HYBRID-POLARITY SAR ARCHITECTURE

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ABSTRACT

A space-based synthetic aperture radar (SAR) designed to provide quantitative information on a global scale implies severe requirements to maximize coverage and to sustain reliable operational calibration. These requirements are best served by the hybrid-polarity architecture, in which the radar transmits in circular polarization, and receives on two orthogonal linear polarizations, coherently, retaining their relative phase. This paper reviews those advantages, summarizes key attributes of hybrid-polarity dual- and quadrature-polarized SARs including conditions under which the signal-to-noise ratio is conserved, and describes the evolution of this architecture from first principles.

1. Introduction

Linear-polarization has been the unquestioned norm for airborne and satellite imaging radars for more than five decades. Whereas remarkable results have been obtained using the conventional synthetic aperture radar (SAR) architecture for single- and multi-polarized systems, it is easily demonstrated that the traditional way is not the optimum way. As standards on quantitative radar measurements become more demanding, it is constructive to revisit fundamental principles of radar polarimetry to explore profitable alternatives. This logic leads to a new and beneficial approach, hybrid-polarity.

Hybrid polarity [1]–transmitting with circular polarization and receiving orthogonal linear polarizations together with their relative phase—is well-suited to the quadrature-polarized SAR mode, as well as to the (coherent) dual-polarized mode. Hybrid-polarity SAR architecture offers significant advantages over any approach that relies exclusively on linearly-polarized transmission and reception. It was for these reasons that in 2008 the DESDynI initiative adopted hybrid-polarity for the quad-pol mode of their L-band SAR. Section 2 of this paper reviews DESDynI, then introduces the hybrid-polarity architecture in section 3. Hybrid-polarity raises potential signal-to-noise ratio (SNR) issues, addressed in section 4, followed by a review in section 5 of the principal advantages of the architecture relative to conventional “all-linear” multi-polarization designs. Section 7 closes the main body of the paper with conclusions. Two appendices are included that formalize the claims on SNR.

2. DESDynI

DESDynI–Deformation, Ecosystem Structure, and Dynamics of Ice—is one of the first-tier missions recommended in The National Research Council’s Earth Science Decadal Survey [2]. The mission, for which initial planning anticipates a launch in the 2010-2013 time frame, is designed to measure surface deformation for solid Earth and cryosphere objectives, and to assess gross vegetation structure to improve understanding of the carbon cycle. DESDynI’s payload has two primary instruments, an L-band SAR, and a multi-beam Lidar. Although one of DESDynI’s themes is the synergy between the SAR and the laser [3, 4], only the radar is relevant to this paper.

The imaging radar sensor is an L-band Interferometric (InSAR) system, with multiple polarization options, including a fully-polarized (quad-pol) mode. The InSAR mode will be used to meet the science measurement objectives for surface deformation, ice sheet dynamics, and ecosystem structure. Quadrature polarimetry has been proven to support estimation of three-dimensional forest structure. Multiple polarization is required for the canopy density profiles needed for ecosystem structure. Polarimetry when combined with InSAR measurements will allow mean tree height estimation relative to the forest floor to an accuracy of a few meters.

DESDynI is to provide routine global coverage for its intended observations. In practice this means that the system must be quasi-operational, in the sense that data reduction must be robust and automated as much as possible. In turn, this implies that calibration must be simple and reliable. Coverage implies that the swath widths be as large as possible within limits imposed by data rate and resolution. It turns out that the hybrid-polarity quad-pol architecture is responsive to those two requirements significantly better than is possible with a conventional linearly-polarized (H and V) SAR.

3. HYBRID-POLARITY SAR ARCHITECTURE

To date all conventional polarimetric imaging radars have been designed such that the receive polarization basis agrees with the transmitted basis. It follows that there always must be a “like-polarized” and a “cross-polarized” channel in the receiver, between which signal levels differ.
by up to 10 dB or more. Performance of a multi-polarization radar usually is limited by the weaker “cross-polarized” link, which is most impacted by additive noise, and by cross-talk and ambiguities from the stronger “like-polarized” signal. The problem is compounded by the fact that the “like-” and “cross-” polarized channels alternate, in response to the interleaved H- and V-polarized transmissions, which may require calibration techniques that compensate for gain or phase characteristics in either channel that may depend on mean signal level.

The key idea behind hybrid-polarity is to recognize that matched transmitted and received polarizations are not necessary. If chosen sensibly, mixed polarization bases work just as well, and indeed offer significant advantages over the usual “all-linear” polarization approach. This fact follows from two high-level fundamental principles—conservation of energy, and sufficient conditions to fully characterize a partially-polarized electromagnetic (EM) field.

### 3.1 Conservation of energy

In response to coherent EM illumination in any polarization basis, the power backscattered from a given scene element will be conserved when split into any pair of orthogonal polarizations. The obvious implication is that the energy will be divided evenly if and only if the receive polarizations have no “like-” or “cross-polarized” relationship to the transmitted polarization. Thus, if circular-polarization is transmitted, the receive polarization bases for a coherent polarimetric radar should be linear. This combination may be contrarian, but it is objectively superior to all alternatives.

### 3.2 EM field characterization

As has been known for more than 150 years, a quasi-monochromatic partially-polarized EM field is fully characterized by knowledge of four prime parameters: the amplitudes of two orthogonal polarizations (in any basis), the relative phase between those two components, and the ratio of the powers of the polarized portion of the field to the total power. In classical optics, these numbers are expressed through the EM field’s 2x2 coherency matrix $J$. Unfortunately, evaluation of either the prime parameters or $J$ implies phase measurement, a challenging task in classical optics. These quantities were elegantly reformulated by G. G. Stokes as four real numbers $[5]$, known universally as the Stokes parameters. The values of the Stokes parameters are independent of the polarization basis in which they are evaluated.

### 3.3 Synthesis

Taken together, these two principles elevate the SAR design paradigm to a higher level. Consider the SAR processor’s output to be a linear transformation of the observed EM field into a focused EM field, which of course is known in the SAR community as a single-look complex image. If one views a dual-polarimetric SAR from this perspective, then it is natural to define the data product in terms of Stokes parameters, $S_{R}$. The values of those parameters are independent of the polarization basis in which they are measured. Hence the choice of polarization basis of the receiver can—indeed should—be determined by radar hardware considerations, rather than by pre-conceived preferences influenced by the intended applications of the data. It then follows that the polarization basis of the orthogonal receive channels should not sustain a “like” or

![Figure 1. Hybrid-quad-pol architecture](image-url)
“cross” polarized relationship to the polarization that the radar transmits. Thus, if the receive polarizations are H and V, then the transmit polarization should be circular. The result is a hybrid-polarity dual-polarized system [6].

3.4 The Quad-Pol Case

The same logical development can be applied to a quadrature-polarized SAR. In any quad-pol SAR, the transmitted field can be fully characterized by four additional Stokes parameters $S_T$, whose values also do not depend on the choice of polarization basis. It follows that both the transmit and the receive polarization bases can be chosen to optimize the radar’s performance from an engineering point of view, independent of measurement requirements. As in the dual-polarized case, radar hardware performance is optimized if and only if the receive polarization bases sustain no “like” or “cross” relationship to the transmitted polarization basis, thus placing the two receive channels “on a level playing field”. Seen from this generalized perspective, hybrid-pol architecture emerges as the most advantageous approach to the design of a quadrature-polarimetric SAR system.

Conventional quad-pol SAR systems interleave transmissions of orthogonal (linear) polarizations at an effective PRF of twice the Nyquist rate, and in each case receive coherently orthogonal (linear) polarizations. In the hybrid-polarity architecture (Fig 1), the transmissions are L- and R-circular, and the receptions are orthogonal lines and their relative phase. The resulting data can be transformed by simple algebraic combination into the more customary linear polarization basis (HH, VV, HV, and their relative phases). Signal-to-noise ratio is preserved for any combination of input and output polarization bases. All advantages of the hybrid polarity architecture are sustained [1], including robust self-calibration strategies. In the quad-pol mode, the architecture leads to a reduction by 6 dB or more in the (odd-numbered) range ambiguities [7, 8]. All analysis algorithms developed for conventional quad-pol radar data can be used without modification.

4. SNR IN HYBRID-POLARITY SAR

For a hybrid-dual-polarity SAR—at least according to “urban legend”—transmitting circular polarization and receiving dual linear polarizations incurs a loss of 3 dB in signal-to-noise ratio (SNR) relative to the standard case in which linear polarization is used on both transmit and receive. It is tempting to believe this rumor, since circular polarization is equivalent to transmitting simultaneously on H and V polarizations, which of necessity divides the transmitted power between the two orthogonal linear polarizations. However, analysis shows (see Appendix I) that SNR is preserved in a hybrid-dual-polarity SAR if and only if the output data products are expressed in circularly-polarized bases. This statement can be generalized, such that for any mixed-polarity dual-pol SAR, SNR is preserved iff the output polarity basis is the same as the transmit polarization basis. For example, in a π/4 compact-pol radar [9], SNR would be preserved iff the output data were expressed in linear polarization at either +45° or −45° with respect to horizontal. The analysis also shows that if one were to constrain the output formats to the familiar like- and cross-polarized linear components (e.g. HH or VV), then not only would there be a loss in SNR, but there would also be unwanted contributions from the cross-pol (HV) term. Thus, a hybrid-dual-pol SAR is not well suited to applications in which unadulterated “linearly-polarized” data products are required.

What is the SNR performance of a hybrid-quad-pol SAR? Analysis shows (see Appendix II) that SNR is preserved in the linear (H and V) output polarization basis if the input polarization basis is circular. This statement can be generalized, such that for any combination of input and output polarizations in a mixed-polarity quad-pol SAR, SNR is preserved. This should not come as a surprise, given the fundamental principles that support fully-polarimetric SAR architectures.

The results of Appendix II merit comment. Note that the noise term ($N_e$) is divided by 2 in the two like-polarized expressions (Eqs II-4 and II-5). This balances the fact that on transmission, the power allocated to either the H or the V polarization is half of the average power actually transmitted.

Note also that the relative noise ($N_e$) in the cross-polarized term (Eqn II-6) is divided by 4. This is a result of the half-power allocation (explained in the previous paragraph) combined with the added benefit of HV/VH reciprocity. This is consistent with same benefit enjoyed in conventional linearly-polarized quad-pol SARs [10].

5. HYBRID-POLARITY ADVANTAGES

5.1 Stokes parameter data products

In the dual-polarized case, the received signals in the linear basis are sufficient to calculate the four Stokes parameters, which are rotationally invariant with respect to geometric trends in the scene since the transmit polarization is circular. Data products derived from the Stokes parameters do not depend on the polarization basis of the observation. All information in the backscattered field is retained. In the quad-pol case, the Stokes parameters (often expressed in the 3x3 compressed format pioneered by JPL [11]) are interchangeable with those from a conventional linearly-polarized SAR. Thus, all analysis tools developed for conventional quad-pol SARs carry over to data products from a hybrid-polarity quad-pol SAR.

5.2 Comparable signal levels

Neither receive channel is disadvantaged by being cross-polarized. Mean signal levels in the two channels of an CL-
pol radar should always be comparable. For the same transmitted average power, the mean signal levels will be weaker by 3 dB than the signal level of the “like” or “expected” polarization in a conventional dual-polarized radar, hence 3 dB to 10 dB stronger than would be seen in the “cross” or “unexpected” polarized channel. Since the mean signal levels in the two receive channels have comparable levels, any cross-talk or other interference that may spill over from one channel into the other will not be further emphasized by a like-to-cross-polarized ratio.

5.3 Calibration

When viewing any scene at normal (e.g. vertical) incidence, the first- and second-order statistics of the signals in the two receive paths should be identical, regardless of the geometrical characteristics of the backscattering elements. This suggests a calibration strategy well-suited to an operational system, since there is no requirement for corner reflectors or other special controlled reference targets for this class of measurements. If in practice there are discrepancies (such as gain or spectral offsets), then these can be measured, and compensated. Likewise, the relative phase between the H and V components of the transmitted (circular) polarization, and the received polarizations (H and V) can be separately observed in real (random) backscatter, then compensated. These self-checking properties are unique to the hybrid-polarity architecture.

5.4 Error Sensitivity

A sensitivity analysis shows that the circular-polarization ratio [12] derived through a CL-pol SAR is less sensitive to channel imbalance by at least a factor of two than if explicitly calculated through the “same sense over opposite sense” ratio which is the traditional form in radar astronomy. The hybrid-polarity error sensitivity advantage is more pronounced when the relative signal-to-noise ratios of the two polarization components are included in the analysis.

5.5 Favorable Flight Hardware

In many specific cases, less RF hardware is required in the CL-pol architecture than for a competitive circularly-polarized design, which implies fewer losses, and fewer sources of potential channel-to-channel mismatch. For planetary or lunar missions, for which mass and power are severely limited, it has been shown that these hardware advantages coupled with the measurement capabilities point to hybrid-polarity as the optimum dual-pol architecture. It also is true that the implementation of a calibrated quad-pol radar is simpler, since there is no need to actively adapt receive channel properties to the expected signal levels between alternating like- and cross- polarized returns [13].

5.6 Range Ambiguities

It can be shown [7, 8] that range ambiguities in a quad-pol SAR are far less troublesome for a hybrid-polarity system than for a conventional linearly-polarized radar. There are two consequences of this advantage that follow immediately, including a wider accessible span of incidence angles, and a somewhat wider swath width.

6. CONCLUSIONS

Hybrid-polarity (transmitting on circular polarization and receiving coherently on orthogonal linear polarizations) emerges as an optimum architecture for any quad-polarized or fully-polarized SAR. This is true, because the engineering aspects of the radar can be optimized (minimum cross-talk, minimum ambiguity interference, ease of calibration, preservation of SNR on any polarization component, etc.) at no compromise—indeed no impact at all—on the measurements required of the system. Hybrid-polarity is also an advantageous form of compact polarimetry, in which only one polarization is transmitted, and the radar is required to be coherently dual-polarized on reception.

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APPENDIX I

Theorem—SNR is preserved in hybrid dual-polarity architecture for data expressed in the circularly polarized bases.

Let the single transmitted signal polarization be right-circular (RCP)

\[ E_R = E_b - jE_v \]  \hspace{1cm} (I-1)

Then the (complex) amplitudes from the H channel and the V channel following RCP transmission are

\[ A_{RH} = a_{Rh} - j a_{Rv} + n_1 \]
\[ A_{RV} = a_{Rv} - j a_{Rh} + n_2 \]  \hspace{1cm} (I-2)

Apply the standard assumptions that (a) the additive noise in each channel is complex zero-mean Gaussian, statistically independent of the signal, and statistically independent of the other additive noises, each of which have the same variance \( \langle |n|^2 \rangle = N_o \); (b) that the cross-polarized terms are reciprocal, such that \( a_{hv} = a_{vh} \); and (c) that the “like” component and its cross-product counterpart are statistically independent, such that \( \langle a_{hh} a^*_hv \rangle \). Then the “RR” component derived from the Stokes parameters is given by

\[ \frac{1}{2}(S_1 + S_2) = \langle |E_{RH}|^2 \rangle + N_o \]  \hspace{1cm} (I-3)

and the “LR” component is given by

\[ \frac{1}{2}(S_1 - S_2) = \langle |E_{RV}|^2 \rangle + N_o \]  \hspace{1cm} (I-4)

QED.

APPENDIX II

Theorem—SNR is preserved in hybrid quad-polarity architecture for arbitrary polarizations

Let the two transmitted signal polarizations, interleaved at Nyquist rate, be left-circular (LCP) and right circular (RCP)

\[ E_L = E_b + jE_v \]
\[ E_R = E_b - jE_v \]  \hspace{1cm} (II-1)

Then the (complex) amplitudes from the H channel and the V channel following the LCP transmission are

\[ A_{LB} = a_{Lh} + j a_{Lv} + n_1 \]
\[ A_{LV} = a_{Lv} + j a_{Lh} + n_2 \]

and following the RCP transmission are

\[ A_{RB} = a_{Rh} - j a_{Rv} + n_3 \]
\[ A_{RV} = a_{Rv} - j a_{Rh} + n_4 \]  \hspace{1cm} (II-3)

Apply the standard assumptions that (a) the additive noise in each channel is complex zero-mean Gaussian, statistically independent of the signal, and statistically independent of the other additive noises, each of which have the same variance \( \langle |n|^2 \rangle = N_o \); (b) that the cross-polarized terms are reciprocal, such that \( a_{hv} = a_{vh} \); and (c) that the “like” component and its cross-product counterpart are statistically independent, such that \( \langle a_{hh} a^*_hv \rangle \). Then the “HH” component derived from the Stokes parameters is given by

\[ \frac{1}{4} \langle |A_{LB} + A_{RB}|^2 \rangle = \langle |a_{hh}|^2 \rangle + \frac{1}{2} N_o \]  \hspace{1cm} (II-4)

Likewise the “VV” component is given by

\[ \frac{1}{4} \langle |A_{LH} - A_{RV}|^2 \rangle = \langle |a_{vv}|^2 \rangle + \frac{1}{2} N_o \]  \hspace{1cm} (II-5)

and the cross-product “VH” component is given by

\[ \frac{1}{16} \langle |A_{LB} - A_{RV} + j(A_{RH} - A_{RV})|^2 \rangle = \langle |a_{hv}|^2 \rangle + \frac{1}{2} N_o \]  \hspace{1cm} (II-6)

QED.
REFERENCES


