Service and Research at Paris Observatory (OPAR) Analysis Center

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Abstract We report on the VLBI-related service and research activity at the Paris Observatory (OPAR) Analysis Center during the years 2021 and 2022. Featured items include the opa2021 diurnal and Intensive solutions, the identification of *Gaia* centroids with pc-scale radio features thanks to absolute VLBI astrometry and VLBA mapping, with insight into locating the emission of γ-ray photons, and the study of several approaches to estimate large-scale systematics in catalogs.

1 General information

The service activities in link with the IVS, including the processing of VLBI data and the maintenance of the website, are ensured by one person (S. Lambert). This does not include the maintenance of the Data Center (see the report on the Data Center in this volume) that is ensured by C. Barache, helped by our IT manager T. Carlucci. The rest of the authors mentioned in this report are involved in the valorization of VLBI data through their scientific exploitation and research but cannot participate directly in IVS activities.

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2 Service

In 2021–2022, OPAR continued the processing of IVS data, both diurnal and Intensive sessions, in the opa2021a and opa2021i solutions with Calc/Solve. SINEX files were produced routinely for opa2021a so that OPAR could contribute to the IVS combination. Solution opa2021a uses the ICRF3 as its a priori radio source catalog and includes a model for the Galactic aberration, i.e., a dipolar displacement field of the quasars toward the Galactic center of amplitude 5.8 µas per year, as recommended by the IVS Working Group 8 (MacMillan et al., 2019) and as used for the production of the ICRF3 catalog (Charlot et al., 2020). The reference epoch of the Galactic aberration modeling is 2015.0, consistent with the ICRF3. As a consequence, the opa2021a quasar coordinate catalog should be read as follows: coordinates listed in the catalog correspond to the apparent position of the sources at 2015.0; at another epoch, the position of the sources should be corrected by the Galactic aberration effect using the above amplitude.

OPAR continued to update radio source coordinate time series, station coordinate time series, and baseline length time series, as non-official products. The radio source coordinate time series are offered in two versions. A first version is obtained with independent session processing of the opa2021a rapid solution, allowing updates as new observations arrive. More accurate time series are obtained by four global solutions in which one fourth of the defining sources are downgraded as local parameters. These series exhibit a substantially lower scatter of the data and allow monitoring of more subtle variations of the position of the radio centroid than with the first version, but they are not up-

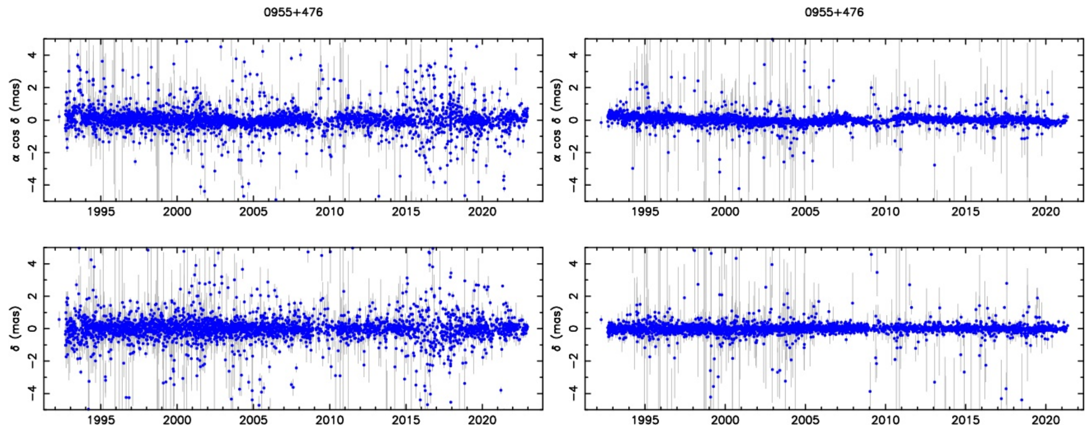

Fig. 1 Time series of the position of the blazar 0955+476 about its mean value.

dated until the processing of new global solutions (see Figure 1).

OPAR also offers a monitoring of the free core nutation (FCN) by fitting its amplitude and phase over a seven year sliding window to the available nutation time series provided by IVS Analysis Centers and the IERS (Figure 2). For each series, we make available a table of yearly amplitudes (that can be used within a routine to model and predict the evolution of the oscillation) and a time series of the FCN values at the epochs of the data.

All these products are made available at the OPAR website (http://ivsopar.obspm.fr).

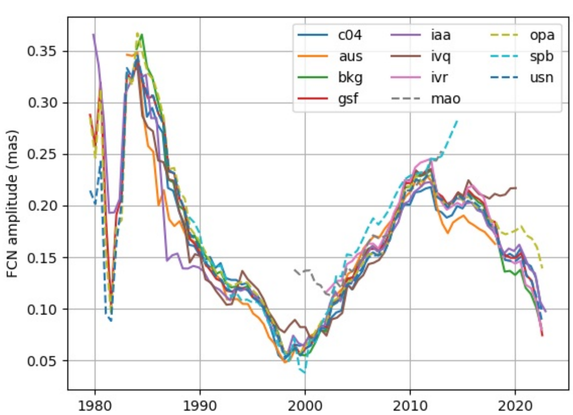

Fig. 2 Amplitude of the free core nutation fitted to several nutation time series.

3 Research

Most of the research using VLBI data in the Paris Observatory team was turned toward the radio-optical offsets between VLBI and *Gaia* with a goal extended to identifying the optical emission mechanism(s) contributing to offsetting the optical centroid with respect to the radio centroid. If the radio centroid designated by geodetic VLBI can be located over a radio structure map with a relatively good accuracy (generally falling close to the brightest feature), the *Gaia* centroid rises from the optical emission integrated over about 100 mas, englobing possibly separate contributions from the jet (one or more knots), the disk, and a halo. Using MOJAVE maps (Lister et al., 2021), we compared absolute ICRF3 and *Gaia* DR3 positions (Prusti et al., 2016; Vallenari et al., 2022) with structures (although ICRF3 is 8 GHz and structures are 15 GHz) to attempt to identify if the *Gaia* emission comes from a radio feature. We showed that, for about 60% of the source sample (with a total sample of about 400 sources), the *Gaia* centroid falls within 3σ of the radio core. For about half of this population, the *Gaia* centroid is susceptible to coinciding with a VLBI component different from close, although very close (called category B for "base"). In contrast, for the rest of this population, the optical centroid falls onto the radio core (category C for "core"). For about 30% of the sample, the *Gaia* centroid coincides with a jet (ejected) component (category J for "jet"). For another 10%, the *Gaia* centroid does not fall onto a clear VLBI feature (category O for "other") (Lambert et al., 2022a). The study

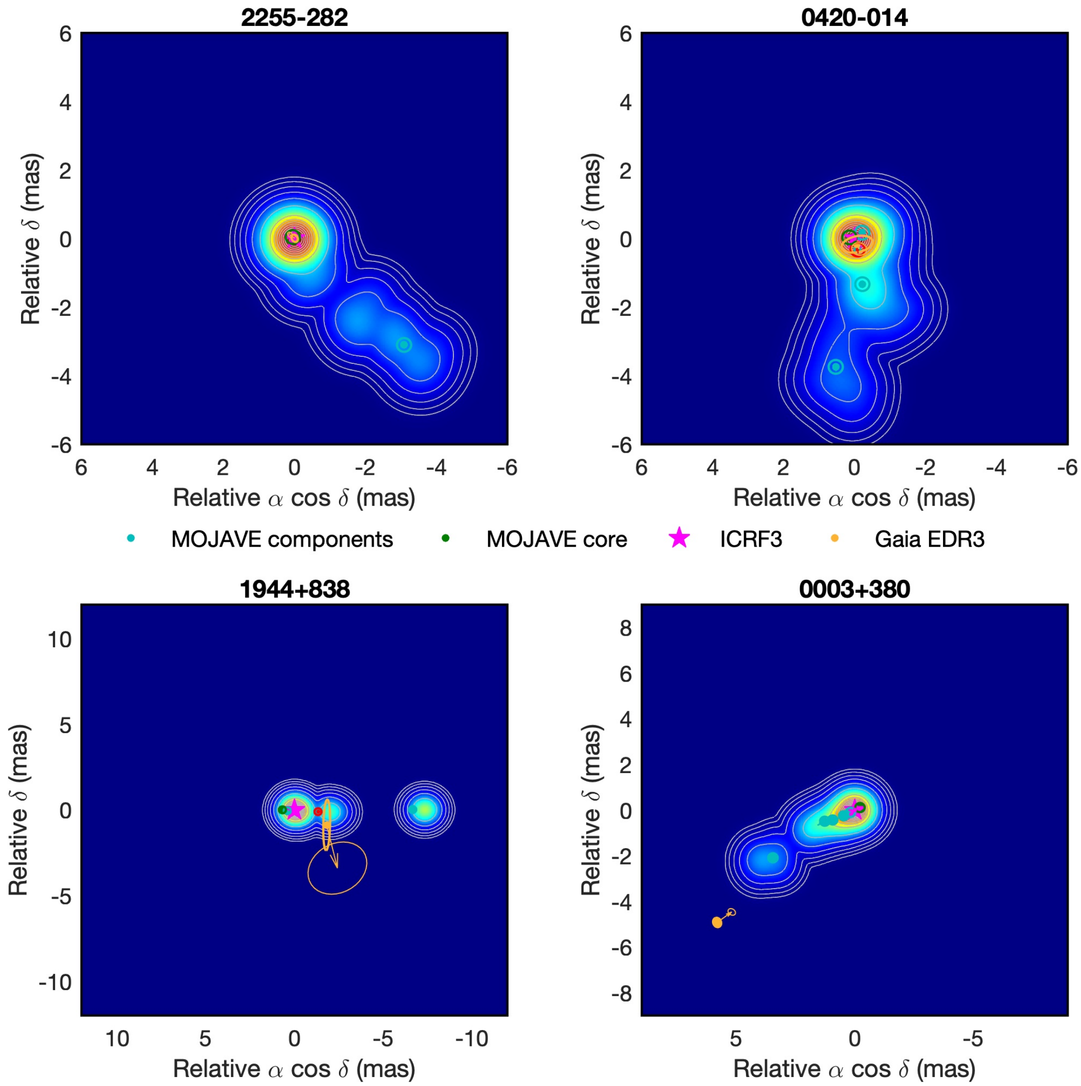

Fig. 3 Example of sources in the four C (2255-282), B (0420-014), J (1944+838), and O (0003+380) categories (see text for details).

of their B-R indices and radio and optical polarization support earlier results from Plavin et al. (2019) and Kovalev et al. (2020). Indeed, the B, J, and O categories exhibit a redder color index than C, favoring a possible contribution of the disk for the latter in contrast to non-thermal (synchrotron) emissions for the former categories. The fractional linear polarization in radio is higher for category J (optically thin in the jet, synchrotron emission in a somewhat organized magnetic field), followed by categories C and B (optically thick cores).

We extended the above comparisons to the very high energy (TeV) domain by using the Fermi-LAT measurements (Abdollahi et al., 2020) together with radio-optical centroid distances and color index B-R (Lambert et al., 2022b; Sol et al., 2022; Lambert et al., 2022c). Time domain correlations observed between optical, X-ray, and γ-ray fluxes suggest correlated mechanisms (inverse-Compton, synchrotron), so that large emissions of radio, optical, and γ photons could originate from the same region. A recent global approach by Kramarenko et al. (2022), based on correlations between Fermi-LAT fluxes and delayed radio fluxes, favored a γ-ray emission outside the broad line region at several parsecs from the core. Using a sample of about 800 sources, we showed that highest γ-ray fluxes coincide with sources exhibiting an intermediate color index and an optical emission close to the base of the jet (but not on the core). For these sources and, more generally, for sources for which the optical centroid is in the jet (i.e., B and J of the previous paragraph), the *Gaia* centroid provides an interesting tool for locating the TeV emission site. For low radio-optical separations, the *Gaia* centroid can also locate the dominant γ-ray emission zone for BL Lacs, but the situation is less obvious for FSRQs because of the disk contribution to the optical emission.

Studies were also devoted to characterizing anomalous offsets and/or proper motion either in the optical or the radio domain. Souchay et al. (2022) used the Large Quasar Astrometric Catalog (LQAC, Souchay et al., 2019) as a statistical basis for isolating anomalous proper motions of *Gaia* DR3 ($>$ 10 mas/year) and separating those potentially due to halos or companions from those requiring specific follow-up in the coming years to determine their causes. In the radio domain, Titov et al. (2022) pointed out VLBI sources showing abrupt variations in positions (several mas) and explained them by abrupt variations in their structure or relative fluxes of components.

A more technical study was devoted to characterizing large-scale deformations in VLBI catalogs. In Lambert and Malkin (2023) we compared several methods for estimating the 16 deformation parameters investigated in Charlot et al. (2020). Our methods were inspired by L1-norm minimization and division of the sphere into cells of equal area (Malkin, 2019) with the classical L2-norm-based methods such as used in Charlot et al. (2020) and the more sophisticated L2-iterative. Using simulated catalogs (for which we knew the true values of the deformation parameters), we concluded that all methods converged on the expected values within a few microarcseconds. The identification and elimination of outliers was best achieved with a hybrid L2/L1 method (L1 being used for outlier identification) or iterative L2 method. These two methods provided the best accuracy in the estimated parameters.

References

Abdollahi S., F. Acero, M. Ackermann, et al. Fermi large area telescope fourth source catalog. *The Astrophysical Journal Supplement Series*, 247(1): 33, 2020.

Charlot P., C. Jacobs, D. Gordon, et al. The third realization of the International Celestial Reference Frame by very long baseline interferometry. *Astronomy & Astrophysics*, 644: A159, 2020.

Kovalev Y., D. Zobnina, A. Plavin, and D. Blinov. Optical polarization properties of AGNs with significant VLBI–Gaia offsets. *Monthly Notices of the Royal Astronomical Society: Letters*, 493 (1): L54–L58, 01 2020.

Kramarenko I., A. Pushkarev, Y. Kovalev, et al. A decade of joint MOJAVE-Fermi AGN monitoring: localisation of the gamma-ray emission region. *Monthly Notice of the Royal Astronomical Society*, 510: 469, 2022.

Lambert S. and Z. Malkin. Estimation of large-scale deformations in VLBI radio source catalogs with mitigation of impact of outliers: A comparison between different L1- and L2-norm-based methods. *Astronomy & Astrophysics*, 2023.

Lambert S., A. Pierron, and H. Sol. Identification of the optical emission detected by Gaia with radio structures in parsec-scale AGN jets. *Astronomy & Astrophysics*, in preparation, 2022a.

Lambert S., A. Pierron, and H. Sol. Parsec-scale Jets in AGN: Insights into the Location of the γ-Ray Emission from Geodetic VLBI, Gaia EDR3, and Fermi-LAT. In *IVS 2022 General Meeting Proceedings, edited by K. L. Armstrong, D. Behrend, and K. D. Baver, NASA/CP-20220018789*, 2022b.

Lambert S., H. Sol, and A. Pierron. Can VLBI-Gaia absolute astrometry and Fermi measurements unveil the location of the gamma-ray emission region? *Astronomy & Astrophysics*, in preparation, 2022c.

Lister M., D. Homan, K. Kellermann, et al. Monitoring of jets in active galactic nuclei with VLBI experiments. XVIII. Kinematics and inner jet evolution of bright radio-loud active galaxies. *The Astrophysical Journal* 923 (1): 30, 2021.

MacMillan D., A. Fey, J. Gipson, et al. Galactocentric acceleration in VLBI analysis. Findings of IVS WG 8. *Astronomy & Astrophysics*, 630: 93, 2019.

Malkin Z. A new equal-area isolatitudinal grid on a spherical surface. *Astronomical Journal*, 158 (4): 158, 2019.

Plavin A., Y. Kovalev, and L. Petrov. Dissecting the AGN disk–jet system with joint VLBI-gaia analysis. *The Astrophysical Journal*, 871 (2): 143, 2019.

Prusti T., J. de Bruijne, A. Brown, et al. The Gaia mission. *Astronomy & Astrophysics*, 595: 1, 2016.

Sol H., S. Lambert, and A. Pierron. Locating the blazar gamma-ray emitting zone from astrometric VLBI and Gaia data? In *Proc. 7th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy (Gamma2022)*, 2022.

Souchay J., C. Gattano, A. Andrei, et al. Lqac-5: The fifth release of the large quasar astrometric catalogue – a compilation of 592 809 objects with 398 697 gaia counterparts. *Astronomy & Astrophysics*, 624: 145, 2019.

Souchay J., N. Secrest, S. Lambert, et al. Quasars with large proper motions: A selection from the lqac-5 catalogue combined with gaia edr3. *Astronomy & Astrophysics*, 660, 2022.

Titov O., S. Frey, A. Melnikov, et al. Unprecedented change in the position of four radio sources. *Monthly Notices of the Royal Astronomical Society*, 512: 874, 2022.

Vallenari A., A. Brown, T. Prusti, et al. Gaia Data Release 3. Summary of the contents and survey properties. *Astronomy & Astrophysics*, 2022.