Report 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 2023 and 2024. 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. Activities on the validation of the VLBI component of the multi-technique GINS software package were continued as well with a focus on the assessment of the accuracy of the geometric model implemented in GINS. Also carried on was our observing program to monitor under-observed optically-bright ICRF3 sources based on the R&D sessions conducted over the period. Further work led to the identification of 920 sources with no or limited optical-radio offsets. These sources are potential defining sources for ICRF4, the next multi-waveband realization of the ICRF, and are to be monitored through the RDV sessions in the coming years. Several VGOS R&D sessions conducted in the period were used to test the new source-centric scheduling strategy, while taking the opportunity of these sessions to densify the VGOS celestial frame. Analysis of K-band observations acquired with the European VLBI Network (EVN) was continued and led to the determination of the geodetic position of four non-geodetic EVN telescopes in the ITRF2020 frame. Global VLBI observations have also been initiated to strengthen the K-band celestial frame prior to generating ICRF4.

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Bordeaux Analysis Center

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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 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. 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 involved in maintaining the VLBI component of GINS and assessing its quality and performance.

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 have been 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 regular imaging of the ICRF sources. 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". Comparison of source positional instabilities and structural evolution is an additional direction of work. Such studies are essential for identifying sources of high astrometric quality, a necessity to define the celestial frame at best.

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 design and scheduling of K-band observations for geodetic, astrometric, and imaging purposes, the selection of sources with no detected optical-radio offsets to be monitored from the RDV sessions, and the identification of new suitable sources from the ICRF3 [2] to be observed by VGOS for the generation of a VGOS celestial frame and its densification.

3 Scientific Staff

During the period 2023 – 2024, 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. Maria Eugenia Gómez, formerly a post-doc in Bordeaux, remains associated with the group through the GINS and K-band activities.

- Patrick Charlot (60%): Researcher with overall responsibility for Analysis Center work. His primary interests include all aspects of the ICRF, comparisons with the Gaia frame, studies of radio source structure and its impact in astrometric VLBI, and astrophysical interpretation. He also leads a global VLBI program recently initiated at K-band.
- Arnaud Collioud (80%): Engineer with a background in astronomy and interferometry, in charge of imaging the sources from the RDV sessions and developing the Bordeaux VLBI Image Database and *IVS Live* tool. He also contributes to research in astrometry and astrophysics based on these data.
- Maria Eugenia Gómez (30%): Researcher from University of La Plata and CONICET (Argentina) contributing to the analysis of K-band observations. She is also involved in the GINS activities, notably in the validation in the underlying VLBI model.
- Stéphane Paulin-Henriksson (10%): Engineer with a background in astronomy, contributing to comparisons of results obtained with the GINS software package and other VLBI software packages.

4 Current Status

As reported previously, one of our standing goals is to implement an operational analysis of the IVS-R1 and IVS-R4 sessions using the GINS software package. Because 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. Based on expertise within the group, we selected the Vienna VLBI Software (VieVS) [3] as the reference software for this assessment. The aim is to evaluate the accuracy of the VLBI modeling in GINS and implement any needed improvements, after which we will compare the estimated parameters and their uncertainties, along with the post-fit residuals, against those from VieVS as a final assessment. As noted in our previous biennial report, the focus was placed initially on comparing the geometric model, excluding station corrections and tropospheric corrections. This comparison revealed a roughly diurnal systematic pattern for each VLBI baseline/quasar pair, with an amplitude of up to 2 mm, between the VLBI delays computed by the two software packages. Despite further investigations, including the examination of different sessions, we have not yet resolved this issue. We expect to intensify the work (which has suffered from limited re-

sources during the past period) in the coming months. Besides the foreseen operational analysis, GINS will be well suited to process data from the upcoming GENESIS mission of the European Space Agency thanks to its multi-technique capability. It is therefore important that the software be made state-of-the-art and be fully validated sooner than later so that it can be sufficiently exercised before the launch of GENESIS in 2028.

Another major part of our activity consists of the systematic VLBI imaging of the sources observed in the RDV sessions. During 2023 and 2024, five such sessions were processed (RV148, RV150, RV152, RV154, and RV156), resulting in 703 VLBI images at either X- or S-band for 242 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 [4, 5] for a definition of these quantities) in order to assess the astrometric source quality. All such information is made available through the Bordeaux VLBI Image Database (BVID)[1] [6]. At present, the BVID comprises a total of 8,707 VLBI images for 1,596 different sources (with links to an additional 6,775 VLBI images from the Radio Reference Frame Image Database of USNO) along with 15,482 structure correction maps and as many visibility maps. These originate from 95 sessions spanning a total of 28 years.

5 Achievements

Apart from the recurring activities described in the previous section, we also developed more research-oriented work. The two broad lines of research in the past period relate to improvements in VGOS observing and preparations for ICRF4, the next realization of the ICRF. Details on this work are given below.

As noted in our previous biennial report, we contributed to developing a new "source-centric" scheduling strategy that optimizes simultaneously for geodesy, astrometry, and imaging [7]. As a natural follow up of the simulations, it was proposed to test the strategy on real data, which was achieved through implementation in five VGOS R&D sessions during 2023 and 2024 (VR2301, VR2302, VR2403, VR2404, and VR2405). The analysis of these sessions revealed that the formal errors of the resulting geodetic and astrometric parameters (EOP, station coordinates, and source coordinates) are either improved (by up to 50%) or similar to those from the regular VGOS operational sessions [8], while at the same time the percentage of sources that could be imaged has more than doubled [9]. These results are in line with the expectations from the simulations. The next stage now is to test the strategy on a larger set of sessions, namely operational VGOS sessions, before a potential general use to generate VGOS schedules.

We also devoted efforts to identify further ICRF3 sources potentially detectable by VGOS besides those already in the catalog. The goal is to establish a specific celestial frame for VGOS in the medium term. The identification of such additional sources was achieved by taking into account expected correlated flux densities to maximize chances of detection. For this purpose, we calculated the median correlated flux density over the u-v plane (for Earth-based baselines) for all ICRF3 sources that have images available in BVID and used the median of this quantity over all epochs as a metric of the expected correlated flux density of each source (Figure 1). Adopting a lower limit of 0.25 Jy at both X- and S-bands for this quantity yielded a total of 153 ICRF3 sources (14 defining sources and 139 non-defining sources) not observed by VGOS at the end of 2022. All such sources were then incorporated into the schedules of several VGOS R&D sessions and successfully observed in 2023 (113 sources) and 2024 (40 sources) along with another 38 sources, resulting in a catalog that grew from 289 sources in 2022 to 418 sources in 2023 [10] and 480 sources in 2024 [8]. This work also showed that a dedicated VGOS celestial frame is mandatory for processing operational VGOS observations, a conclusion also reached in [11].

On the observing side, the monitoring of some under-observed optically-bright ICRF3 sources (i.e., detected by Gaia) based on the R&D sessions was continued. As reported previously [12], only sources with a structure index smaller than 3 that were not observed by the IVS in the 30 days preceding each session were considered for scheduling, with preferences given to those that are brighter than magnitude 18, 19, and 20 (in decreasing order). A total of 20 such R&D sessions were conducted in 2023 and 2024. With the

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

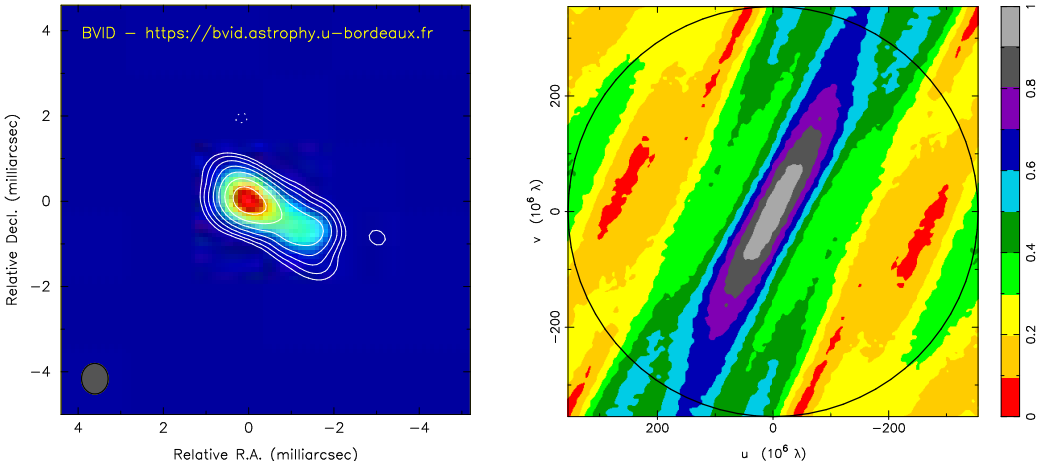

Fig. 1 *Left:* VLBI map of the source 0430+052 (3C120) at X-band for epoch 2016 November 30. *Right:* Visibility computed over the u-v plane from the map in the left panel. The source compactness (defined as the median visibility over the u-v plane, see [5]) is 0.35, which translates to a median correlated flux density of 0.76 Jy after multiplication by the total source flux density (2.17 Jy).

Gaia science observations ending on 15 January 2025, our VLBI program will be carried over for another six months, after which it will be terminated. Still on the observing side, we contributed to a proposal, led by USNO, to double the number of RDV sessions in 2025–2027 (for a total of 12 sessions per year) in preparation for ICRF4. The goal is to monitor 920 ICRF3 sources, north of −45° declination, twice per year (Figure 2). These include 785 sources with optical-radio offsets less than 1-sigma (as determined by comparing the ICRF3-SX and Gaia-CRF3 positions), plus all ICRF3 defining sources with offsets between radio and optical between 1- and 3-sigma. Such sources, with no detected or limited optical-radio offsets, are candidates to serve for the alignment between the VLBI and Gaia frames in ICRF4 [13], hence the importance of observing them on a regular basis.

On the analysis side, we continued the processing of K-band observations previously acquired with the European VLBI Network (EVN). This led to the determination of the geodetic positions of four non-geodetic EVN telescopes (Jodrell Bank, Sardinia, Torun, and KVN-Yonsei) in the ITRF2020 frame with centimeter level precision [14]. Additionally, we obtained further EVN observing time (48 hours scheduled in June 2023) to control the positions of these telescopes and measure their velocities. Aside from such geodetic objectives, the observations were also aimed at strengthening the K-band celestial frame by taking advantage of the long East-West and North-South baselines of the array, while producing high-resolution images of the ICRF3 defining sources, which were specifically targeted, at the same time. Building on these results and extending the collaboration, we proposed global VLBI observations, adding the Very Long Baseline Array to the EVN along with antennas in Australia, for a total of 29 telescopes worldwide. The primary goal of the project is to reobserve all 1,300 sources in the current K-band frame to strengthen its geometry for ICRF4. A total of ten 24-hour experiments have been approved to this end, the first of which was carried out in November 2024.

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 [15]. The website is updated automatically based on the IVS Master Schedule. It now incorporates 15,589 IVS sessions, involving 90 stations and featuring 3,501 sources. The site is used by both astronomers, e.g., for the observation of optically-bright sources described above, and for outreach to show to the public the succession of scans observed in a session. Tracing the connections indicates that there

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

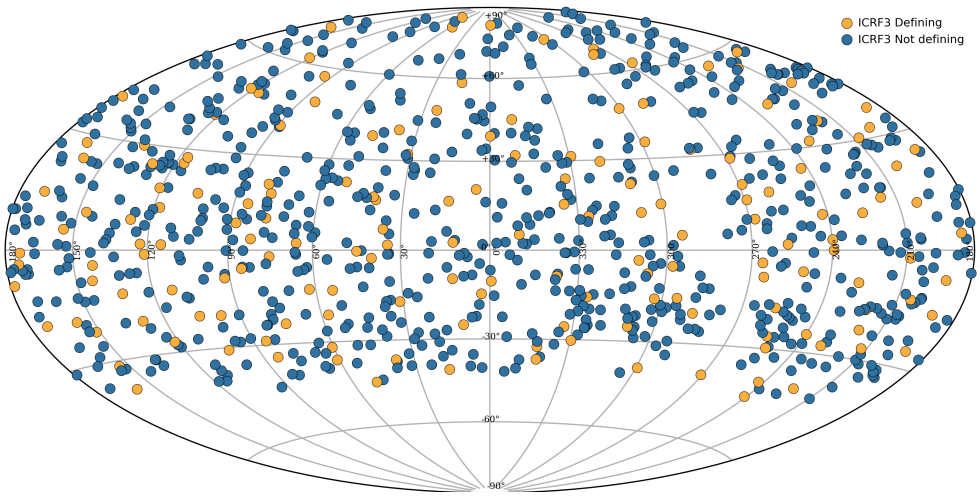

Fig. 2 Sky distribution of the 920 ICRF3 sources to be monitored twice per year based on the RDV sessions, starting from January 2025. The 168 ICRF3 defining sources are plotted in yellow (light gray), while the 752 non-defining sources are plotted in blue (black).

were 734 visits from 434 different users in 40 countries in 2023 and 2024. The statistics of access to the BVID, 2,274 visits from 1,079 different users in 71 countries, are comparable to those during the previous two years.

7 Future Plans

Our plans for the next two years will follow the same analysis and research lines. In particular, we want to have a final assessment of the GINS software package and correct any deficiencies to make it state-of-the-art. The goal is to use GINS routinely for IVS operational analysis and to have the capability of processing the VLBI data from the upcoming GENESIS mission. Imaging the RDV sessions and evaluating the source astrometric suitability, a specificity of the Bordeaux group, is another activity that will be carried on. With twice the number of such sessions to be conducted in the period, the corresponding effort will have to be increased to keep up with the data. Our aim is also to develop astrometric and astrophysical applications making use of the images available in BVID. This includes implementation of source structure corrections in geodetic VLBI analysis, studies of jet evolution and its relationship with source position instabilities, investigation of the relationship between source structure and the observed optical-radio positional offsets, and the identification of suitable sources to serve as defining sources for ICRF4. On the VGOS side, the goal will be to continue identifying and observing more sources to densify the celestial frame. Completing the sky coverage in the deep South is especially desired to make the VGOS frame full sky. Besides these points, high priority will be given to the preparation, post-processing, and analysis of the aforementioned global observations at K-band to be run in the next two years in support of ICRF4.

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