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The EUropean-VGOS Project

W. Alef, J. M. Anderson, S. Bernhart, P. de Vicente, J. González García, R. Haas, L. La Porta, I. Martí Vidal, A. Müskens, A. Nothnagel, C. Plötz, H. Rottmann, T. Savolainen, T. Schüler, D. Small, J. Wagner

Abstract In Spring 2018 the Bonn correlation centre started a collaboration with the three European stations of Wettzell, Onsala and Yebes, equipped with both S/X- and broadband systems, to perform VGOS-like test sessions. The aim is to verify and develop further the processing chain for VGOS experiments end-to-end, from the scheduling to the analysis of the derived observables. We will present the current status of the project.

Walter Alef · Helge Rottmann · Jan Wagner · Tuomas Savolainen
Max Planck Institute for Radio Astronomy, Auf dem Hügel 69, DE-53121 Bonn, Germany

Simone Bernhardt · Laura La Porta
Reichert GmbH/BKG, Hittorfstr. 26, DE-53129 Bonn, Germany

Arno Müskens · Axel Nothnagel
Institute of Geodesy and Geoinformation, University of Bonn, Nußallee 17, DE-53115 Bonn, Germany

Pablo de Vicente · Javier Gonzaléz García · I. Martí Vidal
Observatorio de Yebes (IGN), Cerro de la Palera S/N, Yebes, Guadalajara, Spain

Christian Plötz · Torben Schüler
Geodätisches Observatorium Wettzell, Bundesamt für Kartographie und Geodäsie (BKG), Sackenrieder Str. 25, DE-93444 Bad Kötzting, Germany

Rüdiger Haas
Chlamers University of Technology Onsala Space Observatory, SE-439 92 Onsala, Sweden

James M. Anderson
Technical University of Berlin, Institut für Geodäsie und Geoinformationstechnik, Straße des 17. Juni 135, DE-10623 Berlin, Germany, also at: GFZ German Research Centre for Geosciences, Department 1, Geodesy, Telegrafenberg, DE-14473 Potsdam, Germany

Tuomas Savolainen
Aalto University Department of Electronics and Nanoengineering, PL 15500, 00076 Aalto, Finland, also at: Aalto University Metsähovi Radio Observatory, Metsähovintie 114, FI-02540 Kylmälä, Finland

Des Small
Joint Institute for VLBI ERIC, Oude Hoogeveensedijk 4, NL-7991 PD Dwingeloo, The Netherlands

(Correspondence: alef@mpifr-bonn.mpg.de)

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1 Motivation and aims

The main motivation for starting a scientific investigation on VGOS is the will to speed up the transition from classical geodetic VLBI to broadband observations. According to the initial IVS strategic plan, VGOS production should have started already by the end of 2017, but the complexity of the project and the lack of manpower led to a long delay in implementing production VGOS observations. VGOS telescopes, some of which were inaugurated as early as 2013, are standing idle most of the time much to the chagrin of their funding agencies. So VGOS antennas are available and are ageing, while telescope crews still lack practice in VGOS observing.

In 2015 the Bonn cluster was upgraded following the IVS-VGOS correlation plans of Petrachenko et al. (2014), which foresaw an increasing demand that has not yet become real as of 2019. The cluster will be old in 2020 and should be renewed in 2020 to 2022. Only recently IVS-VGOS data have been made available, which is necessary not only for training correlator personnel, but also for studying the steps in data reduction after correlation.

Since 2015 bi-weekly test sessions have been carried out by the IVS under the lead of the MIT Haystack group, which developed a path for observing, correlating and fringe-fitting of VGOS data (see e.g. Cappallo 2014). Their approach exploits the “pseudo-Stokes-I” (Intensity), which ignores instrumental and source polarisation, as well as changes and differences between the position of the peak in total and in polarised intensity. From astronomical observations it is known that the angle of the source polarisation can vary more rapidly than total intensity. It is also known that instrumental polarisation leakage leads to delay errors.

Investigations of Anderson and Xu (2018) have shown that the effects of source structure on the delays have been underestimated and will affect VGOS to a larger extent due to the expected reduced noise in such data. The whole problem is aggravated by variation of the source structures and the position of the centroid which can change with time. The position of the centroid as a function of frequency is another relevant source of systematic errors in VLBI broadband data.

Unfortunately no scientific investigation exists up to date, which studies the various effects and their contributions to the geodetic residuals of VGOS data.

Wideband astronomical VLBI data as recorded for the Event Horizon Telescope (EHT) have triggered new software efforts for polarisation conversion and for fringe-fitting. While VLBI observations have been performed with circular polarisation, ALMA, a key element of the EHT, can only deliver linear polarisation. It is therefore necessary to convert ALMA data from linear to circular polarisation basis (Martí-Vidal et al., 2016), which is done after correlation. Similarly, VGOS receivers produce linear polarisation, whereas geodetic legacy S/X systems measure circular polarisation.

The standard fringe-fitters (FF) cannot handle wideband data, because they do not take properly into account the effects of ionosphere, source structure and polarisation. A new fringe fitting task for broad and non-contiguous frequency bands, as well as correction for dispersive delays is being developed for the astronomical CASA package (van Bemmel et al., 2019). So there are new options for fringe-fitting geodetic data which should be explored. Some of the astronomical (global) FFs can take the source structure as a natural input, which makes them good candidates also for geodesy involving source structure corrections.

To the authors it is clear that in order to reach 1 mm positional accuracy, all steps of VGOS observing and data reduction have to be optimised. That will require a broad range of expertise and sufficient manpower. The whole geodetic/astronomical community should ideally join forces, given that astronomy is also moving to an era of broadband observations and shares common open issues with geodetic VLBI. The DiFX software correlator community is an example of how successful such an open collaboration can be.

2 Observations and correlation

The first test sessions were dedicated to test the performance of the instruments. Having a minimum of 3 stations allows any problems identified to be isolated at a specific station. The three participating stations are equipped as follows:

- ONSA13NE (ONSA13SW became operational only recently): 13.2 m antenna, QRFH receiver, VLBI back-end DBBC3 with flexbuff recording
- WETTZ13S (WETTZ13N not equipped with broadband receiver yet): 11-feed receiver, VLBI back-end 2 DBBC2 with Mark6 recording
- RAEGYEB: 13.2 m antenna, QRFH receiver, VLBI back-ends are 4 RDBEG with Mark6 recording

The EU-VGOS sessions have been scheduled by using both SKED and SCHED and include standard geodetic sources (time on source ~ 30 sec) and at regular intervals strong calibrators (integration time ~ 120 sec) that cover a wide range of parallactic angles during the observation. Good parallactic angle coverage of a calibrator is necessary for accurate polarisation conversion. The observations last 4 hours and include sources with high and low fractional polarisation in order to test the polarisation leakage calibration method.

So far we have adopted the same frequency setup as used in the IVS-VT sessions — four bands with dual linear polarisation:

- 3000.40 MHz – 3480.40 MHz
- 5240.40 MHz – 5720.40 MHz
- 6360.40 MHz – 6840.40 MHz
- 10200.40 MHz – 10680.40 MHz

In each band we sample 8 channels of 32 MHz bandwidth at a sample rate of 64 MS/s using two bits, thus resulting in a data rate of 8 Gbit/s. Data are recorded either using Flexbuff (JIVE) or on Mark6 modules in VDIF[1] format. The stations generate multi-thread VDIF data in slightly different flavours:

- Onsala (real data) – 1 VDIF file per scan with 8 threads, 8 channels per thread
- Wettzell (real data) – 1 VDIF file per scan with 4 threads (1 for each band), 16 channels (8 channels x 2 linear polarisations) per thread
- Yebes (complex data) – 1 VDIF file per scan with 4 threads, 16 channels per thread

The recorded data are later "e-transferred" to the Bonn correlator via the Internet.

The file-based correlation and the backend setup have hit a few corner case issues in DiFX correlation. The main issue is thread-clumpiness inside recordings. The specifications of the recorded data format and its multi-threaded multi-channel capability allow great flexibility in the time sequencing of data frames inside one file. In EU-VGOS test experiments, station backends and recorder setups have produced VDIF files that adhere to the specifications, but that contain frames of individual threads in long data bursts rather than in a clean round-robin order. This "clumpiness" conspires against DiFX and its buffer-based VDIF decoding approach. High data loss (low visibility data weights) are seen when the burst length exceeds the preset DiFX VDIF decode buffer size. Curiously, the problem persists even when threads of a multi-threaded VDIF file are extracted into single-thread VDIF files that are then correlated simultaneously in DiFX via its "multi-datastream" support.

Conversely, the low data weight issue does not occur when the original Mark6 scatter(-gather) fragment file sets (usually not available via e-transfer) are used as input for correlating a scan. The difference is likely due to the different VDIF reading path that DiFX uses for "scattered" Mark6 versus "gathered" file based correlation.

The above problem has also been reported by MIT Haystack. At Bonn the issue is worked around by a preprocessing step prior to correlation. The multi-threaded multi-channel VDIF files of all stations are converted into single-threaded multi-channel files using DiFX utility "vmux" configured for a very large buffer size (≥ 800 MB). This recovers visibility data weights from a previous worst of ≤20 % to generally ≥99 %. However, due to the overhead at the correlator such a preprocessing step is not ideal. To omit the VDIF preprocessing step, development of improved support for general multi-threaded VDIF was also welcomed by the NRAO and is in progress at Bonn MPIfR. An initial implementation is being tested.

[1] VDIF specifications, cf. https://vlbi.org/vlbi-standards/vdif/

3 Data analysis

The conversion of linear polarization into circular is performed using the PolConvert algorithm (Martí-Vidal et al., 2016). The conversion process needs to be fed with the phase-gain difference and the amplitude-gain ratio between the two linear polarizers (X and Y) of each antenna. These quantities can be estimated using the Global Cross-Polarization Fringe Fitting (GCPFF) algorithm, as implemented in PolConvert, using a scan of a calibrator source (ideally, a source with either a low fractional linear polarization and/or a wide parallactic-angle coverage in the observations).

Before running the GCPFF, we applied an initial estimate of the phase-gain difference between polarizers, based on the values of the phasecal tones found for X and Y at each integration time. The relative gain amplitudes were also estimated from the autocorrelations at each polarizer (after filtering the peaks due to the phasecal tones).

Then, we selected a strong calibrator (3C 84) and solved for any additional X/Y relative phases that could remain (after the phasecal corrections), as well as for additional X/Y amplitude ratios. These additional relative gains (both in phase and amplitude) could be caused, for instance, by different phasecal cabling to the two polarization components, or to the particulars of the signal path of each polarization channel.

These additional X/Y relative phases (which are added to the phasecal differences between X and Y) and X/Y relative amplitudes (which are applied on top of the autocorrelation ratios) are shown in Fig. 1. On the one hand, the X/Y phase difference computed by the GCPFF can be roughly modeled as one single multiband delay across the whole EU-VGOS frequency coverage. On the other hand, the amplitude ratios show different values for each band and can depart substantially from unity (hence introducing a large instrumental ellipticity, if they were not taken into account in the conversion).

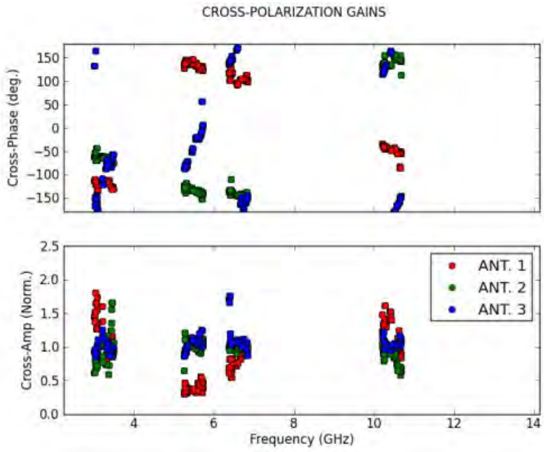

Fig. 1: X/Y relative phases (top) and amplitudes (bottom) for Oe (ANT. 1), Ws (ANT. 2) and Yj (ANT. 3).

3.1 First results

Fig. 2 and Fig. 3, respectively, show the amplitudes of all correlation products, for a scan of a strong calibrator source, before (i.e., XX, XY, YX and YY) and after (i.e., RR, RL, LR, LL) conversion from linear to circular, as a function of frequency channel (each increasing with frequency). It can clearly be seen how most of the power is coherently injected into RR and LL.

In Fig. 4, we show the antenna gains derived for the same calibrator scan using the standard Global Fringe Fitting (GFF) algorithm. The GFF has been applied to the Stokes I fringes in each independent IF. The phasecal tones (which are now the same for the R and L channels) have been applied before the GFF. As it can be seen in the figure, all gain quantities (phase, delay and rate) can be properly connected among the different EU-VGOS bands, hence showing the possibility of performing a consistent multi-band analysis over all the VGOS frequency coverage.

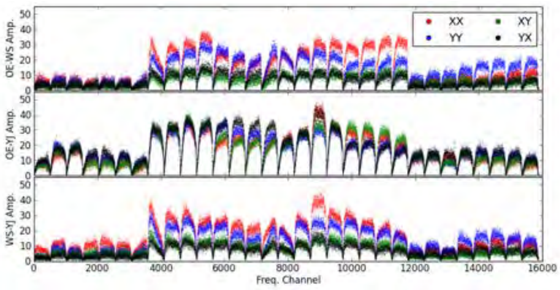

Fig. 2: Linear polarisations (XX, YY, XY, YX) amplitudes of all sampled channels for a scans on 3C84.

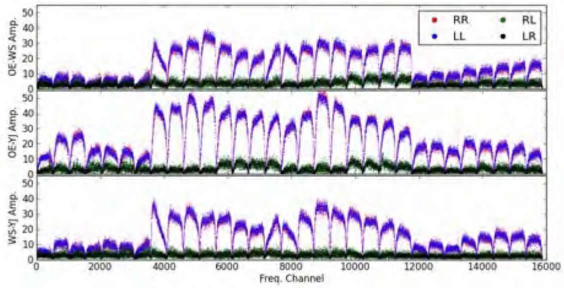

Fig. 3: Circular polarisations (RR, LL, RL, LR) amplitudes of all sampled channels for a scans on 3C84.

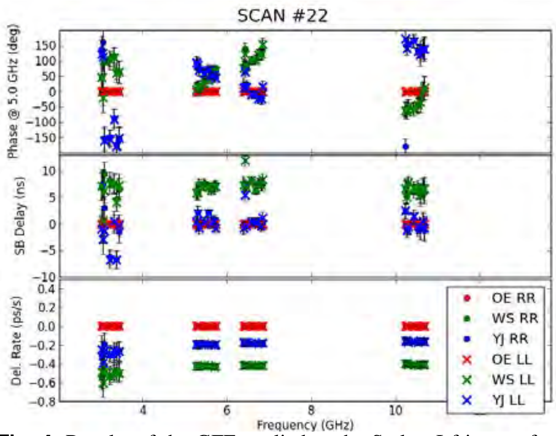

Fig. 4: Results of the GFF applied to the Stokes I fringes of a scan on 3C 84, obtained after polarisation conversion.

The GFF gains can be applied to all four polconverted correlation products, in order to perform an image deconvolution in full polarization. We have performed a multi-frequency synthesis (MFS) image deconvolution (Sault and Wieringa, 1994) using all scans of source 3C 279. The preliminary imaging results are astonishingly good, as can be seen in Fig. 5. White contours show the brightness distribution of Stokes I, while the red contours show the I residuals after subtracting a centered point source. The red contours are well aligned into the same direction as the known jet of 3C 279, hence indicating that EU-VGOS is resolving the source. The orange raster plot shows the brightness distribution in linear polarization, which is shifted from the I peak just in the same direction of the jet. The polarized brightness, polarization angle, and its peak shift roughly agree with published results from dedicated

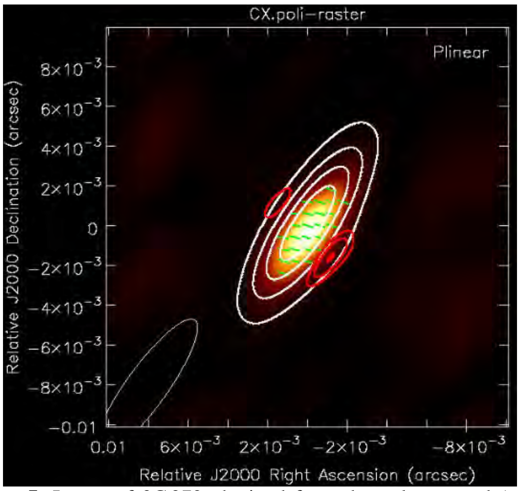

Fig. 5: Image of 3C 279 obtained from the polconverted (and fringe-fitted) EU-VGOS data.

VLBI observations of this source at other frequencies (e.g., Rani et al., 2018).

4 Conclusions and outlook

Both astronomy and geodesy are transitioning to a new era of broadband VLBI observations. That opens new frontiers for both fields of research, as well as new challenges on the way to the results. The EU-VGOS project answers the urgent need to further investigate some aspects related to the new technology and to the methodology in processing and analyzing the data.

Note that the European stations have different backend systems w.r.t. the American sites, therefore they must rely on their own resources to debug them. The correlation constitutes an expensive but powerful diagnostic tool, thus allowing to verify the station performance. We adopt different observational strategies for our sessions, thus allowing us to focus on the various aspects to be tested. We need to characterize the bandpass response of the instruments and how it changes with time, and to verify the performance of the pulse calibration system. We will monitor over many months the stability of the gain (amplitude and phase) in time, as well as its frequency dependency.

The wideband receivers use linearly polarized feeds, so that the baseline correlations are highly mixed among the parallel and cross-hand polarization terms due to the earth geometry. We will determine the instrumental delays between the X- and Y-polarisation components and their leakages. Moreover, we will investigate how the polarisation leakage changes with frequency and with the targeted source. Last but not least, we will check the RFI situation for each station.

All collaborating parties, stations, correlator and analysts, are gaining insights in the various aspects of the project, from the more technical ones, as system settings and data recording at the stations, to the elaboration phases, including data decoding and correlation, and finally to the post-processing of the data. As mentioned in the previous section, we also plan to develop and test against each other alternative FF approaches for processing VGOS data.

Our preliminary results show the potential of VLBI broadband data. We are aware of the huge amount of work necessary to accomplish all our goals and we welcome experts in the VLBI community and other VGOS telescopes who wish to cooperate with us to make VGOS production a reality as fast as possible.

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