Report for 2017–2018 from the Bordeaux IVS Analysis Center

Patrick Charlot, Antoine Bellanger, Géraldine Bourda, Arnaud Collioud, César Gattano

Abstract This report summarizes the activities of the Bordeaux IVS Analysis Center during 2017 and 2018. In this period, analysis activities using the GINS software package were pursued further, together with the systematic VLBI imaging of the RDV sessions. A major achievement was the implementation of a modernized version of the Bordeaux VLBI Image Database, where RDV images and related information (e.g., structure indices, compactness values) are stored. Another highlight was the involvement in the IAU Working Group on the next ICRF (International Celestial Reference Frame) realization, chaired by one member of the Bordeaux group, which culminated with the realization of the ICRF3 and its adoption by the IAU in August 2018. Analysis of the time series of source positions, which revealed that astrometric instabilities often occur along one or two preferred directions on the sky, is another significant accomplishment during this period.

1 General Information

The *Laboratoire d'Astrophysique de Bordeaux (LAB)* is a research center 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.

VLBI activities at the LAB are carried out within the M2A (*Métrologie de l'espace, Astrodynamique, Astrophysique*) team. Contribution to IVS has been mostly concerned with the maintenance, extension, 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 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, VLBI, DORIS, SLR, LLR, satellite altimetry, and other space missions [1]. Those analyses are primarily targeted to estimating Earth Orientation Parameters (EOP).

2 Description of 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, EOP estimates with six-hour resolution were produced. The focus of such 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 group is also engaged in imaging ICRF sources on a regular basis. This is achieved by systematic anal-

Laboratoire d'Astrophysique de Bordeaux

Bordeaux Analysis Center

IVS 2017+2018 Biennial Report

ysis of the data from the RDV sessions (conducted six times a year). This analysis is carried out with the AIPS and DIFMAP software packages. The aim of such regular imaging 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, which is required to optimally define the celestial frame.

3 Scientific Staff

During 2017 and 2018, five individuals contributed to one or more of our IVS 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. In the fall of 2017, the group was joined by César Gattano, a post-doc who got his PhD from Paris Observatory a year earlier. Apart from this arrival, there were no other changes in the IVS staff over the period.

- Patrick Charlot (50%): researcher with overall responsibility for Analysis Center work. His interests include the ICRF densification, extension, and link to the Gaia frame, studies of radio source structure and its impact on astrometric VLBI, and astrophysical interpretation. He was also chair of the ICRF3 Working Group in the period 2015–2018.
- Antoine Bellanger (100%): engineer with a background in statistics and computer science. He is tasked to process VLBI data with GINS and to develop procedures and analysis tools to automate such processing with prospects of implementing an operational VLBI analysis in the future.
- Géraldine Bourda (30%): astronomer in charge of developing the VLBI part of GINS and overseeing the analysis results derived from GINS. She also developed a VLBI observational program for linking the ICRF and the Gaia optical frame and was a member of the ICRF3 Working Group.
- Arnaud Collioud (70%): engineer with a background in astronomy and interferometry. His tasks are to image the sources in the RDV sessions using AIPS and DIFMAP, to develop the Bordeaux VLBI Image Database and *IVS Live* tools, and to conduct simulations for the next-generation VLBI system.
- César Gattano (50%): 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.

4 Current Status

As noted above, one of our goals for the future is to implement an operational analysis of the IVS-R1 and IVS-R4 sessions for the EOP determination using the GINS software package. To reach this goal, a prerequisite is to assess the quality of the results derived with GINS and to validate these against similar determinations obtained with other VLBI software packages, since the VLBI capability of GINS is not widely used. In particular, we wish to compare the individual components of the VLBI delay model in GINS with the same components as derived from other software packages. For various reasons, progress towards this goal has been slow and such comparisons, along with the relevant assessment, still remain to be done.

Another major part of our activity consists in systematic imaging of the sources observed during the RDV sessions. During 2017 and 2018, seven such sessions were processed (from RDV112 to RDV124), resulting in 1,088 VLBI images at either X- or S-band for 386 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]. At present, the BVID comprises a total of 6,117 VLBI images for 1344 different sources (with links to an additional 6,775 VLBI images from the Radio Reference Frame Image Database of USNO) along with 12,892 structure

[1] The Bordeaux VLBI Image Database can be accessed at http://bvid.astrophy.u-bordeaux.fr.

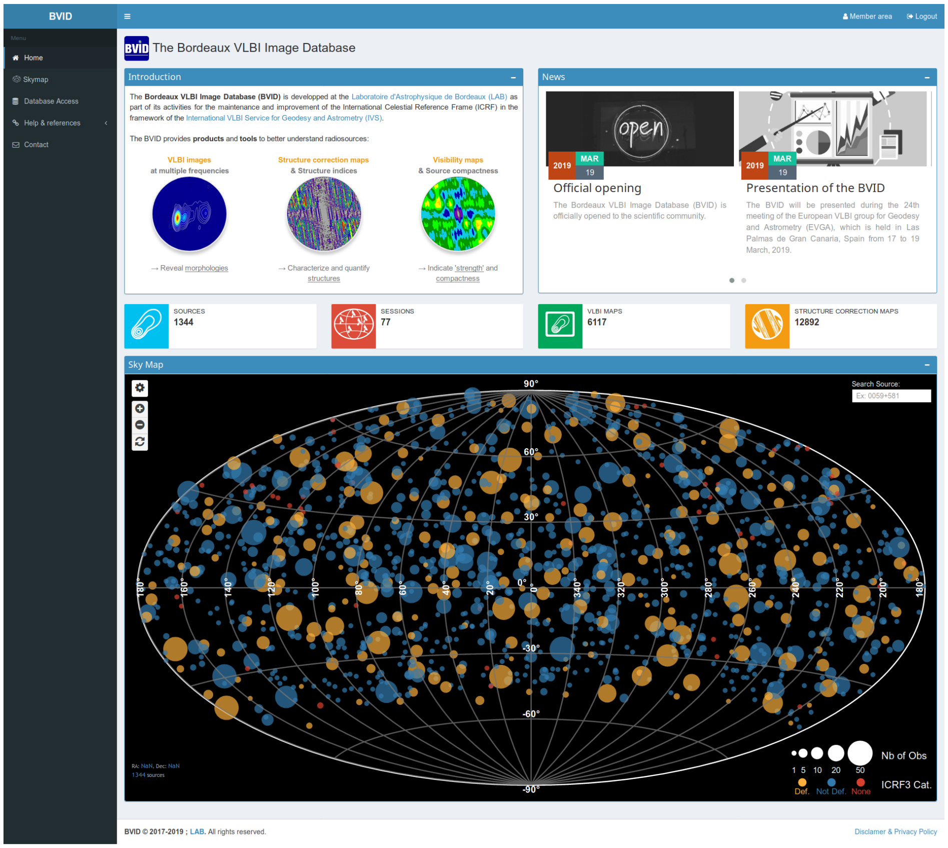

Fig. 1 View of the home page of the second version of the BVID. The interface presents the latest news, some statistics related to the BVID content, and the sky distribution of all the sources included in the BVID, color-coded according to their ICRF3 category.

correction maps and as many visibility maps. These originate from 77 sessions spanning a total of 22 years.

5 Achievements

A major achievement during the period 2017–2018 was the design and implementation of a new, modernized version of the BVID, in replacement of the initial version, built in 2008. This second version has a clean and modern user interface (Figure 1), offers additional tools, and delivers new data and information. Sky maps, interactive charts, and tables permit to navigate easily through the BVID data. Additionally, a multi-criteria form that allows users to refine queries (e.g., based on flux density, structure index) was implemented to supplement already-existing queries from source name, sky coordinates, session name, and date. The new data incorporated into BVID comprise FITS images, source models (CLEAN components), and some associated plots. Furthermore, the second version of BVID is flexible enough to host VLBI images from the community (with full credit to the authors) in addition to those produced in Bordeaux.

Another highlight of the past two years was the realization of ICRF3, which culminated with its adoption by the IAU on 30 August 2018, during the XXXth IAU General Assembly in Vienna. Two members of the group (Géraldine Bourda and Patrick Charlot) were members of the IAU Working Group on the next ICRF realization and as such contributed to the effort towards ICRF3. Their contribution had to do with (i) the assessment of astrometric source quality, a primary criterion to select defining sources, (ii) the actual selection of ICRF3 defining sources, and (iii) the identification of common sources between the ICRF3 three-frequency (S/X, K, and X/Ka bands) frame and the Gaia CRF2

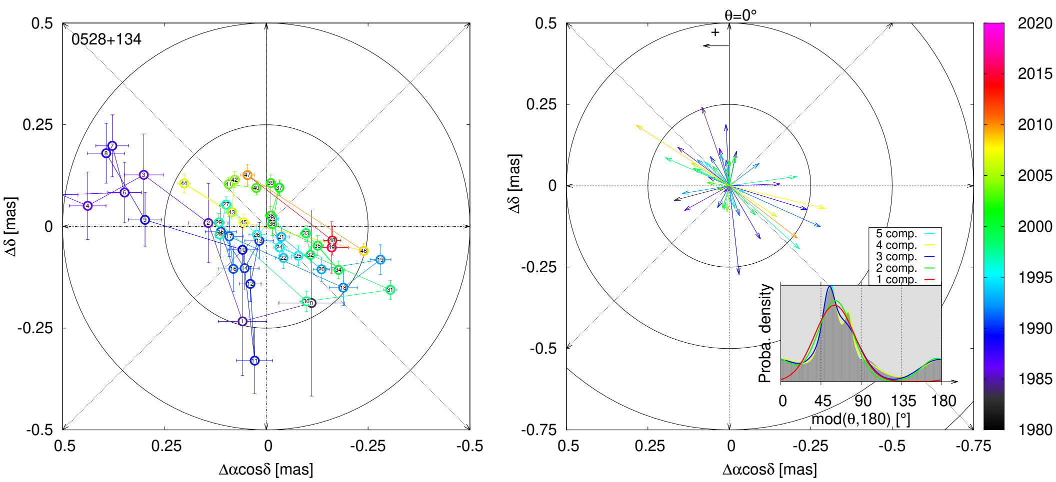

Fig. 2 *Left:* Sky trajectory drawn from the averaged VLBI positions measured over the period 1980–2018 for the source 0528+134. *Right:* Equivalent set of vectors connecting each pair of successive positions. The PDF built from these set of vectors is given as the upper edge of the shaded area in the inset box. Colored lines show fits to the PDF when 1–5 components (directions) are extracted.

optical frame [4]. Patrick Charlot, Chair of the Working Group, also led the overall work. In all, two face-to-face meetings of the Working Group were organized in the period (Bologna, Italy, 13–14 October 2017; Bordeaux, France, 22–23 February 2018) along with fourteen teleconferences, all of which were attended by at least one member from Bordeaux. An open meeting of the ICRF3 Working Group was further held during the IAU General Assembly on 29 August 2018. On the way to ICRF3, an essential element was the preparation of the IAU resolution on ICRF3 and the interaction with the IAU resolution committee on that matter. As Chair of the Working Group, Patrick Charlot also gave presentations on (progress towards) ICRF3 (either invited or contributed) at a number of international conferences to advertise about ICRF3. These include the 23rd EVGA Working Meeting (Gothenburg, Sweden, 15–17 May 2017), EWASS 2017 (Prague, Czech Republic, 26–30 June 2017), IAG–IASPEI Joint Scientific Assembly (Kobe, Japan, 30 July–4 August 2017), Journées des Systèmes de Référence et de la Rotation Terrestre 2017 (Alicante, Spain, 25–27 September 2017), 10th IVS General Meeting (Longyearbyen, Svalbard, 3–9 June 2018), and 14th EVN Symposium (Granada, Spain, 8–11 October 2018). ICRF3 was also presented at two national conferences that took place in Paris (4–7 July 2017) and Besançon (14–15 June 2018). Of course, the most important presentation was that at the IAU General Assembly on 27 August 2018, prior to the voting by the IAU members and the adoption of ICRF3 by the astronomical community.

On the research side, a specific effort was dedicated to the analysis of source coordinate time series in order to characterize astrometric instabilities. Using the Allan standard deviation for such characterization, it was found that the majority of the most observed sources in the geodetic and astrometric VLBI pool since 1979 are unstable [5]. An additional step was taken to determine whether those instabilities occur randomly or along preferred directions on the sky. The method devised to this end is based on the calculation of source trajectory (from averaged sky positions, see left panel in Figure 2) and the identification of any systematic pattern in this trajectory. In practice, each pair of successive positions is transformed into a vector which defines a direction of variation (Figure 2, right panel). A probability density function (PDF) is then built from the distribution of those directions, from which one or several preferred directions are extracted. Applying this scheme to the 215 sources observed more than 200 times at the time of the study, we found that 60% of the sources in this sample show one preferred direction while another 30% show two preferred directions. The overall homogeneous distribution of the directions on the sky (except for a small excess along the declination direction, likely due to the network geometry) is an indication that the origin of those variations is probably intrinsic to the sources, and hence due to astrophysical phenomena, a perspective that we are exploring.

6 Dissemination and outreach

The *IVS Live* Web site[2], a specific tool developed by the Bordeaux group, provides "Live" information about ongoing IVS sessions, including VLBI images of the observed sources [6]. The Web site is updated automatically based on the IVS master schedule. It now incorporates 9,174 IVS sessions, involving 81 stations and featuring 2,588 sources. Tracing the connections indicates that there were 1,685 visits (from 54 countries) in 2017 and 2018. The statistics of access to the BVID, 1,025 visits (from 42 countries) over that period, are about the same. In terms of outreach, a specific text to popularize ICRF3 or to serve as a basis for press releases, was written and distributed following the adoption of ICRF3 by the IAU. As for dissemination, Patrick Charlot taught various aspects of VLBI at two training schools, the April 2018 African VLBI Network training school held in Hartebeesthoek (South Africa) and the 9th summer school of the GRGS (*Groupe de Recherche de Géodésie Spatiale*), that took place in Oléron (France) on 3–7 September 2018.

7 Future Plans

Our plans for the next two years will be focused at first on implementing an operational analysis of the IVS-R1 and IVS-R4 sessions with the GINS software package. This implies validating the quality of the results derived with GINS, hence requiring further comparisons with other VLBI software packages, and demonstrating that we can sustain such operations on the long term. Imaging the RDV sessions and evaluating the astrometric suitability of the sources, a specificity of the Bordeaux group, will be continued along the same lines. Taking advantage of data from the second version of the BVID, we plan to explore further the connection between astrometric instabilities and source astrophysics, while also reactivating our long-standing work on source structure modeling in geodetic and astrometric VLBI. A new post-doctoral fellow, Maria Eugenia Gomez, just joined us in the framework of the EU-funded JUMPING JIVE project. Her work has to do with the implementation of full geodetic capabilities at the European VLBI Network software correlator at the Joint Institute for VLBI-ERIC (JIVE). Although not directly connected to IVS, this project, nevertheless, may have an impact at some point since it will make the JIVE correlator able to process IVS-type data.

[2] The IVS Live Web site can be accessed at http://ivslive.astrophy.u-bordeaux.fr.

Acknowledgements

We would like to thank the OASU for continued support of the Bordeaux IVS Analysis Center. In particular, the development of the second version of the BVID would not have been possible without such support. We are also grateful to the *Programme National GRAM (Gravitation, Références, Astronomie, Métrologie)* of CNRS-INSU with INP and IN2P3 co-funded by CNES for supporting ICRF3 activities all along.

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, St Petersburg, Eds. A. Finkelstein and D. Behrend, p. 345–354.
4. Gaia collaboration, Mignard, F., Klioner, S. A., et al.: 2018, Gaia Data Release 2 – The celestial reference frame (Gaia-CRF2), A&A, 616, A14.
5. Gattano, C., Lambert, S. B., Le Bail, K.: 2018, Extragalactic radio source stability and VLBI celestial reference frame: insights from the Allan standard deviation, A&A, 618, A80.
6. Collioud, A.: 2011, IVS Live: All IVS on your deskstop, Proceedings of the 20th Meeting of the European VLBI Group for Geodesy and Astronomy, Eds. W. Alef, S. Bernhart, and A. Nothnagel, Universität Bonn, Institut für Geodäsie und Geoinformation, Schriftenreihe 22, p. 14–18.