Cross-polarization gain calibration of linearly polarized VLBI antennas by observations of 4C 39.25

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Abstract

Radio telescopes with dual linearly polarized feeds regularly participate in Very Long Baseline Interferometry (VLBI). One example is the VLBI Global Observing System (VGOS), which is employed for high-precision geodesy and astrometry. In order to achieve the maximum signal-to-noise ratio, the visibilities of all four polarization products are combined to Stokes I before fringe-fitting. Our aim is to improve cross-polarization bandpass calibration, which is an essential processing step in this context. Here we investigate the shapes of these station-specific quantities as a function of frequency and time. We observed the extragalactic source 4C 39.25 for six hours with a VGOS network. We correlated the data with the DiFX software and analyzed the visibilities with PolConvert to determine the complex cross-bandpasses with high accuracy. Their frequency-dependent shape is to first order characterized by a group delay between the two orthogonal polarizations, in the order of several hundred picoseconds. We find that this group delay shows systematic variability in the range of a few picoseconds, but can remain stable within this range for several years, as evident from earlier sessions. On top of the linear phase-frequency relationship there are systematic deviations of several tens of degrees, which in addition are subject to smooth temporal evolution. The antenna cross-bandpasses are variable on time scales of 1 hour, which defines the frequency of necessary calibrator scans. We find that this group delay shows systematic variability in the range of a few picoseconds, but can remain stable within this range for several years, as evident from earlier sessions. On top of the linear phase-frequency relationship there are systematic deviations of several tens of degrees, which in addition are subject to smooth temporal evolution. The antenna cross-bandpasses are variable on time scales of 1 hour, which defines the frequency of necessary calibrator scans. The source 4C 39.25 is confirmed as an excellent cross-bandpass calibrator. Dedicated surveys are highly encouraged to search for more calibrators of similar quality.
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Key Points:

\begin{itemize}
  \item The new-generation geodetic radio telescopes observe two orthogonal linear polariza-
    tion directions.
  \item Calibration of the gain differences between the two polarizers is necessary to max-
    imize the signal-to-noise ratio of observations.
  \item We investigate these cross-polarization gain differences and their temporal evo-
    lution for selected antennas.
\end{itemize}

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Abstract

Radio telescopes with dual linearly polarized feeds regularly participate in Very Long Baseline Interferometry (VLBI). One example is the VLBI Global Observing System (VGOS), which is employed for high-precision geodesy and astrometry. In order to achieve the maximum signal-to-noise ratio, the visibilities of all four polarization products are combined to Stokes $I$ before fringe-fitting. Our aim is to improve cross-polarization bandpass calibration, which is an essential processing step in this context. Here we investigate the shapes of these station-specific quantities as a function of frequency and time. We observed the extra-galactic source 4C 39.25 for six hours with a VGOS network. We correlated the data with the DiFX software and analyzed the visibilities with PolConvert to determine the complex cross-bandpasses with high accuracy. Their frequency-dependent shape is to first order characterized by a group delay in the range of a few picoseconds, but can remain stable within this range for several years, as evident from earlier sessions. On top of the linear phase-frequency relationship there are systematic deviations of several tens of degrees, which in addition are subject to smooth temporal evolution. The antenna cross-bandpasses are variable on time scales of ~ 1 hour, which defines the frequency of necessary calibrator scans. The source 4C 39.25 is confirmed as an excellent cross-bandpass calibrator. Dedicated surveys are highly encouraged to search for more calibrators of similar quality.

1 Introduction

Antennas participating in Very Long Baseline Interferometry (VLBI) have traditionally been observing with circularly polarized feeds (Thompson et al., 2017). New developments make it necessary that antennas also observe in linear polarization. One such example, and the subject of this paper, is the VLBI Global Observing System (VGOS, Petrachenko et al., 2009, still under the name of “VLBI2010”). Aimed at improving the precision of geodetic and astrometric VLBI (Sovers et al., 1998) down to mm and sub-mm/year scales, it was recognized that this requires an extension of the observed bandwidth to the range of 2 to 15 GHz. Such a bandwidth is best realized with the use of linear feeds, because $\lambda/4$-plates, necessary for the realization of circular polarization, do not work over such a large frequency range. See, however, Abdalmalak et al. (2020) for the possibility of using circularly polarized log-spiral antennas for reception and Jaradat et al. (2021) for emission of broadband radio signals.

Using linear feeds requires that the telescopes simultaneously observe two perpendicular polarization directions. Throughout this paper, we are going to refer to these polarization directions as “H” for horizontal and “V” for vertical. In the context of VGOS, these polarization directions are also referred to as “X” and “Y”. However, this terminology is invalid because the linear feeds of VGOS antennas are not aligned with celestial coordinate axes. Two polarization directions are necessary because non-zero parallactic angle differences between the telescopes of long baselines generally cause a loss of signal-to-noise ratio (SNR) of the parallel hand polarization products. In order to obtain the full SNR for all parallactic angles it is necessary to combine all four polarization products with each other to form Stokes $I$ for fringe-fitting. The formula for Stokes $I_{ab}$ for a baseline consisting of telescopes a and b is

$$I_{ab} = (H_aH_b + \rho_{ab}\rho_a^*V_aV_b)\cos\Delta + (\rho_{ab}^*H_aV_b - \rho_aV_aH_b)\sin\Delta,$$

(1)

where the terms $H_aH_b$ and $V_aV_b$ are the “parallel-hand” linear polarization correlation products, i.e., $H_aV_b$ and $V_aH_b$ and the “cross-hand” products. The coefficients $\rho_{ab}$ denote the complex gain differences between the H and V polarizers at each antenna a and b, in terms of amplitude $A$ and phase $\varphi$, i.e., $\rho = Ae^{i\varphi}$. Finally, $\Delta$ is the parallactic angle difference between the antennas a and b. Obviously, for the realization
of coherent summation of the correlator visibilities, the computation of Stokes $I$ requires information about the complex gain differences $\rho$ between the two linear feeds of each antenna participating in the observation. We will refer to this quantity, which is a function of frequency over the observed bandwidth, as the cross-polarization bandpass (or simply cross-bandpass). The investigation of the cross-bandpasses, both as a function of frequency and time, i.e., $\rho(\nu, t)$, is the subject of this article. Equation (1) makes it evident that well-determined cross-polarization bandpasses are a key quantity for any VLBI experiments in which linearly polarized antennas participate.

Cross-bandpass calibration is a processing step that is commonly carried out for each VGOS session after correlation and before final fringe-fitting. The approach that is currently being applied is to use observations of the session to be processed also for the determination of the cross-bandpasses. One procedure, developed at MIT Haystack Observatory, applying the program fourfit, is described in Niell et al. (2018), and has become the generally adopted method for the processing of VGOS experiments (A detailed description of the procedure can be found in this document: https://www.haystack.mit.edu/wp-content/uploads/2020/07/docs_hops_000_vgos-data-processing.pdf, accessed on October 2, 2023, as all other links in this article). However, the software PolConvert (Martí-Vidal et al., 2016) offers an alternative route for VGOS data processing. For the investigations at hand, we make use of the capability of PolConvert to estimate the cross-polarization gains with configurable spectral resolution and time averaging.

The principal functionality of PolConvert is to convert visibilities of linearly polarized data to a circularly polarized basis. For optimal results, cross-polarization bandpass calibration is an essential processing step. Compared to the cross-bandpass calibration implemented in the Haystack Observatory Postprocessing System (HOPS), the algorithm in PolConvert is potentially superior, because it makes use of both amplitude and phase of the visibilities, and also offers the possibility to use the instrumental phase-calibration signal (“phase-cal”) to determine delays between H and V polarization. The code performs a least-squares fitting of the visibility data directly without fringe-fitting.

PolConvert has been used to convert ALMA observations from linear to circular for the Event Horizon Telescope (Event Horizon Telescope Collaboration et al., 2019) and also for the Global mm-VLBI Array (Zhao et al., 2022). However, in both of these cases, the cross-bandpasses were calibrated using pre-determined calibration tables. The applicability of PolConvert to VGOS data has been demonstrated by Alef, Tuccari, et al. (2019) and further described by Martí-Vidal et al. (2021), in which case the cross-bandpasses are determined from calibration scans. The different processing steps of PolConvert can be run separately. Here we make use of the step that determines the cross-polarization gains as a tool to estimate these quantities for the analysis presented in this article.

Because cross-polarization bandpass calibration is a crucial step in the VGOS processing chain, the aim of our investigation is to measure and characterize the cross-bandpasses of VGOS antennas. For an optimal measurement, two requirements are of essential importance. First, the observed radio source has to be a suitable calibrator. Prior to our investigations presented here, we examined a number of calibrator scans that were observed as part of research and development (R&D) sessions of the EU-VGOS project (Alef, Anderson, et al., 2019a; Jaron et al., 2021; Albentosa et al., 2023). An inspection of the cross-bandpass solutions from multiple calibrator scans has revealed that there are huge differences in their quality and that there is an obvious dependency on the observed source. There is one source for which the results stand out compared to other sources, and this is the radio-loud active galactic nucleus (AGN) 4C 39.25. Secondly, the observing geometry is critical, in particular the coverage of the parallactic angle. For the research presented here, we designed a session that uses this knowledge for the optimal measurement of the cross-bandpasses of the VGOS antennas that participated in our observations.

Another possibility of realizing dual circular polarization for broadband receivers, such as VGOS, is the use of so-called 3dB/90° microwave hybrid couplers. These devices

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offer a hardware solution to convert dual linear into dual circular polarization, and can
be installed at the telescopes before the low-noise amplifiers. Their potential suitabil-
ity for VGOS has been described in a technical report (García-Pérez, Terceroc, Malo,
& López-Pérez, 2018). In another technical report García-Pérez, Terceroc, Malo, Gal-
lego, and López-Pérez (2018) discuss these devices as a possibility for the BRAND re-
ceiver (Alef, Anderson, et al., 2019b). In the time of writing, the only VGOS observing
mode that has so far been carried out is to record the data in linear polarization and ac-
count for this during the digital data processing after correlation, and we are going to
assume this mode in the remainder of this article. It is important to note that also in
the case that the data are recorded in dual circular polarization, if ones wants to com-
bine the data to Stokes $I$, it is still necessary to determine the cross-polarization band-
pass (between R and L) and to properly calibrate the data. Also, an additional device,
such as a hybrid coupler, comes at the risk of introducing additional systematic errors
(as discussed in the two technical reports mentioned) and degrading the signal-to-noise
ratio. For these reasons, we tentatively conclude that for broadband observations the use
of dual linear polarization along with a software solution is the better option. However,
we strongly encourage experiments to test observing with hybrid couplers. More infor-
mation about hybrid couplers can be found in a number of publications (Malo-Gomez
et al., 2009; Khudchenko et al., 2019; López-Pérez et al., 2021; Kooi et al., 2023).

The paper is organized as follows. We give a brief introduction to the astrophys-
ical object 4C 39.25 in Sect. 2. In Sect. 3 we describe the properties of our VGOS R&D
session. We describe our methods in Sect. 4 and present our results in Sect. 5. We give
our conclusions in Sect. 6.

2 The source 4C 39.25

During the inspection of the results of cross-bandpass calibration from different scans
that were initially scheduled for this purpose in previous sessions, it turned out that the
quality of the results was variable and that there was an apparent dependency on the
radio source under observation. Among the many sources that were each observed mul-
tiple times with 2-3 minute scans, one source always stood out in terms of cleanliness
of the cross-bandpass solution, and that was 4C 39.25. For this reason, we have chosen
this source as the target for our dedicated experiment with the aim of measuring and
investigating the cross-bandpasses of VGOS antennas.

Discovered during a survey of radio sources (Pilkington & Scott, 1965), 4C 39.25
(B1950 name 0923+392) soon became a target of astrophysical interest. Linear polar-
ization of its radio emission was detected (Berge & Scielstad, 1969; Aller, 1970), and Bignell
and Seaquist (1973) even published a time-series of polarization. Nartallo et al. (1998)
classify the source as a “low polarization quasar” (see their Table 2), referring to the re-
search by Impey and Tapia (1990). Indeed, Impey and Tapia (1990) report a polariza-
tion of $p = 0.5 \pm 0.5$, which indicates that $p$ is equal to zero, i.e., that the source is not
polarized. However, this value has been derived for the optical emission from this source
(see their Table 1). In the same article, the authors also come to the conclusion that opti-
tical and radio polarization are not correlated, which in turn means that it cannot be
ruled out that the radio emission from 4C 39.25 could still be polarized to some degree.
Alberdi et al. (2000) present VLBI observations at 15, 22, and 43 GHz, showing that fea-
tures in the jet are polarized while the component that they interpret as the core is not
polarized at radio wavelengths. In addition to that, Alberdi et al. (2000) report some
features in the jet to move at apparently superluminal speeds, implying that Doppler
boosting of the intrinsic emission plays an important role for this source. The source is
also in the MOJAVE Survey (see https://www.cv.nrao.edu/MOJAVE/sourcepages/
0923+392.shtml).
Table 1. List of stations included in the schedule for the session er2201.

<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
<th>Description</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg</td>
<td>MACGO12M</td>
<td>McDonald Geodetic Observatory (MGO), TX, USA</td>
<td>1</td>
</tr>
<tr>
<td>Oe</td>
<td>ONSA13NE</td>
<td>Onsala 13-m antenna north-east, Sweden</td>
<td></td>
</tr>
<tr>
<td>Ow</td>
<td>ONSA13SW</td>
<td>Onsala 13-m antenna south-west, Sweden</td>
<td></td>
</tr>
<tr>
<td>Wf</td>
<td>WESTFORD</td>
<td>Westford, MA, USA</td>
<td></td>
</tr>
<tr>
<td>Ws</td>
<td>WETTZ13S</td>
<td>Wettzell 13-m antenna south, Germany</td>
<td></td>
</tr>
<tr>
<td>Yj</td>
<td>RAEGYEB</td>
<td>13-m at Yebes, Spain</td>
<td>2</td>
</tr>
</tbody>
</table>

1 For Mg, data only partly available after 2 hours.
2 Yj did not observe VGOS band D.

Table 2. Frequency setup. The four VGOS bands are labeled A-D, each has a bandwidth of 480 MHz with a frequency range as given in the table. Each band is further divided into eight IF sub-bands with a bandwidth of 32 MHz each, the upper bounds of which are given in the table.

<table>
<thead>
<tr>
<th>Band</th>
<th>Min. freq.</th>
<th>IF upper bounds [MHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3000.4</td>
<td>3032.4 3064.4 3096.4 3224.4 3320.4 3384.4 3448.4 3480.4</td>
</tr>
<tr>
<td>B</td>
<td>5240.4</td>
<td>5272.4 5304.4 5336.4 5464.4 5560.4 5624.4 5688.4 5720.4</td>
</tr>
<tr>
<td>C</td>
<td>6360.4</td>
<td>6392.4 6424.4 6456.4 6584.4 6680.4 6744.4 6808.4 6840.4</td>
</tr>
<tr>
<td>D</td>
<td>10200.4</td>
<td>10232.4 10264.4 10296.4 10424.4 10520.4 10584.4 10648.4 10680.4</td>
</tr>
</tbody>
</table>

Figure 1. Frequency setup of our observations. The letters A, B, C, and D refer to the VGOS band labels. See Table 2 for details.

3 The VLBI session er2201

For the purpose of measuring the cross-bandpasses of VGOS antennas, we carried out a dedicated R&D session. The principal idea was to observe 4C39.25, which we had identified as an excellent cross-bandpass calibrator, for six hours. Here we describe the details of this session, which was carried out under the name “er2201”.

3.1 Scheduling

The scheduling for the session er2201 was performed with the software VieSched++ (Schartner & Böhm, 2019). The session was observed on September 8, 2022, from 11:30 to 17:30 UTC. The network consisted of the VGOS stations Mg, Oe, Ow, Wf, Ws, and Yj. Details about the stations are given in Table 1.

The frequency setup of our observation is identical to the one currently used for global VGOS sessions (Niell et al., 2018) and is listed in Table 2. We follow the convention of the VGOS community and label the four bands with letters A, B, C, D. Each of these bands has a frequency range of 480 MHz and is further divided into eight sub-bands.
**Figure 6.** Top: Cross-polarization bandpass of the VGOS antenna Onsala West over the full frequency range. The solid line is a functional fit to the data. Bottom: Residuals, i.e., measured phases minus model phases. Grey-shaded areas highlight the frequency ranges of the VGOS bands, as indicated by the labels.
Time-evolution of the differential (H-V) phase-cal phases for stations Mg, Oe, and Ow.
Figure 10. Same as Fig. 9 but for station Wf, Ws, and Yj.
Figure 15. Cross-bandpass solutions for Onsala West from observations of 4C 39.25 in other EU-VGOS sessions. Top: ev9189, scan 115. Middle: ev9203, scan 115. Bottom: ev9217, scan 115.
6 Conclusions

In this article, we presented the results from a six-hour VLBI (VGOS) session consisting of cross-polarization bandpass calibrator scans of the source 4C39.25. These are our conclusions:

1. The radio-loud AGN 4C39.25 is confirmed as an excellent calibrator for the measurement of cross-polarization bandpasses of linearly polarized radio telescopes. Observations of this source still lead to the cleanest measurements that we have seen so far, compared to other sources (e.g., Fig. 14). This statement is based on observations between 3 and 11 GHz. The suitability as a calibrator at other frequencies (e.g., mm wavelengths) should be subject of a future investigation.

2. We measured the cross-bandpasses for the VGOS antennas Mg, Oe, Ow, Wf, Ws, and Yj. The phases are to first order characterized by a group delay in the ∼100 ps regime, which remains stable over the six hours of the experiment with a variability of a few picoseconds. In our example, the remaining temporal variability of this delay is clearly characterized by systematic trends like oscillations and linear drifts (Fig. 13 c).

3. After removing a linear trend (i.e., group delay) from the cross-polarization phases, there is still considerable scatter as a function of frequency. In the time-domain, these phase-residuals show systematic and smooth transitions over the course of six hours of the experiment (cf. Figs 7 and 8).

4. Investigation of the long-term evolution of the cross-polarization delays shows that the delay can remain stable, but that the phase-scatter on top of the delay is still significantly variable (see Fig. 15 and Table 4).

5. The cross-bandpass amplitudes are not constant over sub-bands, but show distinct shapes in frequency. This frequency-dependency has to be taken into account in cross-bandpass calibration.

The results obtained in our investigation can be useful for the adjustment of calibration strategies of VGOS sessions and other VLBI experiments including stations observing with linear feeds. These results show that cross-polarization bandpasses change systematically with time. This means that taking the average, e.g., over one VGOS session is, strictly speaking, not valid. The underlying systemics can be removed from the data by applying a time-dependent calibration. We recommend including dedicated calibration scans in VGOS schedules. Two-minute scans of 4C39.25 can be used for an improved calibration of VGOS data, which has in turn the potential of increasing the signal-to-noise ratio of databases and geodetic and astrometric results. It might be beneficial to update the cross-bandpasses multiple times per session, with a cadence of once per hour. In any case, it is highly recommended to include multiple calibrator scans for the sake of redundancy, because as we have seen here, calibration can at times be subject to corruption (see the three stripes in Figs 7 and 8). The exact impact, which the systematic cross-bandpass variability and its correction may have on the subsequent analysis should be the subject of a future investigation. Concerning the magnitude of the corrections, geophysical models and interpretations have improved down to the millimeter over the last decade. This is discussed, e.g., in the context of the lastest realization of the International Terrestrial Reference Frame (ITRF2020) (Altamimi et al., 2023, and references therein). This means that the quality of the observations needs to be maintained at the same level, i.e., ∼3 ps., which matches the magnitude of the systematic variability of the cross-polarization delay reported here.

Calibrator scans are optimized for the purpose of estimating parameters that are intrinsic to the instrument, this article focusing on the example of cross-polarization gains. In this respect, calibrator scans are useful for removing systematic errors from the data and also increase the signal-to-noise ratio. As a consequence, calibration has the positive effect of improving the accuracy of parameters of interest, estimated during the ana-
alysis of the session. Calibrator scans are, however, not necessarily optimized to be di-
rectly useful, by themselves, for the estimation of these parameters. The following elabor-
ates on potential deteriorating effects which the inclusion of calibration scans might
have on the analysis of the session. The inclusion of calibrator scans into geodetic/astrometric
VLBI sessions comes at the prize of reducing the observing time spent on scans that are
optimized for the actual purpose of the experiment. One important aspect in this con-
text is sky-coverage, which is crucial for the estimation of tropospheric parameters. VGOS
sessions including one two-minute calibrator scan per hour have already been observed,
and the effect of scan loss due to additional calibrator scans is marginal. Current VGOS
schedules contain about 100 scans per hour, i.e., approximately one scan every 36 sec-
onds. Including one 120-seconds scan per hour would potentially mean a loss of three
regular scans per hour, i.e., three per cent of all scans of the session. This loss is not sig-
nificant for the following reasons. In practice, current VGOS sessions are subject to tech-
nical problems that cause a scan loss rate that is already significantly higher than three
per cent. This scan loss has not resulted in any significant degradation of the tropospheric
estimation. In any case, a carefully prepared schedule will include the calibration scans
in such a way that the degradation of sky-coverage will be kept to a minimum. The cur-
rent 100 scans per hour leave a lot of headroom for the present parametrization of the
analysis of VGOS sessions, also for the estimation of the other parameters of interest.
In summary, in a carefully prepared schedule, the positive effects of the calibration will
outweigh the marginal effects of scan loss.

The question of what it is that makes 4C 39.25 such an outstanding calibrator for
the purpose of the measurement of linear cross-polarization bandpasses will be subject
of a future investigation. Certainly, 4C 39.25 is one of the brightest AGN in the radio
sky. However, we have the strong impression that brightness is not the only character-
istic that sets this source apart, because observations of similarly bright sources have,
so far, not given any similarly good results. The analysis of a dedicated survey of a large
number of candidate sources will help to answer this question and increase the number
of useful calibrators. An investigation of this nature is currently in progress and will be
presented in a future publication.

Acronyms

AGN Active Galactic Nucleus
ALMA Atacama Large Millimeter/submillimeter Array
HOPS Haystack Observatory Postprocessing System
IONEX IONospheric map EXchange
MOJAVE Monitoring Of Jets in Active galactic nuclei with VLBA Experiments
MIT Massechusetts Institute of Technology
R&D Research and Development
SNR Signal-to-noise ratio
TEC Total electron content
VLBA Very Long Baseline Array
VLBI Very Long Baseline Interferometry
VGOS VLBI Global Observing System
VSC Vienna Scientific Cluster

Open Research Section

The VLBI Level-1A correlator output data for the experiment er2201 can be ob-
tained from NASA’s crustal dynamics data information system (CDDIS, Noll, 2010) at
https://cddis.nasa.gov/archive/vlbi/ivsdata/swin/2022/20220908_er2201_v001
_swin.tar.bz2 (CDDIS, 2023). Registration is necessary. If you use these data for pub-

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–27–


