Optimizing Global VLBI Calibration with PolConvert

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Abstract This paper presents the application of PolConvert in a global VLBI experiment using the VLBI Global Observing System (VGOS). Through calibration processes and diagnostic tests, we demonstrate the successful conversion of visibilities to a circular basis, essential for achieving high accuracy in geodetic VLBI. Our analysis reveals stable cross-polarization gains over time, suggesting a practical approach of storing these gains in a database for direct application in future experiments. This streamlined process eliminates the need for repeated calibration, facilitating the retrieval of Stokes I values directly from the correlator data. Overall, our findings contribute to enhancing the efficiency and accuracy of VGOS observations for geodetic astrometry.

Keywords VGOS, geodesy, VLBI, calibration

1 Introduction

Geodetic Very Long Baseline Interferometry (VLBI) is a space-geodetic technique that utilizes a globally distributed array of radio telescopes to observe distant radio sources, typically quasars. These observations create a quasi-inertial celestial reference frame, known as the International Celestial Reference Frame (ICRF [1]). VLBI is unique in its ability to measure the Earth's absolute orientation in space, making it crucial for meeting the accuracy requirements of the global geodetic reference frame (GGRF). Additionally, it provides Earth Orientation Parameters (EOPs), which are essential for the operation of satellite missions. Furthermore, astronomical imaging techniques allow the obtaining of images of radio source structures at sub-milliarcsecond (sub-mas) resolution. The impact of source structure on geodetic residuals is comparable to the combined effect of all station-based errors [2]. Consequently, accurate models of source structure from astronomical analysis can help to correct structure delays in geodetic VLBI analysis.

The VLBI Global Observing System (VGOS) is the next-generation geodetic VLBI system coordinated by the International VLBI Service for Geodesy and Astrometry (IVS). Its goal is to achieve 1 mm position accuracy and 0.1 mm/year velocity stability on a global scale. To meet these accuracy requirements, it is necessary to attain picosecond precision in the group delays between the VGOS antennas. Achieving this precision demands the use of ultra-wideband receivers that cover a broad frequency range, from 2 GHz to 14 GHz [3].

There is a dichotomy between polarization receivers in radio astronomy: they employ either a linear basis or a circular basis, each with its own advantages and disadvantages.

The main advantage of circular polarizers is that the parallactic angle (the geometric effect reflecting the orientation of the sky relative to the antenna mount) is a phase correction when observing in a circular polarization basis, making this effect easy to calibrate. For this reason, circular receivers have been commonly used for VLBI observations, which involve extremely long baselines and introduce significant differences in the parallactic angles of each antenna.

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However, circular polarizers require extra hardware for conversion to circular polarization, leading to two main drawbacks. First, this additional hardware may introduce noise and degrade the polarization purity of the receiver, resulting in higher instrumental polarization and a lower signal-to-noise ratio (SNR). Second, circular feeds are optimized for a specific frequency, and larger bandwidths introduce higher instrumental polarization, reducing polarization purity as the frequency deviates from the optimal range.

In contrast, linear feeds offer high polarization purity, resulting in very low instrumental polarization across wider bandwidths and requiring fewer quasi-optical devices in the frontend. For these reasons, linear-polarization receivers are preferred for VGOS, given the extremely wide bandwidths required.

To handle linear feeds in VLBI, we use PolConvert [4], a software containing algorithms that estimate the instrumental cross-polarization bandpass (both in amplitude and phase) between X and Y polarizers for each antenna with linear feeds in the VLBI observations. This information is then used to convert the data as if circular polarizers had been employed. This conversion process, known as *polconversion*, allows us to combine the advantages of both linear and circular receivers. Moreover, it enables the use of legacy VLBI calibration algorithms, which are all based on observations with circular-polarization receivers.

This work is structured as follows. In Section 2, we describe the data calibration process. In Section 3, we present and discuss the results of PolConvert. Finally, in Section 4, we summarize our conclusions.

2 Data Calibration

In this section, we summarize the calibration process for the data obtained during a global VGOS 24-hour session using an approach based on PolConvert. For a comprehensive and detailed description of the entire calibration process, we refer to the publication describing the calibration pipeline [6].

To test the new PolConvert features for use on global arrays, we used data from the VGOS session VO2187, which involved eight antennas: Goddard (GS), Ishioka (IS), Kokee (K2), McDonald (MG), the twin Onsala telescopes (OE and OW), Westford (WF), and Yebes (YJ). The total recorded bandwidth was divided into 32 spectral windows (spw), arranged into four spectral bands, and distributed across a wide frequency range from 3 GHz to 11 GHz.

The conversion from linear to circular polarization is primarily affected by the cross-polarization bandpass, which is produced by the different optical paths and electronic gains of the X and Y channels. Therefore, it is necessary to estimate the cross-polarization gains of each antenna, in both phase and amplitude, for all spectral windows. These gains are then applied to convert the visibilities to a circular polarization basis.

PolConvert selects a calibration scan and uses the phase-calibration tones (phasecal tones) produced by DiFX, which are equally spaced in frequency. It takes the phase difference between the X and Y tones as a priori information and applies this difference to solve the cross-polarization phase from the receiver frontend to the injection of phasecal tones, using a Global Cross-Polarization Fringe Fitting. For amplitude calibration, because we lack a priori information, PolConvert must solve for all the instrumental gains.

We can also use the phasecals to estimate the remaining instrumental phases between the polconverted visibilities. These instrumental phases have two contributions: the ad-hoc phases, which we estimate by subtracting IONEX priors, and the instrumental tone phase, ϕ_{pc}, which we estimate using a multitone mode, similar to that of the fourfit program.

The multitone mode estimates the tone delay, τ_{pc}, from the phasecals, ϕ_i, in each spectral window and computes the instrumental tone phase as the average of the tone residual phases centered at the reference spw frequency, ν_0, after subtracting the tone delay:

$$\phi_{pc} = \left\langle \phi_i - 2\pi\tau_{pc}(\nu_i - \nu_0) \right\rangle . \quad (1)$$

Because the difference between the X and Y phasecal tones is already accounted for in the polconversion, we only need to apply the absolute phasecal in our reference polarization channel. Moreover, as the phase between R and L is calibrated as a byproduct of PolConvert, this absolute phasecal can be interpreted as the phasecal of both R and L.

In Figure 1, we present the residual phasecal tones of the Y polarization channel (i.e., the reference polarization) for three representative antennas across the complete VGOS bandwidth. These residual tones are obtained after subtracting the tone phases estimated using Equation 1. We observe clear outlier phasecals,

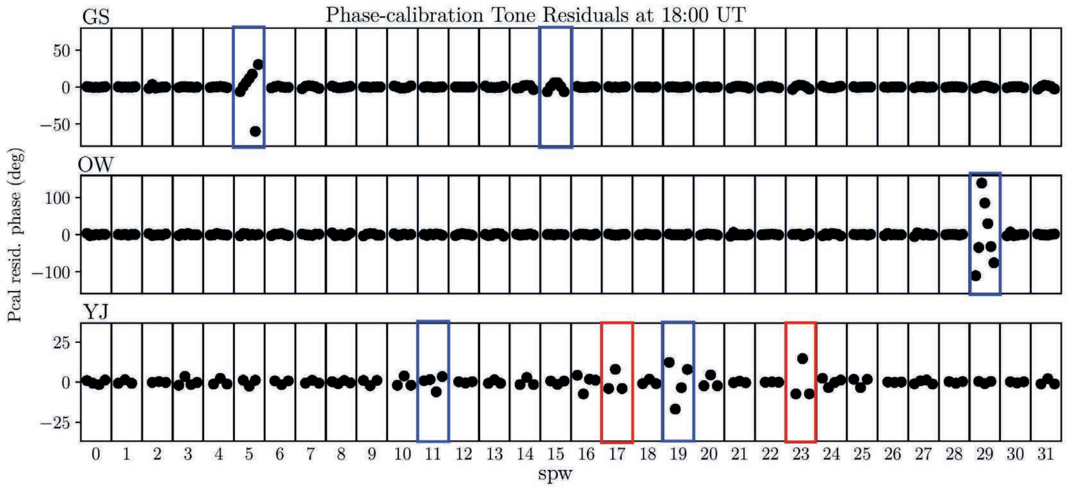

Fig. 1 Residual phase-cal tones after subtraction of the estimated instrumental delays. No outlier tones have been removed. Blue boxes highlight clear outliers, such as those for GS in spws 5 and 15, OW in spw 29, and YJ in spws 11 and 19. Red boxes indicate outliers for YJ in spws 17 and 23, which we were unable to identify.

with non-linear within the spectral window. To estimate the tone delays (τ_{pc}) and retrieve unbiased instrumental tone phases (ϕ_{pc}), we remove these outliers using the available tones. This is feasible because the injection of phasecals covers the full band in intervals of 5 MHz at each station, ensuring six to seven phase-cal tone detections per spw. However, an exception is the Yebes antenna, where the phase-cal tones are spaced at intervals of 10 MHz, resulting in only three to four usable tone detections per spw. This limitation, in cases like YJ spw 23, makes it impossible to identify the actual outlier tone, degrading the instrumental phase calibration, as shown in the following section.

3 PolConvert Results

In this section, we focus on discussing the results obtained from PolConvert, which also serve as diagnostic tests to evaluate its performance.

For the Global Fringe Fitting, clear well-defined fringes (the multi-band X/Y delay peaks) are needed. In Figure 2, we present the cross-polarization bandpass estimated by PolConvert, for one calibration scan. The left panel shows the phase difference and amplitude ratio between X and Y across all spws (from 3 to 11 GHz). The phases exhibit smooth connectivity without discontinuities, indicating that the cross-polarization bandpass across the VGOS bandwidth can be explained by a single-band delay. The amplitude ratios, stable around 1, suggest similar electronic gains for both polarization channels. The right panel shows the bandpass in the delay space, showing clear fringes for each antenna.

In the figure, we include the peak position of the fringes from another session, ER2201 [7], observed months later. The fringes demonstrate stability over time, with differences of only a few picoseconds between the two epochs. Therefore, this phase stability may be consistent across the different experiments. This claim is further supported by an additional comparison, shown in Figure 3, of the X/Y phases between experiments VO2187 and ER2201 and the European VGOS (EU-VGOS) experiment EV0287, conducted two years before the VO2187 campaign. Differences in the X/Y phases are only observed in YJ, due to changes in the phasecal system.

Consequently, we obtain fringes that exhibit stability over time, with small differences of only a few picoseconds, provided that the phasecal system remains stable between epochs. To streamline this process, we propose dedicating a short period between VGOS experiments to estimate the cross-polarization delays of each antenna and store them in a database. These delays would only need updating every few months or in

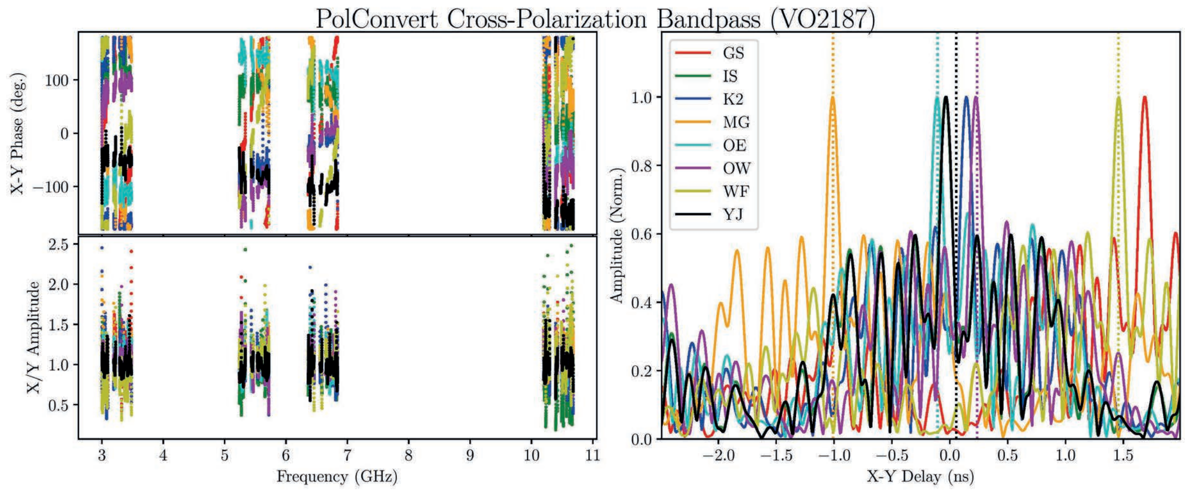

Fig. 2 Left: Cross-polarization bandpasses for experiment VO2187 (phases at top; amplitudes at bottom), as estimated with PolConvert. Right: multiband cross-polarization delays (computed from the values shown at left). Dotted lines (same colors) mark the cross-polarization multiband delays from experiment ER2201.

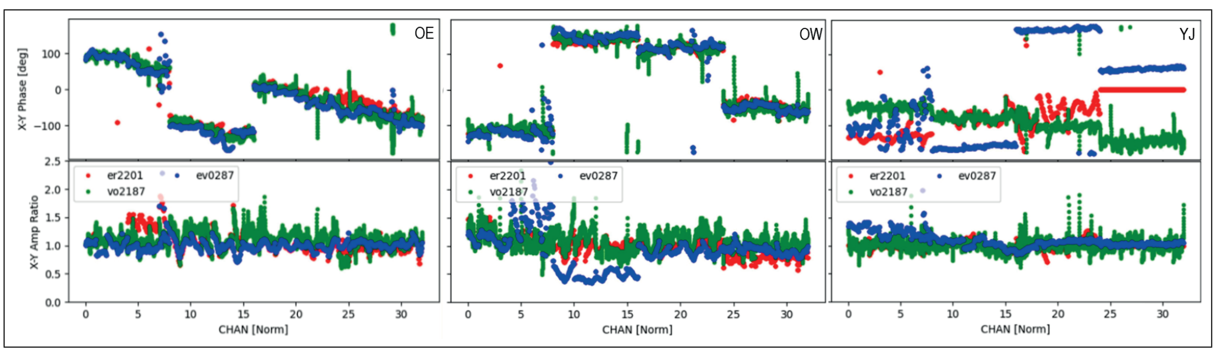

Fig. 3 Cross-polarization bandpasses (phases at top; amplitudes at bottom) for experiments EV0287 (blue), ER2201 (red), and VO2187 (green), for the OE (right), OW (middle), and YJ (right) antennas.

the event of reported changes in the phasecal system of an antenna. By adopting this approach, we can use these fringes to directly convert the visibilities from the correlator to a circular polarization basis, avoiding repeating the entire process.

As a byproduct of PolConvert, the phase difference between the RR and LL visibilities is automatically calibrated. Consequently, rather than a signal divided into the four correlations in the linear basis, we obtain the entire signal coherently combined into one Stokes I value for each spectral window, which is suitable for geodetic astrometry. To prove this, in Figure 5 we present the phase difference between the RR and LL visibilities for all spectral windows, directly after processing by PolConvert and applying the correction of the parallactic angle. The phase offsets are averaged for all scans and sources, revealing a constant and stable phase, with small deviations of only a few degrees and a dispersion across the experiment of approximately one degree.

After applying the fringes to the whole experiment and converting from linear to circular polarization, we expect higher parallel-hand correlations (RR and LL) and lower cross-hand correlations (RL and LR), as they are related to the source intrinsic fractional polarization. To validate our results, we conduct a final test by comparing the fringe amplitudes. In Figure 4, we present the fringe amplitude peaks for all correlation products, showing consistently higher RR and LL correlations for all scans, except for spw 23, proving that PolConvert performed effectively.

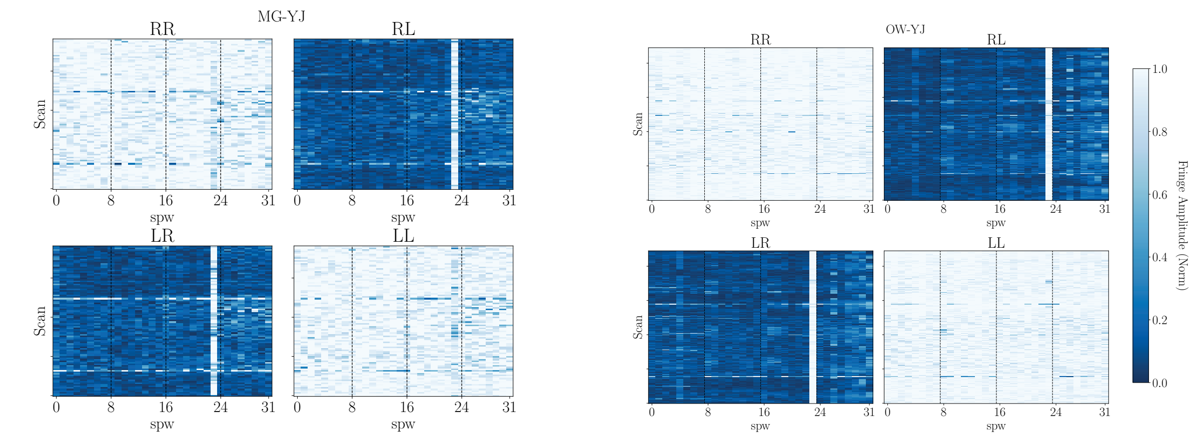

Fig. 4 Fringe peaks for baselines MG–YJ (left) and OW–YJ (right), as a function of spw (horizontal axis) and scan (vertical axis). All four correlation products are shown.

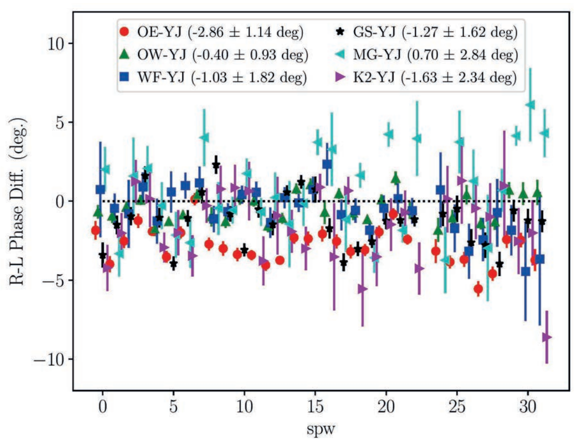

Fig. 5 RR/LL phase for all spw, averaged for all scans and sources. The baselines have been referred to the YJ antenna, after removing spw 23. Different baselines are slightly shifted in the spw axis, for clarity. The complete statistics for each baseline, averaged over spw, are included in the figure labels.

4 Conclusions

In summary, we applied PolConvert to a global configuration of VGOS antennas during a 24-hour experiment with subarraying, where European and American antennas operated separately. Through various assessment tests and sanity checks, we confirm the successful conversion of visibilities to a circular basis.

Furthermore, our analysis indicates that the cross-polarization (X/Y) gains in both phase and amplitude remain stable over scales of several months or years, as evidenced by our examination of European antennas. Based on these findings, we propose storing the gains in a database and directly applying them to convert visibilities from the correlator to a circular basis. This approach allows for the retrieval of Stokes I directly without the need for estimating them anew for each experiment.

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