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Systematic Effects in Apparent Proper Motion of Radio Sources

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Abstract. The galactocentric rotation of the Solar system generates a systematic effect in proper motions known as 'secular aberration drift'. This tiny effect (about five microseconds per year) in the quasar proper motion can be measured by VLBI. However, the motions of relativistic jets from the active extragalactic nuclei can reach several hundred microseconds per year and mimic the proper motions of the observed radio sources. These apparent motions exceed the secular aberration drift by a factor of 10–100. In this paper we search for ways to overcome the difficulties and discuss our estimates of the secular aberration drift using OCCAM software.

1. Introduction

Multifrequency VLBI techniques measure accurate positions of the reference extragalactic radio sources. From the analysis of a global set of VLBI data the positions are estimated with an accuracy of up to 0.1 mas for frequently observed radio sources (more than 10,000 observations per source). However, the effect of the intrinsic source structure causes linear and non-linear variations in the sources' astrometric positions [1]. The apparent proper motion can reach several hundred microarcsec/year for some radio sources. The positional variations are supposed to be uncorrelated over the sky, and do not produce any systematic pattern. Nonetheless, some systematic effects in the apparent radio sources proper motions has been predicted. The galactocentric acceleration of the Solar system barycenter should cause the first order electric type vector spherical harmonic of the magnitude 4–5 microarcsec/year [2, 3, 4, 5, 6]. Primordial gravitational waves in the early Universe would produce second order vector spherical harmonics of electric and magnetic types [2, 7]. A more generalized expression for proper motion in the frame of general relativity has been published [8]. The authors found that in the expanding Universe the proper motion of distant objects could increase with distance.

Some attempts to detect systematic effects have been done by different authors [2, 9, 10]. Gwinn el al. [2] did not find any systematics in the proper motions using data from 1979 until 1996. MacMillan [9] used VLBI data from 1979 until 2002 and detected some systematics but did not give any details. Titov [10] found some statistically significant amplitudes of first and second degree electric-type harmonics using data from 1980 until 2007.

This paper presents more rigorous results than [10] on the systematic effects in radio source proper motion. This includes a separate consideration of the vector spherical harmonics of the first and second order. The second degree 'magnetic' spherical harmonics were added to the list of estimated parameters. More red shifts of the reference radio sources are available from the database recently developed by Malkin and Titov [11].

2. Vector Spherical Functions

Let us consider $\vec{F}(\alpha, \delta)$ as a vector field of a sphere decribed by the components of the proper motion vector ($\mu_\alpha \cos\delta$, μ_δ)

$$\vec{F}(\alpha, \delta) = \mu_\alpha \cos\delta \vec{e}_\alpha + \mu_\delta \vec{e}_\delta,$$

where $\vec{e}_\alpha$, $\vec{e}_\delta$ — unit vectors. A vector field of spherical functions $\vec{F}(\alpha,\delta)$ can be approximated by vector spherical functions as follows

$$\vec{F}(\alpha, \delta) = \sum_{l=1}^{\infty} \sum_{m=-l}^{l} (a_{l,m}^E \vec{Y}_{l,m}^E + a_{l,m}^M \vec{Y}_{l,m}^M),$$

where $\vec{Y}_{l,m}^E$, $\vec{Y}_{l,m}^M$ — the 'electric' and 'magnetic' transverse vector spherical functions, respectively

$$\vec{Y}_{l,m}^E = \frac{1}{\sqrt{l(l+1)}} (\frac{\partial V_{lm}(\alpha,\delta)}{\partial\alpha \cos\delta} \vec{e}_\alpha + \frac{\partial V_{lm}(\alpha,\delta)}{\partial\delta} \vec{e}_\delta),$$

$$\vec{Y}_{l,m}^M = \frac{1}{\sqrt{l(l+1)}} (\frac{\partial V_{lm}(\alpha,\delta)}{\partial\delta} \vec{e}_\alpha - \frac{\partial V_{lm}(\alpha,\delta)}{\partial\alpha \cos\delta} \vec{e}_\delta).$$

The function $V_{lm}(\alpha,\delta)$ is given by

$$V_{l,m}(\alpha, \delta) = (-1)^m \sqrt{\frac{(2l+1)(l-m)!}{4\pi(l+m)!}} P_l^m(sin\delta)\exp(im\alpha),$$

where $P_l^m(sin\delta)$ — the associated Legendre functions.

The coefficients of expansion $a_{l,m}^E$, $a_{l,m}^M$ to be estimated are

$$a_{l,m}^E = \int_0^{2\pi} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \vec{F}(\alpha, \delta) \vec{Y}_{l,m}^{E*}(\alpha, \delta) \cos\delta d\alpha d\delta,$$

$$a_{l,m}^M = \int_0^{2\pi} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \vec{F}(\alpha, \delta) \vec{Y}_{l,m}^{M*}(\alpha, \delta) \cos\delta d\alpha d\delta,$$

where $*$ means a complex conjugation. This system of equations can be solved by the least squares method. In this investigation the coefficients are estimated as global parameters from a large set of VLBI data.

3. Observations and Discussion of Results

The first and second degree spherical harmonics were estimated by the least squares collocation method [12]. The database comprises about 3.9 million observations of group delay with different baselines and sources made in 3,554 24-hour sessions between April 1980 and April 2007. The equatorial coordinates of more than 2,000 radio sources were observed as global or 'arc' parameters (see solution description below). The Earth orientation parameters, corrections to IAU 2000 nutation offsets, and station coordinates were estimated as 'arc' parameters. NNR and NNT constraints were imposed on the station positions for each 24-hour session. Clock offsets, troposphere wet delays, and north-south and east-west gradients were estimated as stochastic parameters for each observational epoch. The vector spherical harmonics were treated as global parameters, similar to the approach used by MacMillan [9].

The first solution was based on all radio sources observed in geodetic and astrometric VLBI programs without separation into 'stable' and 'unstable'. In the second and third solutions no 'unstable' radio sources were used for the reference frame according to the Feissel-Vernier classification [13]. The number of radio sources with measured red shift has increased significantly since the previous publication [10]. The second solution was based on 486 non-'unstable' radio sources with z≤1 and the third solution based on 582 non-'unstable' radio sources with z≥1. Thus, the first solution includes more sources and observations. On the other hand, some of the sources are not astrometrically stable; therefore, the harmonic estimates for the first solution may be corrupted.

Table 1. Estimates of the vector spherical harmonics $l = 1$ for different sets of the reference radio sources

Solution	All radio sources	$z \leq 1$ no 'unstable'	$z \geq 1$ no 'unstable'
Secular aberraton drift, μas/year	25.1 ± 1.1	25.0 ± 2.1	24.3 ± 3.2
Right Ascension Declination	263 ± 3 20 ± 5	269 ± 5 45 ± 7	278 ± 6 40 ± 8

Tabl. 1 presents estimates of the first degree spherical harmonics for three solutions. The estimates of the first degree electric spherical harmonics are stable with respect to changes in reference radio sources. The magnitudes of the differential secular aberration vector lie within their standard deviation errors. The first solution in Tabl. 1 provides better formal statistics. However, the direction of the vector in the first solution is different from the two other solutions, presumably due to the effect of the radio source structure instability.

Table 2. Estimates for the vector spherical harmonics for different combinations of parameters: $l = 1$ only; $l = 1$ and $l = 2$; and $l = 2$ only. All radio sources were used as reference ones

Parameter	(l, m)	$l = 1$ only	$l = 1$ and $l = 2$	$l = 2$ only
Secular aberration drift, μas/year		25.1 ± 1.1	15.6 ± 2.1	
Right ascension, deg		263 ± 3	279 ± 6	
Declination, deg		20 ± 5	26 ± 15	
Electric harmonics, μas/year	(2,0)		0.5 ± 1.8	3.5 ± 1.0
	(2,1)		-5.4 ± 0.9	-11.3 ± 0.6
	(2,−1)		-3.7 ± 0.8	-3.2 ± 0.6
	(2,2)		4.5 ± 0.6	4.6 ± 0.6
	(2,−2)		0.5 ± 0.5	0.7 ± 0.5
Magnetic harmonics, μas/year	(2,0)		-5.9 ± 0.8	-5.6 ± 0.8
	(2,1)		3.2 ± 0.7	2.7 ± 0.6
	(2,−1)		-9.7 ± 0.7	-13.1 ± 0.6
	(2,2)		2.4 ± 0.5	2.3 ± 0.6
	(2,−2)		1.4 ± 0.5	1.4 ± 0.5

Tabl. 2 shows the estimates of $l = 1$ and $l = 2$ spherical harmonics. The first solution was based on all radio sources observed in VLBI programs. The magnitude of the differential secular aberration vector reduces by 40 per cent if the second degree harmonics are added. However, this vector direction does not change significantly. The estimates for the second degree spherical harmonics are statistically significant. Some of them increase if the first degree spherical harmonics are not estimated. Uneven distribution of the reference radio sources results in high correlation among the $l = 1$ and $l = 2$ harmonics (up to 0.8). Until more radio sources in the southern hemisphere are observed, it is necessary to explore whether higher degree harmonics are significant or not.

4. Conclusion

The systematic effects in the reference radio source proper motions have been investigated through a global analysis of geodetic VLBI data. The first and second degree harmonic estimates were statistically significant. A disproportionate reference radio source distribution over the sky causes a high correlation between these parameters and can result in a bias of the harmonic estimates. More astrometric VLBI observations in the southern hemisphere should be done in order to reduce the mutual correlation.

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