Final Report of the IVS Working Group 8 (WG8) on Galactic Aberration

Dan MacMillan[1], Alan Fey[2], John Gipson[1], David Gordon[1], Chris Jacobs[3], Hana Krásná[4,5], Sebastien Lambert[6], Chopo Ma[7], Zinovy Malkin[8,9], Oleg Titov[10], Guangli Wang[11], Minghui Xu[12,13], Norbert Zacharias[2]

[1]NVI, Inc. at NASA Goddard Space Flight Center, United States
[2]United States Naval Observatory, Washington DC, United States
[3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California
[4]Technische Universität Wien, Vienna, Austria
[5]Astronomical Institute, Czech Academy of Sciences, Prague, Czech Republic
[6]SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, LNE, Paris, France
[7]NASA Goddard Space Flight Center, United States
[8]Pulkovo Observatory, St. Petersburg, Russia
[9]Kazan Federal University, Kazan 420000, Russia
[10]Geoscience Australia, Canberra, 2601, Australia
[11]Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai, P.R., China
[12]PGMF and School of Physics, Huazhong University of Science and Technology, Wuhan, P.R, China
[13]Institute of Geodesy and Geoinformation Science, Technische Universität at Berlin, Berlin, Germany

Executive Summary

The recommended value of the aberration constant A_G = 5.8 ± 0.3 µas/yr is based on a solution using VLBI geodetic data from 1979 until May 2018. This is the value used for the ICRF3 solution. It is close to the weighted mean of estimates of the aberration component in the direction of the galactic center from geodetic VLBI solutions performed by working group members that used data until 2016. The aberration vector estimates for most of these solutions had components not directed toward the galactic center that were at most 25% of the estimated aberration vector amplitudes. The working group also considered estimates of the aberration constant derived from estimates of the rotation speed of the solar system about the Galactic center and the distance to the Galactic center that were derived by galactic astrometry measurements of parallax and proper motion of galactic masers. The weighted mean of these estimates based on several recent galactic astronomy investigations was A_G = 4.9 ± 0.2 µas/yr. A possible recommendation would be to average the weighted means of the geodetic and galactic astronomy estimates. However, the WG recommends a geodetic value for analysis of geodetic VLBI data in order to be self-consistent with geodetic VLBI applications, specifically for the generation of the ICRF3 solution.

1. Introduction

The IVS Working Group on Galactic Aberration (WG8) was established by the IVS Directing Board at its meeting in November 2015. The purpose of the group was to investigate the issues related to incorporating the effect of galactic aberration in IVS analysis. Based on these studies, 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. 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., Fanselow 1983, Bastian 1995, Kovalevsky 2003, Kopeikin & Makarov 2006, Gwinn 1997, Sovers 1998, Mignard 2002).

The effect of aberration is to cause apparent source positions to change over time. Several studies in recent years, which we discuss in Section 3, 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 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 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.

2. Terms of Reference

In this section, we summarize the terms of reference and briefly discuss how they were addressed by the working group. The primary objective (ToR-1) of the WG was to develop a recommended aberration correction model to be applied in VLBI analysis. The results of this work are discussed in Section 3. The mandate of WG8 comprised the following objectives (from the charter of WG8):

ToR-1. 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. We will see below that applying the correction causes a change of ±40-50 µas at the epoch J2000.

In Section 3.2 and 3.3, we discuss possible choices of the model aberration constant: 1) a VLBI determined value, 2) a value determined from recent parallax and proper motion measurements of galactic masers, 3) an average of the two techniques. Then in Section 3.4, we consider the effects of applying aberration on estimates of EOP and source positions from VLBI analysis.

ToR-2. Investigate the significance of the non-galactic center components of the VLBI estimated aberration acceleration vector

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.

ToR-3. Consider the redefinition of the ICRS to account for aberration

The ICRF realizes the 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. The ICRS is defined not by the positions of defining sources only, but by its origin (barycenter) properties. ICRS is considered to be a quasi-inertial reference frame. It is known that this concept allows non-zero acceleration of the origin. However, for an inertial reference frame any acceleration of its origin is not allowed. For this reason, ICRS redefinition is not urgent. In any case, a redefinition of ICRS is not something that the IVS can do as it would have to be done by the 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 3). 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.

It is true that applying an aberration proper motion model opens the door to all causes of proper motion. Estimation of the apparent linear proper motions of all sources in a TRF/CRF solution yields a large range of linear proper motions (as large as several hundred µas/yr), many of which are much larger than proper motion due to galactic aberration. In addition, source position time series solutions indicate that apparent proper motion for many sources is nonlinear and not well described by a linear model. Source structure variation is the most likely explanation for the observed apparent proper motion. Correction of source structure effects is a complicated process involving generating time series of source maps and performing consistent registration of the maps in a series.

ToR-3 indicated that the WG would investigate how to optimally handle these other apparent proper motion estimates in the generation of an ICRF. However, it is beyond the scope of the WG investigation to determine the likely source structure corrections that would be needed. In contrast, galactic aberration proper motion is a systematic effect that can be expressed via an analytic model.

3. Results

3. 1 Aberration proper motion

A change in the source direction due to aberration in a time interval $(t - t_0)$ can be expressed as

$$\Delta \boldsymbol{s} = \boldsymbol{s} - \boldsymbol{s_0} = \frac{\boldsymbol{s_0} \times (\Delta \boldsymbol{v} \times \boldsymbol{s_0})}{c} = \frac{[\Delta v - (\boldsymbol{s_0} \cdot \Delta \boldsymbol{v})\boldsymbol{s_0}]}{c}$$

where the change in velocity $\boldsymbol{\Delta v} \equiv \boldsymbol{A}\,(t - t_0)$. $\boldsymbol{A}$ is the acceleration of the observer, t is the observing epoch and $\boldsymbol{s_0}$ is the source position direction at the reference epoch t_0.

The components of the aberration proper motion

$$\boldsymbol{\mu} = \frac{\boldsymbol{s_0} \times (\boldsymbol{A} \times \boldsymbol{s_0})}{c}$$

for a source at right ascension and declination (α, δ) are

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

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

where the A_i are the geocentric components of the acceleration vector.

If $\boldsymbol{A}$ is due only to galactic acceleration, then $\boldsymbol{A} = \boldsymbol{A}_G$ points toward the galactic center (α_G = 266.4°, δ_G = -28.9°) and has components,

$$\boldsymbol{A}_G = |A_G|[cos\delta_G cos\alpha_G, cos\delta_G sin\alpha_G, sin\delta_G\ ].$$

The contribution of aberration to geometric delay is determined from

$$\frac{\partial\tau}{\partial\boldsymbol{A}} = \frac{\partial\tau}{\partial\boldsymbol{s}} \cdot \frac{\partial\boldsymbol{s}}{\partial\boldsymbol{A}} = \frac{\partial\tau}{\partial\boldsymbol{s}} \cdot \frac{\partial\boldsymbol{\mu}}{\partial\boldsymbol{A}} \cdot (t - t_0)$$

where the derivative with respect to each component A_i is the sum of the contributions from the proper motion in declination and right ascension given in (1) above. This expression is used in Calc/Solve to compute the delay contribution for a given value of the acceleration vector. Alternatively, these partial derivatives can be used to estimate the acceleration vector in a Calc/Solve solution.

3.2.1 Geodetic VLBI aberration estimation

Over the last several years, members of our working group made several solutions for the acceleration vector $\boldsymbol{A}$ using Calc/Solve and VieVS. Table 1 shows the estimates and uncertainties of the galactic center component A_G, the magnitude $|\boldsymbol{A}|$ 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, Fey et al., 2015). 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 ***A*** as additional global parameters using the userpartial feature of Calc/Solve (Xu et al., 2012 and 2017 and MacMillan, 2014 and 2016). For the Calc/Solve 'time series' solutions (Titov et al., 2011 and Titov and Lambert, 2013), ***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 ***A*** from these proper motions. Figure 1 shows the aberration proper motions based on the estimate of ***A*** from Titov and Lambert (2013).

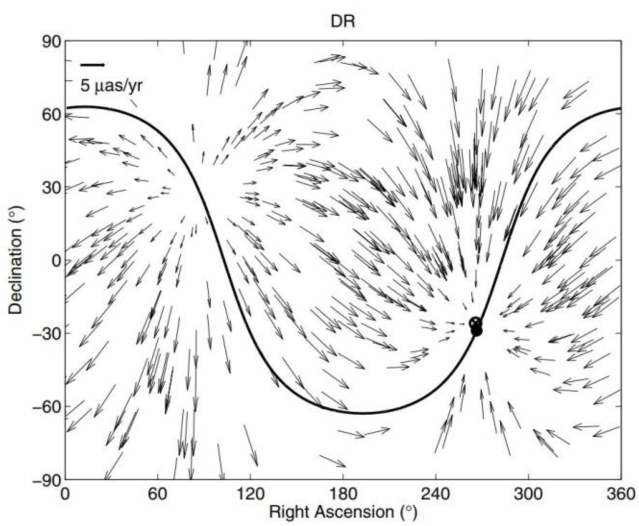

Figure 1. Aberration proper motion with aberration amplitude of 6.4 µas/yr from Titov and Lambert (2013). The Galactic center is indicated by the open circle.

Using the expression for Δs above, the aberration delay is

$$\Delta\tau = -\frac{B \cdot \Delta \boldsymbol{s}}{c} = -\frac{\boldsymbol{B} \cdot \mathbf{A}\Delta t}{c^2} - \frac{F\,\Delta t \boldsymbol{B} \cdot \boldsymbol{s}}{c}$$

$$F \equiv \frac{-(\boldsymbol{A} \cdot \boldsymbol{s})}{c}$$

where ***B*** is the a priori baseline vector, ***s*** is the unit source direction vector, and $\Delta t = (t - t_0)$. The first term contains a contribution to the proper motion of sources. The second term is the contribution to the reference frame scale since F is a scaling factor of the baseline vector. For the 'scale' solution (Titov and Krásná, 2018), a global scale factor parameter *F* was estimated for each source using only this second term and ***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 ***A*** was estimated essentially from the proper motions of all the sources. Titov and Krásná found that the effect of secular aberration drift on the scale factor of the terrestrial reference frame was significant (as large as ± 0.2 ppb over the period 1979-2016). An advantage of their method is that it allows one to estimate ***A*** from different subsets of all sources and thereby remove poorly determined sources from the estimation. For example, one can require that only sources with at least some given number of observations are used to determine ***A***. The scale solution in Table 1 required a minimum of 50 observations to include a source.

Most of the VLBI estimates of ***A*** have relatively small components (less than 25% of |***A***|) not in the Galactic center direction. An exception is the first solution of Xu et al. (2011), where the component of the acceleration ***A*** perpendicular to the Galactic plane was 46% of |***A***|. They suggested several hypothetical mechanisms that could explain this estimate, for example, a companion star orbiting the Sun. The 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 $\boldsymbol{A}_G$ of the estimated aberration acceleration vector.

Table 1. Estimates of the aberration vector from geodetic VLBI solutions

		A_G µas/yr	σ	|A| µas/yr	σ	RA deg	σ	DEC Deg	σ	
Titov et al. (2011)	1990-2010	6.3	1.4	6.4	1.5	263	11	-20	12	C/S, time series
Titov&Lambert (2013)	1979-2013	6.4	1.1	6.4	1.1	266	7	-26	7	C/S, time series
Xu (2013)	1980-2011	5.2	0.5	5.8	0.5	243	4	-11	4	C/S, global
Xu (2017)	1980-2016	6.0	0.3	6.1	0.3	271	2	-21	3	C/S, global
MacMillan (2014)	1979-2014	5.3	0.4	5.6	0.4	267	4	-11	6	C/S, global
MacMillan (2017)	1979-2016	5.7	0.3	5.8	0.3	273	3	-22	5	C/S, global
Titov&Krásná (2018)	1979-2016	6.0	0.3	6.1	0.3	260	2	-18	4	VieVS, global
Titov&Krásná(2018)	1993-2016	5.4	0.6	5.4	0.6	273	4	-27	8	VieVS, global
Titov&Krásná (2018)	1979-2016	5.1	0.3	5.2	0.3	281	3	-35	3	VieVS, global/scale
MacMillan (2018)	1979-2018	5.8	0.3	5.8	0.3	270	3	-21	5	C/S, global, ICRF3

Excluding the ICRF3 solution: weighted mean = 5.6±0.13 µas/yr, weighted rms = 0.4 µas/yr, Galactic center: RA = 266.4 deg, DEC = -28.9 deg

3.2.2 Galactic astrometry aberration estimates

Aberration can also be derived from recent (2009-2017) stellar astronomy measurements (e.g., Reid et al., 2014, Rastorguev et al. 2016, Brunthaler et al., 2011). These measurements are trigonometric parallaxes and proper motions of masers in high-mass star-forming regions in the Milky Way galaxy. These 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 Rastorguev (2017) 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, we determined the aberration constant $A_G = V^2/(Rc)$ and its uncertainty. Table 2 shows the resulting estimates of the aberration constant A_G derived from the estimates of *R* and *V*. Based on the uncertainties of *R* and *V*, the formal uncertainties of A_G are in the range 0.3-0.8 µas/yr. The uncertainties have improved over the period 2009-2016, because more maser data became available. This also had the effect of reducing correlations between galactic parameters that were being estimated. To apply a model based on this aberration constant, technically one would need to transform source motion in the Galactic coordinate system to the equatorial system (Murray, 1983), but Malkin (2014) noted that errors induced by these matrix transformations are less than 0.04 uas/yr.

Table 2. A_G estimates based on recent *V* and *R* measurements from parallax and proper motions

	A_G µas/yr	Σ	V km/s	σ	R kpc	σ	# masers
Reid (2009)	5.4	0.8	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

weighted mean = 4.9±0.17 µas/yr, weighted rms = 0.2 µas/yr

Malkin (2014) averaged available estimates of R and V from 2010-2014 and obtained an average of 5.0 ± 0.3 µas/yr. This is consistent with the mean in Table 2.

3.3 IAU recommendation

Based on recent estimates from galactic astronomy, it appears that the IAU (1985) recommended values of $R = 8.5$ kpc and $V = 220$ km/s should be revised. These IAU values yield a value of $A_G = 3.99$ µas/yr which is significantly less than the estimates from recent (2009-2016) galactic VLBI astrometry and from recent estimates based on geodetic VLBI. IAU should adopt a value for the aberration constant A_G that is based on these recent independent determinations.

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

of the aberration effect. If we are uncertain about which 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 a geodetic solution 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. We recommend the aberration constant 5.8 ± 0.3 μas/yr derived from a solution with all data (1979-May 2018) that was used to generate the ICRF3 solution, which is about two more years of data than any of the other working group solutions. This value is consistent with the mean 5.9 ± 0.2 μas/yr of solutions (Xu (2017), MacMillan (2017), and Titov and Krasna (2018)) in Table 1 that used data from 1979-2016.

3.4 Application of aberration in geodetic VLBI solutions

3.4.1 How to make a new ICRF catalog

In this section, we discuss how the aberration correction should be applied to determine a new ICRF catalog. Initially we thought that it was necessary to take an *a priori* catalog and adjust the positions to J2000.0 using the source mean epochs from the catalog and the aberration proper motions for each source. One problem with this method is that the mean epochs are not reflective of the true data distribution since sessions do not have the same number of observations. It is not known how much each session contributes to the estimated global source position. One could determine some effective mean epoch instead, but this is not required. 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. To verify this, the estimated positions from such a solution were used along with the aberration model to determine the *a priori* positions in a second solution. The resulting estimated global source positions agreed with the input a priori positions. When a new catalog is made, the aberration model should be appended as auxiliary information, but it is not necessary to add proper motions explicitly into the catalog. The aberration contributions to the *a priori* source positions are

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

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

where the aberration proper motions $(\Delta\mu_\alpha cos\delta, \Delta\mu_\delta)$ are given above in (1). 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.

3.4.2 Effects of aberration: Source positions and EOP

We have investigated what is the effect of the aberration on estimated source positions and EOP. Figures 2a and 2b 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. In this case the sources in the source NNR (no net rotation) constraint were uniformly weighted. The source position differences range over ±40-50 µas.

If a Calc/Solve solution is run weighting the contributions in the source NNR constraint using the uncertainties of source positions, the resulting declination differences shown in Figure 3a are not symmetric about RA=12 hours. The RA differences as shown in Figure 3a increase as RA approaches RA=0 hours and RA=12 hours. In this case, the asymmetry was correlated with nutation estimates. It was due to a rotation about the CRF X-axis which corresponds to nutation in obliquity. Alternatively, if nutation is not estimated, this asymmetry effect does not appear.

For comparison, VieVS solution differences where uniform NNR constraints were applied are also shown in Figures 3a and 3b. The VieVS differences were plotted in Figures 3 since they are closer to the Calc/Solve differences with weighted constraints than the differences with uniform weighting. The systematic patterns (e.g. the asymmetry noted above) of differences shown is more pronounced for the Calc/Solve solution than for the VieVS solution. At this point, it is not clear why the VieVS pattern of solution differences are not like those in Figures 2 since apparently uniform NNR constraints were used

Applying the aberration correction has a small effect on EOP. The largest effect is for nutation in obliquity. Using weighted NNR source constraints results in small biases in nutation. Table 3 summarizes the statistics of the differences.

Table 3. EOP with aberration minus EOP without aberration

Uniform NNR source constraints	Offset (2014.0)	Rate (per year)	WRMS
X-pole (µas)	0.43	-0.14	1.84
Y-pole (µas)	2.91	0.09	1.53
UT1 (µs)	0.14	0.01	0.10
Psi (µas)	-1.27	-0.08	3.36
Eps (µas)	-0.18	-0.46	2.75

Weighted NNR source constraints	Offset (2014.0)	Rate (per year)	WRMS
X-pole (µas)	-0.02	-0.15	1.86
Y-pole (µas)	2.81	0.08	1.53
UT1 (µs)	0.21	0.01	0.10
Psi (µas)	-6.49	-0.08	3.36
Eps (µas)	-15.3	-0.46	2.75

If aberration is applied in a solution, the resulting ICRF positions will be rotated. For the nominal aberration constant 5 µas/yr, the XYZ rotation angles are (52.8 µas, -1.8 µas, -1.3 µas)

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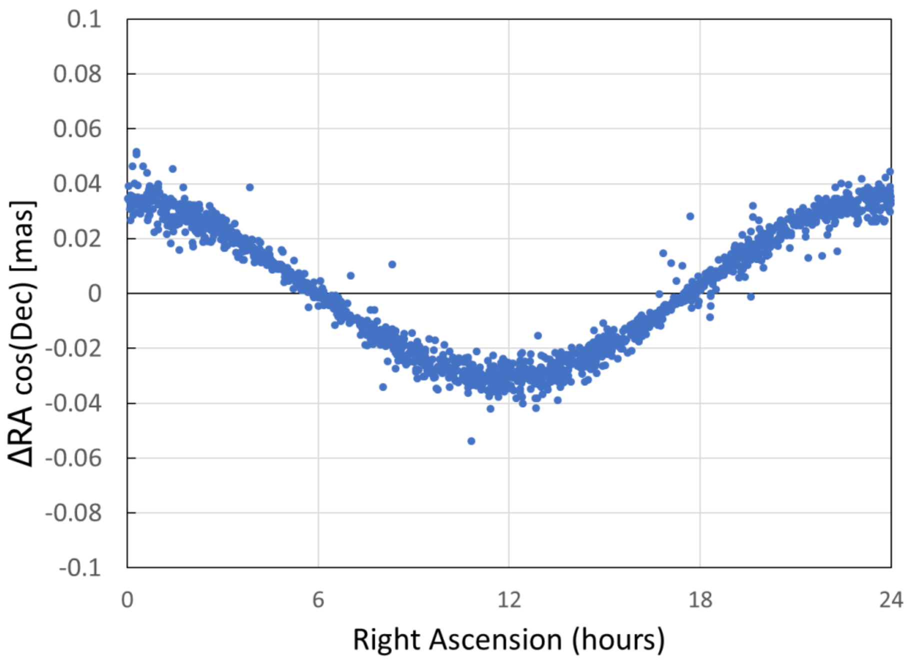


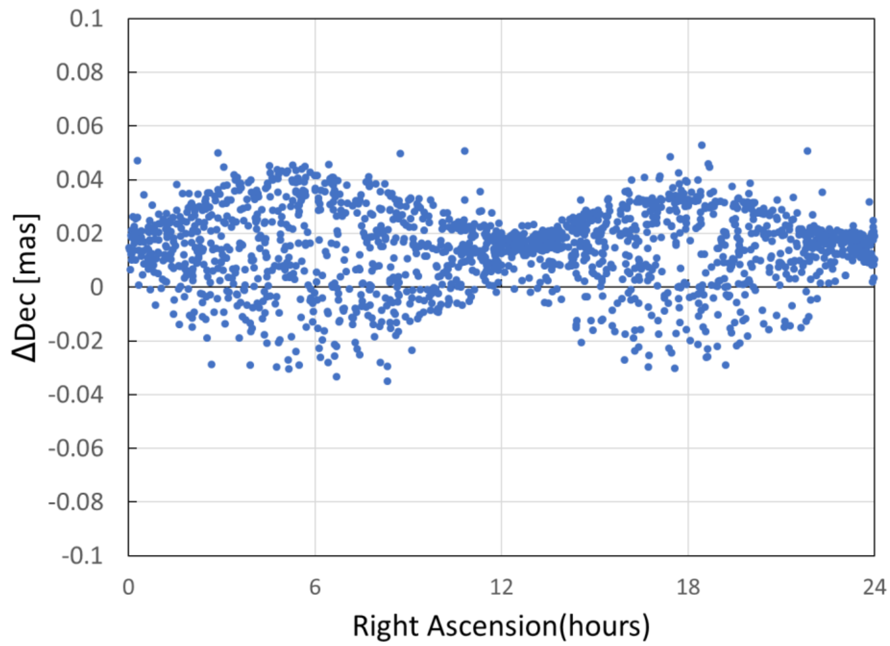
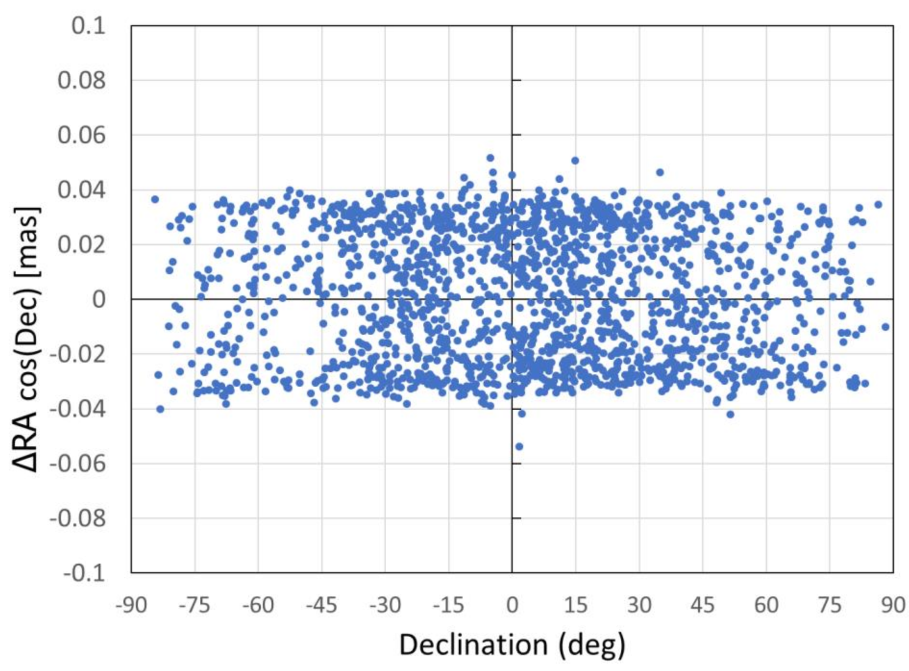


Figure 2a. Right Ascension and Declination differences versus right ascension between solution with aberration applied and not applied. A nominal aberration constant of 5 µas/yr was used. A uniformly weighted NNR condition was applied in the solutions.



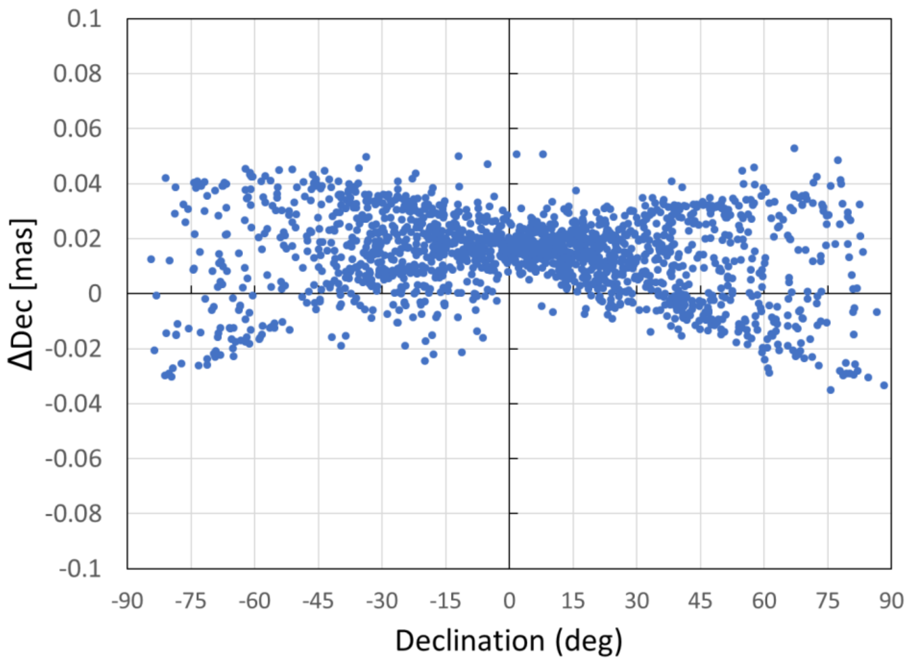


Figure 2b. Right Ascension and Declination differences versus declination between solution with aberration applied and not applied. A nominal aberration constant of 5 µas/yr was used. A uniformly weighted NNR condition was applied in the solutions.

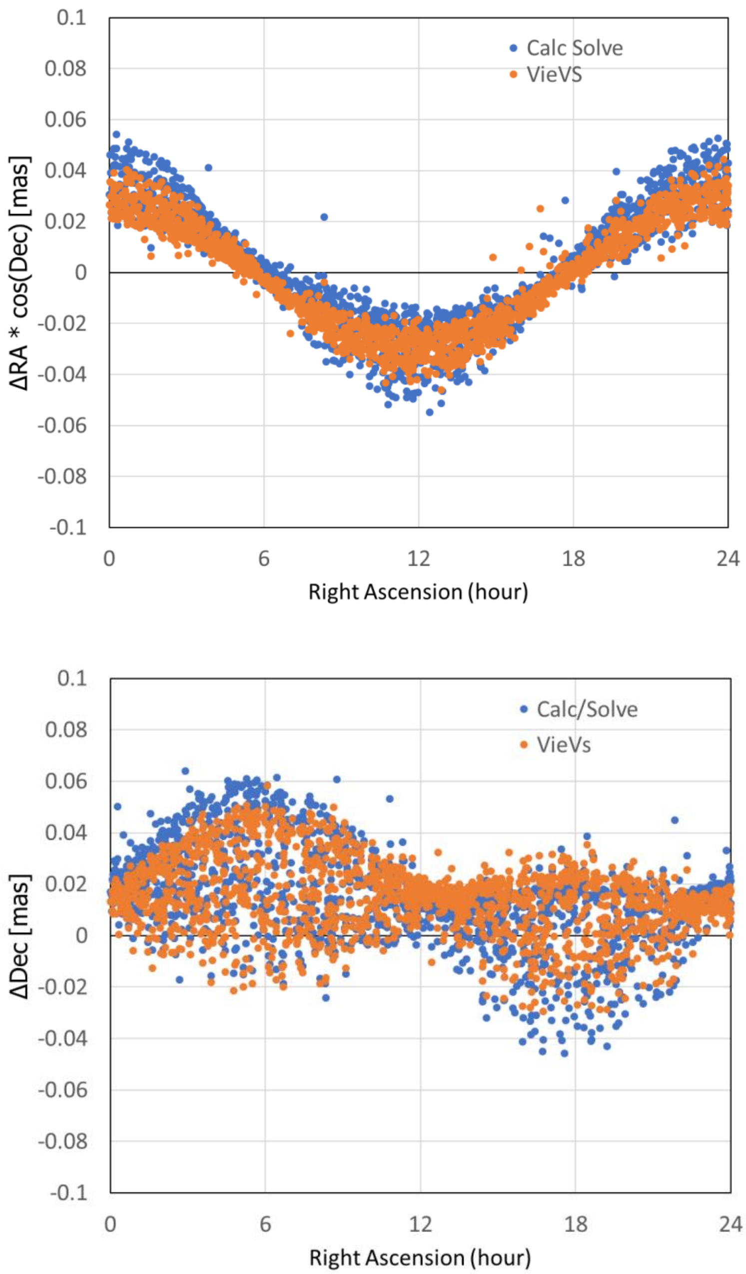
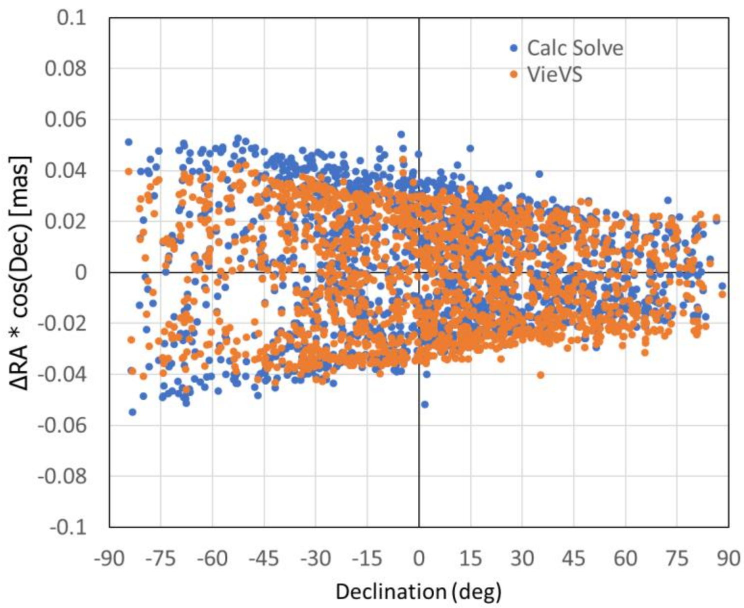


Figure 3a. Right Ascension and Declination differences versus right ascension between solutions with aberration applied and not applied. A nominal aberration constant of 5 µas/yr was used. The NNR condition weighted the included sources by their uncertainties in the Calc/Solve solution but uniformly weighted sources in the VieVS solution.



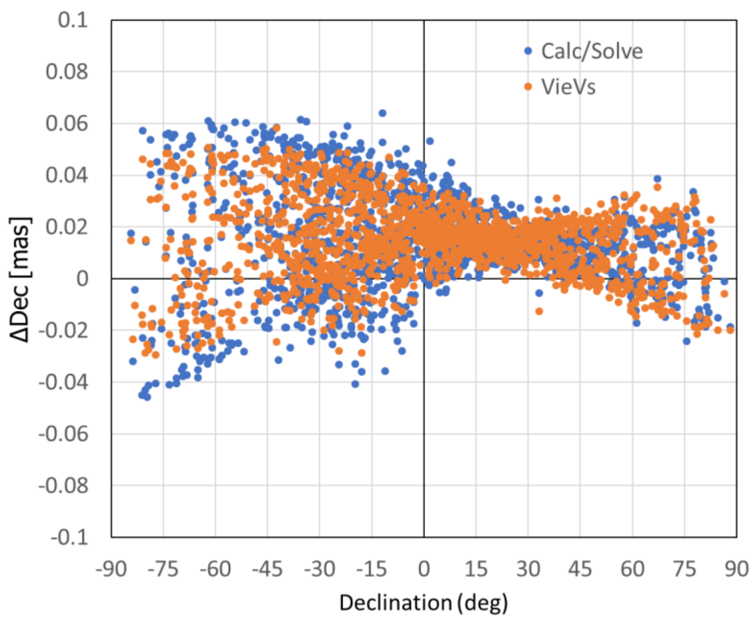


Figure 3b. Right Ascension and Declination differences versus declination between solutions with aberration applied and not applied. A nominal aberration constant of 5 μas/yr was used. The NNR condition weighted the included sources by their uncertainties in the Calc/Solve solution but uniformly weighted sources in the VieVS solution.