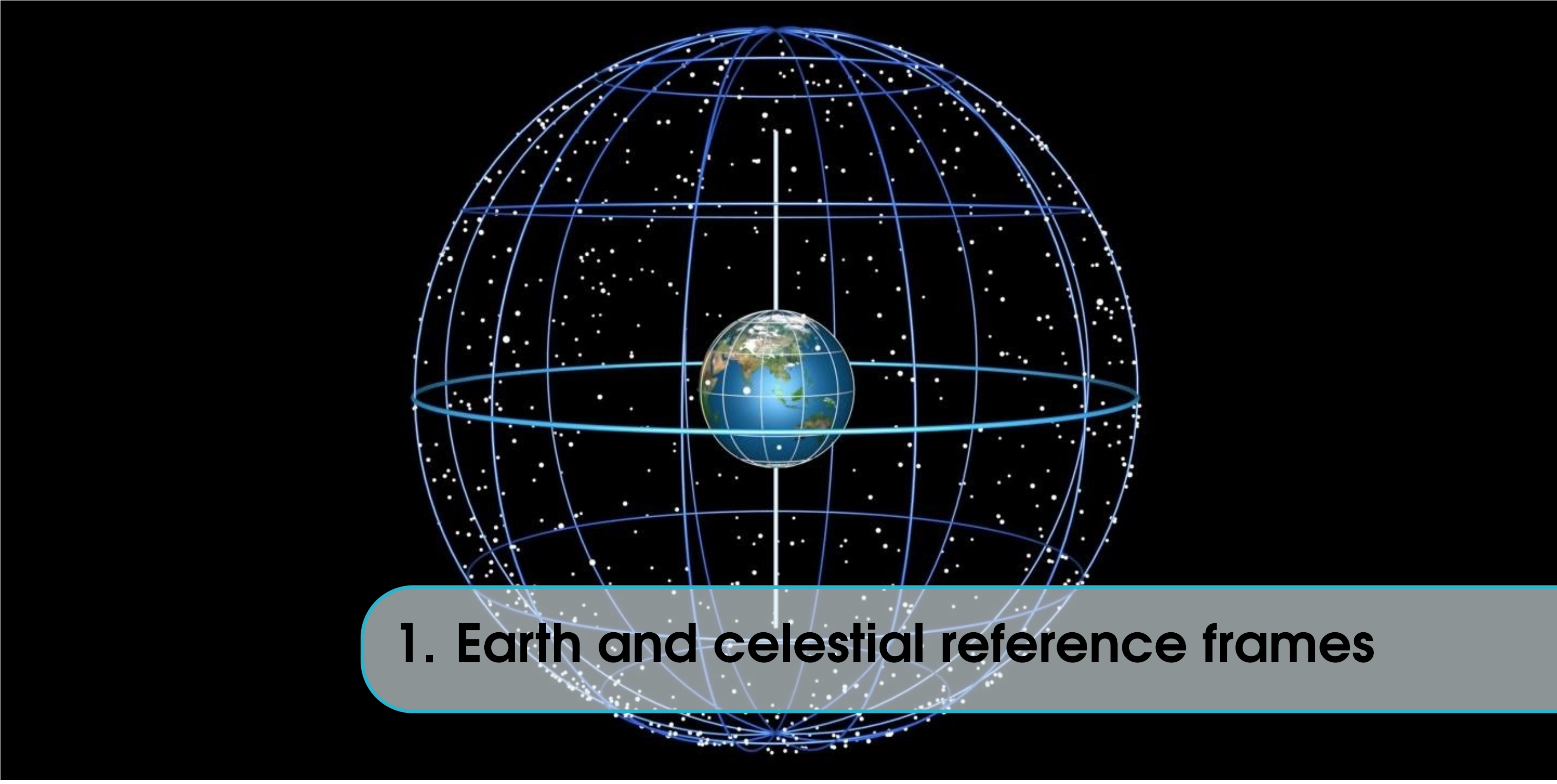

1. Earth and celestial reference frames

1.1 A unique capability for positioning

The determination of the motion of celestial bodies through repeated measurements of their position using astrometric techniques constitutes the foundation of our present understanding of the Universe. For consistency in time and space, and hence comparisons for different celestial bodies, such determinations must be established in well-defined coordinate (or reference) systems. In practice, coordinate axes for celestial systems are not defined directly but only implicitly through the adoption of a set of fiducial directions, precisely identified and highly stable over long timescales. Specific celestial bodies possessing the required properties are used to materialize such directions.

VLBI is a unique tool that allows astronomers to study the compact radio emission of celestial bodies in extreme details and to pinpoint their direction in the sky with unprecedented accuracy. Thanks to this capability, the technique has been used for the past twenty years to establish fundamental celestial reference frames. The objects targeted for this purpose are black-hole powered active galactic nuclei. These possess highly compact central emission (of non-thermal synchrotron origin), ensuring well-defined fiducial directions. Additionally, they have no detected proper motions due to their location at cosmological distances. The number of objects measured in this way grew from a few hundreds in the 1990's to several thousands today. On the celestial sphere, they form a grid of points whose two-dimensional coordinates define a reference frame. Such a grid is also the basis for ultra-precise relative VLBI astrometry, e.g. to determine distances and transverse velocities of Galactic objects out to tens of kpc through measurements of proper motions and parallaxes.

The most comprehensive VLBI reference frame to date is the third realization of the International Celestial Reference Frame, ICRF3 (Charlot et al. 2018), adopted by the IAU in August 2018 to replace the previous realization, ICRF2 (Fey et al. 2015), built ten years earlier, as the new fundamental celestial reference frame. ICRF3 comprises positions for 4536 extragalactic sources, as measured at 8 GHz (Fig. 1.1), 303 of which, uniformly distributed on the sky, are identified as *defining sources* and as such serve to define the axes of the frame. Positions at 8 GHz are supplemented with positions at 24 GHz for 824 sources and at 32 GHz for 678 sources. In all, 600 sources have three-frequency positions available. The positions have been estimated independently at each of the frequencies

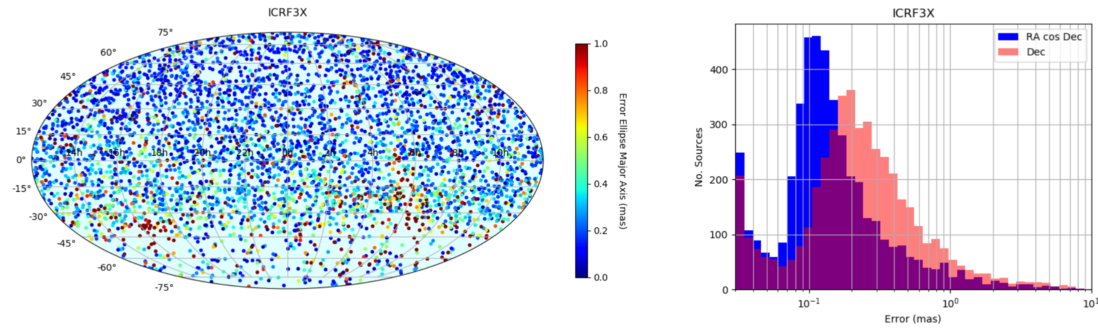

Figure 1.1: *Left*: sky distribution of the 4536 extragalactic sources comprised in ICRF3 (8 GHz frequency) with color coding according to position accuracy. *Right*: histogram of errors in right ascension and declination for those sources plotted with a log-scale.

in order to preserve the underlying astrophysical content behind such positions. The frame shows median positional errors of the order of 100 μas in right ascension and 200 μas in declination with a noise floor of 30 μas in the individual coordinates (Fig. 1.1).

1.2 Fundamental physics and astronomy

The newly-released ICRF3, with its increased positional accuracy, but also thanks to an observing span approaching 40 years (1979–2018), will allow the scientific community to tackle new questions in astronomy and fundamental physics. The long time base now makes mandatory the modeling of Galactocentric acceleration, a secular effect introduced by the rotation of the Solar System barycenter around the Galactic center. This effect, first detected by Titov and Lambert (2013), has emerged from the ICRF3 data set with a magnitude of 5.8 ± 0.3 μas/yr and manifests itself through apparent long-term proper motions of the radio sources if not accounted for in the modeling. Continued observing and accumulation of data in the future will further improve that value and determine whether the motion of the Solar System is purely towards the Galactic center or whether it has an off-plane component. In a similar way, the low-frequency ($< 10^{-9}$ Hz) gravitational wave background, although not detected at present, may be revealed in the future through such quasar proper motions (Gwinn et al. 1997, Titov et al. 2011, Darling et al. 2018). VLBI is also essential for testing General Relativity, e.g. through the determination of the relativistic parameter γ (Lambert and Le Poncin-Lafitte 2011) or for trying alternate theories (Le Poncin-Lafitte et al. 2016). Here also, accumulation of data and extending the time base will further improve the level of such tests.

1.3 Astrophysics of active galactic nuclei

The multi-frequency positional information in ICRF3 together with the optical positions recently derived with the Gaia space mission which show similar accuracies (Mignard et al. 2018) provide new insights into the physics of active galactic nuclei. At radio frequencies, these objects generally feature a bright compact core and a single-sided relativistic jet with blobs of emission moving away from the core on time scales of months to years (Fig. 1.2). Future reference frames will have to account for such time-varying extended internal structures for the highest accuracy, a perspective that motivates systematic VLBI imaging programs to monitor the structure of the ICRF sources. In

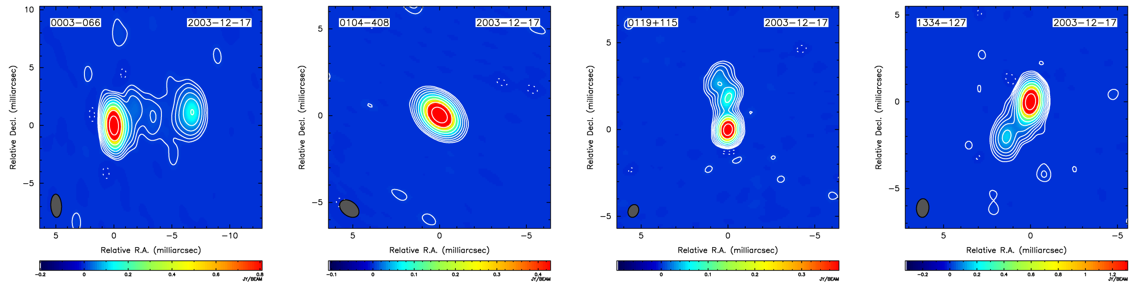

Figure 1.2: A sample of VLBI maps from the Bordeaux VLBI Image Database (Collioud and Charlot 2009) showing the predominantly core-jet structure of the ICRF sources on milliarcsecond scales.

the light of such extended emission, comparison of the ICRF3 and Gaia positions becomes essential to understand whether the radio emission and optical emission are superimposed in these objects. Initial estimates of such radio-optical “core shifts” indicated that they amount to 100 μas on average (Kovalev et al. 2008), which is significant considering the VLBI and Gaia position accuracies. While potentially affecting the alignment between the two frames, the radio-optical positional differences also offer a unique opportunity to directly determine those core-shifts and probe the geometry of quasars in the framework of unified AGN theories. In particular, such measurements may help to locate the optical region relative to the relativistic radio jet and determine whether the dominant optical emission originates from the accretion disk or the inner portion of the jet. Taking advantage of the first two Gaia data releases, it was found that significant VLBI-Gaia offsets do exist for about 10% of the sources (Kovalev et al. 2017, Petrov et al. 2018) and that these occur preferably along the jet direction, which was interpreted as a manifestation of the presence of bright optical jets (Petrov and Kovalev 2017). Future Gaia data releases may reveal offsets for an increased fraction of objects thanks to further improved positional accuracy, in synergy with VLBI measurements.

1.4 Rotational motion and dynamics of the Earth

Another unique capability of VLBI is its ability to track the rotational motion of the Earth in the quasi-inertial frame defined by the distant quasars. This motion includes a secular drift and periodic oscillations of the Earth’s rotation axis (i.e. precession and nutation, see Fig. 1.3) along with a daily rotation around it. The latter, which may be expressed as the length of day, is irregular and unpredictable at some level since it is closely tied to the atmospheric conditions, thus requiring continuous VLBI observations to be followed. The nutational motion depends on the geophysical properties of the Earth and allows one to learn about the Earth’s interior (Mathews et al. 2002, Rosat et al. 2017). Key challenges in this area are the detection of the Earth’s solid inner core, independently of seismic data, and the understanding of the origin and variability of the free core nutation, the latter also requiring progress in global circulation models and in the theory of the Earth’s rotation. Another closely related question is whether the annual term of the nutation can possibly vary. All such challenges requires VLBI monitoring over long time scales and with high accuracy. In the future, this should be accomplished with the VLBI Global Observing System, a new array consisting of fast-moving 12 m antennas that is currently set up by the International VLBI Service for geodesy and astrometry and designed to observe 24 hours a day all year long. On the geodesy side, the goal of such an array, permanently observing, is to reach millimeter positional accuracy. Achieving a terrestrial reference frame at that level is essential to understand deformations

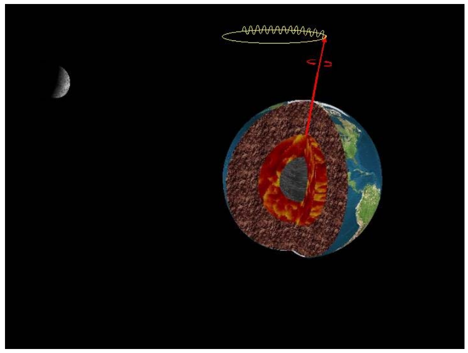

Figure 1.3: Schematic representation of the Earth's precession and nutation motion with the different components of its interior structure depicted (mantle, liquid outer core, solid inner core).

of the Earth crust (e.g. seasonal signals, seismic and post-seismic effects) and more generally to monitor global changes that affect our planet, among which sea level rise.

1.5 Contribution of EVN

All scientific topics addressed above should benefit from future improvements of the VLBI celestial reference frame. As shown from Fig. 1.1, there are two obvious areas of improvements: (i) position accuracy in the southern sky, which is typically degraded by a factor of 2 compared to that in the northern sky since the VLBI networks used to build ICRF3 were predominantly East-West, and (ii) lower sky density in the far South (i.e. below -45° declination) due to the sparseness of VLBI radio telescopes in the southern hemisphere. In respect of these improvements, the EVN has a significant role to play. By providing long North-South baselines, from Europe to the Hartebeesthoek antenna in South Africa and in the future to antennas of the developing African VLBI Network (Gaylard et al. 2011), it can help to break the North-South asymmetry in position accuracy. Incorporating SKA1-MID as an element of the array will also largely improve its sensitivity, hence permitting to expand considerably the celestial frame, with the goal of obtaining a more complete radio counterpart of the Gaia celestial frame. With its location in the southern hemisphere, SKA1-MID will further help to correct the currently uneven sky distribution, as noted above. Also to be mentioned is the capability of the EVN to observe at higher frequencies, especially at 22 GHz, which is one of three ICRF3 frequencies, and hence its potential to contribute to the development of the celestial frame at this frequency. Incorporation of observations on long North-South baselines to Hartebeesthoek, here again, would be especially useful to enhance the geometry of the frame.

REFERENCES

Charlot, P., Jacobs, C. S., Gordon, D., Lambert, S., de Witt, A., Böhm, J., Fey, A. L., Heinkelmann, R., Skrurikhina, E., Titov, O., Arias, E. F., Bolotin, S., Bourda, G., Ma, C., Malkin, Z., Nothnagel, A., Mayer, D., MacMillan, D. S., Nilsson, T. & Gaume, R., 2018, *A&A* (in preparation)

Collioud, A. & Charlot, P., 2009, *Proceedings of the* 19^{th} *European VLBI for Geodesy and Astrometry Working Meeting*, Eds. G. Bourda, P. Charlot & A. Collioud, Université Bordeaux1 – CNRS, OASU-LAB, p. 19

Darling, J., Truebenbach, A. E. & Paine, J., 2018, *ApJ*, **861**, 113

Fey, A. L., Gordon, D., Jacobs, C. S., Ma, C., Gaume, R. A., Arias, E. F., Bianco, G., Boboltz, D. A., Böckmann, S., Bolotin, S., Charlot, P., Collioud, A., Engelhardt, G., Gipson, J., Gontier, A.-M., Heinkelmann, R., Kurdubov, S., Lambert, S., Lytvyn, S., MacMillan, D. S., Malkin, D. S., Nothnagel, A., Ojha, R., Skurikhina, E., Sokolova, J., Souchay, J., Sovers, O. J., Tesmer, V., Titov, O., Wang, G. & Zharov, V., 2015, *AJ*, **150**, 58

Gaylard, M. J., Bietenholz, M. F., Combrick, L., Booth, R. S., Buchner, S. J., Fanaroff, B. L., MacLeod, G. C., Nicolson, G. D., Quick, F. H., Stronkhorst, P. & Venkatasubramani, T. L., 2011, *Proceedings of SAIP2011, the 56th Annual Conference of the South African Institute of Physics*, Eds. I. Basson and A. E. Botha, p. 425

Gwinn, C. R, Eubanks, T. M., Pyne, T., Birkinshaw, M. & Matsakis, D. N., 1997, *ApJ*, **485**, 87

Kovalev, Y. Y., Lobanov, A. P., Pushkarev, A. B. & Zensus, J. A., 2008, *A&A*, **483**, 759

Kovalev, Y. Y., Petrov, L. & Plavin, A. V., 2017, *A&A*, **598**, L1

Lambert, S. B. & Le Poncin-Lafitte, C., 2011, *A&A*, **529**, 70

Le Poncin-Lafitte, C., Hees, A. & Lambert, S. B., 2016, *Phys. Rev. D*, **94**, 125030

Mathews, P. M., Herring, T. A. & Buffett, B. A., 2002, *JGR*, **107(B4)**, ETG 3-1

Mignard, F. et al., 2018, *A&A*, **616**, A14

Rosat, S., Lambert, S. B., Gattano, C. & Calvo, M., 2017, *GJI*, **208**, 211

Petrov, L. & Kovalev, Y. Y., 2017, *MNRAS*, **471**, 3775

Petrov, L., Kovalev, Y. Y. & Plavin, A. V., 2018, *MNRAS* (in press)

Titov, O. & Lambert, S., 2011, *A&A*, **559**, A95

Titov, O., Lambert, S. B. & Gontier, A.-M., 2011, *A&A*, **529**, A91