Report for 2019–2020 from the Bordeaux IVS Analysis Center

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Abstract This report provides an overview of the activities of the Bordeaux IVS Analysis Center in 2019 and 2020. In this period, the imaging of the RDV sessions proceeded in continuation of our previous work, disseminating the resulting images and related information (e.g., structure indices, source compactness, flux densities) through the Bordeaux VLBI Image Database. We carried on with our observing program to monitor optically-bright ICRF3 sources, taking advantage of the ongoing R&D sessions. On the other hand, analysis activities using the GINS software were on hold for most of the time due to personnel leaving. Related to our imaging activity was the development of an algorithm that determines the VLBI jet direction in an automatic way from any given VLBI image. Comparing such directions to preferred directions of astrometric variability shows close consistency for about half of the sources, indicating that this variability is likely due to source structure evolution. Finally, another achievement was the validation of the new geodetic capabilities of the JIVE correlator as part of our contribution to the EU-funded JUMPING JIVE project.

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 the participation in national and international services such as 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. Contributions to the IVS have been mostly concerned with maintaining and improving 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 celestial 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].

2 Description of the Analysis Center

The Bordeaux IVS group is engaged in analyzing the IVS-R1 and IVS-R4 sessions with the GINS software package. From these sessions, Earth Orientation Pa-

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rameter (EOP) estimates with six-hour resolution were produced. The focus of this 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 imaging 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 the 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 these 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 best define the celestial frame.

Occasionally, the group is also involved 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) and the validation of the newly-implemented geodetic capabilities of the Joint Institute for VLBI-ERIC (JIVE) correlator (within the JUMPING JIVE project), both of which are described below.

3 Scientific Staff

The period 2019–2020 was marked by some changes in personnel. As noted in our previous report, a new post-doctoral fellow, Maria Eugenia Gomez, hailing from the University of La Plata (Argentina), had joined us just before that, in November 2018, for a two-year contract. On the other hand, César Gattano completed his post-doctoral stay at the end of 2019, after more than two years with us. Additionally, two long-standing staff members, Antoine Bellanger and Géraldine Bourda, left the group in mid-2019, moving to other activities. Since both of them were involved in analyses and developments relating to the GINS software package, the consequence was that such activities remained on hold until a new person, Stéphane Paulin-Henriksson, from the POREA unit in OASU, took over during 2020. In all, five individuals contributed to one or more of our VLBI analysis and research activities in the period. A description of what each person worked on, along with an estimate of the time spent on it, is given below.

- Patrick Charlot (50%): 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 on astrometric VLBI, and astrophysical interpretation. He also leads 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.
- César Gattano (50%, until December 2019): post-doctoral fellow funded by the CNES. His interest is in the celestial frame, in particular in the characterization of the time series of source positions and the connection of the observed instabilities with the source astrophysics. He is now with the Astronomical Institute at the University of Bern (Switzerland).
- Maria Eugenia Gomez (until November 2020): post-doctoral fellow funded by the JUMPING JIVE project to validate the geodetic capabilities of the JIVE correlator and to determine the positions of the European VLBI Network (EVN) telescopes. She is now back at the University of La Plata.
- Stéphane Paulin-Henriksson (70%): 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 have selected the Vienna

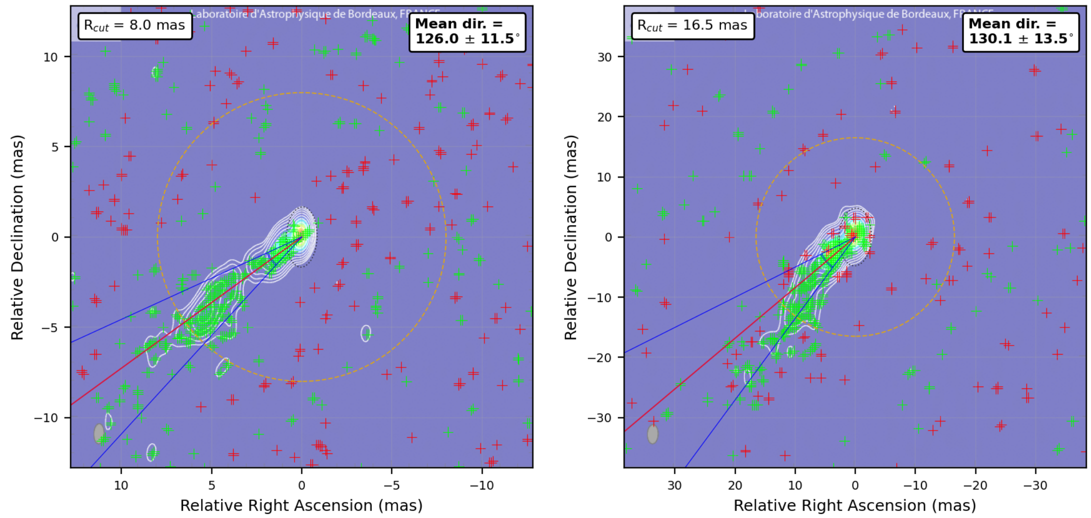

Fig. 1 VLBI contour maps of the ICRF3 source 0333+321 at X band (left panel) and S band (right panel) for epoch 2009 July 29. The superimposed green and red crosses show the underlying clean components which define the source model. Also superimposed onto each map are the jet direction and its uncertainty (shown as red and blue straight lines), as determined automatically with the method that we devised. The yellow circle indicates the cutoff radius that served to extract the clean components used in the calculation.

VLBI Software (VieVS) as the reference software for these comparisons. Unfortunately, due to the change of personnel outlined above, this work was on hold for most of the period and was reactivated only recently.

Another major part of our activity consists in systematically imaging the sources observed in the RDV sessions. During 2019 and 2020, four such sessions were processed (RV126, RV128, RV140, RV142), resulting in 591 VLBI images at either X- or S-band for 228 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 6,992 VLBI images for 1,420 different sources (with links to an additional 6,775 VLBI images from the Radio Reference Frame Image Database of USNO) along with 13,767 structure correction maps and as many visibility maps. These originate from 83 sessions spanning a total of 26 years.

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

5 Achievements

Apart from the recurring activities described in the previous section, we have also developed specific work to take the BVID images further. One line of investigation was aimed to estimate VLBI jet directions in an automatic way, directly from the BVID images and without going through the usual (and time-consuming) model-fitting approach. The algorithm that we devised for this purpose first determines the distribution of flux density in a VLBI image as a function of azimuth, considering all clean components within a given radius (as measured from the central VLBI component position), which is steadily increased up to a certain cutoff value depending on the image noise level. The overall jet direction is then derived as the mean of the directions calculated for all radius values considered. Figure 1 plots the jet directions obtained in this way for the source 0333+321 at X-band and S-band based on the BVID images from the RDV76 session. As shown in this figure, the estimated jet directions agree well with those observed by inspecting visually the contour maps which are superimposed in each panel. A practical application of such a calculation is the optimization of scheduling in a way that avoids observing scans in a configuration where the sky-projected VLBI baseline is parallel to the jet, since these scans are subject to large structural delay effects for extended sources like 0333+321.

The determination of the VLBI jet directions with the method described above has also allowed us to further explore the connection between VLBI astrometric variability and source astrophysics. As reported in our previous biennial report and more recently in [5], we found that more than half of the 215 sources most-observed in geodetic VLBI may be characterized by at least one preferred direction of astrometric variability, with three-quarters of these showing a unique preferred direction and the rest showing two or more such directions. We presupposed that these preferred directions reflect astrophysical phenomena occurring within the VLBI jets, which modify the apparent source structure and hence the observed VLBI astrometric position. To assess this hypothesis, we compared the set of preferred directions derived from the source position time series and the jet directions extracted from the BVID source maps for a sample of 115 common sources. For each of these sources, an averaged jet direction was calculated by combining the jet direction extracted from all available images (i.e., at multiple epochs). The average jet direction was then compared to the preferred direction(s) extracted from the position time series. From this comparison, we found that the first or second preferred direction of astrometric variability lies within 15° of the VLBI jet direction for 55 of the sources, that is about half of the sample, hence indicating that the observed astrometric variability is most likely due to the changing VLBI jet morphology for those sources.

On the observing side, we have taken advantage of the R&D sessions to pursue further the monitoring of some under-observed optically-bright ICRF3 sources (i.e., detected by Gaia). Starting from summer 2020, our initial strategy [6] was refined in a way that the list of targets is now adjusted prior to each R&D session. Only sources that have not been observed for the past 30 days, taking into account all IVS sessions, are scheduled, with preference 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 3 (as previously). 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.

Another achievement during the period was the validation of the newly-implemented geodetic capability of the EVN software correlator at JIVE (SFXC) as part of our contribution to the JUMPING JIVE project [7]. Although not directly related to IVS activities, this capability is nonetheless of interest to the IVS community, since it now makes the SFXC correlator fully able to process IVS-style data and export them through the standard Mark4-HOPS-vgosDB geodetic route. For exercising this route, the data from the IVS-R1872 session, originally correlated with the Bonn DIFX correlator, were reprocessed with the SFXC correlator, fringe-fitted with HOPS, and exported to vgosDB format, after which the content of the resulting vgosDB file was compared to that of the original file produced in Bonn. Looking at the multi-band delays (Figure 2), the comparison indicates that the differences between the two sets of quantities have a weighted rms of 5.5 ps and fall within the calculated uncertainty for 95% of the data, which is in line with the expectations [8]. Taking advantage of this new capability, we have also gone further and conducted two dedicated EVN experiments, in June 2018 and October 2020, for the purpose of determining the geodetic positions of the EVN non-geodetic antennas, also one of the goals of the JUMPING JIVE project. Here again the new route was successfully exercised and the corresponding data are being analyzed.

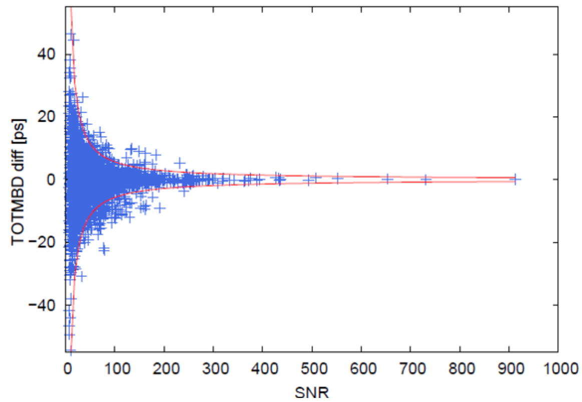

Fig. 2 Comparison of the total X band delay derived with the Bonn and JIVE correlators for the data of the session IVS-R1872 conducted on 10 December 2018. Differences are plotted with respect to SNR. The red curve materializes the $\pm 1\sigma$ uncertainty.

Finally, it is worth pointing out that the ICRF3 work has also been fully published during the period [9]. Besides the frame presentation and various comparisons, including between radio and optical positions, the paper also addresses the future evolution of the ICRF and prospective observations by the IVS for this purpose.

6 Dissemination and Outreach

The *IVS Live*[2] website, a specific tool developed by the Bordeaux group, provides "Live" information about ongoing IVS sessions, including VLBI images of the observed sources [10]. The website is updated automatically based on the IVS master schedule. It now incorporates 10,396 IVS sessions, involving 87 stations and featuring 2,992 sources. Tracing the connections indicates that there were 896 visits from 611 different users in 37 countries during 2019 and 2020. The statistics of access to the BVID, 1,149 visits from 594 different users in 57 countries over that period, are of the same magnitude. As for dissemination, Patrick Charlot taught various aspects of VLBI at two training schools, the 3rd IVS Training School on VLBI for geodesy and astrometry held in Las Palmas (Gran Canaria, Spain) on 14–16 March 2019 and the African VLBI Network training school that took place in Hartebeesthoek (South Africa) in May 2019. Also to be mentioned is the preparation of a poster about IVS that is now hanging in the main conference room of the OASU building.

7 Future Plans

Our plans for the next two years will follow the same analysis and research lines. We expect at first to validate the quality of the geodetic VLBI results derived with GINS by extensive comparisons against those drawn from other VLBI software packages, in particular the Vienna VLBI software. After this validation, the aim will be to move towards an operational analysis of the IVS-R1 and IVS-R4 sessions. Imaging the RDV sessions and evaluating the astrometric suitability of the sources, a specificity of the Bordeaux group, will be pursued further. Based on the images available in BVID, we also plan to explore the relationship between source structure and the positional offsets that are observed between the three ICRF3 frequencies and between VLBI and Gaia for some sources [9], taking also advantage of the algorithm that we developed to determine the VLBI jet directions. On the geodesy side, our goal will be to complete the analysis of the two dedicated experiments that have been conducted to estimate the positions of several non-geodetic EVN antennas.

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

Acknowledgements

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References

1. Bourda, G., Charlot, P., Biancale, R.: 2007, GINS: A New Tool for VLBI Geodesy and Astrometry, 18th EVGA Working Meeting, Eds. J. Böhm, A. Pany, and H. Schuh, IGG Vienna, p. 59–63.
2. Fey, A. L., Charlot, P.: 1997, VLBA Observations of Radio Reference Frame Sources. II. Astrometric Suitability Based on Observed Structure, ApJS, 111, 95–142.
3. Charlot, P.: 2008, Astrophysical Stability of Radio Sources and Implication for the Realization of the Next ICRF, 5th IVS General Meeting, Eds. A. Finkelstein and D. Behrend, p. 345–354.
4. Collioud, A., Charlot, P.: 2019, The Second Version of the Bordeaux VLBI Image Database (BVID), 24th Meeting of the European VLBI Group for Geodesy and Astrometry, Eds. R. Haas, S. Garcia-Espada, and J. A. López Fernández, p. 219–223.
5. Gattano, C., Charlot, P.: 2021, Characterizing the astrometric instability of extragalactic radio source positions measured with geodetic VLBI, A&A, 648, A125.
6. Le Bail, K., Gipson, J., Gordon, D., et al.: 2016, IVS Observation of Gaia-ICRF2 transfer sources, AJ, 151, id. 79.
7. Colomer, F., Kettenis, M., Campbell, R. M., Charlot, P., Szomoru, A.: 2019, Geodetic capabilities of the JIVE SFXC correlator, 10th IVS General Meeting, Eds. K. L. Amstrong, K. D. Baver, and D. Behrend, NASA/CP-2019-219039, p. 117–120.
8. Gómez, M. E., Charlot, P., Campbell, R. M., Kettenis, M., Keimpema, A.: 2020, Geodesy at K band with the European VLBI Network, Journées 2019, "Astrometry, Earth Rotation and Reference Systems in the Gaia Era", Ed. C. Bizouard, Observatoire de Paris, p. 181–184.
9. Charlot, P., Jacobs, C. S., Gordon, D., et al.: 2020, The third realization of the International Celestial Reference Frame by very long baseline interferometry, A&A, 644, A159.
10. Collioud, A.: 2011, IVS Live: All IVS on your deskstop, 20th Meeting of the European VLBI Group for Geodesy and Astrometry, Eds. W. Alef, S. Bernhart, and A. Nothnagel, Universität Bonn, IGG, Schriftenreihe 22, p. 14–18.