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The Galactic Aberration and Its Impact on Astronomical Reference Frames[†] [⋆]

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Abstract The Galactic aberration effect, also known as the secular aberration drift, is a consequence of the centripetal acceleration of the Solar System Barycenter in the circular orbit around the Galactic center. It causes distance-independent apparent proper motions (the amplitude is about 5 μas $\cdot$ yr^{-1}) for extragalactic sources which were regarded as motionless before 21th century. As the very long baseline interferometry (VLBI) has been greatly developed, and the ESA (European Space Agency) space mission *Gaia* has provided ultra high-precision astrometric data, the Galactic aberration effect has becoming important. It causes slow spin of the reference frame due to the non-uniform distribution of extragalactic sources. Therefore systematic corrections have to be applied to the Earth rotation parameters. For the precession rate, the correction is about 1 μas $\cdot$ yr^{-1}. For the very high accurate VLBI and *Gaia* reference frames, the Galactic aberration effect will introduce small distortion which is a crucial systematic effect for the link of the two reference frames.

Key words astrometry—proper motions—quasars: general—reference systems

1. INTRODUCTION

It is well known that the finite speed of light and the motion of an observer (first derivative of the position with respect to time) will result in difference between the observed and real directions of a celestial object. This distance-independent observational effect is called "aberration". Similarly, the acceleration of the observer (the second derivative of the position with respect to time) will cause the change in the observed velocity of a celestial object which can be called the "aberration drift" leading to variation of proper motions of sources on the celestial sphere[1,2].

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At present the fundamental astronomical reference system is called the International Celestial Reference System (ICRS). The origin of the reference system is located at the solar system barycenter (SSB) which is regarded stationary or in linear motion[3]. In 2019, the International Astronomical Union (IAU) adopted the third International Celestial Reference Frame (ICRF3) as the formal realization of the ICRS[4,5]. To ensure the inertia of the reference system, the ICRF3 catalogue contains a group of extragalactic radio sources (such as galaxies, active galactic nucleus, and quasars) observed by the very long baseline interferometer (VLBI) technique. The accuracy of the source positions has reached a level of sub-milliarcsecond. Because of extremely large distances of sources (at least millions of parsecs) and limited accuracy of VLBI in the past years, one usually assumes that the transversal motion of extragalactic sources are zero (i.e. the proper motions are too small to be detectable)[6]. According this precondition, the celestial coordinates of these remote extragalactic sources are constants, therefore an quasi-inertial reference system independent of epoch can be established. However the origin of the ICRS, i.e. SSB, obviously has its own curvature motion in our Galaxy. Based on the concept of aberration drift, the acceleration of the SSB produces distance-independent proper motions such that the benchmark points of the reference frame are no longer motionless. The effect originated from the acceleration of the SSB was labeled as the "secular aberration drift"[7−9]. In recent years, several studies on this phenomenon have been carried out. Titov et al.[10,11] analyzed VLBI data over the period 1990-2010 to produce the coordinate time series of 555 radio sources, and obtained the proper motions of sources. Then the acceleration of the Sun was derived with a least squares fit. Malkin[12] and Xu et al.[13,14] have made a direct estimation of the acceleration of the Sun using 30 years of VLBI data. In a theoretical study, Liu et al.[15] evaluated the influence of the Galactic aberration on the reference frame and Earth rotation parameters.

In our Galaxy, the acceleration of the SSB contains two parts: (1) the peculiar part with respect to the local standard of rest (LSR), and (2) the galactocentric acceleration of the LSR. It has already been proved, based on the epicycle theory, that due to the peculiar acceleration of the SSB, the amplitude of apparent proper motions is about 1 μas yr^{-1}, which is only about ten times less than the effect resulting from the galactocentric acceleration[16]. Neglecting the the minor part, only the galactocentric acceleration (in a circular orbit) with constant amplitude and changing direction would be considered. This aberrational effect from this centripetal acceleration is called the "Galactic aberration (referred to as GA for brevity in following discussions)". This effect has also referred to as "aberration in proper motions"[8], "secular aberration"[16], or "secular aberration drift"[9], but no official nomenclature has been adopted so far. Titov[9] and Malkin[17] called attention to the need of taking the Galactic aberration effect into account in high-precision astrometric data reductions in the future development of the ICRF and in geodetic/astrometric VLBI software packages[18].

Within the reference system centered on the SSB, the real direction of a celestial object $\boldsymbol{p}$ is going to be observed at its apparent position $\boldsymbol{p}'$, since we consider that the SSB is accelerating[15,16]:

$$\boldsymbol{p}' = \boldsymbol{p} + \frac{1}{c}\,\boldsymbol{p}\times(\boldsymbol{v}\times\boldsymbol{p}) + \frac{1}{c}\,\boldsymbol{p}\times(\boldsymbol{a}\times\boldsymbol{p})(t-t_0)\,, \tag{1}$$

where c is the speed of light in the vacuum, $\boldsymbol{v}$ the orbital velocity the SSB, and a the acceleration of the SSB toward the Galactic center. Note that the second or higher order terms of the velocity are neglected. In the above expression, the first two terms in the right hand side are constants, while the third term corresponds to the Galactic aberration drift to be discussed in this paper. In a circular orbit, we define a vector $\boldsymbol{g}$[8]:

$$\boldsymbol{g} = \frac{V_0\omega_0}{c}\boldsymbol{g}_0 = \frac{R_0\omega_0^2}{c}\boldsymbol{g}_0 = \frac{V_0^2}{R_0 c}\boldsymbol{g}_0 = g\cdot\boldsymbol{g}_0\,, \tag{2}$$

in which ω_0 and V_0 are the linear and angular velocities of the SSB, respectively, R_0 the distance from the SSB to the Galactic center. $\boldsymbol{g}_0$ is the unit vector from the SSB to the Galactic center, and g denotes the magnitude of $\boldsymbol{g}$ known as the aberration constant: it has the same unit as angular proper motions ($\mu\mathrm{as}\cdot\mathrm{yr}^{-1}$).

This review paper is organized as follows. Section 2 describes in detail the aberration constant g and the expressions of apparent proper motions from the Galactic aberration effect. Sections 3 and 4 introduce the systematic effect of GA on the reference frame realized by extragalactic sources and the Earth rotation parameters, respectively. In the following section 5, discussion on the link between the optical and radio reference frames is presented. Finally, conclusions and prospects are given in Sect. 6.

2. EXPRESSIONS FOR THE GALACTIC ABERRATION

2.1 Expansion of vector field with vector spherical harmonics

To interpret the source proper motions of the Galactic aberation effect more strictly, the vector spherical harmonics (VSHs) should be applied[19,20]. Any vector field $\boldsymbol{V}(\alpha,\delta)$ defined on the surface of a sphere can be expanded in a unique linear combination of the VSH:

$$\boldsymbol{V}(\alpha,\delta) = \boldsymbol{V}^{\alpha}(\alpha,\delta)\boldsymbol{e}_\alpha + \boldsymbol{V}^{\delta}(\alpha,\delta)\boldsymbol{e}_\delta \;\; = \sum_{l=1}^{\infty}\sum_{m=-l}^{l}\left(t_{lm}\boldsymbol{T}_{lm} + s_{lm}\boldsymbol{S}_{lm}\right)\,. \tag{3}$$

In Eq. (3), $\boldsymbol{e}_\alpha$ and $\boldsymbol{e}_\delta$ are the orthogonal unit vectors on the tangential plane at (α, δ), and they point to the directions of increasing right ascension and declination, respectively. The VSHs split into two basic categories referred to as the toroidal $\boldsymbol{T}_{lm}$ and spheroidal $\boldsymbol{S}_{lm}$ functions of lth degree and mth order. When performing the expansion, we usually adopt an upper limit of degree $l_{\max}$, and discuss the features of the field by investigating the coefficients t_{lm} and s_{lm} of each component. By increasing $l_{\max}$, it is expected to see more details of the vector field in smaller regions. In particular, the very first degrees ($l=1$ and $l=2$) show global or "long wavelength" features.

The apparent proper motion field coming from the GA effect corresponds to the simplest vector field, and it is only related to the lowest degree of VSH, having no projected components on the basis function $\boldsymbol{T}_{lm}$ (i.e. $t_{lm} = 0$). If the acceleration vector $\boldsymbol{g}$ pointing to the Galactic center can be written as $\boldsymbol{g} = (g_1, g_2, g_3)$ in the equatorial coordinate system, we have the VSH form of the vector field:

$$\begin{aligned}\boldsymbol{v}_g &= s_{10}\boldsymbol{S}_{10} + s_{11}\boldsymbol{S}_{11} + s_{1,-1}\boldsymbol{S}_{1,-1} \\ &= \boldsymbol{u} \times (\boldsymbol{g} \times \boldsymbol{u}) = \boldsymbol{g} - (\boldsymbol{g} \cdot \boldsymbol{u})\boldsymbol{u}\,,\end{aligned} \tag{4}$$

where $\boldsymbol{u} = (\cos\alpha\cos\delta, \sin\alpha\cos\delta, \sin\delta)$ is the radial unit vector at a source with coordinates $(\alpha,\, \delta)$. Decomposing $\boldsymbol{v}_g$ on the tangential plane perpendicular to $\boldsymbol{u}$, we have proper motion components in right ascension and declination:

$$\begin{cases} \mu_\alpha^* = \mu_\alpha \cos\delta = \boldsymbol{v}_g \cdot \boldsymbol{p} = \boldsymbol{p} \cdot \boldsymbol{g} \\ \mu_\delta = \boldsymbol{v}_g \cdot \boldsymbol{q} = \boldsymbol{q} \cdot \boldsymbol{g} \end{cases}, \tag{5}$$

where $\boldsymbol{p} = (-\sin\alpha, \cos\alpha, 0)$ and $\boldsymbol{q} = (-\cos\alpha\sin\delta, -\sin\alpha\sin\delta, \sin\delta)$ are also unit vectors. Clearly, $(\boldsymbol{p}, \boldsymbol{q}, \boldsymbol{u})$ forms an orthogonal triad. Finally one gets expressions for the apparent proper motions as follows:

$$\begin{cases} \mu_\alpha^* = -g_1 \sin\alpha + g_2 \cos\alpha \\ \mu_\delta = -g_1 \cos\alpha \sin\delta - g_2 \sin\alpha \sin\delta + g_3 \cos\delta \end{cases}. \tag{6}$$

Once the aberration vector $\boldsymbol{g}$ and the coordinates of a source on the celestial sphere are available, the apparent proper motions from GA can be calculated using Eq.(6).

2.2 Estimation of the Galactic aberration constant

Theoretically, the acceleration of the SSB is pointing to the Galactic center at ($\alpha_0 \simeq 266.4°, \delta_0 \simeq -28.4°$)[21,22] or ($\ell = 0, b = 0$), where ℓ and b are respectively the Galactic longitude and latitude of a source. To calculate proper motions in right ascension and declination, it is necessary to determine the aberration constant g which determines the amplitude of the aberration effect. The most straightforward way is to use the relationship for the circular orbit of the SSB in the Milky Way (see Eq.(2)). The latest researches have provided the best estimations for the distance from the Sun to the Galactic ($R_0 = 8.2\ kpc$) and the angular velocity for the orbital motion ($\omega_0 = 29.5\ \mathrm{km \cdot s^{-1} \cdot kpc^{-1}}$ or $6.22\ \mathrm{mas \cdot yr^{-1}}$)[23], then we immediately obtain the value for the aberration constant:

$$g = 5.02\,\mu\mathrm{as \cdot yr^{-1}}\,. \tag{7}$$

In the equatorial coordinate system, the vector $\boldsymbol{g}$ reads

$$\begin{pmatrix} g_1 \\ g_2 \\ g_3 \end{pmatrix} = \begin{pmatrix} g\cos\alpha_0\cos\delta_0 \\ g\sin\alpha_0\cos\delta_0 \\ g\sin\delta_0 \end{pmatrix} \simeq \begin{pmatrix} -0.28 \\ -4.39 \\ -2.42 \end{pmatrix} \mu\mathrm{as \cdot yr^{-1}}\,, \tag{8}$$

with a relative error of 5%−10%[17] according to the present accuracy of R_0 and ω_0.

In 2011, Titov et al.[10] fitted proper motions of 555 extragalactic sources with their position time series observed by VLBI, and obtained $g = 6.4 \pm 1.5\,\mu\mathrm{as}\cdot\mathrm{yr}^{-1}$. The apex of the vector $\boldsymbol{g}$ locates at the α=263 ± 11°, $\delta = 20 \pm 12\,°$, and there is a 10° separation from the Galactic center (or Sgr A*) $\alpha = 265°$, $\delta = -29°$. In 2013, the authors added new VLBI observations in the data reduction, and improved the data selection criteria and the least squares methods. The uncertainty for the updated result $g \simeq 6.2 \pm 1.3\,\mu\mathrm{as}\cdot\mathrm{yr}^{-1}$ has been reduced by about 20%, and the angular distance to the Galactic is about 7°[11].

In 2018, Titov & Krásná[24] developed a new method based on the Earth's scale factor from VLBI observations. They obtained the aberration constant $g \simeq 5.2 \pm 0.2\,\mu\mathrm{as}\cdot\mathrm{yr}^{-1}$ with an angular distance of 20° to the Galactic center. This method is completely independent of source proper motions. Taking it as a global parameter in the VLBI software Calc/Solve, Xu et al.[13] made another estimation (independent of the Galactic kinematics) of the acceleration of the SSB, indicating that the apex of the resulting acceleration is about 33° from the Galactic plane to the north because of the very significant value of the z-component acceleration, but this is not predicted by the current theory[13]. More recently, Liu et al.[25] analyzed again the VLBI data of source position time series to solve the acceleration of the SSB. As a result, the vector $\boldsymbol{g}$ has an amplitude of about 5 $\mu\mathrm{as}\cdot\mathrm{yr}^{-1}$and direction to the Galactic center. In the following discussion, we adopt

$$g = 5.02\,\mu\mathrm{as}\cdot\mathrm{yr}^{-1}\,, \tag{9}$$

and Galactic center as the direction of the acceleration. Table 1 listed the amplitudes and directions of the Galactic aberration vector published in recent literatures.

Table 1 The estimates of the Galactic aberration parameters from recent publications[a]

	TLG11[10]	XWZ12[13]	TL13[11]	Mac14[26]	TD17[27]	TK18[24]
$g/(\mu\mathrm{as}\cdot\mathrm{yr}^{-1})$	6.4 ± 1.5	5.8 ± 0.4	6.4 ± 1.1	5.6 ± 1.0	1.7 ± 0.3	5.2 ± 0.2
α /°	263 ± 11	243 ± 4	266 ± 7	267 ± 3	275 ± 10	281 ± 3
δ /°	-20 ± 12	-11 ± 4	-26 ± 7	-11 ± 3	-29 ± 9	-35 ± 3
ζ^{b}/°	9	28	3	18	8	15

[a] The references listed in line 1 are labeled with the author names.

[b] ζ is the angular distance between the direction of $\boldsymbol{g}$ and the Galactic center. The position of the Galactic center is located at $\alpha_0 = 266.4°$ and $\delta_0 = -28.4°$.

3. IMPACT OF THE GALACTIC ABERRATION ON THE REFERENCE FRAME OF EXTRAGALACTIC SOURCES

The apparent proper motions come from the Galactic aberration show regular pattern on the celestial sphere[16,17]: each and every source is moving on the great circle that connects the Galactic center and the anti-Galactic center. The magnitude of the proper motions only relies on its position on the sphere, or more strictly, on the angular distance to the Galactic center ζ:

$$\mu = g \sin\zeta\,. \tag{10}$$

Clearly the largest proper motions (equal to $g = 5.02\,\mu\text{as}\cdot\text{yr}^{-1}$) appear on the great circular perpendicular to the diameter connecting the Galactic center and the anti-Galactic center (where $\zeta = 90°$), while at the direction of the Galactic center and the anti-Galactic center, the sources are not affected by the Galactic aberration since $\zeta = 0°$ or $180°$. According to 303 defining sources in the ICRF3 catalogue, the pattern of apparent proper motions from the GA effect are plotted in Fig. 1.

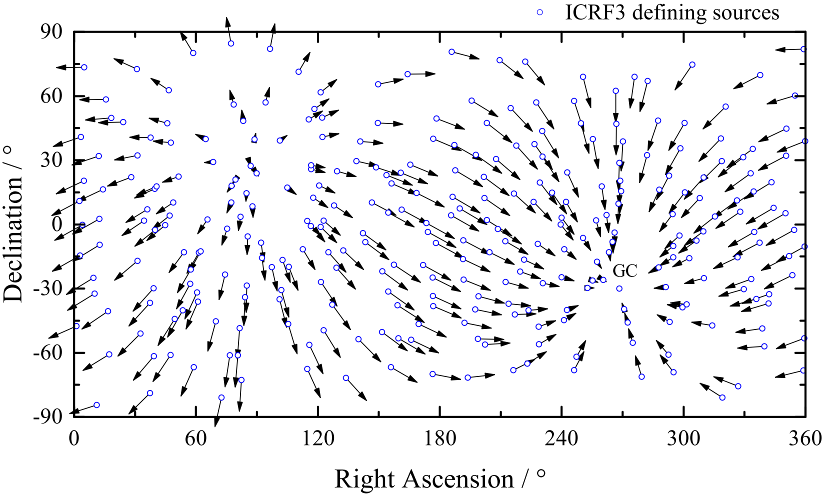

Fig. 1 The defining sources in the ICRF3 and the distribution of apparent proper motions resulting from the Galactic aberration effect

Generally it must be imposed that the three space axes of the reference systems are perpendicular to each other, so that the transformation between them should only be described by a rigid rotation to keep the orthogonality. Since the effect of the GA gives rise to apparent proper motions for all of the distant extragalactic sources, the inertial reference system (ICRS) will suffer a small rigid rotation. The transformation between ICRS and the rotated ICRS′ is defined by the following equation[15,28]:

$$[\text{ICRS}'] = \mathcal{M}(\epsilon_1, \epsilon_2, \epsilon_3)\cdot[\text{ICRS}]\,. \tag{11}$$

In which the 3×3 matrix $\mathcal{M}$ has the form:

$$\mathcal{M}(\epsilon_1, \epsilon_2, \epsilon_3) = \begin{pmatrix} 1 & +\epsilon_3 & -\epsilon_2 \\ -\epsilon_3 & 1 & +\epsilon_1 \\ +\epsilon_2 & -\epsilon_1 & 1 \end{pmatrix}, \tag{12}$$

where

$$\epsilon_1 = \omega_1 t,\ \epsilon_2 = \omega_2 t,\ \epsilon_3 = \omega_3 t\,. \tag{13}$$

In the above formula, $\epsilon_{1,2,3}$ represent the rotation angles around three axes of the ICRS, and $\omega_{1,2,3}$ are the corresponding rotation rate caused by the proper motions of sources which can be evaluated by the least squares using the following equations[29]:

$$\begin{cases} \mu_\alpha^* = -\omega_1 \cos\alpha \sin\delta - \omega_2 \sin\alpha \sin\delta + \omega_3 \cos\delta \\ \mu_\delta = +\omega_1 \sin\alpha - \omega_2 \cos\alpha \end{cases}. \tag{14}$$

It should be helpful to stress the difference between Eq. (6) and Eq. (14): the former one is used to calculate the apparent proper motions given the celestial coordinates of sources, while the latter is for estimating the global rotation of the reference system once the proper motions in aberration are already known. In 2012, Liu et al.[15] used the sources in the ICRF1 and ICRF2 catalogues to evaluate the global rotation of the ICRS. The authors conclude that the rotation coming from the GA strongly depends on the distribution of sources that are used to realize the celestial reference system. From the numerical results in Table 1 of Liu et al.[15], the largest global rotation estimated using 212 defining sources in ICRF1 is up to $(1.10{\pm}0.14)\,\mu\mathrm{as}\cdot\mathrm{yr}^{-1}$because most of these defining sources are concentrated in the northern hemisphere. As for the more homogeneously distributed 608 sources in the ICRF1, the global rotation introduced by the Galactic aberration is only about $(0.22 \pm 0.09)\,\mu\mathrm{as}\cdot\mathrm{yr}^{-1}$. In case of an ideal uniform distribution, the global rotation vanishes.

Note that the GA is produced by the centripetal acceleration of the SSB in a circular orbit, it is more convenient to use the Galactic coordinate system[30−33] (whose X axis points to the Galactic center, and the Z axis to the north Galactic pole) to depict the geometric feature of the apparent proper motions. Given the Galactic longitude and latitude of an extragalactic source, the proper motions in longitude and latitude are such that

$$\begin{cases} \Delta\mu_\ell \cos b = -g \sin\ell \\ \Delta\mu_b = -g \cos\ell \sin b \end{cases}, \tag{15}$$

which also gives out zero proper motions at the Galactic center/anti-Galactic center and the largest proper motions at the great circular with the Galactic center at its pole. In the Galactic coordinate system, the rotation around the X axis is always zero no matter what source distribution we have. The full rotation vector is normal to the X axis, depending on the source distribution[15].

4. EFFECT OF THE GALACTIC ABERRATION ON THE EARTH ORIENTATION PARAMETERS

The IAU (International Astronomical Union) and the IERS (International Earth Rotation and Reference System Service)[34] recommend to use the time variation of X and Y to describe the orientation of the Earth rotation pole[35,36] which is called the precession-nutation[37−39]. The quantities X and Y can also be understood as the direction cosines of the CIP (the celestial intermediate pole) in the GCRS (Geocentric Celestial Reference System). Another parameter for describing the spin of the Earth about the CIP is known as the Earth Rotation Angle (ERA)[40]. As X, Y, and ERA must be measured in certain reference system, small changes will occur for the Earth orientation parameters (EOP) when the reference system is rotating slowly owing to the Galactic aberration.

To assess the effect of the Galactic aberration on the precession rate, Malkin[12] introduced the GA effect in the VLBI data processing, and obtained the corrections to the rate of X and Y:

$$\begin{cases} \Delta\dot{X} = +0.1 \pm 0.5\ \mu\text{as}\cdot\text{yr}^{-1} \\ \Delta\dot{Y} = +0.2 \pm 0.6\ \mu\text{as}\cdot\text{yr}^{-1} \end{cases} . \tag{16}$$

Liu et al.[15] developed the theoretical formula for the EOP corrections due to the global rotation ($\omega_{1,2,3}$) of the reference system:

$$\begin{cases} \Delta X = +\epsilon_3 Y - \epsilon_2 Z \\ \Delta Y = -\epsilon_3 X + \epsilon_1 \\ \Delta\text{ERA} = -\epsilon_3 Z - \dfrac{1}{2}\left(\epsilon_1 X + \epsilon_2 Y\right) \end{cases} , \tag{17}$$

where $Z = \sqrt{1 - X^2 - Y^2}$. In the next step, the corrections for the precession rates were calculated based on the ICRF catalogues and the IAU precession-nutation models. As a result the magnitude of the corrections for the precession rates is consistent with Malkin (2011) at the level of $1\,\mu\text{as}\cdot\text{yr}^{-1}$.

To conclude, the Galactic aberration effect introduces systematic differences in EOP estimations up to tens of microarcseconds over 30 years. This is more significant than the uncertainties of the precession-nutation. Such systematic effects should be avoided in the VLBI analysis by taking the apparent proper motions of sources into account[41].

5. EFFECT OF GALACTIC ABERRATION ON THE LINK BETWEEN THE RADIO AND OPTICAL REFERENCE FRAMES

We have discussed the influence of the Galactic aberration on ICRF realized by extragalactic sources at radio band. As for the more generally used optical telescopes, it is difficult to observe most of radio sources since they are too faint (usually the magnitude is larger than 17). To make the ICRF practical in visible wavelength, an optical realization of the reference system should be adopted. Of course the ICRF at both the optical and radio bands have the same meaning: they realize a rotating free reference frame defined by remote extragalactic sources.

In the 1990s, the first generation space astrometric satellite *Hipparcos* has provided excellent observational data for constructing a high accurate optical reference frame. The *Hipparcos* acquired astrometric data for stars brighter than the 11th magnitude with typical precision of 1 mas for positions and parallaxes and $1\,\mathrm{mas}\cdot\mathrm{yr}^{-1}$for proper motions[4,42]. Thanks to the wide-angle observation mode, the *Hipparcos* catalogue can naturally form an inertia reference frame that is compatible with its observational precision. However the *Hipparcos* celestial reference frame (HCRF) cannot be directly linked to the radio ICRF1 since the limiting magnitude of *Hipparcos* (about 13) is not enough to observe sufficient faint radio sources in optical band. To implement the link of the reference frames, various indirect methods were applied including (1) observations of radio stars; (2) photometric observations of optical counterparts of extragalactic radio sources; (3) Earth orientation comparison and so on. Kovalevsky et al.[4] and Lindegren & Kovalevsky[43] carried out two independent synthesis of the results coming from different techniques, and the mean value of the two methods was adopted as the final solution of the link. The orientation and spin vectors components are all nominally zero, while the standard errors of the parameters were estimated as 0.6 mas for each component of $\boldsymbol{\epsilon}$ and $0.25\ \mathrm{mas}\cdot\mathrm{yr}^{-1}$for each component of $\boldsymbol{\omega}$. Conceptually, the radio ICRF and optical HCRF have exactly the same orientation in space without any differential rotation. Therefore the above two numerical values mean that the orientation difference between ICRF and HCRF is $0 \pm 0.6\,\mathrm{mas}$, while the differential rotation is $(0 \pm 0.25)\,\mathrm{mas}\cdot\mathrm{yr}^{-1}$. The uncertainty of the link is at the level of hundreds of microarcseconds so that the Galactic aberration is completely negligible for the HCRF.

5.1 *Gaia*observation of extragalactic sources and the third International Celestial Reference Frame (ICRF3)

The ESA's second generation space astrometry mission *Gaia*[44], launched in late 2013, has published the second data release (DR2) containing positions, proper motions, parallaxes, and photometric data for more than 1.7 billion objects[45]. The much fainter limiting magnitude of 21 enables *Gaia* to observe sufficient optical counterparts of extragalactic radio sources (more than 50,000 sources mainly in the range of 18−20 mag). In the *Gaia* DR2, the median error of positional error for the extragalactic sources is about 0.4 mas[46]. The observational principle of *Gaia* stays similar to that of the *Hipparcos*, which ensures that *Gaia* observations can be reduced to an inertial and rigid reference frame in optical wavelength. Essentially, the *Gaia* reference frame is realized by extragalactic sources in optical band, while the HCRF is based on Galactic stars. Another important aspect is that the *Gaia* reference frame contains hundreds of thousands sources that are three orders more than the ICRF.

Mignard et al.[47] analyzed the properties of *Gaia*-CRF2 (the second *Gaia* celestial reference frame) compared to the prototype of the ICRF3. They claimed that the orientational difference between these two reference frames is $(0 \pm 30)\,\mu$as for each axes. More interestingly, *Gaia* published proper motions for more than 50,000 quasars, but the systematic error (about 10 $\mu\text{as} \cdot \text{yr}^{-1}$) prevents us to recover the acceleration of the SSB by fitting these proper motions to Eq. (6). This may be attributed to the low accuracy at the faint magnitude and source structure which bring additional systematic effects[48−50].

During the 30th IAU General Assembly, the third International Celestial Reference Frame (ICRF3) began to take effect as the fundamental reference frame to replace its previous version ICRF1 (608 sources)[51] and ICRF2 (3414 sources)[52]. Besides the X/S (2.3/8.4 GHz) bands that were used for the ICRF1 and ICRF2, higher frequency K (24 GHz) and X/Ka (8.4/32 GHz) bands were added to the ICRF3 catalogues[5]. The ICRF3 catalogue contains 4536 radio sources, and 303 sources for S/X bands were selected as defining sources in view of their longer observation history, stable positions, and higher accuracy. The Galactic aberration effect has been taken into account for the first time in the ICRF3. In such a case, source positions will no longer be time independent but associated with different mean observation epochs. The source positions can be reduced to an standard epoch by subtracting the motions coming from the GA in the time interval. Under the hypothesis that the acceleration of the SSB is toward the Galactic center, the only parameter to be determined is the amplitude of the aberration vector g. The working group of the ICRF3 selected a series of values for g between $3-10\,\mu\text{as} \cdot \text{yr}^{-1}$in the VLBI data process. At the standard epoch of J2015.5 (the same as the mean epoch of the *Gaia* DR2), the difference between VLBI and *Gaia* positions is computed. As shown in Fig. 2, when the selected g lies in the range $5-6\,\mu\text{as} \cdot \text{yr}^{-1}$, the global positional difference has minimum values. Therefore the working group decided to adopt the amplitude of the Galactic aberration:

$$g = 5.8\,\mu\text{as} \cdot \text{yr}^{-1}\,. \tag{18}$$

In case of ultra high precision is required, one should calculate time depend positions of sources by adding the GA apparent proper motions to the positions at the mean epoch of J2015.5. This is the main difference compared to the ICRF1[51] and ICRF2[52] where the sources are considered motionless.

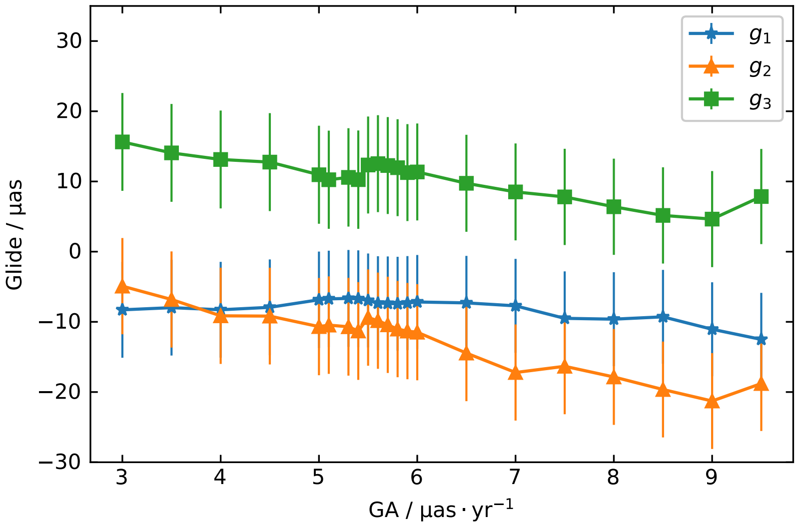

Fig. 2 The glide between the VLBI and the *Gaia*DR2 positions as a function of the Galactic aberration constant g. The parameters g_1, g_2, and g_3 stand for the dipolar deformation along the X-, Y-, and Z-axis, respectively.

5.2 Link between the radio and optical reference frame

In the past five years, *Gaia* and VLBI have brought significant progress in the constructing the optical and radio reference frames. To achieve higher accuracy, the GA effect should be considered, and consequently the concept of the reference frames is changing. The link between the *Gaia*-CRF and ICRF3 is an important subject to be studied promptly[41,53].

The working group of *Gaia* and ICRF proposed that at the time of *Gaia* completion, the radio reference frame established by VLBI should remain the fundamental reference frame. To make a consistent reference frame at multiwavelength, the optical *Gaia* frame should be connected to the ICRF3. The ICRF3, materialized by thousands of radio sources, is still regarded as the inertial reference without consideration of any proper motions. On the other hand, the wide-angel observation principle in space enables *Gaia* can produce an ideal inertial optical reference that is compatible with its observational accuracy. This can be regarded as intermediate reference frame (AGIS)[54], and there exist small orientation and rotation between the AGIS and the ICRF3.

In the AGIS, source positions are reduced to a the mean epoch of *Gaia*, but the apparent proper motions of quasars are composed of at least four parts[55]:

$$\boldsymbol{v}_{\text{gaia}} = \boldsymbol{v}_{\omega,\text{gaia}} + \boldsymbol{v}_{g,\text{gaia}} + \boldsymbol{v}_{\text{intrinsic}} + \text{noise}\,. \tag{19}$$

The first two terms on the right hand side, $\boldsymbol{v_\omega}$ and $\boldsymbol{v_a}$, represent velocities induced by the global spin and the GA effect, respectively. The third terms in Eq. (20) stands for the velocities resulting from source intrinsic motion. These specific sources should be excluded such that only compact sources are retained in the final alignment of the reference frames. The last term is stochastic, having no systematics on the orientation and rotation of the reference frame.

To align the *Gaia* to the ICRF, the first step is to evaluate the vector $\boldsymbol{\omega}$ representing the global rotation and $\boldsymbol{g}$ representing the Galactic aberration using quasars observed by *Gaia*. Based on the analysis of Liu et al.[25], the accuracy of $\boldsymbol{g}$ and $\boldsymbol{\omega}$ can reach a level of tens of microarcseconds per year. In the second step, these contributions are removed from the proper motions to make sure that the corrected proper motions has no rotation and GA effects in global sense. For the last step, thousands of common sources in the *Gaia* and VLBI catalogues are employed to eliminate the orientation difference $\boldsymbol{\epsilon}(T)$ at certain epoch T, i.e. correct all of the *Gaia* source positions using the rotation generated by the vector $\boldsymbol{\epsilon}(T)$. This procedure ensures that the radio and optical reference frames are exactly coincide with each other without mutual rotation.

Liu et al.[55] considered source proper motions in both optical and radio observations (as what was done for the AGIS frame). The authors proposed a new scheme for the link of the reference frames based on the new astrometric model of quasars. Similar to the expression in optical band, the proper motions in radio bands also involve four parts as mentioned before:

$$\boldsymbol{v}_{\rm vlbi} = \boldsymbol{v}_{\omega,{\rm vlbi}} + \boldsymbol{v}_{g,{\rm vlbi}} + \boldsymbol{v}_{\rm intrinsic} + {\rm noise}\,. \tag{20}$$

In contrast to the hypothesis that the extragalactic sources are stationary, it is more reasonable to adopt the new astrometric model to match the micro-arcsecond astrometry, for which the radio sources have non-zero transverse velocities. Moreover, the expression for a source with different bandpass should have the same form. Likewise, the observed VLBI reference frame is regard as an intermediate reference equivalent to the AGIS provided by *Gaia*. One obtains the global rotation vector $\boldsymbol{\omega}$ and Galactic aberration vector $\boldsymbol{g}$ by using proper motions of all sources in the VLBI catalogue. Once these systematics are removed from the observed proper motions, a non-rotating and rigid reference frame in radio band is produced. Finally, the revised *Gaia* and VLBI reference frame are tied at a certain epoch T to eliminate the orientation difference among three axes. Despite of the methods of linking, the orientation is estimated to be $100 \pm 25\,\mu$as at J2015.5.

6. CONCLUSION AND PROSPECT

Originated from the centripetal acceleration of the solar system barycenter around the Galactic center, the Galactic aberration (GA) produced systematic proper motions toward the Galactic center for all of the sources on the celestial sphere. The apparent proper motions have an amplitude of about $5\,\mu{\rm as}\cdot{\rm yr}^{-1}$, and only depend on the angular separation between the source and the Galactic center (see Eq. (10)).

In the era of micro-arcsecond astrometry, the role of the Galactic aberration effect is becoming significant: the distant extragalactic sources adopted as the base points of inertial reference frame are moving slowly due to various effects, among which the GA is at least one of the most important contributions. The GA is responsible for a variation with time of the orientation of the ICRS axes with a rate depending on the source distribution. Except for the rigid global rotation of the reference system, the regional distortion introduced by the GA is unsolved yet. Reflected on the Earth orientation parameters, the changes of the reference frame lead to about $1\,\mu\text{as}\cdot\text{yr}^{-1}$for precession rate. This small effect increases with time and is not negligible when solving the new precession-nutation models. For the link of the *Gaia* reference frame and the ICRF3, the GA is an effect needs special attention thus a working group was set up to evaluate its contributions to the reference frames.

From practical point of view, the small effect from the Galactic aberration is already detectable from VLBI data, however different methods and data gave out inconsistent parameters. At present, the relatively large systematic errors are found in the *Gaia* data release 2, which prevents us to detect the aberration effect unambiguously. This may attribute to the uncertainties (larger than the GA effect itself) and more importantly less knowledge about the structure of the sources in optical and radio bands[56]. In 2019, Xu et al.[57] investigated the source structure index based on the closure delay in the VLBI data reduction: this will be crucial for the future studies of the Galactic aberration and the link between reference frames.

Clearly, the Galactic aberration has similar effect on the Galactic stars. Kovalevsky[8] and Liu et al.[58] pointed out that the apparent proper motions depend on both the accelerations of the SSB and the stars in the Galaxy, as well as on the distance of the star to the Galactic center. In the area near the center of the Galactic center, the amplitude of the apparent proper motions is pronounced to about $100\,\mu\text{as}\cdot\text{yr}^{-1}$, while in the other regions, the magnitude is only $1\,\mu\text{as}\cdot\text{yr}^{-1}$. According to the *Gaia* data release, the astrometric uncertainties in the region of the Galactic center are much larger than $100\,\mu\text{as}\cdot\text{yr}^{-1}$owing to long distance to the observer and strong distinction near the Galactic center, therefore we conclude that the Galactic aberration for the stars is not necessarily be considered at this stage.

In view of the principle of the Galactic aberration, the effect can be fully eliminated if the origin of the reference system was moved from the SSB to the Galactic center such that the the origin suffers no extra acceleration. Nevertheless, this would require that developments of high-precision theories of the potential and the metric tensor are available for the whole Galaxy (as they are for the solar system in the current IAU models)[59], which may not be the case even when the *Gaia* mission is completed, owing to imperfect knowledge of the Galaxy.

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