2\Omega}{2} \quad \text{or} \quad \frac{1}{2F_R}\left(\frac{m_{vh}^{tri}}{m_{hh}^{tri}} - \frac{m_{vh}^{di}}{m_{hh}^{di}}\right) + \frac{\tan 2\Omega}{2} \tag{13}$$

$$C_2 = \frac{1}{2F_T}\left(\frac{m_{hv}^{tri}}{m_{hh}^{tri}} + \frac{m_{hv}^{di}}{m_{hh}^{di}}\right) - \frac{\tan 2\Omega}{2} \quad \text{or} \quad \frac{1}{2F_R}\left(\frac{m_{vh}^{tri}}{m_{hh}^{tri}} + \frac{m_{vh}^{di}}{m_{hh}^{di}}\right) + \frac{\tan 2\Omega}{2} \tag{14}$$

NUMERICAL TEST

To evaluate the performance of the above approach, we have carried out some numerical tests by assuming parameter values as $F_R = F_T = 0.7$, $C_1 = -0.1$, $C_2 = 0.1$ and $\Omega = 20°$. The above parameters were estimated with the proposed algorithm as $F_R = F_T = 0.7$, $C_1 = -0.116$, $C_2 = 0.086$ and $\Omega = 20.49°$, respectively. Fig. 1 shows the polarization signatures of a trihedral for co- and cross-pols before calibration.

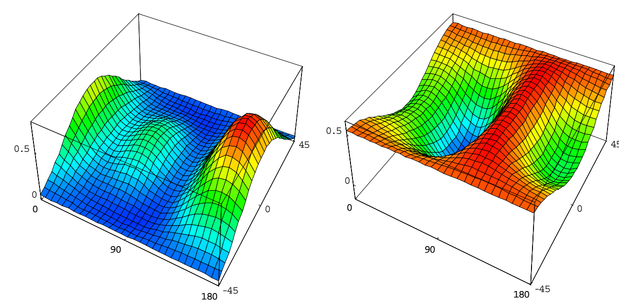

Fig. 1. Polarization signatures of a trihedral before calibration. (left: co-pol, right: cross-pol)

Then, the polarimetric calibration was performed to the trihedral response shown in Fig. 1 by using the estimated parameter values described above. The result is shown in Fig. 2.

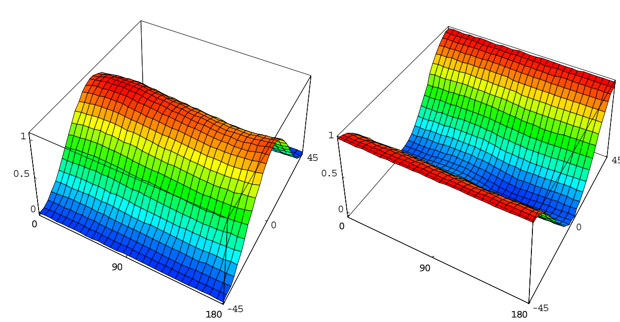

Fig. 2. Polarization signatures of a trihedral after calibration. (left: co-pol, right: cross-pol)

By comparing Figs. 1 and 2, it can be clearly seen that the present approach effectively worked to remove the influence of Faraday rotation as well as that of the polarization transfer matrices for transmit and receive. In the above calculation, we assumed that the reference targets have no errors, i.e. they had the theoretical scattering matrices. Actually, however, they must have errors. So, in the following, we evaluate the influence of hardware errors on the performance of polarimetric calibration. The error model of the targets are given simply as follows:

$$
\begin{aligned}
tri &= \begin{pmatrix} 1 & \delta \\ \delta & 1+\delta^2 \end{pmatrix} \\
p &= \begin{pmatrix} 1 & 1+\delta \\ -1+\delta & -1+\delta^2 \end{pmatrix} \qquad (15) \\
di &= \begin{pmatrix} 1 & \delta \\ \delta & -1+\delta^2 \end{pmatrix}
\end{aligned}
$$

Here, we put $\delta = 0.1$ and 0.0316 to specify the order of errors to be –20 and –30 dB relative to the hh element. Channel imbalance and cross-polarization noise measured from the trihedral responses are summarized in Table 1.

Table 1. Influence of hardware errors on calibration performance

δ	-20 dB	-30 dB
Channel imbalance	0.18 dB	0.08 dB
Cross-pol noise	-20.2 dB	-31.8 dB

Although the number of calculations was not enough to discuss the statistical characteristics of the algorithm performance, roughly speaking, it is necessary to reduce the hardware errors less than –30 dB, if we need to suppress the channel imbalance and cross-pol noise less than 0.1 dB and –30 dB, respectively.

Fig. 3 shows the polarization signature of a 22.5°-rotated dihedral for co- and cross-pols calculated from the measured scattering matrix under the parameter values described previously.

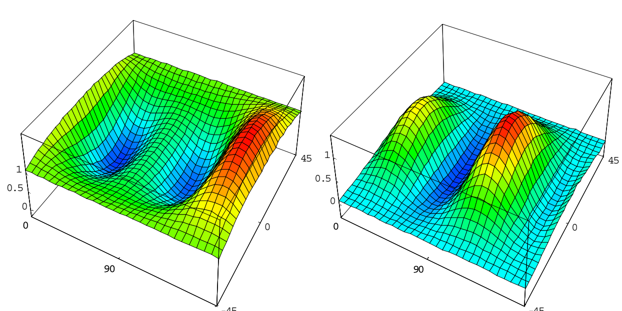

Fig. 3. Polarization signatures of a 22.5°-rotated dihedral before calibration. (left: co-pol, right: cross-pol)

As can be seen clearly, the signatures are distorted due to the rotation of polarization direction by Faraday effect. Fig. 4 shows the polarization signatures after applying the present polarimetric calibration algorithm.

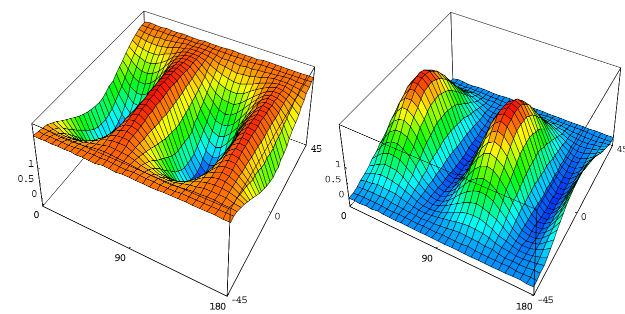

Fig. 4. Polarization signatures of a 22.5°-rotated dihedral after calibration. (left: co-pol, right: cross-pol)

The above figure clearly shows that the distortions appeared in Fig. 3 are compensated completely, and they are almost identical with the theoretical responses. However, as discussed previously, there may exist errors in the reference targets used in the polarimetic calibration. Fig. 5 shows the polarization signatures of the a 22.5°-rotated dihedral when the reference targets have errors of –20 dB, i.e. $\delta = 0.1$.

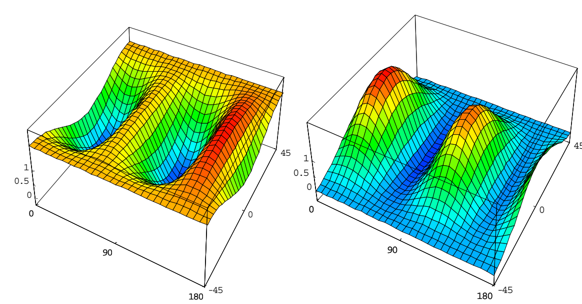

Fig. 5. Polarization signatures of a 22.5°-rotated dihedral after calibration using erroneous reference targets. (left: co-pol, right: cross-pol)

Although the signatures in Fig. 5 were improved as compared to that from the measured scattering matrix, the improvement was not enough and there exists a difference in the response between two orthogonal polarizations. This was due to the hardware errors assumed in the calculation.

From the experience of performing polarimetric calibration experiments, we have a guideline of hardware errors that it should be less than –30 dB. If this guideline is satisfied, the calibration results must be satisfactory.

The present approach will be applied to the PALSAR polarimetric calibration experiment. In the experiment, we are going to use the retrodirective PARC [6] that was developed especially for the PALSAR experiment..

CONCLUDING REMARKS

Polarimetric calibration procedure of space SAR data subject to Faraday rotation was proposed using three reference targets. Results of numerical test showed that the approach corrected the distortion of measured scattering matrix due to Faraday rotation as well as that caused by radar hardware. The influence of target errors was evaluated also with numerical calculations. It was shown that the hardware error should be reduced less than –30 dB to make the calibration results acceptable.

The present approach will be applied to the forthcoming calibration experiment of PALSAR onboard the ALOS satellite that will be launched hopefully in a near future.

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