

The Influence of Galactic Aberration on Precession Parameters Determined from VLBI Observations

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Abstract—The influence of proper motions of sources due to Galactic aberration on precession models based on VLBI data is determined. Comparisons of the linear trends in the coordinates of the celestial pole obtained with and without taking into account Galactic aberration indicate that this effect can reach $20 \mu\text{as}$ per century, which is important for modern precession models. It is also shown that correcting for Galactic aberration influences the derived parameters of low-frequency nutation terms. It is therefore necessary to correct for Galactic aberration in the reduction of modern astrometric observations.

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1. INTRODUCTION

With growth in the accuracy of astronomical position measurements, the requirements for the models used in the associated astrometric reduction are likewise increased. It becomes necessary to take into account finer effects influencing the measured positions and motions of celestial objects. One of these is secular aberration, due to the motion of the observer together with the motion of the solar-system barycenter (SSB). The existence of secular aberration has long been understood. Already 200 years ago, the Greenwich astronomer J. Pond indicated the presence of a shift in the apparent positions of celestial bodies due to the motion of the solar system [1]. Secular aberration is a fairly complex phenomenon. The full effect is composed of several components, corresponding to various components of the velocity of the SSB: the motion of the SSB relative to the Local Standard of Rest (LSR), the motion of the LSR relative to the center of the Galaxy, the motion of the Galaxy relative to the Local Group, the motion of the Local Group relative to the Local Supercluster, the motion of the Local Supercluster etc. The motion of galaxies on scales larger than tens of Mpc ($z \gtrsim 0.02$) remains poorly studied. Moreover, there are fundamental difficulties with such computations, associated with the selection of a suitable coordinate system [2].

Fortunately, the motion of the SSB is linear to a high degree, which makes the aberrational shift for a given object nearly constant over the comparatively short historical period over which accurate astronomical observations have been available. Since

this shift cannot be determined from observations or calculated theoretically with sufficient accuracy, it has not been usual historically to correct for secular aberration in astrometric data reduction, although it can comprise up to several arcminutes. At the same time, deviations from linear motion of the SSB give rise to apparent proper motions of about $5 \mu\text{as}/\text{yr}$. As was shown in [3, 4], the main contribution to the curvature of the motion of the SSB is made by the circular rotation of the Galaxy, while the influence of the remaining components of the SSB motion is at least an order of magnitude smaller. Therefore, in view of the smallness of the effect, we will further be concerned only with the circular motion of the LSR, and will call the corresponding component of the secular aberration Galactic aberration (GA).

Until recently, the proper (apparent) motions of celestial bodies due to GA were much smaller than the observational accuracy, and were therefore ignored. However, it became clear as early as the 1980s that, with time, they would have to be taken into account in the reduction of high-accuracy Very Long Baseline Interferometry (VLBI) data obtained with ground networks [5–7], as well as data from space astrometric missions [3, 4, 8, 9]. If not taken into account, these aberration proper motions can distort observational results with microarcsecond accuracies. This is relevant first and foremost to the determination of secular variations in astronomical parameters.

One example of important such quantities derived from long-term series of VLBI observations are parameters of precession models [10, 11]. The required accuracy for these parameters is about one microsecond over a century [10]. Currently, these parameters

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are refined using series of coordinates of the celestial pole (CP) derived from VLBI data, which are available starting from 1979 (although it is common to omit from consideration the first few years of observations, which have relatively low accuracy, as we have done in the current study). Failure to correct the observed motions of radio sources for GA directly influences the results of observations designed to refine precession models. Since this effect depends on several factors, such as changes in the observing program, the distribution of observed sources on the celestial sphere, etc, it is difficult to estimate its magnitude theoretically. The current study investigates the strength of the influence of GA in practice.

2. INFLUENCE OF GA ON PROPER MOTIONS

The proper-motion vector of a celestial object due to GA is directed along the Galactocentric-acceleration vector; i.e., toward the center of the Galaxy. Its magnitude is given by [3]

$$A = \frac{V_0 \Omega_0}{c}, \quad (1)$$

where V_0 is the linear speed of the LSR due to the rotation of the Galaxy, Ω_0 is the angular speed of the LSR about the Galactic center, and c is the speed of light. We will call this quantity the Galactic-aberration constant.

Let us rewrite (1) by expressing A in terms of fundamental quantities, determined using Galactic-astronomy methods:

$$A = \frac{R_0 \Omega_0^2}{c}, \quad (2)$$

where R_0 is the distance from the SSB to the Galactic center. To calculate the GA constant, we adopt the mean values $R_0 = 8.2$ kpc and $\Omega_0 = 29.5 \text{ km s}^{-1} \text{ kpc}^{-1}$ (6.22 milliarcsecond/year [mas/yr]) [13–15], which yields the GA constant $A = 5.02 \text{ } \mu\text{as/yr}$. The linear rotational speed of the LSR about the Galactic center is $V_0 = 242 \text{ km/s}$, and the rotational period is 208 million years.

The influence of GA on the coordinates of celestial bodies in Galactic coordinates can be expressed as [3]:

$$\begin{aligned} \mu_l \cos b &= -A \sin l, \\ \mu_b &= -A \cos l \sin b, \end{aligned} \quad (3)$$

where l and b are the Galactic longitude and latitude of the object, respectively.

Since most astrometric calculations, including VLBI data processing, are carried out in equatorial

coordinates, we present the following formulas from [12], carrying over the multiplication of A by $1/c$:

$$\begin{aligned} \mu_\alpha \cos \delta &= -A_1 \sin \alpha + A_2 \cos \alpha, \\ \mu_\delta &= -A_1 \cos \alpha \sin \delta \\ &\quad - A_2 \sin \alpha \sin \delta + A_3 \cos \delta, \end{aligned} \quad (4)$$

where

$$\begin{aligned} A_1 &= A \cos \alpha_0 \cos \delta_0, \\ A_2 &= A \sin \alpha_0 \cos \delta_0, \\ A_3 &= A \sin \delta_0, \end{aligned} \quad (5)$$

and α_0, δ_0 are the equatorial coordinates of the Galactic center. With $\alpha_0 = 266.405100^\circ$, $\delta_0 = -28.936175^\circ$, we obtain $A_1 = -0.28 \text{ } \mu\text{as/yr}$, $A_2 = -4.39 \text{ } \mu\text{as/yr}$, $A_3 = -2.43 \text{ } \mu\text{as/yr}$. The proper motions of celestial objects due to GA in both coordinate systems are shown in Fig. 1.

Since GA has generally not been taken into account, it is present in all catalogs of coordinates of celestial objects, which are thus apparent coordinates. To derive the intrinsic coordinates (corrected for GA), the corrections (4) must be subtracted from the catalog positions.

The accuracy with which corrections for GA can be calculated depends on the accuracy of A ; i.e., the accuracy of R_0 and Ω_0 or equivalent parameters, such as the Oort constants. As the data of the survey [13] and the later data [14, 15] show, this accuracy is no better than 5%. There is also ambiguity in the transformation between Galactic and equatorial coordinates [16]. All these circumstances means that the accuracy of (3), (4) is 5%–10%.

The continuous accumulation of VLBI observations and enhancement of their accuracy leads us to pose the question of whether it is possible to refine the parameters of the Galactic rotation based on VLBI observations of extragalactic radio sources [17, 18]. Unfortunately, results obtained by different authors applying different methods to different data are somewhat contradictory, and yield values of the GA constant that can differ appreciably [18–23]. However, there is hope that, as new observational material is accumulated and VLBI technology is developed, for example, as a result of the realization of the next-generation VLBI network VLBI2010 [24], the accuracy of these estimates will grow, and new VLBI data together with the results of space astrometric measurements will enable the refinement of stellar-astronomy data over the next ten to fifteen years. However, already now, the accuracy of the GA constant is sufficient to calculate GA with uncertainties below $1 \text{ } \mu\text{as/yr}$, which enables reliable estimation of possible systematic effects in VLBI observations due to GA. Here, we will consider the influence of GA on derived precession parameters.

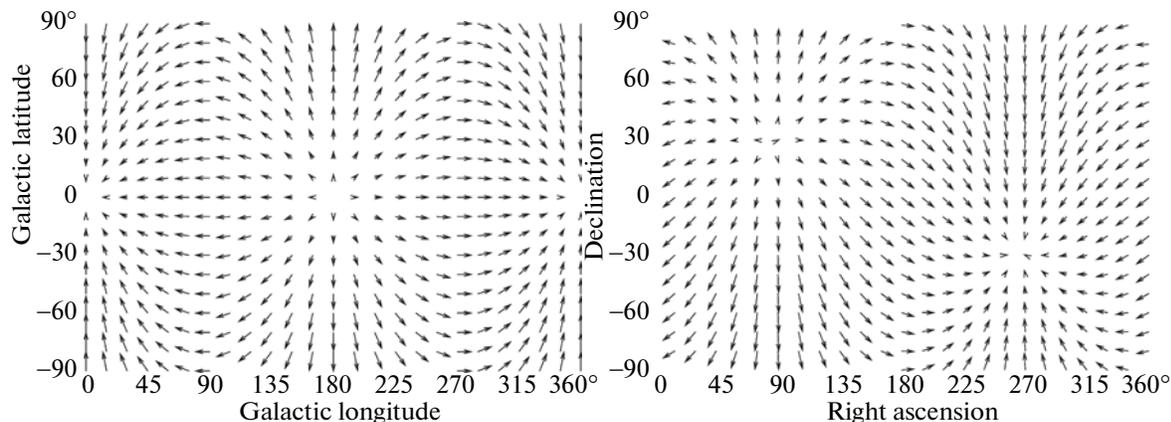


Fig. 1. Proper motions of sources due to GA in Galactic (left) and equatorial (right) coordinates. Arrows of the maximum length correspond to a proper motion of $5 \mu\text{as/yr}$.

3. INFLUENCE OF GA ON ESTIMATES OF PRECESSION PARAMETERS

Corrections to the precession parameters based on VLBI observations can be derived from analyses of series of coordinates of the CP obtained from individual 24-hour observing sessions carried out on global VLBI networks. On average, about three such sessions are conducted each week, primarily using networks with good geometrical characteristics, making it possible to obtain high-accuracy estimates of the Earth-rotation parameters, including the coordinates of the CP [25]. A brief description of the main observational programs engaged in this work is given in [26, 27].

In practice, VLBI observations measure the offset in the position of the CP—(Celestial Pole Offset,

CPO) dX and dY —representing the difference between the measured and theoretical coordinates of the CP. After correcting for the free core nutation (FCN), which does not appear in the precession–nutation theory and is modeled as an empirical effect [28], the CPO measurements are interpreted as reflecting errors in the adopted precession–nutation model. The observed trend in the series of dX and dY measurements can be used to refine the precession parameters [10, 11]. However, this trend could also be due to errors in taking into account proper motions of the observed objects, including those due to GA, which depend on the position of the object on the celestial sphere. Note that, in the ideal case, when using a single set of objects uniformly distributed over the celestial sphere over an extended observing period, the errors in the precession parameters should be zero. However, neither of these conditions are fulfilled in practice. The distribution of sources in right ascension is fairly uniform, apart from some small “gaps” near the Galactic equator, but the same is not true of the declination distribution of the sources. Because the majority of VLBI stations are located in the Northern hemisphere, most of the observed radio sources are located in the Northern sky (see, for example, [29, 30]). Below, we present additional data on the declination distribution of the observed radio sources.

Here, we consider VLBI observations in the database of the International VLBI Service for Geodesy and Astrometry (IVS) [26]. Observations from 3136 sessions conducted between January 5, 1984 and March 12, 2010 were reduced, comprising 5.6 million observations (radio-interferometric delays) in all. The data reduction was carried out in two ways. The first applied the traditional method, in which the coordinates of the radio sources were taken

Linear trends and 18.6-year harmonics in the CPO series

	Series	Without correction for GA	With correction for GA
Version 1	Linear trends, $\mu\text{as/yr}$		
	dX	9.6 ± 0.5	9.7 ± 0.5
	dY	-18.8 ± 0.6	-18.6 ± 0.6
Version 2	Linear trends, $\mu\text{as/yr}$		
	dX	3.6 ± 0.8	3.6 ± 0.8
	dY	-14.0 ± 0.8	-14.0 ± 0.8
	Amplitudes of the 18.6-year harmonics, μas		
	dX	60.9 ± 5.7	62.6 ± 5.7
	dY	55.5 ± 5.5	54.7 ± 5.5

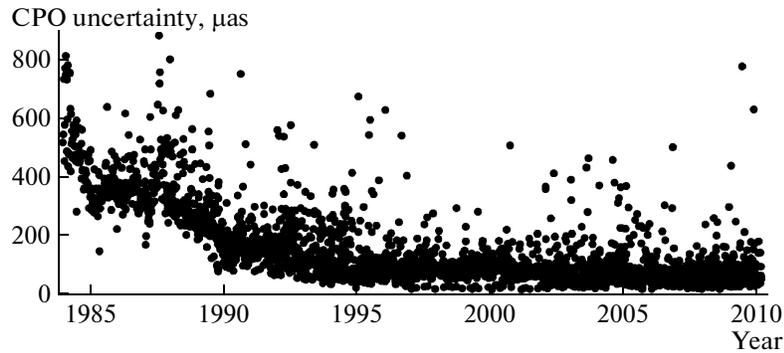


Fig. 2. Uncertainties in the positions of the CP derived from individual sessions of VLBI observations.

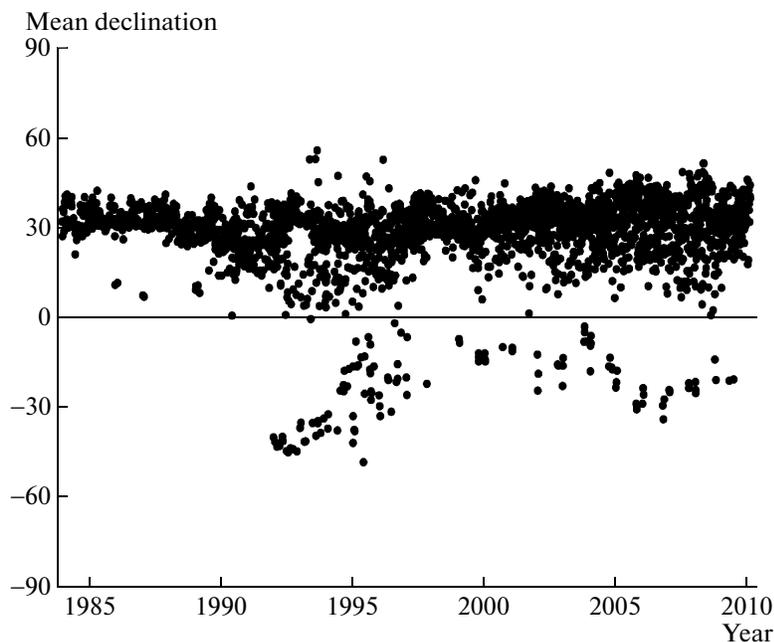


Fig. 3. Mean declination of radio sources for individual sessions processed in the current study.

to be equal to their values in the ICRF2 catalog [30] at all epochs. In the second, the source coordinates at the observing epoch were calculated taking into account their aberration proper motions using (4). This yielded two CPO series consisting of 3136 estimates of dX and dY with median uncertainties of $66 \mu\text{as}$. Nineteen measurements were excluded from the reduction because they corresponded to anomalously large CPO values or had anomalously large uncertainties. The noise in both CPO series was estimated using a modified version of WMADEV, which yields a two-dimensional weighted estimate of the noise in a time series [32]. This noise proved

to be $159 \mu\text{as}$ for both series. This value is a mean characteristic of the accuracy of CPO values derived from VLBI observations obtained over 26 years. As was shown in [33], the accuracy of these observations grew appreciably over this time period. Figure 2 presents the revised data for the two-dimensional uncertainties in the coordinates of the CP calculated as the square root of the squared uncertainties in dX and dY . The uncertainties in the CPO were reduced appreciably in the first roughly 10 years of the observing period, after which they have remained essentially the same.

In addition, the mean clustering of the observed radio sources for each session is presented in Fig. 3,

which shows the substantial asymmetry in the declination distribution of these sources.

We removed the component corresponding to the FCN from the 26-year series of dX and dY measurements using the ZM2 model [28]. Further, we obtained a least-squares fit to calculate the parameters of the linear trend, applying weights calculated as the inverse squares of the uncertainties in dX and dY . The calculation of the parameters of the linear trend was then repeated simultaneously fitting for the parameters of the main nutation term with a period of 18.6 years. The results are presented in the table.

Our calculations show that the influence of GA on the precession parameters derived from VLBI observations could comprise up to $20 \mu\text{as}$ per century, depending on the reduction methods used. We have also determined the influence of GA on the parameters of low-frequency nutation terms.

4. CONCLUSION

We have estimated the influence of GA on the parameters of precession models derived from VLBI observations, which are currently the main method for refining precession–nutation theory. We analyzed a series of VLBI measurements covering 26 years, consisting of 3126 CPO estimates obtained from 24-hour global-VLBI observing sessions. We compared the parameters of linear trends in the measured CP coordinates obtained with and without including the effect of GA, finding differences reaching $0.2 \mu\text{as}/\text{year}$, or $20 \mu\text{as}$ per century. Allowing for GA also influences the corrections to the amplitudes of long-period nutation terms at the level of one to two μas , which, in turn, leads to a dependence of the coefficients of the linear trend, and thereby of the precession parameters, on the refined parameters. Note that modern requirements for the accuracy of precession theory are $1 \mu\text{as}$ per century [10].

Thus, our results indicate that the influence of GA on estimates of precession parameters based on VLBI observations is small but not negligible. Therefore, in spite of the fact that this effect is smaller than the uncertainty with which it can be determined, it is necessary to include the effect of Galactic aberration in standard algorithms for the reduction of modern astrometric observations. Although current calculated values of the GA constant are only accurate to about 10%, this is sufficient to take into account the main influence of GA. Naturally, increasing this accuracy to 1%–2% is very desirable to enable fuller correction for this effect in the future.

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