Design of a Circularly-Polarized VGOS Frontend for Simplified Mixed-Mode VLBI Observations

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Abstract In the interest of minimizing the complexity and the associated development costs necessary to conduct mixed-mode legacy/VGOS observations, a linear-to-circular polarization conversion network for linearly-polarized VGOS-compatible feeds was designed. Because this network is an integral component of the receiver frontend and the conversion is performed in hardware, this solution provides relief to requirements for data rates and correlation processing for mixed-mode observations. Furthermore, this solution circumvents software developments that would be necessary to support linearly-polarized observations by the IVS. In this paper, a network designed to convert linearly-polarized signals to a circular-basis is outlined. Numerical simulation of the conversion network's cross-polarization isolation indicates that it meets the VGOS signal chain 20 dB cross-polarization isolation requirement.

1 Introduction

Broadband radio telescope feeds with hardware realizations that meet the VGOS requirements [1, 2] are linearly-polarized (LP). However, as concluded in MMA Memo 208 [3], the arguments against the LP feed outweigh the arguments against circularly-polarized (CP) feeds. In fact, the argument that

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circular feeds are inherently narrow bandwidth [3] is void in consideration of the conversion network design described in Section 3. Furthermore, the need to measure an absolute polarization angle is not a requirement for VGOS observations. Hence, based on the MMA Memo 208 [3], one could argue that there are no drawbacks or limitations associated with CP feeds for the VGOS application.

In contrast to VGOS compatible feeds, legacy IVS stations are outfitted with S- and X-band feeds that observe the CP basis. This polarization dissimilarity does not inhibit mixed-mode (i.e., legacy vs. VGOS) observations, but the difference would complicate such observations in two important ways.

1.1 Observing Implications

Observation complexity arises because the signal-to-noise ratio of a single correlation is coupled to the difference in parallactic angle between the two linearly-polarized VGOS stations. The signal-to-noise ratio can be decoupled from the difference in parallactic angle, but this necessitates recording and correlating twice the amount of data in the mixed mode scenario than is necessary if both receivers detected circular polarization. As such, dissimilar polarization sensing in mixed-mode observations has significant implications for those stations that are data transfer bandwidth limited and software correlators that are computing limited.

1.2 Operational Implications

Dissimilar polarization sensing also complicates the VLBI experimental setup relative to existing procedures. Assurance of accurate data flow through the IVS processing chain will require significant development, testing, and integration of software to support mixed-mode and new VGOS observing scenarios. The development of such software will extend across a major portion of the IVS processing chain from station scheduling to post-correlation data processing. Because the development of such software will necessarily span across multiple subsystems, the time and cost to develop and verify the performance of these efforts in the overall processing chain is quite significant.

2 Assessment of Conversion Network Performance

The performance of the LP-to-CP conversion network is assessed by exciting the proposed network with orthogonal phasor voltages V_x and V_y that are linear representations of right and left hand circularly-polarized wavefronts [4], RCP and LCP, respectively:

$$\left\{V_x = 1, V_y = e^{-i\frac{\pi}{2}}\right\} \equiv RCP$$
$$\left\{V_x = 1, V_y = e^{i\frac{\pi}{2}}\right\} \equiv LCP \quad (1)$$

The phasors V_x and V_y are combined with appropriate $90°$ phase shifts to form phasors equivalent to those that would be detected at the RCP and LCP ports of a dual circular feed. An ideal $90°$ hybrid [5] implements the necessary combination to achieve this result which is described succinctly by the following:

$$\begin{bmatrix} V_{RCP} \\ V_{LCP} \end{bmatrix} = \begin{bmatrix} 1 & e^{i\frac{\pi}{2}} \\ 1 & e^{-i\frac{\pi}{2}} \end{bmatrix} \begin{bmatrix} V_x \\ V_y \end{bmatrix} \quad (2)$$

When the network is excited with the V_x and V_y RCP phasors given in Equation 1, the cross-polarization isolation (CP_{iso}) performance of the network is given by the following:

$$CP_{iso} = 20\log_{10}\left(\frac{V_{RCP}}{V_{LCP}}\right) \quad (3)$$

The matrix elements in Equation 2 are defined by the ideal hybrid and describe an equivalent amplitude and $90°$ phase relationship between the V_x/V_y phasors. In practice, it is not possible to maintain a perfect amplitude and phase match between V_x and V_y with physical components, particularly over more than a decade of bandwidth. Deviation from these match conditions results in cross-polarization contamination and degrades the performance of the network. In the following section, the expected level of contamination is outlined given the performance of a physically realizable hybrid and the LNAs necessary to support low noise operation of the receiver frontend.
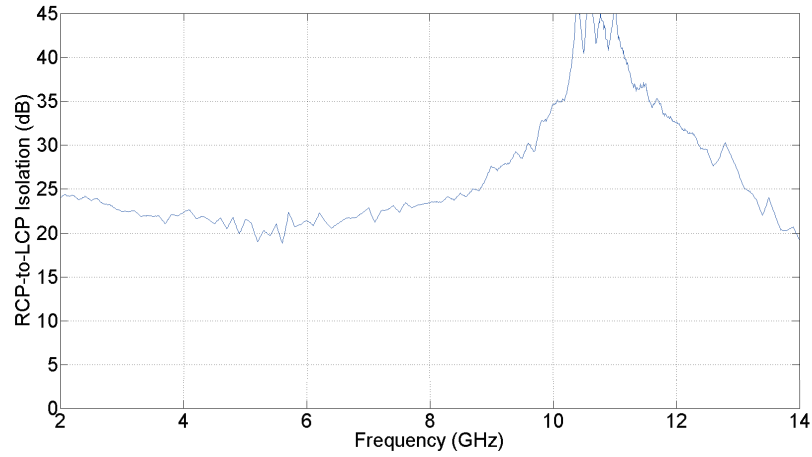
3 Conversion Network Design

Figure 1 outlines a block diagram of the conversion design including the $90°$ hybrid, low noise amplifiers (LNAs), an amplitude matching attenuator, and a phase matching delay line.

The LNAs are both Caltech model CRYO1-11; serial numbers 127 and 128 were purchased by Haystack Observatory. The $90°$ hybrid is Krytar model 1830, and the delay line is Pasternack model PE8200, while the attenuator is a generic model (e.g., MiniCircuits). The attenuator and delay line are incorporated to improve the amplitude and phase matching between the V_x and V_y phasors in order to maximize the cross-polarization performance [6]. To assess the performance of the LP-to-CP conversion network, the 2–14 GHz electrical network parameters (i.e., S-parameters) of each component were measured individually. The cascade shown in Figure 1 was analyzed through numerical simulation by importing each set of network parameters into a MATLAB RF simulation to assess the performance of the conversion network design. For each frequency, the simulation computes the four elements of the matrix presented in Equation 2 given the imperfections in the individual components. The cross-polarization performance at each frequency is computed by applying Equation 3, and the resulting performance is shown in Figure 2. In order to achieve the performance shown in Figure 2, it was necessary to attenuate and delay the V_y phasor by 3 dB and 5.5 ps, respectively.
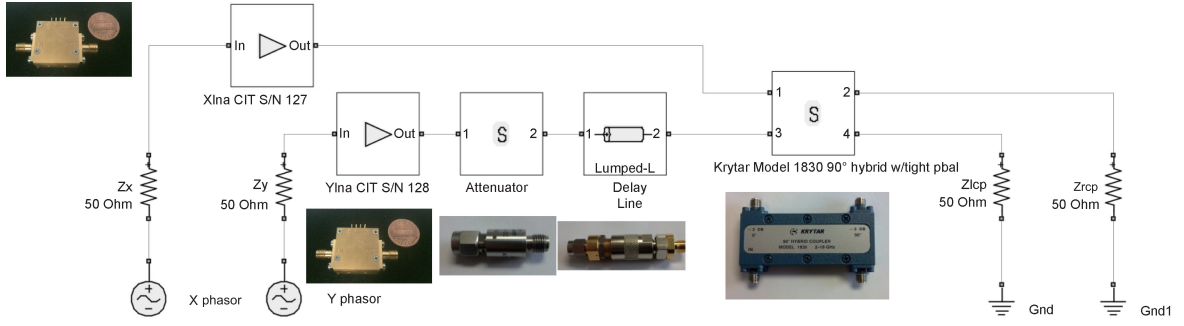
Fig. 1 Schematic diagram of the LP-to-CP conversion network. Also shown are the LNAs, attenuator, phase trimmer, and 90° hybrid that were measured to analyze the performance of the network.

Fig. 2 Cross-polarization isolation performance of the conversion network shown in Figure 1. This performance was obtained from numerical simulation of the conversion network incorporating the measured electrical parameters of the components also shown in Figure 1.

4 Conclusions/Future Work

The drawbacks of a linearly-polarized VGOS radio telescope feed outweigh those of a circularly-polarized feed. Regarding IVS observations and operations in LP, the drawbacks are increases in data rate for mixed mode observations and operational software support for LP operations. Support of LP observations will require significant software development that spans IVS sub-systems from scheduling to post-correlation processing as outlined in Section 1. As described in Section 1, according to [3], one can argue that there are no drawbacks associated with CP feeds; however, this presupposes that such a radio telescope feed is in existence. While the design of a conversion network necessary to emulate a CP feed that will meet VGOS cross-polarization requirements [7] exists (see Section 3), this feed has yet to be fabricated and tested in an anechoic chamber. Fabrication costs are of order 5K USD with a one time verification testing cost of approximately 10K USD. The fabrication and testing of such a feed could be completed in approximately six months with dedicated efforts, which is considerably less time than to overhaul the various software packages from scheduling to post-processing so that they may support LP observations in the IVS network.

It should also be noted that other techniques were proposed for converting LP signals to CP in backend processing and/or post-correlation processing. These techniques suffer from the need to observe a fiducial

source to calibrate the time-dependent amplitude and phase differences between the two LP channels. These differences are introduced by instrumental effects, and their removal through calibration is necessary to ensure adequate cross-polarization isolation between the RCP and LCP channels. One may argue that phase and noise calibration corrections can compensate for such instrumental errors; however, implementation of these corrective measures plays a crucial role in the utility of this information to perform polarimetric corrections. Specifically, it is crucial that phase and amplitude calibration signals be injected at the same physical point in the receiver chain (i.e. before the LNA). If not, systematic errors may be introduced through the correction procedure.

Such a calibration procedure is not necessary for standard operations with the design outlined in Section 3; the cross-polarization performance is verified through independent measurements in the anechoic chamber. Because this design incorporates a bare minimum of active components (i.e. only LNAs), this performance is not expected to drift over time. This assumption can be asserted if the conversion network is contained within the frontend vacuum chamber, though not necessarily cooled by the refrigerator. However, the LNA amplitude and phase must also remain stable over time to avoid degradation in the cross-polarization isolation performance of the conversion network. While there is no reason to expect the LNA's gain and phase to drift over time while cooled in the cryogenic chamber, this must be verified as part of the testing process. Furthermore, LNAs can fail for a variety of reasons. Because the conversion network is balanced based upon the characteristics of the LNAs, replacement of an LNA will require the network's amplitude and phase trim settings to be modified in order to maintain matching and good cross-polarization isolation performance.

Acknowledgements

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