Galactic Aberration in VLBI Analysis:

Findings of IVS WG8

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Abstract The IVS Working Group on Galactic Aberration (WG8) was established to investigate issues related to incorporating the effect of galactic aberration in IVS analysis. Secular aberration drift is caused by the acceleration of the Solar System barycenter. It is mainly due to the rotation of the barycenter about the center of the Milky Way galaxy. Studies made by working group members have shown that aberration can be estimated from VLBI geodetic data. The VLBI estimates of the aberration amplitude are in the range 5.1 to 6.4 μas/yr. These estimates are close to independent estimates of 4.8 to 5.4 μas/yr that were derived from astrometric measurements of proper motions and parallaxes of masers in the Milky Way galaxy. For the recommended aberration constant, a geodetic value 5.8 μas/yr based on data until May 2018 was chosen by the Working Group in order to be consistent with geodetic VLBI applications, specifically for the generation of the ICRF3 solution. In this paper, we discuss the investigation of the Working Group and its findings.

Keywords Galactic aberration, ICRF, Proper motion

1 Introduction

The IVS Working Group on Galactic Aberration (WG8) was established by the IVS Directing Board at its meeting in November 2015 with the work beginning in 2016. The purpose of the group was to investigate the issues related to incorporating the effect of galactic aberration in IVS analysis. Based on this investigation, the WG was tasked to formulate a recommendation for an aberration correction model to be applied in IVS data analysis and to be provided to the ICRF3 Working Group.

Secular aberration drift is caused by the acceleration of the Solar System barycenter. It is mainly due to the rotation of the barycenter about the center of the Milky Way galaxy as illustrated in Figure 1. This motion induces an apparent proper motion of extragalactic objects observed by VLBI. It was predicted theoretically to have a dipolar structure with an amplitude of 4-6 μas/yr (see e.g., [1], [6], [5]).

Figure 2 shows the proper motion induced by galactic aberration [13] where the aberration amplitude was 6.4 μas/yr. The proper motion vectors stream away from the anti-galactic center towards the galactic center in a dipolar pattern where the maximum proper motion occurs for sources that are 90 ° away from the galactic center (RA = 266.4°, DEC = -28.9°).

The effect of aberration is to cause apparent source positions to change over time. Several studies in recent years, which we discuss in Section 2, have shown that aberration can be estimated from VLBI geodetic data. The VLBI estimates of the aberration amplitude are in the range 5-7 μas/yr. These estimates are reasonably close to independently determined estimates of 4.8-5.5 μas/yr that can be derived from recent astrometric measurements of proper motions and parallaxes of masers

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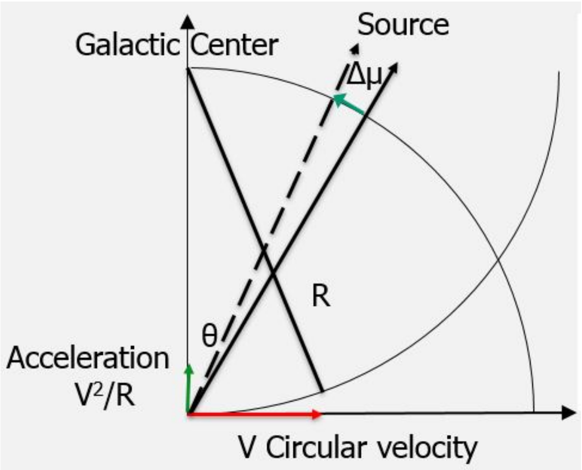

Fig. 1 Galactic aberration. Induced proper motion $\Delta\mu$ of a source is $V^2/(\mathrm{Rc})\sin\theta$.

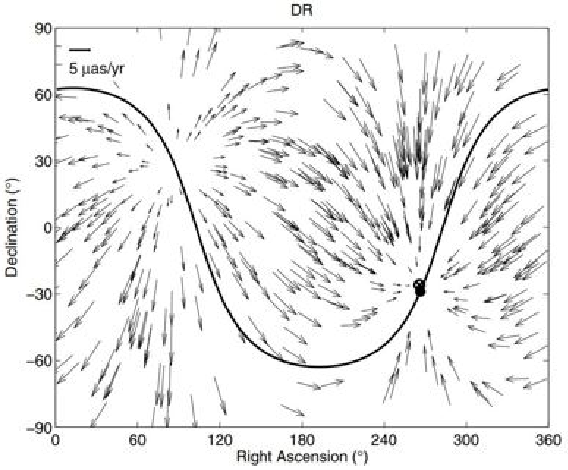

Fig. 2 Aberration proper motion (Titov and Lambert, 2013).

in the Milky Way galaxy. Although the effect of aberration is small, it is not negligible in terms of future micro-arcsecond astrometry. The systematic drift due to an aberration drift of 5 μas/yr would lead to a dipole systematic error of 100 μas after 20 years. One of the effects of applying an aberration model is to change the source positions for a given reference epoch. If the reference epoch of the aberration model is J2000, when the correction is defined to be zero, the aberration corrections to radio source positions at J2000 are as large as 40–50 μas depending on the source coordinates. This arises from the distribution of the median epochs of observation of the sources observed by VLBI over the last three decades. The correction increases as the temporal difference between the median epoch and the reference epoch increases.

Generally the aberration vector estimates from most of the VLBI WG member solutions have components not directed toward the galactic center, which are at most 25% of the aberration amplitude. The WG investigated whether this could be due to how VLBI analysis is performed. Among the issues investigated were 1) dependence of aberration estimates on experiment sessions included in solutions, 2) dependence on sources included, and 3) dependence on solution parametrizations.

The primary objective of the WG was to determine a value of the secular aberration drift constant to be applied in an a priori model of aberration. The application of an a priori model of aberration will most importantly account for the systematic error that is committed without the model. Clearly the dipole systematic due to aberration is significant compared to the CRF noise floor, which in the case of ICRF2 was 40 μas.

The ICRF realizes the International Celestial Reference System (ICRS) by the positions of a set of defining sources that are assumed to have no measurable proper motion. An underlying issue is that applying apparent proper motion corrections due to aberration in VLBI analysis could require a redefinition of the ICRS. However, a redefinition of the ICRS is not something that the IVS can do as it would have to be done by the International Astronomical Union (IAU). The working group found that it was not necessary to redefine the ICRS. We can simply apply an aberration proper motion correction in VLBI analysis by a procedure that is similar to that followed in VLBI analysis to account for other effects like precession or annual aberration (see Section 4). For non-VLBI applications requiring source positions at an epoch other than J2000, one would need to apply the galactic aberration model proper motions with reference epoch J2000 to the source positions given in a catalog generated with the model.

In Sections 2 and 3, we discuss possible choices of the model aberration constant: 1) a geodetic VLBI determined value, 2) a value determined from recent parallax and proper motion measurements of galactic masers, and 3) an average of the two techniques. Then in Section 4, we consider the effects of applying aberration to estimates of source positions from VLBI analysis.

2 Geodetic VLBI Solutions

Figure 3 shows the proper motion field computed from source position time series where the RA and DEC uncertainties were better than 50 μas/yr. These observed proper motions can be as large as a few hundred μas/yr, which are likely due to apparent motion caused by source structure effects. In contrast, systematic galactic aberration proper motions are less than 6 μas/yr. To estimate the systematic effect, one has to assume that source structure effects are random over the sky.

A change in the source direction away from the nominal direction $\mathbf{s_0}$ due to the aberration acceleration $\mathbf{A}$ in a time interval Δt can be expressed as

$$\Delta \mathbf{s} = \frac{\mathbf{s_0} \times (\mathbf{A}\Delta t \times \mathbf{s_0})}{c} \tag{1}$$

The components of the aberration proper motion $\Delta/\mathbf{s}\Delta t$ for a source at right ascension and declination (α, δ) are

$$\Delta \mu_\alpha cos\delta = \frac{1}{c}(-A_1 sin\alpha + A_2 cos\alpha) \tag{2}$$

$$\Delta \mu_\delta = \frac{1}{c}(-A_1 cos\alpha sin\delta - A_2 sin\alpha sin\delta + A_3 cos\delta) \tag{3}$$

Over the last several years, members of our working group made several solutions for the galactic acceleration vector $\mathbf{A}$ using Calc/Solve and VieVS. Table 1 shows the estimates and uncertainties of the galactic center component $\mathbf{A_G}$, the magnitude $|\mathbf{A}|$ of the vector, and the direction of the vector that was estimated for each solution. We usually inflate Calc/Solve parameter estimate uncertainties by a factor of 1.5, which was derived in decimation studies (for example, [3]). To be consistent, the uncertainties of all the amplitudes in the table were all scaled up by this factor.

The global Calc/Solve solutions estimated the components of $\mathbf{A}$ as additional global parameters using the userpartial feature of Calc/Solve ([14] and Xu et al., 2017; [7] and MacMillan, 2016). For the Calc/Solve time series solutions ([12] and [13]), $\mathbf{A}$ was estimated in three steps: 1) estimate source position time series in Calc/Solve solutions, 2) estimate source apparent proper motions from these time series, and 3) estimate $\mathbf{A}$ from these proper motions.

For the scale solution, [11] expanded Equation (1) so that the aberration delay becomes

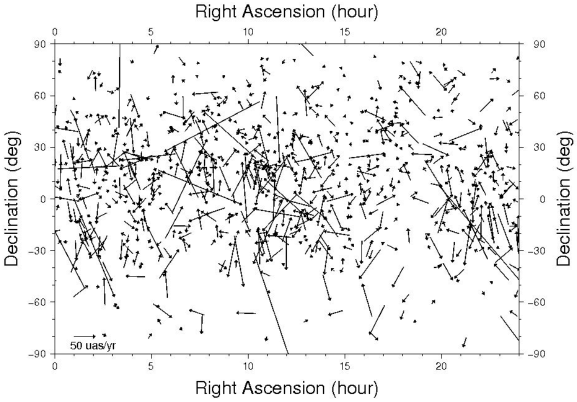

Fig. 3 Proper motion field computed from source position time series (with RA and DEC uncertainties better than 50 μas).

$$\Delta\tau = -\frac{\mathbf{B}\cdot\Delta\mathbf{s}}{c} = -\frac{\mathbf{B}\cdot\mathbf{A}\Delta t}{c} - \frac{F\Delta t\mathbf{B}\cdot\mathbf{s_0}}{c} \tag{4}$$

$$F \equiv -\frac{\mathbf{A}\cdot\mathbf{s}_0}{c}. \tag{5}$$

A global scale factor parameter F was estimated for each source using only the second term in (4), and $\mathbf{A}$ was then derived from the estimated scale factor parameters for all sources using the expression above for F. In the Calc/Solve global solutions, no such separation was made, and $\mathbf{A}$ was estimated essentially from the proper motions of all the sources. An advantage of the method in [11] is that it allows one to estimate $\mathbf{A}$ from different subsets of all sources and thereby remove poorly determined sources from the estimation.

Most of the VLBI estimates of $\mathbf{A}$ have relatively small components (less than 25% of $|\mathbf{A}|$) not in the Galactic center direction. An exception is the first solution of Xu et al., [14], where the component of the acceleration $\mathbf{A}$ perpendicular to the Galactic plane was 46% of $|\mathbf{A}|$. They suggested several hypothetical mechanisms that could explain this estimate, for example, a companion star orbiting the Sun. A second solution of Xu et al. made in 2017 has significantly smaller components not in the direction of the Galactic center. Further investigation of possible physical means for producing non-galactic center components could provide a bound for the VLBI estimates of these components. For the recommended model, we will just consider the Galactic center component A_G of the estimates of the aberration acceleration vector.

Table 1 Geodetic VLBI Aberration Estimates.

		A_G	σ	$\lvert A\rvert$	σ	RA	σ	DEC	σ
		μas/yr		μas/yr		deg		deg	
Titov et al. (2011)	1990-2010	6.3	1.4	6.4	1.5	263	11	-20	12
Titov+Lambert(2013)	1979-2013	6.4	1.1	6.4	1.1	266	7	-26	7
Xu (2013)	1980-2011	5.2	0.5	5.8	0.5	243	4	-11	4
Xu (2017)	1980-2016	6.0	0.3	6.1	0.3	271	2	-21	3
MacMillan (2014)	1979-2014	5.3	0.4	5.6	0.4	267	4	-11	6
MacMillan (2017)	1979-2016	5.7	0.3	5.8	0.3	273	3	-22	5
Titov+ Krasna (2018)	1979-2016	6.0	0.3	6.1	0.3	260	2	-18	4
Titov+Krasna (2018)	1979-2016	5.4	0.6	5.4	0.6	273	4	-27	8
Titov+Krasna (2018)	1979-2016	5.1	0.3	5.2	0.3	281	3	-35	3

3 Galactic Astrometry Estimates

Aberration can also be derived from recent (2009–2017) stellar astronomy measurements (e.g., [10], [8], [2]). These measurements are trigonometric parallaxes and proper motions of masers in high-mass star-forming regions in the Milky Way galaxy. The measurements were made using the Very Long Baseline Array (VLBA), the European VLBI network (EVN), and the Japanese VLBI Exploration of Radio Astronomy Project (VERA). The most recent investigation noted here [8] used a maser sample of 136 sources. Using these parallax and proper motion measurements, different investigators have derived models of the galaxy. Among the parameters of these models are the radial distance R (kpc) to the galactic center and circular rotation speed V (km/s) of the solar system barycenter. Based on the estimated parameters R and V and their uncertainties from each investigator, one can determine the aberration constant A_G=V^2/(Rc) and its uncertainty. Table 2 shows the resulting estimates of the aberration constant A_G. Based on the uncertainties of R and V, the formal uncertainties of A_G are in the range 0.3-0.8 μas/yr.

4 Application of Aberration in Geodetic VLBI Solutions

In this section, we discuss how the aberration correction should be applied to determine a new ICRF catalog. One can simply run a solution with an aberration correction that has a reference epoch of t_0 = J2000. The estimated positions will then be self-consistent with the correction. The aberration contributions to the a priori source positions are

$$\Delta\alpha(\alpha,\delta) = \Delta\mu_\alpha(t-t_0) \qquad (6)$$

$$\Delta\delta(\alpha,\delta) = \Delta\mu_\delta(t-t_0) \qquad (7)$$

where the aberration proper motions ($\Delta\mu_\alpha\cos\delta$, $\Delta\mu_\delta$) are given above in (2) and (3). For non-VLBI applications requiring positions at epoch t, the catalog positions at J2000 would be corrected by applying the Galactic aberration model correction for epoch t.

We have investigated what is the effect of the aberration on estimated source positions. Figures 4, 5, 6, and 7 show the Calc/Solve differences in source positions (RA, DEC) versus RA and DEC when the aberration constant A_G is a nominal 5 μas/yr. The variation (scatter) of the differences at RA or DEC in these plots is due to the fact that the difference in the mean epoch from the reference epoch (e.g., J2000) varies significantly over the set of sources. In this case the sources in the source NNR (no net rotation) constraint were uniformly weighted.

5 IAU Recommendation

Possible options for the IVS working group recommendation for the aberration constant AG are: 1) VLBI weighted mean, 2) galactic astronomy weighted mean, and 3) the average of 1) and 2). If the two were equally weighted A_G = 5.3 ± 0.3 μas/yr. The average of the two sets of measurements differ from the means of each group by at most 0.4 μas/yr which is less than 10% of the aberration effect. If we are uncertain about which

Table 2 Galactic Astronomy Derived Estimates.

	A_G μas/yr	σ	V km/s	σ	R kpc	σ	masers
Reid (2009)	5.4	0.08	254	16	8.40	0.60	18
Brunthaler (2011)	5.1	0.3	246	7	8.30	0.23	18
Honma (2012)	4.9	0.6	238	14	8.05	0.45	52
Reid (2014)	4.8	0.3	240	8	8.34	0.16	103
Rastorguev (2017)	4.8	0.3	238	7	8.24	0.12	136

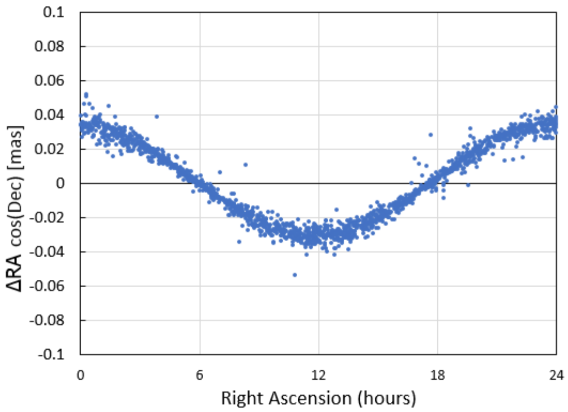

Fig. 4 Aberration effect on right ascension versus right ascension with an aberration constant of 5 μas/yr.

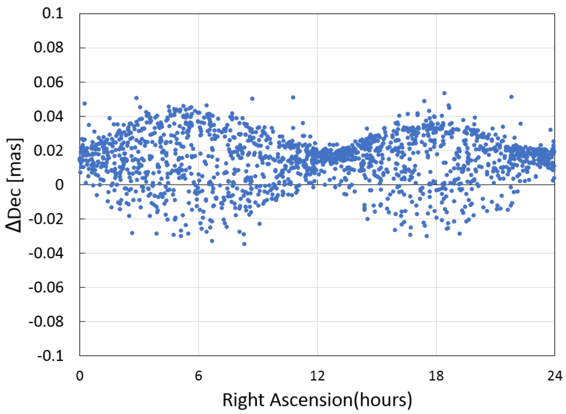

Fig. 6 Aberration effect on declination versus right ascension with an aberration constant of 5 μas/yr.

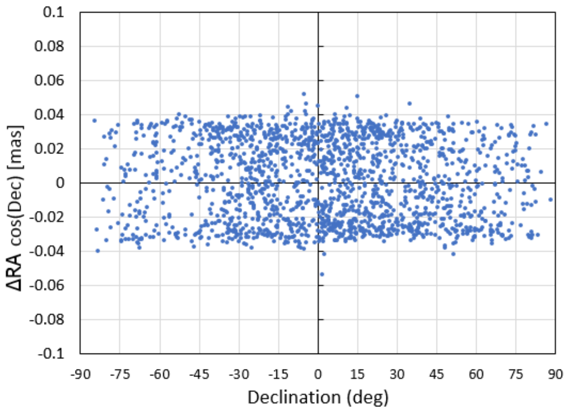

Fig. 5 Aberration effect on right ascension versus declination with an aberration constant of 5 μas/yr.

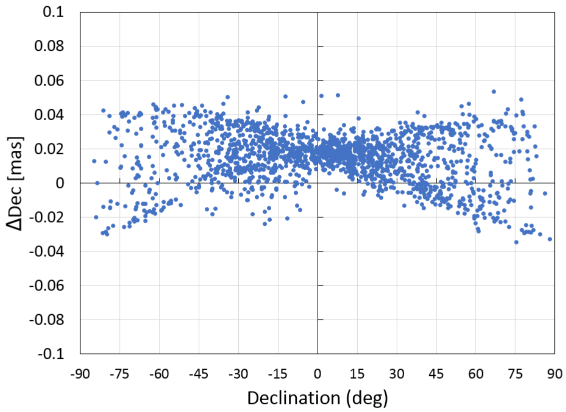

Fig. 7 Aberration effect on declination versus declination with an aberration constant of 5 μas/yr.

group of measurements may be biased from the truth, this would appear to be the best option.

However, we recommend that the IAU ICRF3 working group should use option 1) for the value of A_G when a galactic aberration contribution is applied. The rationale is that since the correction was derived via geodetic VLBI solutions, it should be applied in the analysis of geodetic VLBI sessions, specifically for the ICRF3 solution, in order to be self-consistent. Since none of the solutions reported in Table 1 used all of the available data, a new Calc/Solve global solution was run using all of the data used for the

ICRF3 solution (from 1979 through May 2018). The resulting estimated aberration constant 5.8 μas/yr is not significantly different from the value from the solution (MacMillan, 2016) that used data until 2016. This aberration constant was taken to be the final recommended value.

6 Conclusions

The Working Group recommended an aberration constant derived only from geodetic VLBI data analysis in order to be consistent with geodetic VLBI solutions (and specifically for the ICRF3 solution) rather than averaging geodetic and galactic astronomy estimates. The ICRF3 was derived using an aberration constant estimated using all the data used for the ICRF3 solution, which was about two more years of data than any of the previous VLBI solutions. The recommended value of 5.8 μas/yr is reasonably close to the constant derived from recent Galactic astronomy measurements. An issue that remains to be studied further is to understand the cause of non-galactic center components of the estimated aberration vector estimates from the different WG solutions although their magnitudes are generally less than 25% of $|\mathbf{A}|$. This could be due to some unmodeled physical aberration effect or possibly to how the VLBI analysis was done.

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References

1. U. Bastian, In M. A. Perryman and F. Van Leeuwen, editors, Proc. RG0-ESA Workshop on Future Possibilities for Astrometry in Space, ESA SP-379, 99, 1995.
2. A. Brunthaler, M. J. Reid, K. M. Menten, et al. The bar and spiral structure legacy (BeSSeL) survey: Mapping the Milky Way with VLBI astrometry. *AN*, 332(5), 461, 2011.
3. A. Fey, D. Gordon, C. S. Jacobs, et al. The second realization of the international celestial reference frame by very long baseline interferometry. *AJ*, 150, 58, 2015.
4. M. Honma, T. Nagayama, K. Ando, et al. Fundamental parameters of the Milky Way Galaxy based on VLBI astrometry. *PASJ*, 135, 64, 2012.
5. S. M. Kopeikin and V. V. Makarov. Astrometric effects of secular aberration. *AJ*, 131, 1471, 2006.
6. J. Kovalevsky. Aberration in proper motions. *A&A*, 404, 743, 2003.
7. D. S. MacMillan. Determination of galactic aberration from VLBI measurements and its effect on VLBI reference frames and Earth orientation parameters. In AGU Meeting abstracts, San Francisco, CA, 2014.
8. A. S. Rastorguev, N. D. Utkin, M. V. Zabolotskikh, et al. Galactic masers: kinematics, spiral structure and the disk dynamic state. *Astrophys. Bull.*, 72, 122, 2017.
9. M. J. Reid, K. M. Menten, X. W. Zheng, et al. Trigonometric parallaxes of massive star- forming regions. VI. Galactic structure, fundamental parameters, and noncircular motions. *ApJ*, 700, 137, 2009.
10. M. J. Reid, K. M. Menten, A. Brunthaler, et al. Trigonometric parallaxes of high mass star forming regions: the structure and kinematics of the Milky Way. *ApJ*, 783, 130, 2014.
11. O. Titov and H. Krásná. Measurement of the solar system acceleration using the Earth scale factor. *A&A*, A36, doi.org/10.1051/0004-6361/201731901, 610, 2018.
12. O. Titov, S. B. Lambert, and A. -M. Gontier. VLBI measurement of the secular aberration drift. *A&A*, A91, 529, 2011.
13. O. Titov and S. B. Lambert. Improved VLBI measurement of the solar system acceleration. *A&A*, A95, 559, 2013.
14. M. H. Xu, G. L. Wang, and M. Zhao. The solar acceleration obtained by VLBI observations. *A&A*, A135, 544, 2012.