THE SECULAR ABERRATION DRIFT AND FUTURE CHALLENGES FOR VLBI ASTROMETRY

O. TITOV
Geoscience Australia
PO Box 378, Canberra, 2601, ACT, Australia
e-mail: oleg.titov@ga.gov.au

ABSTRACT. The centrifugial acceleration of the Solar system, resulting from the gravitational attraction of the Galaxy centre, causes a phenomenon known as 'secular aberration drift'. This acceleration of the Solar system barycentre has been ignored so far in the standard procedures for high-precision astrometry. It turns out that the current definition of the celestial reference frame as epochless and based on the assumption that quasars have no detectable proper motions, needs to be revised. In the future, a realization of the celestial reference system (realized either with VLBI, or GAIA) should correct source coordinates from this effect, possibly by providing source positions together with their proper motions. Alternatively, the galactocentric acceleration may be incorporated into the conventional group delay model applied for VLBI data analysis.

1. SECULAR ABERRATION DRIFT

This barycentre reference system was adopted by the International Astronomical Union as the International Reference System (ICRS). The Very Long Baseline Interferometry (VLBI) technique measures precise group delay differences in arrival times of radio waves at two radio telescopes and produces very accurate coordinates of the reference radio sources. The ICRS is based on a set of theoretical concepts. Practical realization of the ICRS - International Celestial Reference Frame (ICRF) is presented in a form of astrometric catalogue of the reference radio source accurate coordinates.

The second realization of the ICRF (ICRF2) contains 295 "defining" sources (Fey, Gordon and Jacobs, 2009). The floor error of the most observed radio sources among the 295 ICRF2 "defining" is about 41 μas. The median error for 1217 radio sources (295 "defining" and 922 "non-defining") was found to be 174 μas in right ascension and 194 μas in declination.

All the reductions for high-precision VLBI data are done in the reference system with an origin in the barycentre of the Solar system. In this definition, the axes of the ICRS are defined by the adopted positions of a specific set of extragalactic objects (presumably, very distant quasars), which are assumed to have no measurable proper motions. However, the acceleration of the Solar System barycenter would cause a dipole systematic effect in the proper motion described by the first order electric type vector spherical harmonic with magnitude of 4–6 μas/yr. After an early mention by Fanselow (1983), this effect known as secular aberration drift (SAD) was discussed in more detail later (e.g. Bastian, 1995; Gwinn et al., 1997; Sovers et al., 1998; Kovalevsky, 2003; Kopeikin and Makarov, 2006). Finally, it has been confirmed, for the first time, by Titov, Lambert & Gontier (2011) by the least squares adjustment of the apparent proper motion of 555 reference radio sources. Its magnitude, 6.4 ± 1.5 μas/yr, corresponds to the Galactocentric acceleration of $(3.2 \pm 0.7) \times 10^{-13}$ km/s^2, in good agreement with the theoretical predictions.

Figure 1 displays $\mu_\alpha \cos\delta$ versus α for the 40 astrometricaly stable radio sources observed in more than 1,000 sessions. The plot reveals dipole systematic effect even without adjustment by the least squares. Individual proper motions of 555 radio sources are shown in Figure 2. Though, no systematic effect is observed in this plot, the least squares found the dipole as on Figure 3.

Independent analysis of the SAD was done using 328 individual proper motions obtained by Vladimir Zharov using the alternative software ARIADNA (Zharov et al. 2010). The magnitude estimate is 4.8 ± 1.4 μas/yr, and coordinates of the acceleration vector are estimated as $270° \pm 30°$ in right ascension and $-54° \pm 17°$ in declination. The consequences of the secular aberration drift discovery are discussed in this paper.

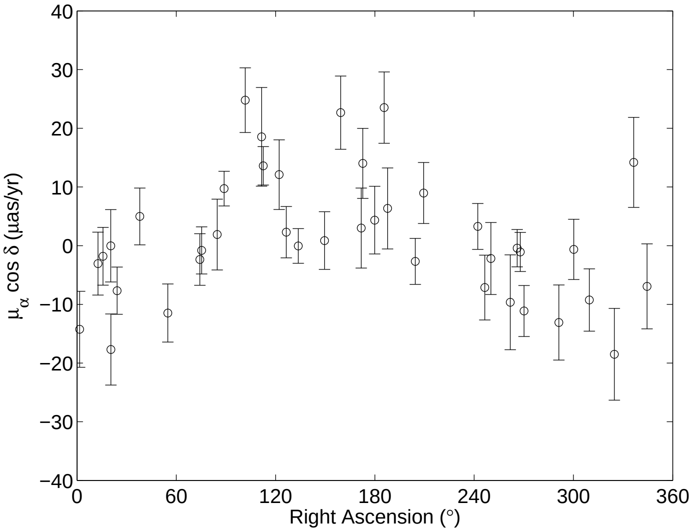

Figure 1: The proper motion in right ascension vs. the right ascension of 40 sources observed in more than 1000 sessions.

2. FUTURE CHALLENGES FOR VLBI ASTROMETRY

In accordance with the IAU Resolutions, the adopted International Celestial Reference System (ICRS) is quasi-inertial, i.e. its fundamental axes do not rotate. However, acceleration of the origin is allowed, in opposition to the definition of the inertial reference system. This theoretical concept of the quasi-inertial system is realised in a form of the catalogue of accurate coordinates of extragalactic radio sources, known as ICRF2 (Fey, Gordon and Jacobs, 2009). Directions of the fundamental axes are fixed by positions of the 295 ICRF2 "defining" radio sources. This theoretical concept of quasi-inertiality as well as practical efforts for production of new catalogues are used to focus on control of the net rotation which may be induced by the variations of the intrinsic structure of the radio sources. All the non-rotational systematic effects in proper motions were considered to be negligibly small and, eventually, ignored. As a result, the No-Net-Rotation constraints which are commonly used to suppress the forbidden rotational systematic also suppress the dipole systematic effect, theoretically allowed. Nonetheless, due to unprecedented improvement of the geodetic VLBI data precision, the dipole systematic effect should not be ignored. Otherwise, the conventional reductional model would become increasingly inadequate. Therefore, the geodetic VLBI faces three challenges which should be solved in near future.

2.1. How To Implement This Effect?

The dipole proper motion induced by the SAD would result in displacement of the actual positions of the reference radio sources from the positions published in catalogues, i.e. ICRF2. This displacement may reach 130 μas over the 20-year period of observations, exceeding the 3-σ level of the ICRF2 floor error (41 μas). If this effect is ignored, estimates of some other parameters may be biased, for instance, corrections to the nutation angles, or the variations UT1-UTC estimated from the Intensive sessions. Therefore, it is reasonable to discuss a possible way to implement the SAD in the conventional procedure of VLBI data reductions.

One possibility is to introduce the dipole proper motion for all reference radio sources as an extension to their ICRF2 coordinates. For a distant body of equatorial coordinates (α, δ), the proper motions are estimated as follows

$$\begin{aligned} \Delta\mu_\alpha \cos\delta &= -d_1 \sin\alpha + d_2 \cos\alpha, \\ \Delta\mu_\delta &= -d_1 \cos\alpha \sin\delta - d_2 \sin\alpha \sin\delta + d_3 \cos\delta, \end{aligned} \quad (1)$$

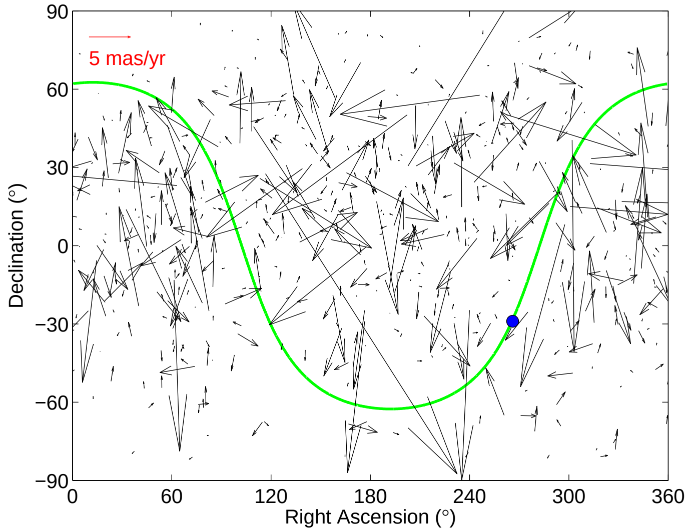

Figure 2: The proper motions of the 555 sources. The green curved line represents the equator of the Milky Way, whose center is indicated by the large blue point.

where the d_i are the components of the acceleration vector in unit of the proper motion calculated as

$$\begin{aligned} d_1 &= d\cos\alpha_0\cos\delta_0 \\ d_2 &= d\sin\alpha_0\cos\delta_0 \\ d_3 &= d\sin\delta_0, \end{aligned} \tag{2}$$

where d is the magnitude of the SAD, and (α_0, δ_0) — apparent equatorial coordinates of the Galactic centre.

This approach will result to moving away from the attractive idea of the treatment the extragalactic radio sources as fixed fiducial points on the celestial sphere. It may not be appropriate to introduce the systematic proper motion for the radio reference frame only, but keeping in mind the future space astrometric missions (i.e. GAIA, see Perryman et al., 2001; Mignard, 2002), it should be considered as one of the possible options.

Another possibility is to revise the conventional group delay model developed about 20 years ago and recommended by the IERS and IAU (Kopeikin, 1990; Soffel et al. 1991). It was shown (Titov 2010) that SAD may be implemented by the replacement of the barycentric velocity vector $\vec{V}$ by the sum $\vec{V} + \vec{a}\Delta t$, where $\vec{a}$ is the vector of Galactocentric acceleration and Δt is the period of time since an initial epoch. This approach keeps the extragalactic radio sources technically free of the apparent transversal motion. However, it is suitable only for the reduction of the geodetic VLBI data, and it is not clear how to proceed with the data from the space astrometric missions. More detailed analysis of this problem should be initiated to determine the most appropriate solution.

2.2. Are There More Systematic Effects?

Apart from the SAD, more systematic effects may be detected, although with a smaller chance of success. The quadrupole component may come either from the Hubble constant anisotropy or the primordial gravitational waves (i.e. Kristian & Sachs 1966; Eubanks, 1991; Pyne et al., 1996; Gwinn et al. 1997; Book & Flanagan, 2011). Observational results impose constraints on the upper limit of the quadrupole systematic effect (3 μas/yr for a 3-σ standard error (Titov, Lambert & Gontier 2011). The amplitude spherical harmonics were estimated to be very close to the 3-σ level, therefore, it will be useful to check these parameter after collection of more observational data.

The rotational harmonics are unlikely to be separated from the Earth orientation parameters. Although, the differential rotation possible within of a scope of the formula by Kristian and Sachs (1966),

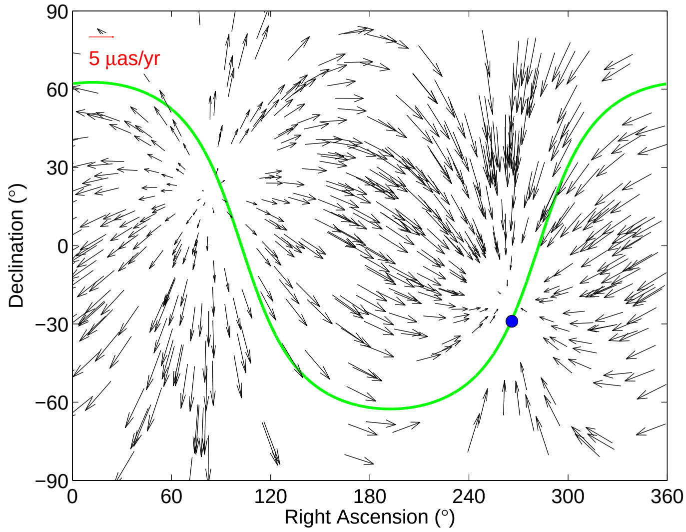

Figure 3: The estimated dipole component of the velocity field.

$$\begin{aligned}\frac{de^{\mu}}{dt} =& h^{\mu\nu}\left\{e^{\beta}(\sigma_{\nu\beta}+\omega_{\nu\beta})+r\left[e^{\beta}(\sigma_{\nu\beta}+\omega_{\nu\beta})u_{\mu\nu}-e^{\beta}E_{\mu\nu}\right.\right.\\ &\left.\left.+\frac{1}{2}e^{\beta}e^{\gamma}(u_{\nu\beta\gamma}-\epsilon_{\nu\beta\gamma}H_{\mu\nu})+e^{\beta}e^{\gamma}e^{\lambda}(\sigma_{\nu\gamma}+\omega_{\nu\gamma})\sigma_{\beta\lambda}\right]+...\right\}\end{aligned} \tag{3}$$

may be disclosed. Where σ - notation for the shear tensor, ω - for the rotation tensor, E, and H - for the tensors describing the electric and magnetic-type gravitational waves, respectively. The distance r before the squared brackets means that if at least one of the tensors in not negligible at level of μas/yr, then the corresponding component will increase for more distant radio sources. Kristian and Sachs (1966) considered the case of gravitational waves with wavelengths of the Universe size $\lambda_{Gr} \sim R_{Un}$. Later papers argued that if $\lambda_{Gr} < R_{Un}$, then the corresponding spherical harmonics are independent of the distance (Pyne, 1996; Gwinn et al., 1997; Book & Flanagan, 2011). So, the first part of Equation (3) should be developed as follows

$$\frac{de^{\mu}}{dt} = h^{\mu\nu}\left\{e^{\beta}(\sigma_{\nu\beta}+\omega_{\nu\beta})-e^{\beta}E_{\mu\nu}+\frac{1}{2}e^{\beta}e^{\gamma}(u_{\nu\beta\gamma}-\epsilon_{\nu\beta\gamma}H_{\mu\nu})\right\} \tag{4}$$

The spherical harmonics of order three (octopole) and higher accommodate only 15 % of the total power of the gravitational waves (Gwinn et al., 1997), and we have not found statistically significant harmonics in the proper motion analysis. Nonetheless, these higher harmonics may be still studied in future. To estimate the distance-dependent effects in the spherical harmonics, more proper motions at redshift $z > 2$ are required to be measured.

2.3. Challenge 3. "Observational"

The proper motions of 555 radio sources have been used so far to estimate the SAD components by use of the least squares method, increasing the figure to 2000 will improve the formal accuracy by a factor of two. In fact, several thousand radio sources were observed in one or two VCS sessions (VLBI Calibrator Survey) for the last decade (i.e. Beasley et al., 2002). Therefore, we are able to calculate new proper motions by undertaking regular observations of the VCS sources in further one–two sessions separated from the original epochs by a sufficient time span.

The mutual correlation between different spherical harmonics will vanish for homogeneous coverage of the celestial sphere with observational data. Unfortunately, the shortage of proper motions for the radio sources around the South Pole leads to a correlation between parameters in the matrix of normal equations (Titov & Malkin, 2009). This correlation could be reduced by increasing the data at this zone of the celestial sphere. It is planned to use the Australian VLBI network (AuScope) and New

Zealand station Warkworth (Lovell et al., 2010) for regular observations of those radio sources which have comparatively strong flux (> 0.4 Jy) but are observed only occasionally.

3. CONCLUSION

Appearance of the systematic effects in the apparent proper motion of extragalactic radio sources observed with Very Long Baseline Interferometry requires a revision of some basic assumptions used for many years to establish the fundamental reference frame. The gravitational acceleration of the Solar system barycentre needs to be incorporated to the analytical models for high-precision astrometric data reduction. More work needs to be done in theory, in observations and in data analysis to reveal the small signals with confidence. In particular, observations of the quasars in the southern hemisphere are highly essential.

Acknowledgements. We are thankful to Vladimir Zharov for providing the independent results from the ARIADNA software and Laura Stanford for help in preparation of the manuscript. This paper has been published with permisson of the Geoscience Australia CEO.

4. REFERENCES

Bastian, U. 1995, "Direct detection of the Sun's galactocentric acceleration", In: M. A. C. Perryman & F. Van Leeuwen (Eds.), Proc. RGO-ESA Workshop on Future Possibilities for Astrometry in Space, ESA SP-379, 99.

Beasley, A. J., Gordon, D., Peck, A. B., et al. 2002, "The VLBA Calibrator Survey-VCS1", AJSupp141, pp. 13–21.

Book, L.G., Flanagan, E., 2011, "Astrometric Effects of a Stochastic Gravitational Wave Background", Phys. Rev. D, 83(2).

Eubanks, T. M., 1991, "A consensus model for relativistic effects in geodetic VLBI", In: Proceedings of the U.S. Naval Observatory Workshop on Relativistic Models for use in Space Geodesy, pp. 60–82.

Eubanks, T. M., 1991, "Astrometric Cosmology using Radio Interferometry", In: Proc. of 179th AAS Meeting, Atlanta, Georgia, p. 1465.

Fanselow, J. L. 1983, "Observation Model and Parameter Partials for the JPL VLBI Parameter Estimation Software MASTERFIT-V1.0", JPL Publication 83-39.

Fey, A. L., Gordon, D. G., & Jacobs, C. S. (Eds.) 2009, "The Second Realization of the International Celestial Reference Frame by Very Long Baseline Interferometry", Presented on behalf of the IERS / IVS Working Group, International Earth Rotation and Reference Systems Service (IERS) Technical Note 35, Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie.

Gwinn, C. R., Eubanks, T. M., Pyne, T., et al., 1997, "Quasar proper motions and low-frequency gravitational waves", ApJ485, pp. 87–91.

Kopeikin, S. M., & Makarov, V. V. 2006, "Astrometric effects of secular aberration", AJ 131, pp. 1471–1478.

Kopeikin, S. M., 1990, "Theory or relativity in observational radio astronomy", Sov. Astron. 34(1), pp. 5–10.

Kovalevsky, J. 2003, "Aberration in proper motions", A&A 404, pp. 743–747.

Kristian, J., & Sachs, R. K. 1966, "Observations in cosmology", ApJ, 143, pp. 379–399.

Lovell, J., Dickey, J., Gulyaev, S., et al. 2010, "The AuScope project and Trans-Tasman VLBI", In: D. Behrend & K. D. Baver (Eds.), Proc. of the 2010 IVS 6th General Meeting, pp. 50–54.

Mignard, F. 2002, "Fundamental Physics with GAIA", In: O. Bienaymé & C. Turon (Eds.), GAIA: A European Space Project, EAS Publication Series, 2, pp. 107–121.

Perryman, M. A. C., de Boer, K. S., Gilmore, G., et al. 2001, "GAIA: Composition, formation and evolution of the Galaxy", A&A 369, pp. 339–363.

Pyne T., Gwinn, C.R., Birkinshaw, M., et al., 1996, "Gravitational radiation and Very Long Baseline Interferometry", ApJ, 465, pp. 566–577.

Soffel, M. H., Muller, J., Wu, X., & Xu. C., 1991, "Consistent Relativistic VLBI Theory with Picosecond Accuracy", AJ 101, pp. 2306–2310.

Sovers, O. J., Fanselow, J. L., Jacobs, C. S. 1998, "Astrometry and geodesy with radio interferometry: experiments, models, results", Rev. Mod. Phys. 70, pp. 1393–1454.

Titov, O., 2009, “Systematic effects in the radio source proper motion”, In: G. Bourda et al. (Eds.), Proc. 19th European VLBI for Geodesy and Astrometry (EVGA) Working Meeting, pp. 14–18.
Titov, O., 2010, “Estimation of the Acceleration of the Solar-System Barycenter Relative to a System of Reference Quasars”, Astronomy Reports 55, pp. 91–95.
Titov, O., Malkin, Z., 2009, “Effect of asymmetry of the radio source distribution on the apparent proper motion kinematic analysis”, A&A 506, pp. 1477–1485.
Titov, O., Lambert, S., & Gontier A.-M., 2011, “VLBI measurement of secular aberration drift”, A&A 529, pp. A91–A97.
Zharov, V., Sazhin, M., Sementsov, V., & Sazhina, O. 2010, “Long-term Variations of the EOP and ICRF2”, In: D. Behrend & K. D. Baver (Eds.), Proc. of the 2010 IVS 6th General Meeting, pp. 290–294.