# Determination of Galactic Aberration from VLBI Measurements and Its Effect on VLBI Reference Frames and Earth Orientation Parameters

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## Introduction

Galactic aberration is due to the motion of the solar system barycenter around the galactic center. It results in a systematic pattern of apparent proper motion of radio sources observed by VLBI (Very Long Baseline Interfereometry). This effect is not currently included in our standard VLBI analysis. Estimates of the size of this effect indicate that it is important that secular aberration drift be accounted for in order to maintain an accurate celestial reference frame and allow astrometry at the several microarcsecond level. This presentation will discuss 1) the estimation of galactic aberration from VLBI data and 2) the effect of aberration on the Terrestrial and Celestial Reference Frames (TRF and CRF) and the Earth Orientation Parameters (EOP) that connect these frames.

## Aberration Effect in the Proper Motion Field

We start by looking at the raw picture of estimated source proper motions. Figure 1 shows the distribution of proper motions estimated for 580 radio sources, where the proper motion formal uncertainties range from 10 µas/yr to 500 µas/yr depending on how frequently a given source has been observed. The precision of proper motion estimates for Southern declination sources below 40 to 50 S is poorer than for higher declination sources because there are only a few geodetic antennas in the Southern hemisphere. There is no obvious apparent systematic effect present in Figure 1 or any dependence on declination or right ascension.

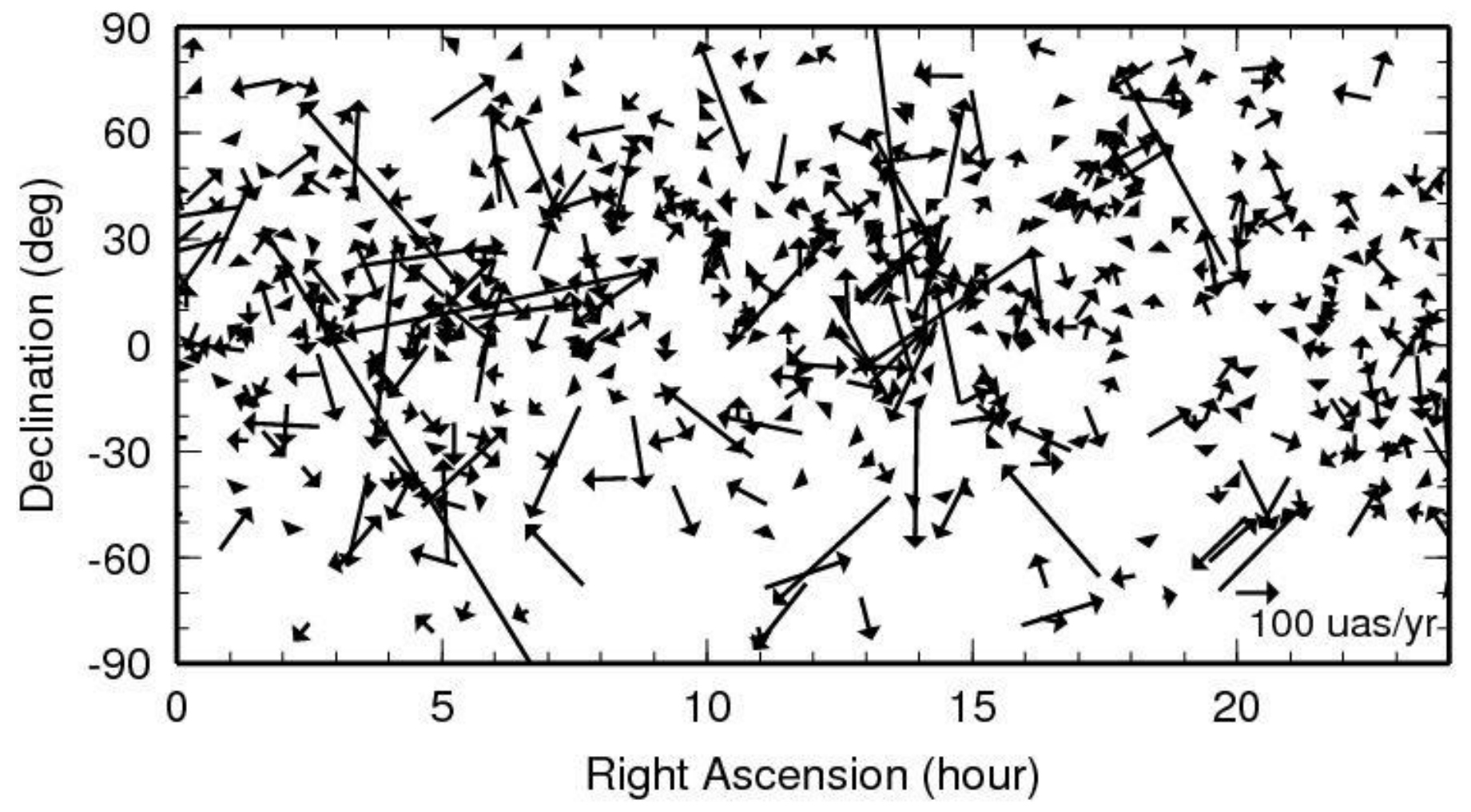


Figure 1. Estimated proper motion of sources

Source structure variations are known to be correlated with variations in the apparent position as measured by VLBI. For the bulk of the sources we observe, we do not know how much the effect of source structure variation is causing apparent linear motion. Studies have been made of specific sources like 4C39.25, but to determine the effect of source structure for the large number of sources in our VLBI solutions would require significant effort. For the purpose of the work done here, we make the assumption that the proper motion effect of source structure is random across the sky.

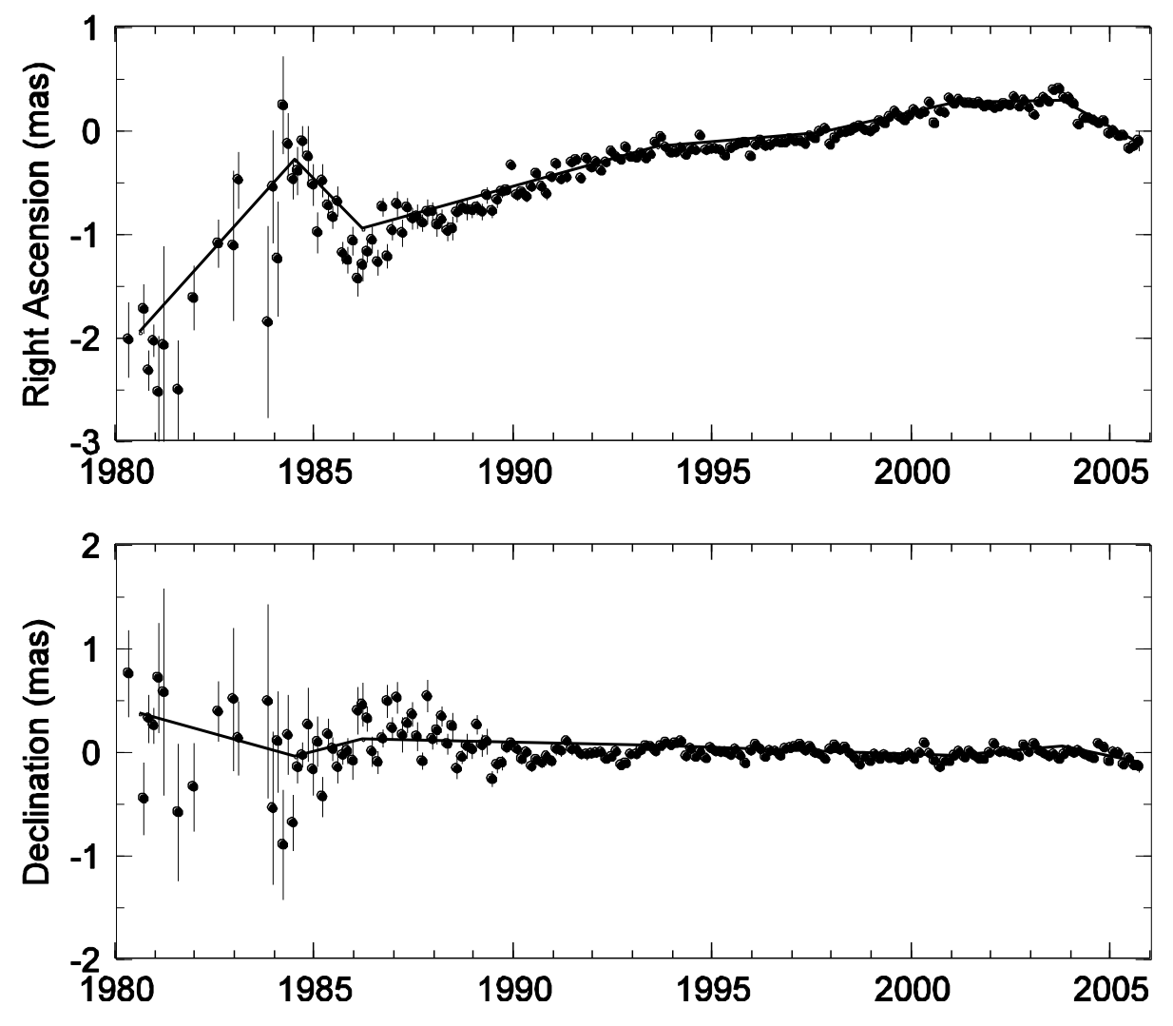
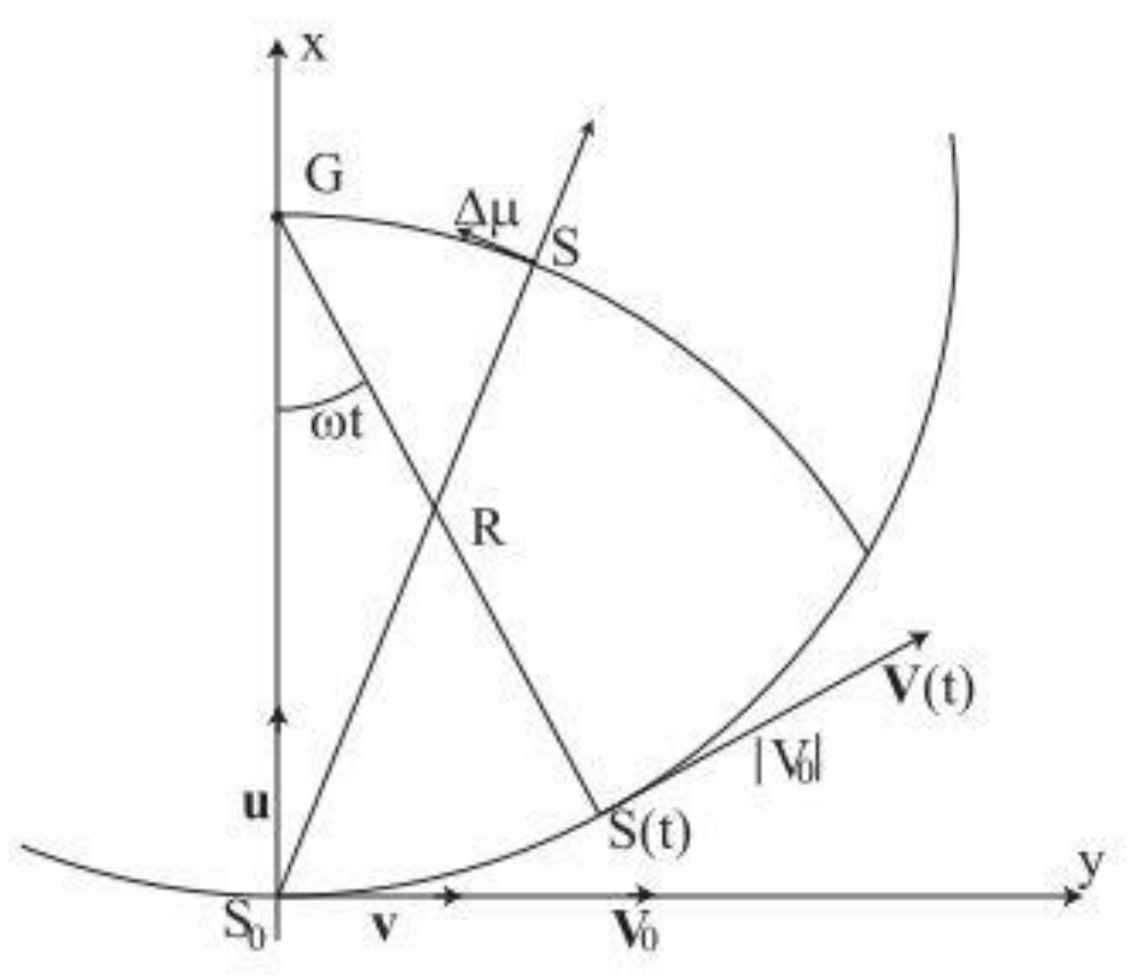


Figure 2. Estimated position of the source 4C39.25 in declination and right ascension.

Galactic aberration causes an apparent secular variation in the positions of distant objects. This is caused by the acceleration of the Solar System barycenter due to the rotation of the Milky Way. Galaxy. Various techniques have been used to determine the distance, R to the Galactic center and the circular rotation speed V. For instance, by measuring trigonometric parallaxes of massive star regions, Reid et al. (2009) and Reid et al. (2014) determined V and R. Using these measurements, one can determine the resulting pattern of dipolar apparent proper motion of distant radio sources, which has an amplitude of $d=V^2/Rc$ (see Kovalesky 2003). => $d=5.4\pm0.7$ µas/yr and $4.9\pm0.4$ µas/yr toward the Galactic center, which is located at a position with right ascension and declination of $\alpha_G = 266.4^o$ and $\delta_G = -28.4^o$. The characteristic dipolar pattern from one of our VLBI solutions is shown in Figure 4.

Table 1. Measurements of R and V

| | R (kpc) | V (km/s) | d (µas/yr) |
|---|---|---|---|
| Reid et al. (2009) | 8.4 ± 0.6 | 254 ± 16 | 5.4 ± 0.7 |
| Reid et al. (2014) | 8.34 ± 0.16 | 240 ± 8 | 4.9 ± 0.4 |



$$\Delta\mu = \frac{\omega V}{c}\hat{u} = \frac{V^2}{Rc}\hat{u}$$

Figure 3. Figure 1 from Kovalevsky (2003)

## Aberration Estimation from VLBI

VLBI TRF/CRF solutions were performed using all VLBI observations from 1979 to 2014. For these solutions, site positions and velocities, and radio source positions were estimated along with Earth Orientation parameters (polar motion, UT1 and nutation). The site position estimates were constrained via no net translation and rotation constraints to ITRF2008 and the source positions to a priori ICRF2. positions. Station clocks, wet zenith troposphere delay and troposphere gradient parameters were estimated as piecewise linear functions. Post-seismic position changes following Earthquakes at Concepcion (Chile), Tsukuba (Japan), Fairbanks (Alaska) were modeled with global spline parameters.

We have analyzed the observed VLBI data to determine whether systematic patterns in proper motion field are present. The observed field is expressed as an expansion of transverse vector spherical E (electric) and M (magnetic) harmonics. The real and imaginary parts of the coefficients are estimated. The L=1 M-harmonics are simple rotations and are therefore indistinguishable from Earth rotation. The L=1 E-harmonics correspond to galactocentric acceleration or possibly to quasar/galaxy acceleration.

$$\Delta\vec{\mu} = (\Delta\mu_\alpha \cos\delta, \Delta\mu_\delta) = \sum_{l,m}\left(a^E_{l,m}Y^E_{l,m} + a^M_{l,m}Y^M_{l,m}\right)$$

where δ is source declination and α is right ascension.

Simplifying this for L=1 E=1, one gets the components of proper motion in RA and DEC:

$$\Delta\mu_\alpha \cos\delta = -d_1 \sin\alpha + d_2 \cos\alpha$$
$$\Delta\mu_\delta = -d_1 \cos\alpha \sin\delta - d_2 \sin\alpha \sin\delta + d_3 \cos\delta$$

In our VLBI solutions, components of the acceleration vector, **d,** are estimated as additional global parameters in a TRF/CRF solution. Table 2 presents the estimated values of **d** for several different solutions. Solution dm6j estimated only the 1st order and Solution dm6j1 estimated both the 1st and 2nd order terms. The amplitude of the acceleration vector is nearly unchanged but its direction changes by about 10º.

Additionally, the results from analyses by other researchers are shown. Solution TL (2013) DR estimated only 1st order terms and DRQ estimated both 1st and 2nd order terms [Titov and Lambert, 2013]. They performed their analysis using proper motions derived from position time series estimates. Xu et al. (2012) estimated 1st order terms as global parameters.

The acceleration vector is also given in Table 2 in Galactic coordinates (X,Y, Z) => (direction of the Galactic center, direction of Galactic rotation, direction of the North Galactic pole). Comparison of the VLBI estimates of proper motion due to the Galactocentric X-component with the estimates in Table 1 derived by parallax measurements shows reasonably good agreement. At this point in our investigation, it is unclear whether our estimates of the Y and Z components are artifacts of our solution procedure or whether they are evidence of aberration not due to Galactic rotation. Xu et al. (2012) have hypothesized that a companion star orbiting the Sun could explain their estimate of the Z-component. On the other hand Titov and Lambert (2013) see essentially no variation in Y and Z.

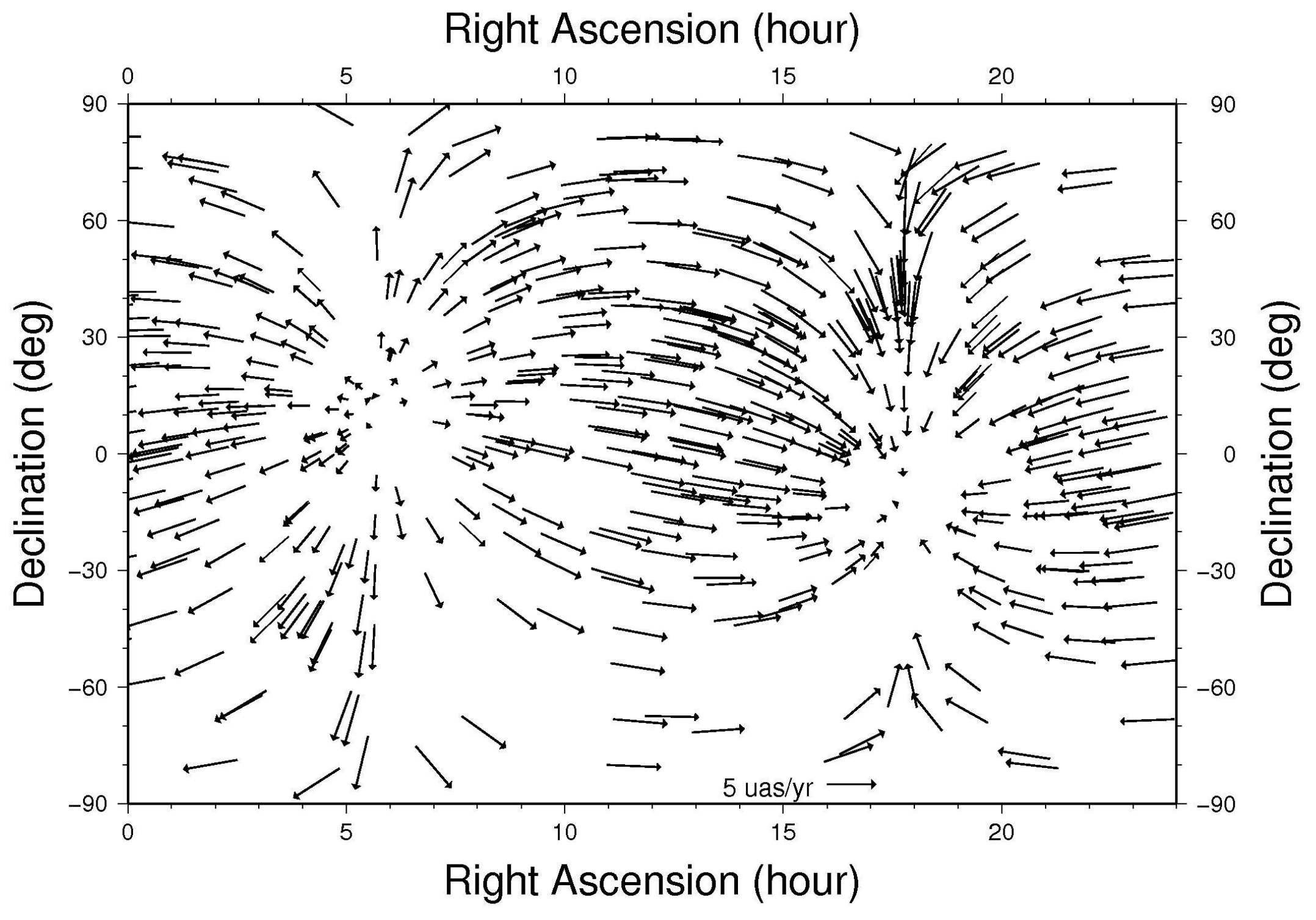


Figure 4. The dipole variation characteristic of aberration, where the proper motion vectors are directed toward the galactic pole (and away from the anti-pole). This plot is based on the acceleration vector from solution 2014a_dm6 j in Table 2. Here the vectors are directed toward a pole at δ = -11º and α = 267º close to the Galactic pole.

Table 2. Estimate Acceleration Vector **d** (µas/yr)

| | dm6j | dm6j1 | TL (2013) DR | TL(2013) DRQ | Xu (2012) |
|---|---|---|---|---|---|
| $d_1$ | -0.3 ± 0.3 | 0.8 ± 0.4 | -0.4 ± 0.7 | 0.7 ± 0.8 | -2.6 ± 0.3 |
| $d_2$ | -5.4 ± 0.3 | -5.6 ± 0.4 | -5.7 ± 0.8 | -6.2 ± 0.9 | -5.1 ± 0.3 |
| $d_3$ | -1.1 ± 0.5 | -0.7 ± 0.9 | -2.8 ± 0.9 | -3.3 ± 1.0 | -1.1±0.4 |
| Amplitude | 5.6 ± 0.4 | 5.7 ± 0.4 | 6.4 ± 1.1 | 7.1 ± 1.3 | 5.8 ± 0.4 |
| Direction in DEC | -11 ± 3 | -7 ± 3 | -26 ± 7 | -28 ± 7 | -11 ± 4 |
| Direction in RA | 267 ± 3 | 278 ± 3 | 266 ± 7 | 277 ± 7 | 243 ± 4 |
| GX | 5.3 ± 0.3 | 5.1 ± 0.4 | 6.4 ± 0.8 | 7.0 ± 0.8 | 5.2 ± 0.3 |
| GY | 1.4 ± 0.4 | 2.3 ± 0.5 | 0.2 ± 0.8 | 0.6 ± 0.9 | 0.1 ± 0.4 |
| GZ | 0.9 ± 0.3 | 1.0 ± 0.4 | 0.2 ± 0.9 | -0.9 ± 0.8 | 2.7 ± 0.3 |

In Table 3, we compare estimates of 2nd order terms from our solution , dm6j1 with those from Titov and Lambert (2013). The agreement is remarkably good for most terms despite the fact that the estimation techniques were significantly different. The process of estimating the proper motion field from source position time series and then performing the vector spherical expansion on the proper motion field apparently resulted in much larger parameter uncertainties than our method of estimating global amplitudes directly in a TRF/CRF solution.

Table 3. Estimates of 2nd Order Terms (µas/yr)

| 2nd Order | dm6j1 | TL (2013) DRQ |
|---|---|---|
| $a^{E}_{2,0}$ | 0.7 ± 0.2 | 1.3 ± 1.0 |
| $a^{M}_{2,0}$ | 0.2 ± 0.5 | 0.3 ± 0.8 |
| $a^{E,\mathrm{Re}}_{2,1}$ | 1.4 ± 0.3 | 1.7 ± 1.0 |
| $a^{E,\mathrm{Im}}_{2,1}$ | -0.5 ± 0.3 | 0.9 ± 1.1 |
| $a^{M,\mathrm{Re}}_{2,1}$ | -1.8 ± 0.3 | -1.8 ± 1.0 |
| $a^{M,\mathrm{Im}}_{2,1}$ | 1.5 ± 0.3 | 2.3 ± 0.9 |
| $a^{E,\mathrm{Re}}_{2,2}$ | 0.4 ± 0.1 | 0.5 ± 0.5 |
| $a^{E,\mathrm{Im}}_{2,2}$ | -1.1 ± 0.3 | -1.0 ± 0.4 |
| $a^{M,\mathrm{Re}}_{2,2}$ | 0.5 ± 0.1 | 2.3 ± 0.6 |
| $a^{M,\mathrm{Im}}_{2,2}$ | 0.8 ± 0.1 | -1.3 ± 0.6 |

## Effects on EOP and TRF

Table 4 shows the effect of the estimation of aberration in a TRF/CRF solution on nutation (X and Y) and UT1. The effect on the TRF scale is $-0.040 \pm 0.003$ ppb and $-0.0048 \pm 0.0003$ ppb/yr. The effect on frame translation and rotation was less than 0.2 mm and less than 0.01 mm/yr.

Table 4. Effect of Aberration on EOP

| | |
|---|---|
| dΔX/dt | 0.04 µas/yr |
| dΔY/dt | 0.6 µas/yr |
| dUT1/dt | 0.01 uas/yr |

## Conclusions and Future Work

Our estimate of the component of the aberration vector in the direction of the galactic center is close to estimates made from parallax measurements. In future work, we plan to investigate 1) the aberration vector components not in the direction of the galactic center, 2) the dependence on the data period used in analysis, 3) dependence on radio sources included in the analysis, and 4) the effect of the strategy of troposphere gradient estimation.

## References

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