The Bonn Correlation Center

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Abstract We present a status report of the Bonn Distributed FX (DiFX) correlator for the years 2019 and 2020. This software correlator is operated jointly by the Max-Planck-Institut für Radioastronomie (MPIfR), the Institut für Geodäsie und Geoinformation der Universität Bonn (IGG), and the Bundesamt für Kartographie und Geodäsie (BKG) in Frankfurt, Germany. One of the most notable recent achievements was its contribution to the first picture of a black hole published in 2019.

1 General Information

The Bonn correlator is hosted at the MPIfR[1] VLBI correlator center in Bonn, Germany. It is operated jointly by the MPIfR in Bonn and the Federal Agency for Cartography and Geodesy (BKG)[2], with the support of the IGG [3]. The MPIfR hosts the correlator facility and shares with the BKG the costs of the cluster, of most of the staff, and of the Internet connectivity. The IGG contributes to the connectivity of the cluster and pays one member of the geodetic staff. Since January 2017, the geodetic personnel responsible for the correlation are employed by the BKG via a private contractor, the Reichert GmbH.

2 Correlator Capabilities

Several versions of the Distributed FX software correlator (Deller et al. 2011) are available at the Bonn correlator, and in particular, a branch version developed by J. Anderson and others specifically for RadioAstron[4] experiments (Bruni et al. 2014) with important upgrades and bug fixes made recently by J. Wagner. For geodetic production we use the latest stable DiFX release, and before switching to a newer DiFX version we perform a comparison of the resulting observables. In 2020, we switched from DiFX-2.5.2 to DiFX-2.6.1.

The correlator is running on a High Performance Computing (HPC) cluster, which was renewed in 2015 to match both VGOS and mm-VLBI requirements. Its specifications can be gathered from the previous biennial report (La Porta et al. 2020).

The raw data are recorded at the stations on Mark 5 or Mark 6 modules, or on storage servers usually referred to as Flexbuffs. For geodetic experiments the data are mostly e-transferred to the HPC cluster that is connected to the Internet through two 1-Gbit lines, one of which is a duplex line. Both are part of the German Research Network (Deutsches Forschungsnetz - DFN) where the non-duplex line is connected to the DFN via the Bonn University high speed network.

Various data formats have already been correlated in Bonn: Mk4, Mk5, DVP, and various flavors of VDIF. The correlated data (SWIN files) can be exported to FITS and HOPS (MK4) formats. For post-processing the following software packages are available: AIPS,

1. Reichert GmbH
2. Bundesamt für Kartographie und Geodäsie
3. Max-Planck-Institut für Radioastronomie
4. Institut für Geodäsie und Geoinformation der Rheinischen Friedrich-Wilhelms Universität Bonn

Bonn Correlator

IVS 2019+2020 Biennial Report

[1] https://www.mpifr-bonn.mpg.de/

[2] https://www.bkg.bund.de/

[3] https://www.gib.uni-bonn.de/

CASA, PIMA, and HOPS (Haystack Observatory Post-processing System), the latter of which is the standard tool for geodesy. In the course of geodetic VGOS (test) correlations, the HOPS package was upgraded to HOPS 3.21 in 2020 (currently rev 2937). The correlator outputs and other important files (e.g., VEX and v2d files) are backed up daily on the HPC cluster. The final products are archived on the MPIfR archive server, where they will be kept for at least ten years.

The EXPAD and COMEDIA tools are used for bookkeeping of experiments correlated in Bonn. They are the frontends to a local data-base which records all relevant information such as the observation date, participating stations, modules, and status of the experiment.

3 Staff at the Bonn correlator

The **geodesy group at the Bonn correlator** has 2.1 FTEs.

A. Müskens – scheduler of various IVS sessions, namely of INT3, EURO, T2, and OHIG, generated with the VieVS software (VieSched++). He went on a sabbatical in April 2020 and will retire in spring 2021.

S. Bernhart and **Yoon Kyung Choi** – coordinate the data logistics including e-transfer and module shipment, prepare and supervise the correlation, carry out the post-processing, and deliver the resulting observables to the IVS repository in form of databases. Besides these standard duties, they provide the stations with feedback on their performance and support tests of the VLBI systems, in particular for the Wettzell Observatory.

Laura La Porta – performed the same duties but left the group in August 2019.

The **MPIfR staff at the Bonn correlator** is a subgroup of the VLBI Technical Department, headed by W. Alef before his retirement in November 2019 and handing over his duties to H. Rottmann. Its members are A. Roy, J. Wagner, Y. Pidopryhora, M. Lisakov, S. Dornbusch, and G. Tuccari (guest). In addition to the scientific staff, there is one technician (R. Märtens), one engineer (M. Wunderlich), and one operator (H. Sturm) until he retired in May 2020.

The group is responsible for keeping the cluster software up to date, for hardware maintenance and repair, as well as for IT support and software correlator improvements. The group members are involved in several astronomical projects, which are focused on very high resolution imaging especially with the Event Horizon Telescope (EHT).

W. Alef – (retired) head of the VLBI technical department, computer systems and cluster administration, manager of the BRoad bAND (BRAND) receiver project, VLBI expert, and consultant to the EU-VGOS project.

H. Rottmann – (new) head of the VLBI technical department, computer systems and cluster administration, responsible for the beamforming software of ALMA, DiFX developer.

A. Roy – project manager for VLBI at the Atacama Pathfinder EXperiment (APEX), for DBBC3 commissioning, and head of the polarization conversion effort for Atacama Large Millimeter/submillimeter Array (ALMA) VLBI and the BRAND system.

G. Tuccari – guest scientist from INAF, leader of the Digital Base Band Converter project (DBBC) and the Fila10G development, as well as project engineer of the BRAND receiver.

J. Wagner – developer of DiFX, Mark 5 and Mark 6 software, responsible for correlation of EHT VLBI experiments, support scientist with instrumentation and observing-related work in mm-VLBI (EHT and GMVA).

Y. Pidopryhora – organizes, conducts, correlates, and performs the post-processing of the Global mm-VLBI Array (GMVA) sessions and of various soft/hardware related tests.

M. Lisakov – takes care of the correlation and post-processing of the RadioAstron imaging observations. He also participates in the DiFX software correlator improvement for the needs of space VLBI.

S. Dornbusch – developer of firmware and software for the DBBC3 backend, responsible for maintenance of software for the DBBC2 backend, test and verification of the DBBC2 and DBBC3, support for stations that use a DBBC2 or a DBBC3. He is also active developer of soft- and firmware of the BRAND receiver system.

The Bonn correlator also serves as an inherent testbench for the DiFX and e-transfer software, so that all its personnel contribute to the debugging of these tools.

4 Activities During the Past Two Years

IVS regular sessions: During 2019 and 2020 we correlated 104 R1, ten EURO, eleven T2, 72 INT3, and thirteen OHIG. Since May 2018 the databases are produced solely via the nuSolve software (vgosDbMake) in vgosDB format.

Scheduling: A. Müskens had tested the VieVS scheduling program (VieSched++) in collaboration with the Vienna group. In 2019, scheduling of the INT3 sessions with VieSched++ was initiated yielding good results. In spring 2021, A. Müskens will retire. Since he began a sabbatical in April 2020, the scheduling tasks were handed over to Christian Plötz from the Geodetic Observatory Wettzell and Matthias Schartner, who in the meantime moved from the Vienna correlator to ETH Zurich.

EU-VGOS Project: The collaboration among the three European stations of Wettzell, Onsala, and Yebes and the Bonn correlator, which started in March 2018, is still ongoing; it was intermittently joined by the Ishioka and Svetloe stations. The aim of the project is to verify the processing chain for VGOS experiments end-to-end, from the scheduling to the geodetic analysis of the derived observables.

Since the beginning of the project, 41 sessions have been observed until the end of 2020. 23 observations have been correlated and partly been post-processed in single band and pseudo Stokes I mode, the latter based on the Haystack VGOS post-processing chain which was released with HOPS 3.20 in 2019. Four of the sessions have also been used to test the polarization conversion for VGOS data based on the PolConvert software for VGOS developed by I. Marti-Vidal (Marti-Vidal et al. 2015).

VGOS test correlations: In 2020, a VGOS Intensive session and a 24-hour VGOS experiment were processed at the Bonn correlator in order to compare the results with those of Haystack and other Correlation Centers (Barrett et al. 2020).

RadioAstron: Six experiments have been correlated in Bonn in 2019–2020. Three experiments were recorrelated and an extensive fringe search was performed upon requests from P.I.s. Those sessions involved up to 36 antennas and baseline lengths up to ten Earth diameters. The H-maser onboard the satellite stopped working in September 2017. Since then, there were two modes employed: a closed-loop mode (a.k.a. coherent mode) as default and a rubidium clock mode. To implement the closed-loop correlation mode, the RadioAstron-related version of the DiFX software correlator was patched by J. Wagner. The results were compared to those of the ASC correlator (Moscow) by M. Lisakov and J. Wagner. As a result, the DiFX correlator in Bonn is now capable of correlating all imaging experiments performed within the RadioAstron project.

Global Millimeter VLBI Array (GMVA): Four sessions with 20+ antennas were correlated in Bonn during the past two years. Starting from spring 2018, the GMVA network includes the brand new Greenland telescope, GLT. Although normally a part of the GMVA spring sessions, ALMA did not observe either in 2019 or in 2020 due to harsh weather conditions in 2019 and the COVID-19 crisis in 2020. The standard recorded data rate of 2 Gbps (except for ALMA which always recorded at 16 Gbps), became 4 Gbps in autumn 2019, thus doubling the data storage requirements. The three antennas of the Korean VLBI network also switched to the 4-Gbps recording mode (previously they observed in a 1-Gbps mode).

The VLBA stations now observe in a 4×128 MHz frequency configuration. To match it to the 8×64 MHz configuration of the other stations, the correlation requires to use the so-called "zoom bands", which allow to split the wider bands.

Event Horizon Telescope (EHT): The Bonn cluster is used also to correlate one half of EHT mm-VLBI experiments. The other half of the data is correlated at the MIT Haystack Observatory. The observing campaign of April 2017 lead to the first image of a black hole (The EHT Collaboration 2019).

The EHT campaigns in April 2017 and in April 2018 were carried out on five days using the phased ALMA and SMA, and up to seven single mm-VLBI antennas. The frequency setup consisted of four or eight 2048-MHz-wide IFs sampled by R2DBE backends. Each IF was recorded in dual polarization on separate Mark 6 units.

The April 2017 session had two IFs (2×2048 MHz dual polarization) and was recorded on two Mark 6 recorders using eight modules at a total data rate of 32 Gbps. The April 2018 session had four IFs (4×2048 MHz dual polarization) and was recorded on four Mark 6 units recording on 16 modules at 64 Gbps total. Aggregate rates are reaching 0.5 Tbps, with total storage requirements of around 5–10 PB for

raw recordings, and 5 TB for the correlated and final polarization converted visibility data.

Correlation is limited by the available playback units; 32 Mark 6 with 32 expansion chassis would be required for a full 4-IF correlation assuming that eight stations participated in the observations. Hence the correlation load is shared between the MIT Haystack Observatory and the Bonn MPIfR/BKG correlators. The full 230 GHz (1.3 mm) session is split by IF such that the Mark 6 modules of one IF subset are processed in Bonn and the other at MIT Haystack. Playback rate alone via fuseMk6 from a 2×2-module group is slightly above real-time and averages 2.4 GB/s total (18 Gbps).

Digital Backends (DBBC3): Noteworthy results from 2019 and 2020 include: development and testing of the DDC U firmware (universal) for the DBBC3, providing 16 BBCs for each IF with a selectable bandwidth from 2 MHz up to 128 MHz for each BBC. This mode provides up to 16 Gbps output data rate for each IF. Further technical modifications of the DBBC3 hardware, improving system stability, synchronization, and power consumption.

BRAND: The project is a collaborative effort of five European institutes. According to plan the BRAND prototype receiver should have produced fringes on the Effelsberg telescope together with VGOS antennas towards the end of 2020. The COVID-19 pandemic with its restrictions caused delays in the delivery of parts and the collaborative work due to severe travel restrictions. It is expected that the work can be finished in 2021. While all analogue parts could be finished, the so-called digital frontend which samples the BRAND band from 1.5 GHz to 15.5 GHz in one chunk could only be partly tested in the lab.[5].

5 Current Status and Future Plans

- After the first successful correlation of an official VGOS 24-hour experiment in October 2020, the Bonn correlator has started regular correlation of VGOS 24-hour experiments in January 2021. The current schedule comprises one experiment per month.

[5] https://events.mpifr-bonn.mpg.de/indico/event/154/session/4/contribution/15

The real challenge for VGOS turns out to be the data logistics, particularly since some correlators can only handle e-transferred data. Moreover, data storage is getting tight for both recording to Mark 6 modules and storing data on hard disk systems not only at the stations but also at the correlators. Moreover, the Internet connection partly still requires upgrades to adequate bandwidths at stations and correlators.

- The current bandwidth of two times 1 Gbps will be upgraded in the first half of 2021 to 10 Gbps. Due to the high prices of the German Research Network (DFN), the contract will most likely be awarded to a commercial contractor for the duration of two years.
- A. Müskens tested the VieVS scheduling program (VieSched++) in collaboration with the Vienna group for INT3 sessions in 2019, which yielded good results. Since he began a sabbatical in April 2020 and will retire in April 2021, the scheduling tasks were handed over to Christian Plötz from the Geodetic Observatory Wettzell and Matthias Schartner, who in the meantime moved from the Vienna correlator to ETH Zurich.
- In order to reduce the workload for Bonn, seven of the previous EU-VGOS experiments will be or have already been correlated by the colleagues from the Vienna correlator. Further observations will be carried out in 2021 for testing purposes. This is desired by all partners in light of the IVS-VGOS sessions. In particular, most of the European stations have different back-end systems compared to the American sites; therefore, the European stations must rely mostly on their own resources to debug their systems together with the correlator and the DBBC team in Bonn.
- Correlation of all remaining RadioAstron observations will be finished within 2021–2022.
- Recently the upgraded NOrthern Extended Millimeter Array (NOEMA), the next generation of IRAM'S Plateau de Bure instrument, joined the GMVA network. A first fringe test was successful.
- During the GMVA session carried out in spring 2019, the VLBA recorded for the first time on Mark 6 units so that the recording data-rate for the GMVA can be increased now to 4 Gbps.
- During the autumn 2019 GMVA session, DBBC3 was used in parallel with the standard DBBC2 for Pico Veleta. Not only was the test successful, but

the DBBC3 data were actually used for the production correlation of that session.

- A number of post-correlation analysis tools were developed by Y. Pidopryhora to help in assessment of the GMVA correlation results. AMON (alist monitor) uses a GUI to present a "bird-eye view" overview of a correlation for the whole project and at the same time to easily access detailed fringe plots for any particular scan-baseline combination of interest. ant_rep (antenna report) aggregates all the correlation and fringe-fitting logs and compiles essential statistics in easily readable text form, that can also be converted to histograms or plots as needed. Starting from 2019 outputs generated by these tools are included into the GMVA session reports.
- J. Wagner is working on DiFX output bands feature for DiFX 2.7. The feature is based on earlier stand-alone de-zooming 'difx2difx' he developed to recover and correlate GMVA+ALMA 2017 (Issaoun et al. 2019). It will enable correlation of VLBI experiments that have inconvenient sky-frequency IF placements and bandwidth mixtures of (non-)overlapping 32/58/62.5/64/128/2048 MHz wide bands.
- He is also working on a Mark 6 reading layer in DiFX together with FUSE layer fuseMk6, as well as improvements towards multi-datastream handling in DiFX native Mark 6 support. He implemented some improvements for playback of lossy or "clumpy" multi-threaded VDIF recordings affecting some VGOS stations and for the PolConverter conversion flow.

Even though the COVID-19 pandemic cut down activities in many places, the production correlation at the Bonn correlator and related (debugging) tasks were fortunately unaffected in this regard.

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