# PROPER MOTIONS OF REFERENCE RADIO SOURCES

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

ABSTRACT. The motions of relativistic jets from the active extragalactic nuclei can reach hundred several microseconds per year and mimic proper motion of the distant radio sources observed by VLBI. Individual proper motion of these quasars is not correlated and exceed the small systematic effects induced by the rotation of the Solar system around the centre of the Galaxy. In this paper we search for the systematic effect and discuss the results.

## 1. INTRODUCTION

Multi-frequency VLBI can measure accurate positions of reference extragalactic radio sources. Several hundred such sources (mostly quasars and radio-galaxies) have positions known to an accuracy of better than 1 mas with respect to the Solar system barycentre (Ma et al, 1998). Apparent proper motions of these sources, presumably induced by the source structure changes, reach several hundred $\mu$as/year for selected radio sources (Ma et al. 1998, Fey et al. 2004, These variations of the radio source structure are supposed to have random orientations, therefore, the apparent proper motions should not be systematic. (Due to their large distances, transverse proper motions caused by the Solar system motion are negligible (Sovers et al, 1998).) However, systematic effects in the radio source positions can appear due to a variety of reasons, for instance, secular aberration drift, gravitational waves and the Hubble constant anisotropy, and in principle could be used to provide information about various cosmological processes.

## 2. SECULAR ABERRATION DRIFT, GRAVITATIONAL WAVES AND THE HUBBLE CONSTANT ANISOTROPY

On the Galactic scale, the Solar system barycenter rotates around the center of mass of the Galaxy with period about 200 million years. Centrifugal galactocentric acceleration of the Solar system barycentre results in the appearance of another effect of special relativity (secular aberration drift) that systematically changes positions of all celestial bodies (Gwinn et al., 1997, Sovers et al., 1998; Kovalevsky, 2003; Klioner, 2003; Kopeikin, Makarov, 2005). For the distance of the centre of the Galaxy of 10 kpc the magnitude of the galactocentric acceleration vector is about 5 $\mu$as/year and directed towards the center of the Galaxy. As a result, positions of all quasars should change in a form of additional systematic proper motion.

The effect of gravitational waves in the radio source proper motions has been described by Pyne et al. (1996) and (Gwinn et al., 1997). It can be detected as a degree 2 spherical harmonic (both 'magnetic' and 'electric' type) of the expansion of vector spherical functions (5/6 of the total effect comes to the l=2 spherical harmonic and 1/6 - to the l=3 spherical harmonic).

In a case of shear-free isotropic expansion of the Universe, the Hubble constant is uniform around the sky, so any transverse proper motion vanishes. However, if the Universe expansion is anisotropic, then the Hubble law $V = HR$ for the isotropic Universe should be replaced by

$$V = (e_{33}\sin^2\delta + \frac{1}{2}(e_{11}+e_{22})\cos^2\delta + \frac{1}{2}(e_{11}-e_{22})\cos 2\alpha\cos^2\delta)R = (H + \Delta H_3\sin^2\delta + \Delta H_{12}\cos 2\alpha\cos^2\delta)R \tag{1}$$

where $e_{11}$, $e_{22}$, $e_{33}$ - diagonal elements of the expansion tensor. The Hubble constant here

$$H = \frac{1}{2}(e_{11} + e_{22}), \tag{2}$$

and two parameters that describe the Hubble constant anisotropy are given by

$$\Delta H_3 = e_{33} - \frac{1}{2}(e_{11} + e_{22}) \tag{3}$$

$$\Delta H_{12} = e_{11} - e_{22} \tag{4}$$

It is more essential that the transversal proper motions be given by

$$\mu_\alpha = -\frac{1}{2}(e_{11} - e_{22}) \sin 2\alpha \cos^2 \delta = -\Delta H_{12} \sin 2\alpha \cos^2 \delta \tag{5}$$

$$\mu_\delta = (e_{33} - \frac{1}{2}(e_{11} + e_{22})) \cos\delta \sin\delta - \frac{1}{2}(e_{11} - e_{22}) \cos 2\alpha \sin\delta \cos\delta = \frac{\Delta H_3}{2} \sin 2\delta - \frac{\Delta H_{12}}{2} \cos 2\alpha \sin 2\delta \tag{6}$$

It is obvious that if $e_{11} = e_{22} = e_{33}$ then $\Delta H_3 = \Delta H_{12} = 0$ and (1) reduces the conventional Hubble law and all proper motions (5)-(6) are to be zero.

## 3. RESULTS AND DISCUSSION

OCCAM software (Titov, Tesmer, Boehm, 2004) analysis VLBI data by the least squares collocation method (LSCM) (Titov, 2004). The LSCM minimizes a functional similar to the conventional least-squares method and, additionally, it takes into account intra-day correlations between observations. These correlations are calculated from external data, in the case of VLBI, from the data about stochastic behavior of hydrogen clocks and wet component of troposphere delays and gradients. All estimated parameters are split into three groups on their properties: stochastic, estimated for every epoch (hydrogen clock function and wet troposphere delays), daily or 'arc' parameters to be approximately constant within a 24-hour session, and so-called 'global' parameters whose are constant over the total period of observations. We treated the reference radio source positions and the secular aberration drift as global parameters (MacMillan, 2003).

The internal motion of relativistic jets in quasars produces significant changes in the observed radio source coordinates. Therefore, the positions of these astrometrically unstable quasars are treated as daily parameters to reduce the effect of instability on the estimates of other parameters. The first solution based on the ICRF radio source classification ("defining", "candidate" and "other" sources) (Ma et al, 1998). The second solution based on the radio source classification by Feissel-Vernier (2003) ("stable" and "unstable" sources). Though these two lists of radio sources are not independent, this approach allows accessing the sensitivity of results to variation of the list of reference radio sources. For the last two solutions all reference sources were split into the "no unstable close" (with redshift z≤1) and " no unstable distant" (z≥1) ones to produce independent estimates. The number of available redshifts in the existing database as large as 4.3 is limited by 352 "no unstable" radio sources therefore these last solutions based on 172 and 150 reference radio sources with a mean redshift z=0.57 and z=1.97, correspondingly.

Estimates of the secular aberration drift components are presented in Table 1. One can conclude that the overall average value (23 $\mu$as/year) provides a reasonable meaning for the indicated effect of secular aberration drift with the maximum $1\sigma$ standard error of 2.5 $\mu$as/year. The estimates of declination for all four solutions are in a good agreement. However, the estimates of right ascension for two first solutions and two last solutions are different, due to a decreased number of reference radio sources in last two solutions, especially it the southern hemisphere. We consider the coordinates from two last solutions as less reliable. From two first solutions the estimated aberration vector is directed towards the point with equatorial coordinates ($\alpha$ = 265 +/- 3, $\delta$ = 41 +/- 7 ). This effect causes apparent proper motions of all towards this 'focal point' with a maximum magnitude 23 $\mu$as/year (Fig 1).

The estimates of second order harmonic A(2,0), A(2,±1), A(2,±2) are less significant than for the secular aberration drift (Table 2 and 3). A deficit of radio sources in the southern hemisphere causes assymetry of their distribution around the sky, and, eventually, large correlation between some parameters. Also these parameter estimates are sensitive to the solution strategy, for instance, when NNR-constraints are introduced to the solutions. The $3\sigma$ standard error of 3-6 $\mu$as/year corresponds to uncertainty in the Hubble constant of 15-30 km/sec*Mpc. It exceeds the Hubble constant anomalies (10-12 km/s*Mpc) found by McClure and Dyer (2007) from the astrophysical data.

Nevertheless, for the 'distant' radio sources all these harmonic estimates (expect A(2,0)) are statistically significant, whereas, the same harmonics are negligible for the 'close' radio sources. It means that the unknown factor generating in the second degree electric spherical harmonics (either gravitational waves, or the Hubble constant anisotropy) increases with distance to quasars.

More observations of distant radio sources in the southern hemisphere (under $\delta$ = -40 ) should be done in order to make more reliable conclusion. An addition, it is necessary to estimate the magnetic harmonics of the second degree within the procedure to verify an existence of the gravitational waves.

| Solution | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Reference radio sources | All except 102 'other' | All except 163 'unstable' | Close and not 'unstable' | Distant and not 'unstable' |
| Number of reference radio sources | 1559 | 1441 | 172 | 150 |
| Number of obs of reference radio sources | 2.449,601 | 2.699,600 | 1.312,924 | 1.113,180 |
| Secular aberration drift ($\mu$as/year) | 25.3 +/- 2.2 | 21.9 +/- 2.0 | 23.2 +/- 2.4 | 21.7 +/- 2.5 |
| Right Ascension | 265 +/- 3 | 264 +/- 3 | 278 +/- 5 | 287 +/- 6 |
| Declination | 41 +/- 6 | 41 +/- 7 | 43 +/- 7 | 37 +/- 9 |

Table 1: Estimates of the vector harmonics l=1 for different sets of reference radio sources

| Solution | 1 | 3 | 4 |
|---|---|---|---|
| Reference radio sources | All except 102 'other' | Close and not 'unstable' | Distant and not 'unstable' |
| Number of reference radio sources | 1559 | 172 | 150 |
| Number of obs of reference radio sources | 2.449,601 | 1.312,924 | 1.113,180 |
| A(2,0) ($\mu$as/year) | 3.7 +/- 2.1 | 3.7 +/- 2.2 | 6.4 +/- 2.8 |
| A(2,1) ($\mu$as/year) | 7.4 +/- 0.9 | 1.6 +/- 1.0 | 8.2 +/- 1.5 |
| A(2,-1) ($\mu$as/year) | -1.9 +/- 0.9 | 0.1 +/- 1.0 | 8.2 +/- 1.6 |
| A(2,2) ($\mu$as/year) | -0.7 +/- 0.5 | -1.4 +/- 0.6 | 4.4 +/- 0.9 |
| A(2,-2) ($\mu$as/year) | -2.8 +/- 0.5 | 1.6 +/- 0.6 | -1.2 +/- 0.9 |

Table 2: Estimates of the vector harmonics l=2 with NNR-constraints for different sets of reference radio sources

| Solution | 1 | 3 | 4 |
|---|---|---|---|
| Reference radio sources | All except 102 'other' | Close and not 'unstable' | Distant and not 'unstable' |
| A(2,0) ($\mu$as/year) | 7.3 +/- 4.3 | 2.7 +/- 5.2 | 11.2 +/- 5.2 |
| A(2,1) ($\mu$as/year) | 7.9 +/- 1.0 | 0.6 +/- 1.3 | 5.5 +/- 1.6 |
| A(2,-1) ($\mu$as/year) | -1.2 +/- 0.9 | -3.2 +/- 1.3 | -6.9 +/- 1.6 |
| A(2,2) ($\mu$as/year) | -2.2 +/- 0.6 | -1.4 +/- 1.0 | 5.0 +/- 1.1 |
| A(2,-2) ($\mu$as/year) | -8.0 +/- 1.3 | 1.5 +/- 1.9 | 4.1 +/- 2.1 |

Table 3: Estimates of the vector harmonics l=2 without NNR-constraints for different sets of reference radio sources

*Acknowledgement.* The paper is published with the permission of the CEO, Geoscience Australia.

## 4. REFERENCES

Ma, C. et al., 1998, “The international celestial reference frame as realised by very long baseline interferometry”, AJ 116, pp. 516–546.

Fey, A. L., C. Ma, E.F. Arias, P. Charlot, M. Feissel-Vernier, A.-M. Gontier, C.S. Jacobs, J. Li, D.S. MacMillan, 2004, “The second extension of the ICRF - Ext.1 ”, AJ 127, pp. 3587–3608.

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.

Gwinn, C. R., Eubanks, T.M., Pyne, T., Birkinshaw, M., Matsakis, D. N., 1997, “Quasar proper motions and low-frequency gravitational waves”, ApJ 485, pp. 87–91.

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

Klioner, S., 2003, “A practical relativistic model of microarcsecond astrometry in space”, AJ 125, pp. 1580–1597.

Kopeikin, S. M. Makarov, V. V., 2005, “Astrometric effects of secular aberration”, AJ 131, pp. 1471–1478.

Pyne. T., C. R. Gwinn, M. Birkinshaw, T. M. Eubanks, M. N. Demetrios, 1996, “Gravitational Radiation and Very Long Baseline Interferometry”, ApJ 465, pp. 566–577.

Titov, O., Tesmer, V., Boehm, J., 2004, “OCCAM v.6.0 software for VLBI data analysis”, In International VLBI Service for Geodesy and Astrometry 2004 General Meeting Proc (eds. Vandenberg N. V. and Baver, K. D.) NASA/CP-2004-212255, pp. 267–271.

Titov, O., 2004, “Construction of a celestial coordinate reference frame from VLBI data”, Astron. Rep. 48, pp. 941–948.

MacMillan, D.S., 2003, “Quasar apparent proper motions observed by geodetic VLBI networks. In Future Directions in High Resolution Astronomy”, The 10th Anniversary of the VLBA (eds. Romney, J. D. and Reid, M. J.) http:///www.arXiv:astrop-ph/0309826v1.

Feissel-Vernier, M., 2003, “Selecting stable extragalactic compact radio sources from the permanent astrogeodetic VLBI program”, A&A 403, pp. 105–110.

McClure M. L., C. C. Dyer, 2007, “Anisotropy in the Hubble constant as observed in the HST Extragalactic Distance Scale Key Project Results”, New Astronomy, 12, pp. 533–543.