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On the visualization of polarimetric response

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Abstract. Measurements from polarimetric radar systems are often represented in the form of a pair of polarization response curves, one showing the co-polarized response, the other the cross-polarized. This representation is effectively a latitude–longitude plot of the Poincaré sphere. Despite its familiarity in the literature, this presentation of the polarimetric response fails to present optimally the data in an intuitive and straightforward manner. As an alternative, this work describes a polar projection that presents the data in a manner that is more effective at communicating the key aspects of the polarization response. The key advantages are that the orientation and helicity are immediately apparent, and that the equal area projection does not bias the visual emphasis towards circular polarizations.

1. Introduction

Measurements from polarimetric radar systems are often represented in the form of the Stokes scattering operator **K**, which completely characterizes the polarimetric response from the imaged scene (as long as the target is composed of symmetrical scatterers) (Boerner *et al.* 1998). From **K**, the technique of polarization synthesis can be used to simulate the response for any arbitrary combination of transmit and receive polarizations. This is achieved by multiplication of **K** by the Stokes vectors S for the transmit and receive polarizations (subscripted t and r respectively), so that

$$P(\chi,\psi)=S_r\mathbf{K}S_t \tag{1}$$

where $S=[1\ \cos2\psi\cos2\chi\ \sin2\psi\cos2\chi\ \sin2\chi]^T$, with the superscript T denoting the transpose, ψ the orientation angle (from 0–180° from horizontal) and χ is the ellipticity angle which ranges from $-45°$ (right-hand circular) to $+45°$ (left-hand circular).

Since the range of 2χ and 2ψ can be taken as polar coordinates within a Poincaré sphere (Ulaby and Elachi 1990) the synthesized polarization response P, for any given S_t and S_r, can be considered as an intensity pattern across the sphere. Alternatively, if the magnitude of $P(\chi,\ \psi)$ represents the range from the centre of the sphere, then the result can be thought of as an irregular surface that characterizes the polarimetric response. Visualization of such a response is therefore not straightforward.

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Initial visualizations, developed by Huynen, plotted contours of equal power on the Poincaré sphere, which were termed gamma spheres. This requires the use of two projections to map the left- and right-handed polarizations (van Zyl *et al.* 1987). This technique was subsequently redeveloped to form the classical polarization response graph. This consists of a 3-D surface (or 2-D contour plot) of $P(\chi, \psi)$ using what amounts to a latitude–longitude representation of the aforementioned gamma sphere (i.e. simple linear axes of χ and ψ) (van Zyl *et al.* 1987, Zebker *et al.* 1987). Normally two graphs are produced: the 'co-pol' response, where the transmit and receive polarizations are the same, and the 'cross-pol' response, where the two states are orthogonal (corresponding to the antipodal point on the Poincaré sphere).

Despite now being a familiar method in the literature, the traditional presentation of polarimetric response fails to present optimally the data in an intuitive and straightforward manner, making it difficult to interpret and analyse and thus hindering its widespread use. In particular, while the method continues to be used within the technical radar community, it has failed to be widely adopted within the field of applied research.

As an alternative, a visualization method that tries to maintain the integrity of the Poincaré space, while at the same time optimizing the ease of interpretation of the polarimetric response, is described in this Letter.

2. Problems with the traditional method

The interest in the use of polarimetric response graphs (or, more usually, pairs of co- and cross-pol graphs) is that they offer the potential of an almost instant overview of the key features of the polarimetric data. They do not display the full range of information contained within polarimetric data (they do not display information on phase, for instance — see Agrawal and Boerner 1989 for a method that attempts this) but they do characterize the full range of polarimetric backscattered power for a symmetric target. In this way idealized scatterers such as spheres, diplanes and dipoles exhibit distinctive patterns in the graphs. Although the term 'polarimetric signature' has been used for such patterns, the response is not unique to a target — very different targets (e.g. a trihedral corner reflector and a smooth surface) can have identical response patterns (Ulaby and Elachi 1990). Although their size and isometric presentation make such graphs unsuitable for the synoptic representation of data, they are still effective at displaying some of the key properties of polarimetric information within a pixel or collection of pixels. The traditional means of graphically displaying the polarization response, however, is non-optimum for a number of reasons.

First, the use of a linear axis means that even though orientation is a continuous parameter, it must be interrupted so that two ends of the graph actually represent the same data. The continuity of this parameter is not immediately apparent from the presentation, and so for analysis the orientation angle must be clumsily read from an axis. This problem is compounded by the confusion caused by inconsistent labelling of the orientation axis such that in some publications it ranges from 0–180° and in others from −90–90° (for example, compare results from Ulaby and Elachi 1990 with Zebker *et al* 1987).

Secondly, the use of a latitude–longitude representation means that such graphs suffer from the associated distortions — i.e. in this case neither the shape nor the area of the Poincaré sphere is preserved, with the distortion most severe at the poles (Robinson *et al.* 1995). The visual emphasis of the graph is, therefore, inappropriate since areas near the Poincaré poles are stretched and represented as much larger regions in the response curve, which is both visually misleading, as well as introducing redundancy, as orientation becomes less significant as the magnitude of the ellipticity angle increases.

Finally, the handedness of the elliptical/circular polarization is not intuitively clear from the diagram and must first be read from the axis before being deciphered.

3. Description of a new graphical presentation

In contrast to the simple latitude–longitude plot of the traditional method, the use of an equal area, polar azimuthal (Lambert's) projection of the Poincaré sphere is proposed (Robinson *et al.* 1995). In effect, this projection looks down on one of the poles, with ellipticity (χ) measured from the pole to the equator (i.e. along lines of longitude) and orientation (ψ) measured around the circumference (i.e. around lines of latitude). This represents a development of a technique used to map the polarization behaviour of discrete objects, which were presented using an orthogonal projection of the Poincaré sphere mapped onto the equatorial plane, described as 'polarization charts' (Giuli 1986). However, the current method also utilizes the fact that the orientation angle is measured modulo 180° so it is possible to represent both the left-handed and right-handed polarization states (the 'Northern' and 'Southern' Poincaré hemispheres) on the one circle — this overcomes one of the main limitations of the polarization chart. Such an approach also has the added advantage of mapping the horizontal polarizations to 0° and 180°, and the vertical polarizations to 90° and 270°.

The complete structure of the projection is given in figure 1 with the latitude–longitude projection shown for comparison. This approach has a number of key advantages, which are as follows. The equal area projection (in contrast to the aforementioned orthogonal equatorial projection) results in a visual emphasis that is more appropriately weighted with regards to the surface of the Poincaré sphere. This also minimizes the visual redundancy in the diagram, as the data for the circular polarizations are no longer duplicated for all orientation values. Both improvements reduce the wasted space of the traditional graphic, giving an improved 'data–ink ratio' (Tufte 1986). Perhaps most importantly, orientation is now represented as a continuous range of angles, rather than along a broken linear scale, aiding visual interpretation as well as characterizing the data in a more physically meaningful way. This provides a direct perceptual link between data and graphic. It is, therefore, possible to determine relationships between orientation angle and backscatter without reference to an axis. This is apparent within the schematic of figure 1.

One of the most appealing aspects of this method is that by placing the projection of the left-handed hemisphere on the left, and the right-handed hemisphere on the right of the diagram, the handedness of the polarization is immediately apparent by an asymmetry across the centre of the graph. This requires no axis reading or knowledge of which angle represents which handedness. It is a good indication of the effectiveness of this method that the polarization response can be instantly interpreted even when no numerical axes are displayed.

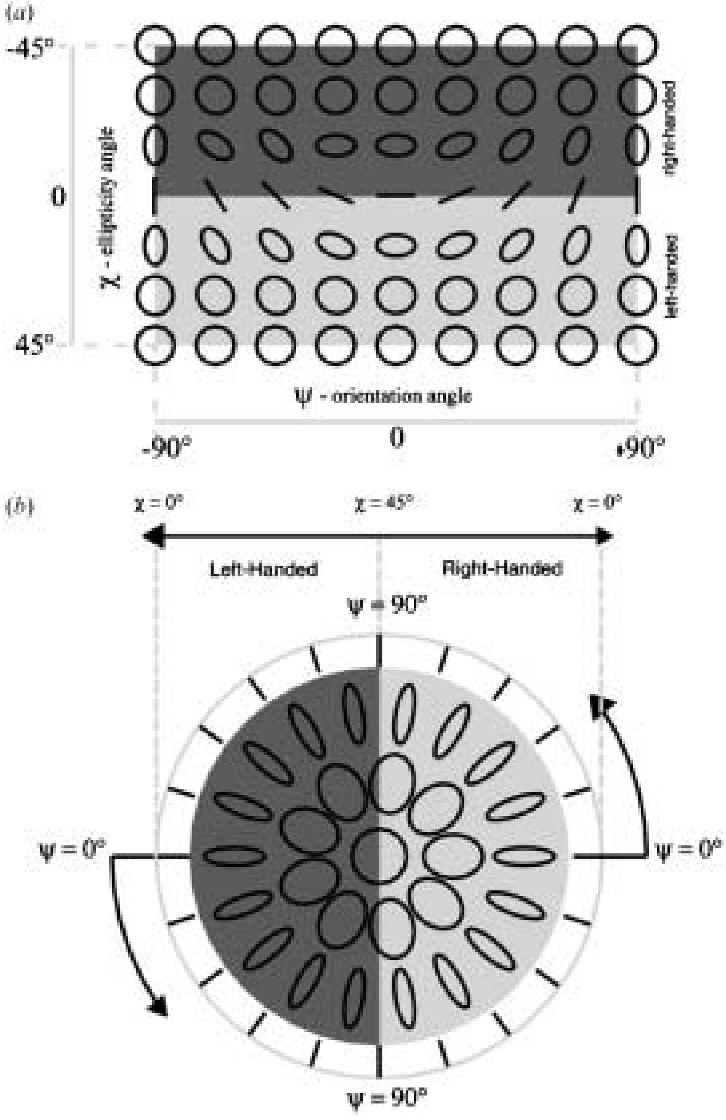

Figure 1. Comparison of visualization techniques: traditional latitude–longitude representation (*a*) versus a Polar Azimuthal projection (*b*). Note that the circular polarization in the polar projection now occupies only a single point, rather than a line, and that the orientation angle is now explicit within the display.

4. Some examples

Figure 2 gives a comparison of the two techniques for a number of idealized responses. Example (*a*) demonstrates the responses of a flat surface, showing the change in rotation that occurs as a result of such interactions. Note that this becomes less relevant as the ellipticity of the impinging wave decreases. Example (*b*) shows the characteristic cross shape produced by a dihedral corner reflector. The orientation of such scatterers is more clearly visible using the new technique.

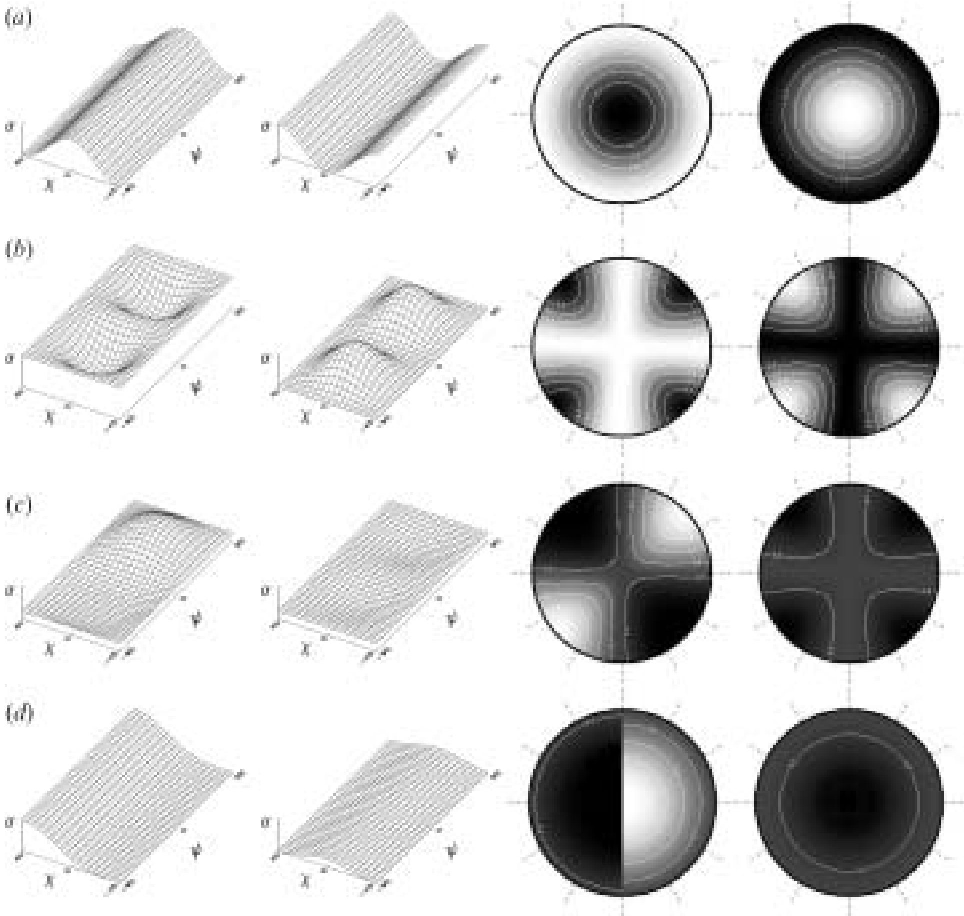

Figure 2. Polarimetric response of idealized targets, visualized using the traditional (left) and new (right) representations. Targets are (*a*) Surface, (*b*) dihedral, (*c*) cylinder oriented at 45° and (*d*) a left-handed helix. In both cases, the co-polarized response is the left column and the cross-polarized response is the right. Backscatter values are normalized across both the co- and cross-pol responses.

Finally, examples (*c*) and (*d*) illustrate the benefits of the new technique for examining the orientation and helicity of scattering objects.

In figure 3, response globes and graphs are produced using data collected over a forested area near Siggefora, Sweden (Woodhouse and Hoekman 2000). For clarity only the co-pol response patterns are shown as examples to facilitate ease of comparison. Each of the examples illustrates polarimetric characteristics which can be clearly identified using the new visualization technique. Response (*a*), for example, is the result of a diplane interaction, producing a graph with a characteristic cross shape. With the new method, however, it can also be observed that there is a preference for the horizontal linear polarization, which is less clear in the traditional graph. Within a forest, such a response suggests not only ground–trunk interactions, but also from the horizontal ground or larger branch

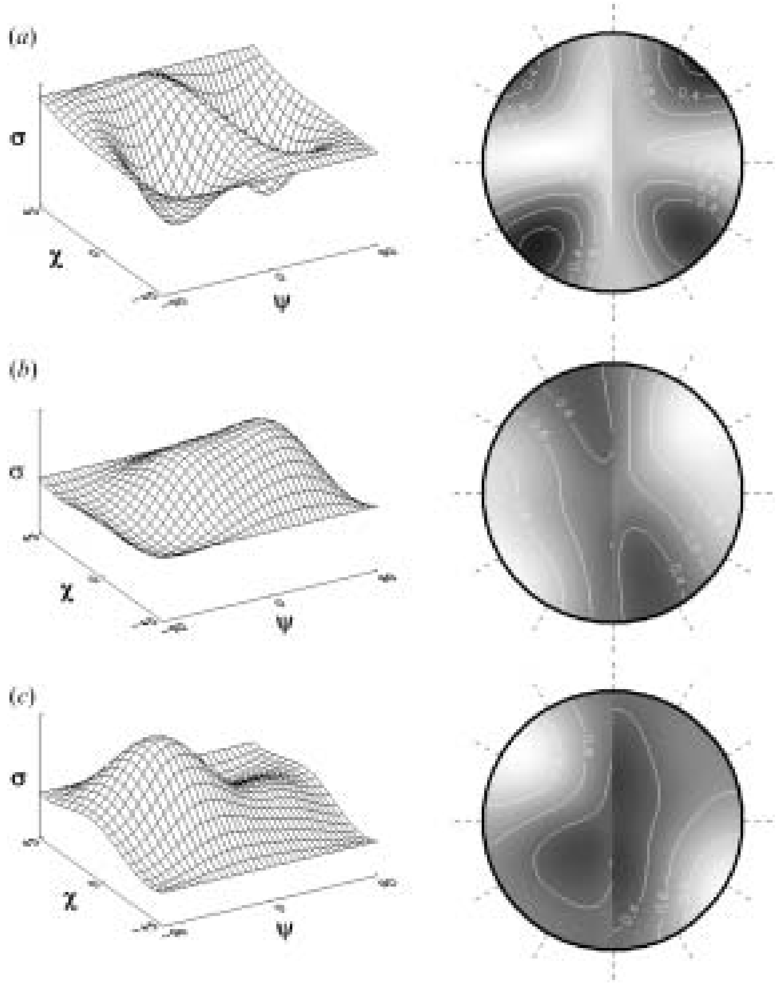

Figure 3. The new visualization technique (right) applied to the co-polarization response from multi-look pixels from L-band data over Siggefora, Sweden, with polarization response graphs given (left) for comparison; (*a*) represents a dihedral response with a preference for horizontal linear polarizations, (*b*) is a mainly depolarized response with some preferred orientation, and (*c*) appears to be an oriented surface (with a preferred orientation of $-30°$).

structures. A small preference for left-handed helicity is also apparent in the new projection.

Example (*b*) in figure 3 demonstrates a typical depolarized response. In traditional polarization response graphs, a depolarized response is characterized by a 'pedestal' (Zebker *et al*. 1987), and usually indicates a high volume scattering contribution (such as a vegetation canopy). Such an effect is evidenced in the new visualization by a marked lack of contrast in the diagram. Orientation preferences in the polarized component of the measurement, however, are still clearly visible, but there is no evidence of any helicity.

It may be argued that depolarization effects are more apparent in a surface plot than a grey-scale image, but of course it is possible to present both methods as either a grey-scale, contoured plot or as an isometric surface if that is preferred.

Finally, response (*c*) appears to be an oriented surface with an orientation of -30°. The new visualization is consequently characterized by a relatively dark centre (representing the circular polarizations) surrounded by a lighter circumference with maxima indicating a preferred orientation. This pattern is less clear in the traditional response graph, especially in terms of resolving the preferred angle of orientation.

5. Summary

For polarimetric data to become widely used for remote sensing applications, there will always be the need for analysis tools that are informative, effective and straightforward to use. The traditional method of visualizing the synthesized polarimetric response does not achieve these ideals. As an alternative, the use of a modified projection was proposed that presents the same information as a traditional response graph, but in a more efficient and intuitive manner. Although rigorous user tests have not been carried out, anecdotal evidence suggests that newcomers find the new graphs far easier to learn to interpret than the traditional method. The current authors believe this to be reason enough to justify the adoption of the new visualization method as an alternative to the traditional polarization response curve.

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