Report for 2021–2022 from the Bordeaux IVS Analysis Center

Patrick Charlot[1], Arnaud Collioud[1], María Eugenia Gómez[2], Stéphane Paulin-Henriksson[3]

Abstract This report provides an overview of the activities of the Bordeaux IVS Analysis Center in 2021 and 2022. In this period, the imaging of the RDV sessions proceeded in the continuity of our previous work, disseminating the resulting images and related information (structure indices, source compactness, flux densities, etc.) through the Bordeaux VLBI Image Database. Based on all the images available, a study comparing the direction of the VLBI jets (calculated with an algorithm of our own) with that of the optical-radio offset vectors showed that the two directions are within 30° in about half of the sources. Activities related to the GINS software package were reactivated with a focus on the assessment of the quality of the geodetic results provided by GINS. Also carried on was our observing program to monitor optically-bright ICRF3 sources, taking advantage of the ongoing R&D sessions. In addition, observations dedicated to measuring the geodetic positions of the non-geodetic antennas of the European VLBI Network were pursued as part of our contribution to the EU-funded JUMPING JIVE project. Carried out at K-band, these observations proved also useful to image the sources with high resolution. Finally, another activity was targeted to simulate VLBI images from actual and trial VGOS schedules. The purpose was to investigate new VGOS scheduling schemes that allow for imaging, while maintaining or improving the quality of the geodetic results at the same time.

1 General Information

The *Laboratoire d'Astrophysique de Bordeaux (LAB)* is a research unit funded by the University of Bordeaux and the *Centre National de la Recherche Scientifique (CNRS)*. It is part of a bigger organization, the *Observatoire Aquitain des Sciences de l'Univers (OASU)*, formerly Bordeaux Observatory. The OASU has a wider scope, covering environmental sciences besides historic activities in astronomy and astrophysics. A specific role of the observatory is to provide support for acquiring, analyzing, and archiving observations of various types in these fields, including participation in national and international services like the IVS. Delivering such support, specifically, falls within the mandate of the *Pluridisciplinarité au service de l'Observation et de la Recherche en Environnement et Astronomie* (POREA) service unit of the OASU.

VLBI activities at the LAB are carried out within the M2A (*Métrologie de l'espace, Astrodynamique, Astrophysique*) team. The contribution of the LAB to the IVS does in the first place concern the maintenance and improvement of the International Celestial Reference Frame (ICRF). This includes regular imaging of the ICRF sources and evaluation of their astrometric suitability, as well as developing specific VLBI observing programs for enhancing the frame. In addition, the group conducts VLBI analyses with the GINS software package, a multi-technique software developed by the CNES (*Centre National d'Etudes Spatiales*) which has the ability to process data from most space geodetic techniques, including GNSS, DORIS, SLR, LLR, VLBI, satellite altimetry, and other space missions [1]. In conjunction with this analysis activity, the group is also engaged in assessing the VLBI part of GINS based on comparisons with other VLBI software packages.

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1. OASU–Laboratoire d'Astrophysique de Bordeaux
2. University of La Plata, MAGGIA and CONICET, Argentina
3. OASU–Pluridisciplinarité au service de l'Observation et de la Recherche en Environnement et Astronomie

Bordeaux Analysis Center

IVS 2021+2022 Biennial Report

2 Description of Analysis Center

The Bordeaux IVS group is engaged in the analysis of the IVS-R1 and IVS-R4 sessions with the GINS software package. From these sessions, Earth Orientation Parameters (EOP) estimates with six-hour resolution were produced. The focus of such analysis work is placed upon developing a state-of-the-art operational VLBI solution with the goal of contributing to the IVS primary EOP combination in the future.

The Analysis Center is further engaged in the imaging of ICRF sources on a regular basis. This is achieved by a systematic analysis of the data from the RDV sessions, which is carried out with the AIPS and DIFMAP software packages. The aim of such regular imaging work is to assess the astrometric suitability of the sources based on the so-called "structure index." Characterization of the source positional instabilities and comparison of those instabilities with their structural evolution is an additional direction of work. Such studies are essential for identifying sources of high astrometric quality, a requirement to define the celestial frame at the best level.

Occasionally, the group leads or participates in specific observing programs or other VLBI developments. For the present period, these include the monitoring of optically-bright ICRF sources (i.e., detected by the Gaia mission), the carrying out of K-band observations for geodetic purposes as part of the EU-funded JUMPING JIVE project, and imaging simulations to assess the potential for imaging of new VGOS scheduling methods.

3 Scientific Staff

During the period 2021–2022, four individuals contributed to one or more of our VLBI analysis and research activities. A description of what each person worked on, along with an estimate of the time spent on it, is given below. As noted in our previous biennial report, María Eugenia Gómez returned to her home institute in La Plata, Argentina, in November 2020. Since then, she has continued working closely with us and therefore is associated to this biennial report.

- Patrick Charlot (60%): researcher with overall responsibility for Analysis Center work. His primary interests include all aspects of ICRF, comparisons with the Gaia frame, studies of radio source structure and its impact in astrometric VLBI, and astrophysical interpretation. He also led a work package about geodesy in the JUMPING JIVE project.
- Arnaud Collioud (90%): engineer with a background in astronomy and interferometry. His duties include imaging the sources observed in the RDV sessions using AIPS and DIFMAP and developing the Bordeaux VLBI Image Database and *IVS Live* tool. He also contributes to research in astrometry and astrophysics making use of these data.
- María Eugenia Gómez: researcher from the University of La Plata and CONICET, formerly a post-doc in Bordeaux. Her contribution is with the analysis of observations acquired by the EVN at K-band for the purpose of the JUMPING JIVE project and beyond. She is also involved in the GINS activities, notably in the validation at the underlying VLBI model.
- Stéphane Paulin-Henriksson (25%): engineer with a background in astronomy. His tasks are to maintain the GINS software package installation locally, to contribute to comparisons with other VLBI software packages, and to develop procedures to automate the processing for future operational analyses.

4 Current Status

As reported previously, one of our goals is to implement an operational analysis of the IVS-R1 and IVS-R4 sessions using the GINS software package. Since the VLBI capability of GINS has not been widely used, a prerequisite is to assess the quality of the results derived with GINS by validating them against equivalent results obtained with other VLBI software packages. In particular, we wish to compare the individual components of the VLBI delay model in GINS with the same such components calculated independently. Based on expertise within the group, we selected the Vienna VLBI Software (VieVS) as the reference software for these comparisons. The focus was placed first on comparing the geometric model, excluding station corrections and tropospheric corrections. This assessment shows that the calculated GINS and VieVS delays (limited to that part of the model) are within about 2 mm (see Figure 1). While this level of agreement is

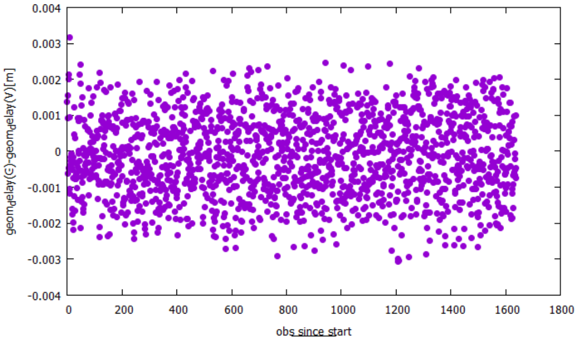

Fig. 1 Comparison of the geometric VLBI delay calculated with the GINS and VieVS software packages, excluding station corrections and tropospheric corrections, for the data of the session IVS-R1309 conducted on 2 January 2008. Differences (given in meter) are plotted as a function of the observation number.

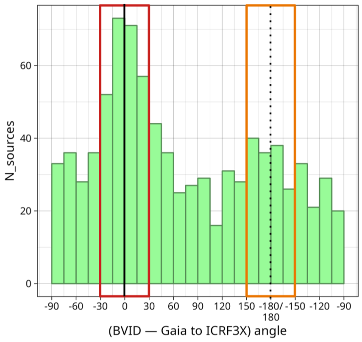

Fig. 2 Distribution of the angle between the BVID jet direction and the Gaia-CRF3 to ICRF3 S/X-band offset vector direction for 865 sources. The red and orange rectangles represent the block of sources where the optical-radio offset vector is aligned within a range of ±30° with the VLBI jet direction.

already fairly good, it is not at the level we expect for such a comparison, the goal being rather to reach differences one order of magnitude smaller. Furthermore, a closer look at those differences reveals that they are not random but show a roughly diurnal systematic pattern for each VLBI baseline/quasar pairs. This issue is being investigated and once resolved, we will pursue the comparison for the rest of the VLBI delay model, i.e., station corrections and tropospheric modeling.

Another major part of our activity consists in systematically imaging the sources observed in the RDV sessions. During 2021 and 2022, seven such sessions were processed (RV130, RV132, RV134, RV136, RV138, RV144, and RV146), resulting in 1,012 VLBI images at either X- or S-band for 309 different sources. The imaging work load has been shared with USNO since 2007 (starting with RDV61); the USNO group processes the odd-numbered RDV sessions while the Bordeaux group processes the even-numbered ones. The VLBI images are used in a second stage to derive structure correction maps and visibility maps along with values for structure indices and source compactness (see [2, 3] for a definition of these quantities) in order to assess astrometric source quality. All such information is made available through the Bordeaux VLBI Image Database (BVID)[1] [4]. At present, the BVID comprises a total of 7,862 VLBI images for 1,514 different sources (with links to an additional 6,775 VLBI images from the Radio Reference Frame Image Database of USNO) along with 14,637 structure correction maps and as many visibility maps. These originate from 89 sessions spanning a total of 26 years.

5 Achievements

Apart from the recurring activities described in the previous section, we also developed more research-oriented work. One line of investigation was aimed to compare the direction of the VLBI jets seen in the BVID images with the direction of the offset vectors joining the ICRF3 and Gaia-CRF3 positions. For this comparison, the VLBI jet directions were determined in an automatic way for all available BVID images, based on an algorithm that we devised (see details in our previous Biennial Report). The optical-radio offset vector angles were derived in a manner similar to that used for the comparison of the ICRF3 and Gaia-CRF2 in [5]. As reported in [6], the results of this comparison show that the optical-radio offset vector predominantly aligns with the jet direction. More precisely, the alignment is within 30° for almost half of the sample (393 sources), with 253 and 140 sources in the same and opposite directions, respectively (see Figure 2). Additionally, it was found that the portion of such sources grows as the separation between the optical and radio positions (in a normalized sense) increases. For example, when the separation is larger

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[1] See http://bvid.astrophy.u-bordeaux.fr.

than 6σ, the property is verified for almost all sources (96%).

On the observing side, we are taking advantage of the R&D sessions to further pursue the monitoring of some under-observed optically-bright ICRF3 sources (i.e., detected by Gaia). Starting from summer 2020, our initial strategy [7] was refined in a way that the list of targets is now adjusted prior to each R&D session. Only sources not observed for the past 30 days, taking into account all IVS sessions are scheduled, with preferences given to those that are brighter than magnitude 18, and then 19 and 20 (in decreasing order), all of which are subject to having a structure index smaller than three (as previously mentioned). This new scheme was made possible thanks to the *IVS Live* web tool (see below) which allows us to obtain the observing status of any given source at any given moment. A total of twenty such R&D sessions were scheduled in 2021 and 2022.

Additionally, we pursue observations at K-band with the European VLBI Network (EVN). The initial objectives of these observations were (i) to exercise the geodetic capability of the EVN software correlator at JIVE (SFXC) that was implemented as part of the JUMPING JIVE project and (ii) to determine the geodetic positions of the EVN non-geodetic antennas, also a goal of JUMPING JIVE. To this end, two dedicated EVN experiments were carried out in June 2018 and October 2020. The analysis of the data from these experiments allowed us to derive the position of the EVN antennas in the ITRF2014 terrestrial reference frame with centimeter-level precision [8]. The data are currently being re-analyzed to place those positions directly in the newly-released ITRF2020 terrestrial frame. In the course of the project, it was also realized that the network may also be quite suitable for VLBI imaging thanks to the large number of antennas with K-band capability. The experiment from October 2020 was used as a test bed for this purpose. Figure 3 shows one of the images produced, confirming the potential of the EVN for imaging ICRF3 sources at K-band through these geodetic-style experiments [9].

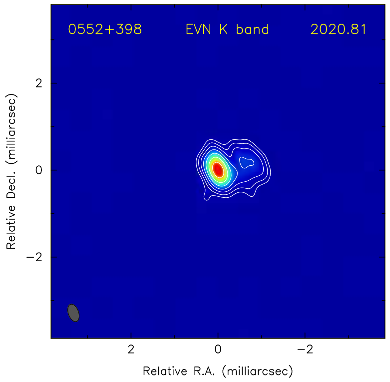

Fig. 3 VLBI image at K-band of the source 0552+398 observed during the EVN experiment EC076, conducted on 23 October 2020. Contour levels are drawn at ±1, 2, 4, 8, 16, 32, and 64% of the peak brightness of the image.

Besides the above activities, the period also gave us the opportunity to reactivate the imaging simulations that we developed when the VLBI2010 system was designed. This emerged from discussions within the VTC source structure sub-group, chaired by Patrick Charlot, which showed the need to investigate new scheduling methods that would allow for source structure imaging from routine VGOS sessions. To this end, the pipeline previously built [10] was used again to simulate images in the four VGOS bands based on trial schedules generated with the VieSched++ software package. Statistics on the image quality were derived by using the image dynamic range as an indicator of such quality. Interestingly, the simulations showed that the UV coverage does depend on the VGOS band—it degrades from band A to band D—although one might think otherwise. This is due to the (fixed) bandwidth becoming a smaller fraction of the total frequency as the frequency increases. Additionally, the dynamic range was also found to depend at some level on the source structure. In all, the work contributed to the development of a new “source-centric” scheduling approach that allows for imaging twice as many sources compared to the standard “station-centric” scheduling scheme, while also leading to improved geodetic performance [11].

6 Dissemination and Outreach

The *IVS Live* website[2], a specific tool developed by the Bordeaux group, provides “Live” information about ongoing IVS sessions, including VLBI images of the observed sources [12]. The website is updated automatically based on the IVS Master Schedule. It now incorporates 12,124 IVS sessions, involving 88 stations

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[2] Available at http://ivslive.astrophy.u-bordeaux.fr.

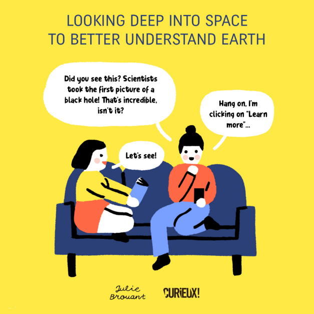

Fig. 4 First slide of the English version of the VLBI comic.

and featuring 3,113 sources. Tracing the connections indicates that there were 614 visits from 481 different users in 43 countries in 2021 and 2022. The statistics of access to the BVID, 2,167 visits from 1,250 different users in 75 countries, reveal increased interest, with twice as many visits and users compared to the previous period. As for dissemination, Patrick Charlot gave a lecture on radio sources at the 4th IVS Training School on VLBI for Geodesy and Astrometry, held online between 22–25 March 2022. During 2021 and 2022, he also gave seven lectures about geodetic VLBI, also online, for African students participating in the DARA (Development in Africa with Radio Astronomy) program. Of interest is also the development of a cartoon about VLBI as part of the outreach activities for the JUMPING JIVE project. In the comic, two friends embark in a journey through space sparked by curiosity after seeing the first image of a black hole. In their journey they learn about VLBI and its applications. The comic is available in both French and English (Figure 4).

7 Future Plans

Our plans for the next two years will follow the same analysis and research lines. In particular, we expect to have a final assessment of the quality of the GINS results by performing additional comparisons against the VieVS software package. Imaging the RDV sessions and evaluating the source astrometric suitability, a specificity of the Bordeaux group, will also be carried on. Going beyond our study on the alignment of the optical-radio offset vectors and VLBI jet directions, we plan to further explore the relationship between source structure and the observed positional offsets—either between optical and radio or between the three ICRF3 bands—by taking advantage of all of the images available in BVID. On the observing side, the R&D sessions dedicated to monitor under-observed optically-bright ICRF3 sources are expected to be carried on until the end of the Gaia mission around 2025. In addition, we plan to conduct further EVN observations at K-band, in the continuation of JUMPING JIVE, for mixed geodesy, astrometry, and imaging goals.

Acknowledgements

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