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Interaction Types and Their Like-Polarization Phase-Angle Difference Signatures

Jack F. Paris

GeoInformation Processing Systems
California State University, Fresno
Fresno, California 93740-0073

1. Introduction

The JPL Airborne SAR (AIRSAR) measures the full polarimetric properties of scene objects. AIRSAR data contain a complete set of *magnitudes* {for all linearly-polarized combinations [*viz.*, VV, HH, and CS (cross polarization)]} and *phase-angle differences* (for all pairs of linearly-polarized components) for each image pixel. Radar image users have been greatly interested in the like-polarization (LK) phase-angle difference parameter, $\Delta\varphi_{LK}$. Usually, it is associated with the *type* of interaction between microwaves and scene-object scattering-elements. One value of $\Delta\varphi_{LK}$ is said to be produced by a dominant single scattering (or reflection) event, and another value is said to be the result of a dominant double-scattering (or double reflection) event. These are often called "single bounce" and "double bounce" interaction signatures, respectively. There appears to be a significant amount of confusion about how the interaction processes produce the characteristic values of $\Delta\varphi_{LK}$ and about what value of $\Delta\varphi_{LK}$ should be associated with each specific type. This paper attempts to address this issue.

2. Polarized Reflection Coefficients for a Smooth Interface

Most electromagnetic (EM) wave theory references present equations for calculating the (electric-field) reflection coefficients, ρ_H and ρ_V, of a smooth interface between two media, where ρ_H is for the case of the electric-field vector oscillating in the direction *normal to the plane of incidence* [*viz.*, the TE or horizontal polarization (*H*) case], and ρ_V is for the case of the electric-field vector oscillating *within the plane of incidence* [*viz.*, the TM or vertical polarization (*V*) case]. It is important to note that ρ is a complex number which relates the magnitude and phase of the electric field of the reflected wave to the magnitude and phase of the electric field of the incident wave *near the interface*.

There are many ways to express the ρ equations. One set is as follows:

$$\rho_H = \frac{n_1 \cos\theta_1 - n_2 \cos\theta_2}{n_1 \cos\theta_1 + n_2 \cos\theta_2} \quad \text{and} \quad \rho_V = \frac{n_1 \cos\theta_2 - n_2 \cos\theta_1}{n_1 \cos\theta_2 + n_2 \cos\theta_1} \qquad \text{(1a, 1b)}$$

where n_1 is the complex index of refraction for Medium 1, n_2 is the complex index of refraction for Medium 2, θ_1 is the incidence angle in Medium 1, and θ_2 is the refraction angle in Medium 2. The reader may notice that Eq. (1b) has the *opposite sign* to expressions for ρ_V given in some reference materials. In other words, the numerator terms in Eq. (1b) are sometimes reversed in standard references.

It is important to understand the reason for the sign discrepancy in expressions for ρ_V. Interestingly, a sign discrepancy never occurs in expressions for ρ_H. The genesis of the error is the way in which the reflection problem is posed. For the H case, the incident and reflected electric fields are both parallel to the interface and are, therefore, parallel to each other. Thus, phase-angle comparisons are easy to made for this case. For the V case, however, the incident and reflected electric fields are, in general, not parallel to each other (see Fig. 1b). Since phase-angle comparisons between oscillating electric fields must be made for parallel components, one has to chose which set of components to use for the V case. For this case, one set of electric field components is perpendicular to the interface, and the other set is parallel to the interface. **When the perpendicular components of the incident and reflected waves are chosen, the derived expression for ρ_V has a sign error. When the components parallel to the interface are chosen, the sign for ρ_V is correct.** This simple error has led to the confusion referenced above.

3. The Single-Bounce Case

The correctness of Eq. (1b) is easily verified by considering the case where $\theta_1 = \theta_2 = 0$ (i.e., the case of *normal incidence*). This is the case for a *single-bounce interaction* that can produce significant "backscattering" to a SAR imaging system. In this case, both ρ_H and ρ_V are equal to $[(n_1 - n_2) / (n_1 + n_2)]$. If the sign of Eq. (1b) were reversed, the expected equality of reflection coefficients for normal incidence fails to occur. Also, note that both reflection coefficients are always *negative* for the usual case where $n_2 > n_1$. **An important implication of the above is that the phase angles of the electric fields for *both* polarizations change by 180 degrees due to normal (single-bounce) reflection from a denser medium.** If Medium 1 and/or Medium 2 are lossy (i.e., have significant imaginary parts), then the phase angle shift will differ somewhat from 180 degrees. **Nevertheless, for normal incidence, ρ_H.and ρ_V are the same , and $\Delta\varphi_{LK}$ equals 0.**

Since a double-bounce interaction appears to be simply two single-bounce interactions, one after the other, one might believe that $\Delta\varphi_{LK}$ will still be zero for this type of interaction. This is not the case. AIRSAR data analysts often observe values of $\Delta\varphi_{LK}$ for double-bounce objects that are 180 degrees away for the values of $\Delta\varphi_{LK}$ for single-bounce objects. The solution to this perplexing inconsistency is given in the next section of this paper.

4. The Double-Bounce Case

Consider the double-bounce case for H polarization in Fig. 1a. Due to the reflection from Interface A, the H wave undergoes a reversal of phase. For the usual case of $n_2 > n_1$, $(n_2 \cos \theta_2)$ is always greater than $(n_1 \cos \theta_1)$. Thus, the phase of the reflected H wave will always be reversed by the reflection. Another phase reversal occurs in the H wave as the result of the second reflection from Interface B. Thus, the phase-angle difference between the incident wave and the corner-reflected "backscattering" wave will be near zero (depending on the material complex indices of refraction for the media on both sides of the two interfaces involved). The V wave (see Fig. 1b) undergoes similar changes in phase during each of the two reflections; however, one must be careful to apply the phase reversals to the electric field components of the V wave which are parallel to the two interfaces involved. When this is done, one sees that the corner-reflected "backscattered" wave will be approximately 180 degrees out of phase with the incident wave. Therefore, the difference in the phase-angles of the H wave and the V wave, $\Delta\varphi_{LK}$, will be about 180 degrees for this double-bounce interaction. Thus, it is the geometry of the corner reflection itself, that "turns" the direction of the electric field for V-polarization without a corresponding "turning" the H polarization, which causes the unique like-polarization phase-angle difference signature of double-bounce dominated scene objects [e.g., wetlands and some forests and woodlands (with a smooth, wet substrate)]. An exception will occur when any local angle of incidence exceeds the Brewster angle on either interface. This (Brewster condition) happens when ($n_1 \cos \theta_2$) is greater than ($n_2 \cos \theta_1$). In this case, the phase shift of the V wave is affected, and $\Delta\varphi_{LK}$ reverts to near zero. For angles near the Brewster condition, the magnitude of the V component also drops towards zero; therefore, the use of phase-angle differences for near the Brewster condition is ill advised. Other propagation phenomena also affect $\Delta\varphi_{LK}$. For example, birefringent media for some volume-scattering situations (e.g., a corn crop with highly-oriented vertical stalks) will also alter $\Delta\varphi_{LK}$ through the effects of differential speeds of propagation with polarization. Since single-scattering interactions affect more pixels than other interactions, one may calibrate $\Delta\varphi_{LK}$ by noting the mode of its distribution.

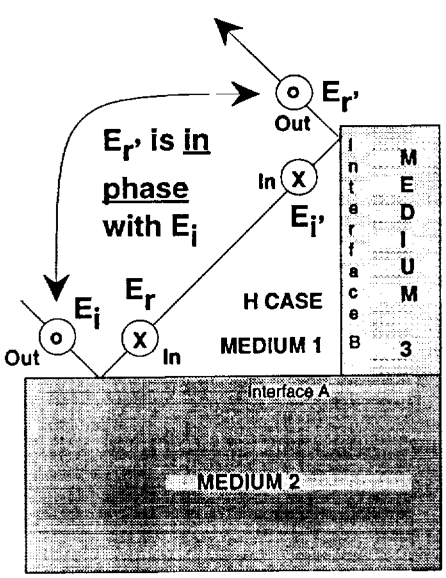

Figure 1A. Horizontal Polarization.

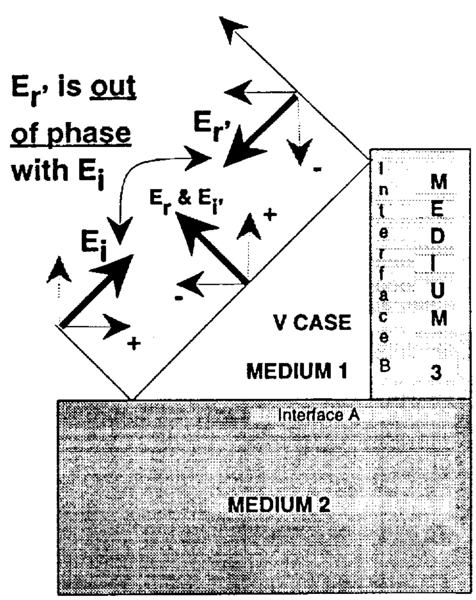

Figure 1B. Vertical Polarization.