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Co-polarization channel imbalance determination by the use of bare soil

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ABSTRACT

This paper describes a novel technique which determines the co-polarization channel imbalance by the use of natural bare soil, instead of a trihedral corner reflector (CR). In polarimetric synthetic aperture radar (PolSAR) remote sensing, the polarimetric calibration (PolCAL) is the key technique in quantitative earth parameter measurement. In general, the current PolCAL process can be separated into two parts. The first part tries to estimate the crosstalk and the cross-polarization (x-pol) channel imbalance components by the reflection symmetry and the reciprocity properties, without a CR. Then, at least one trihedral CR is required to determine the co-polarization (co-pol) channel imbalance; however, it is not always possible to deploy a CR in difficult terrain such as desert. In this paper, we utilize bare soil as a stable reference target, and four common natural constraints of bare soil are evaluated to determine the co-pol channel imbalance, without the use of a CR. It should be mentioned that we do not propose to replace the CR by a natural target, but we utilize the natural target to enhance the PolCAL accuracy when a CR is missing. The four constraints are: (1) the consistency of the polarimetric orientation angle (CPOA) between the PolSAR POA and the digital elevation model (DEM) derived POA; (2) the unitary zero POA (UZPOA) of a flat ground surface; (3) the zero helix (ZHEX) component of the ground surface; and (4) the unitary version of the previous zero helix (UZHEX). In the theoretical part of this paper, we demonstrate that the forth constraint is the most suitable in different scenes. We then propose a multi-scale algorithm to further improve the robustness of the co-pol channel imbalance determination. In the experimental part, we apply our new methods to simulated airborne SAR (AIRSAR) and real uninhabited aerial vehicle SAR (UAVSAR) data. Without the use of any CR, the recovered results show that the estimated amplitude and phase error of the co-pol channel imbalance are less than 0.5 dB and 5°, respectively.

1. Introduction

Polarimetric synthetic aperture radar (PolSAR) offers a full polarimetric operation mode which is very important for land-cover mapping (Shi et al., 2012), biomass estimation (Ghulam et al., 2014; Tanase et al., 2014), and soil dielectric measurement (Jagdhuber et al., 2013). The polarimetric radar transmits the horizontal/vertical (H/V) polarization wave and receives the H/V backscattering wave to produce a 2×2 polarimetric scattering matrix. However, the measurement scattering matrix is always influenced by the transmission and reception polarimetric distortion matrices (PDMs) of the radar systems (Sheen et al., 1989). For the quantitative application of PolSAR data, it is critical to recover the observed PolSAR data by rolling back to the non-distorted measurement, which is termed polarimetric calibration (PolCAL).

In general, when ignoring the additive instrument noise and the thermosphere-caused Faraday rotation angle (FRA), the PDMs can be separated into the crosstalk, the cross-polarization (x-pol), and co-polarization (co-pol) components. In the early days, Freeman et al. (Sheen et al., 1989) tried to solve all of the PDM components by the use of several trihedral and dihedral reflectors. To reduce the cost of deploying corner reflectors (CR), the radar and target reciprocal assumption and the reflection symmetrical property of natural targets were introduced to recover the crosstalk elements (Van Zyl, 1990) with Jet Propulsion Laboratory (JPL) airborne SAR (AIRSAR) data. Furthermore, in what has become one of today's standard PolCAL approaches, Quegan (1994) utilized the target reflection symmetrical and reciprocal properties to estimate the crosstalk and x-pol channel imbalance. In 2006, Ainsworth et al. (2006) relaxed the reflection symmetrical constraint of natural targets and utilized only the target scattering reciprocity

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Nomenclature

AFO	amplitude filter operation
CPOA	consistency of POA
CR	corner reflector
EK	estimated channel imbalance k
FRA	faraday rotation angle
FEK	filtered EK
PFO	phase filter operation
PolCAL	polarimetric calibration
PDMs	polarimetric distortion matrices
POA	polarimetric orientation angle
SR	system reciprocity
TR	target reciprocity
TRS	target reflection symmetry
TEC	total electron content
UZHEX	unitary zero helix
UZPOA	unitary zero POA
ZHEX	zero helix
ZPOA	zero POA

as the weakest constraint to solve both the crosstalk and x-pol channel imbalance elements. However, in all the previous algorithms, at least one trihedral CR is required to calibrate the co-pol channel imbalance in the scenes. In a recent publication, Shimada (2011) combined the PolCAL model with the three-component Freeman–Durden decomposition method to estimate all the PDM elements, without the use of a CR. Even though this model-based PolCAL method was successfully applied in the dense rainforest of Brazil with high randomness volume scattering, two drawbacks are apparent. Firstly, the degree of volume randomness must be high enough when solving the unknowns; however, highly stochastic forest is rare, as is desert. Secondly, when retrieving the unknowns, the surface-like scatter needs be selected to provide the theatrical phase difference between the HH and VV channels. The final calibration accuracy is therefore highly dependent on the manual selection of the surface-like scatter.

As a common natural target, bare soil presents many stable characteristics in most image scenes, such as the low-rank of the polarimetric covariance matrix, which has been utilized to calibrate the crosstalk distortion in previous research (Freeman et al., 1992), the robust polarimetric orientation angle (POA) estimation results (Lee et al., 2002), and the low helix component (Yamaguchi et al., 2005). In a full polarimetric system, the POA is defined as the angle between the normal ground surface and the incident plane, which can be retrieved from both the digital elevation model (DEM) and the PolSAR image (Lee et al., 2002). This is the reason why the PolSAR POA is usually explored to recover a local DEM (Chen et al., 2009). Although the POA consistency of DEM and PolSAR have been reported in some publications (Lee et al., 2002), the accuracy of the PolCAL work needs to be strictly evaluated. In addition, the helix component originates from the helix-like structures such as orientated vegetation and buildings. Bare soil is, however, simple enough, and the helix component is usually ignored in most scenes (Yamaguchi et al., 2011). To better extend the non-CR calibration work, this paper chooses bare soil as the ground reference scatter to automatically recover the co-pol channel imbalance. It should be stressed that we do not propose to replace the CR with a natural target, but we utilize the bare soil to enhance the PolCAL accuracy when a CR is missing, as in emergency events (Zhao et al., 2013). In all scenes, a CR will still give the best accuracy because of the simple physical structure, and it is also a reliable PolCAL source. In this paper, four possible natural constraints of bare soil are proposed and evaluated: (1) the consistency of the POA (CPOA), which means that the PolSAR image POA should be equal to the DEM POA; (2) the unitary zero POA (UZPOA) on flat ground, as a special case of CPOA; (3) the zero helix (ZHEX) property of the ground surface; and (4) the unitary version of the zero helix (UZHEX).

The rest of this paper is organized as follows. Section 2 introduces the PolCAL model, and we briefly summarize the current PolCAL methods. The mathematical constraints of natural bare soil are introduced, and the relative expression of the co-pol channel imbalance is proposed in Section 3. In Section 4, a simulation experiment is implemented with airborne SAR (AIRSAR), and real uninhabited aerial vehicle SAR (UAVSAR) data is calibrated by the proposed method. The relationships between the crosstalk, the x-pol, and co-pol channel imbalances are further discussed in Section 5. Finally, the conclusion and further work are presented in Section 6.

2. The general PolCAL framework

2.1. Distortion model

In general, the polarimetric measurement matrix $[O]$ is distorted by several different error sources, which include the thermosphere-induced Faraday rotation (FR) matrix $[\Omega]$, the additive instrument noise $[N]$, and the transmitted $[T]$ and received $[R]$ distortion matrices. The un-distorted scattering matrix $[S]$ can then be linked to the measurement by:

$$[O] = [R][\Omega][S][\Omega][T] + [N]. \quad (1)$$

The FR can be eliminated by external means, such as a CR and the dual-frequency global positioning system (GPS) measurement total electron content (TEC) (Rogers and Shaun, 2014), and the instrument noise can also be estimated when the PolSAR sensor investigates calm water or shadow. In this research, we mainly focus on the distortion matrices, and the FR/noise is omitted. Eq. (1) can be rewritten as:

$$\begin{bmatrix} O_{hh} & O_{hv} \\ O_{vh} & O_{vv} \end{bmatrix} = \begin{bmatrix} r_{hh} & r_{hv} \\ r_{vh} & r_{vv} \end{bmatrix} \begin{bmatrix} S_{hh} & S_{hv} \\ S_{vh} & S_{vv} \end{bmatrix} \begin{bmatrix} t_{hh} & t_{hv} \\ t_{vh} & t_{vv} \end{bmatrix}. \quad (2)$$

The subscript h/v means the horizontal/vertical transmit/receive channel. The scattering matrices $[O]$ and $[S]$ can be converted to a vector format, O and S:

$$\begin{bmatrix} O_{hh} \\ O_{vh} \\ O_{hv} \\ O_{vv} \end{bmatrix} = Y \begin{bmatrix} 1 & w & v & vw \\ u & 1 & uv & v \\ z & wz & 1 & w \\ uz & z & u & 1 \end{bmatrix} \begin{bmatrix} \alpha & 0 & 0 & 0 \\ 0 & \alpha & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} k^2 & 0 & 0 & 0 \\ 0 & k & 0 & 0 \\ 0 & 0 & k & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} S_{hh} \\ S_{vh} \\ S_{hv} \\ S_{vv} \end{bmatrix} \rightarrow O = YXQKS. \quad (3)$$

The 2-by-2 transmitted and received distortion matrices then generate the new calibration expression (Quegan, 1994; Ainsworth et al., 2006), where the crosstalk components are set as u, v, w, and z, and the values of k and α are treated as the co-pol and x-pol channel imbalance, and the rest as the absolute calibration factor Y. X, Q, and K are the distortion matrices of the crosstalk, the x-pol, and the co-pol channel imbalance, respectively. The complex elements are defined as: