Galactic Aberration in VLBI Analysis: Findings of the IVS WG8

Dan MacMillan
NVI Inc. at NASA/GSFC
and the IVS Working Group 8 Members

IVS General Meeting
Longyearbyen, Norway – June 5, 2018

WG Members

Dan MacMillan[1], Alan Fey[2], John Gipson[1], David Gordon[1],

Chris Jacobs[3], Hana Krásná[4], Sebastien Lambert[5],

Chopo Ma[6], Zinovy Malkin[7], Oleg Titov[8],

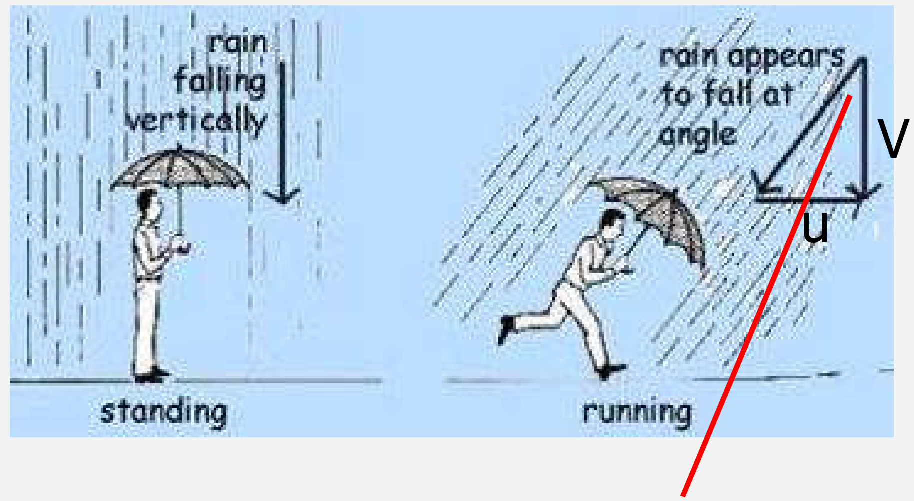
Guangli Wang[9], Minghui Xu[9], Norbert Zacharias[2]

[1]NVI, Inc. at NASA Goddard Space Flight Center, United States
[2]United States Naval Observatory, Washington DC, United States
[3]Jet Propulsion Laboratory, Pasadena, California
[4]Technische Universität Wien, Vienna, Austria
[5]Paris Observatory, SYRTE, Paris, France
[6]NASA Goddard Space Flight Center, United States
[7]Pulkovo Observatory, St. Petersburg, Russia
[8]Geoscience Australia, Canberra, 2601, Australia
[9]Shanghai Astronomical Observatory, Shanghai, PR China

Overview

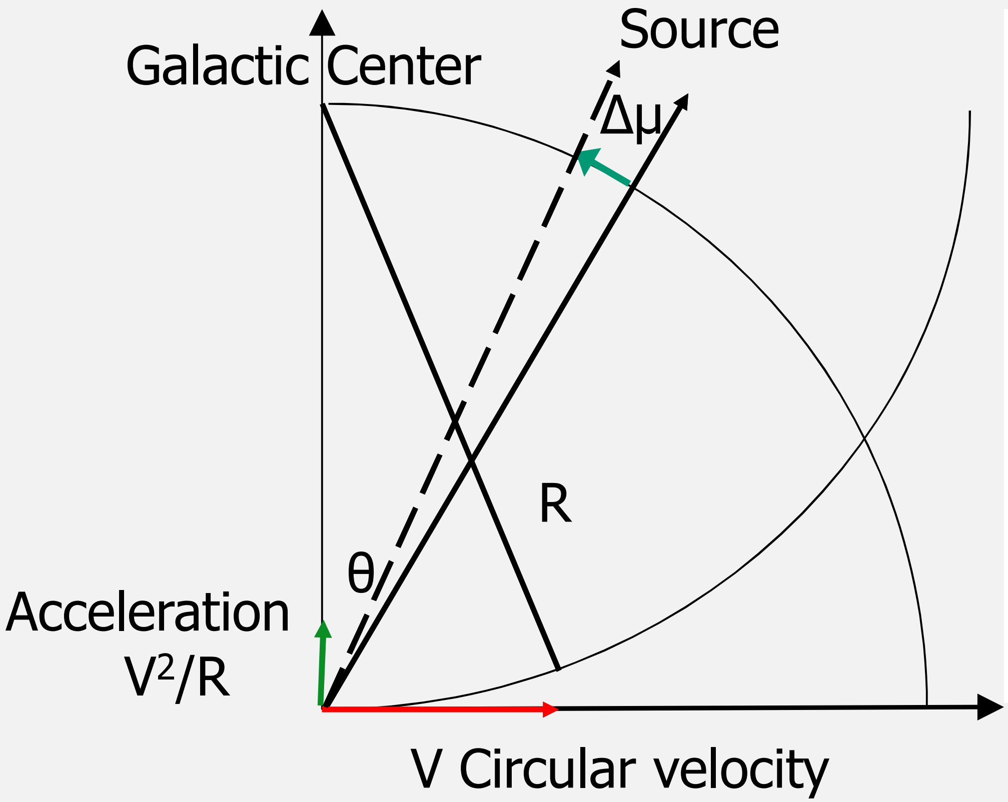
NVI, INC.

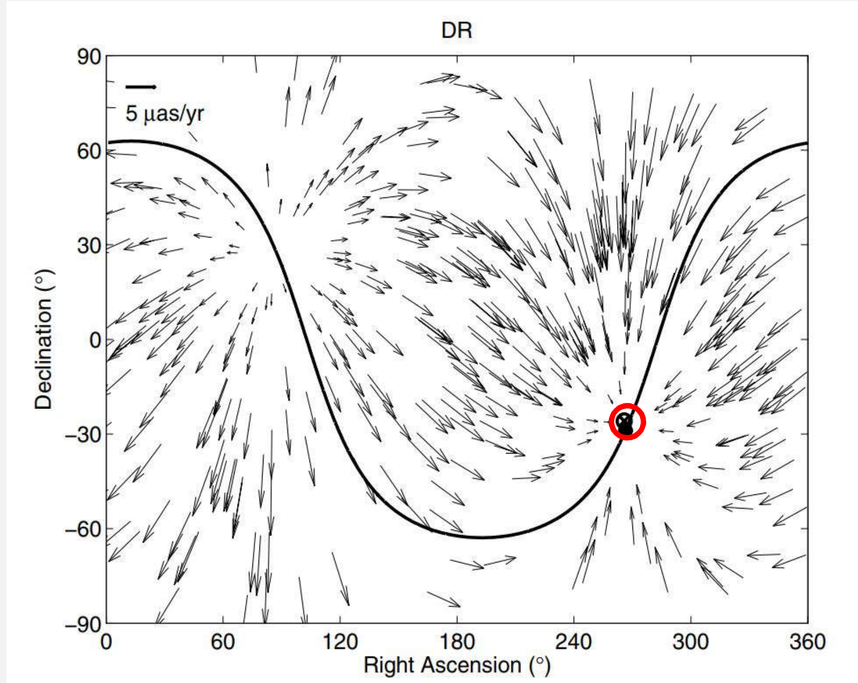
- What is secular Galactic aberration?
- Working group charter
- How is GA estimated?
  - Geodetic VLBI
  - Galactic astronomy
- Estimates from WG
- Recommendation
- Effects of GA (EOP, source position)



small angle
$\Delta\theta \sim u/V$

What is Secular Galactic Aberration?





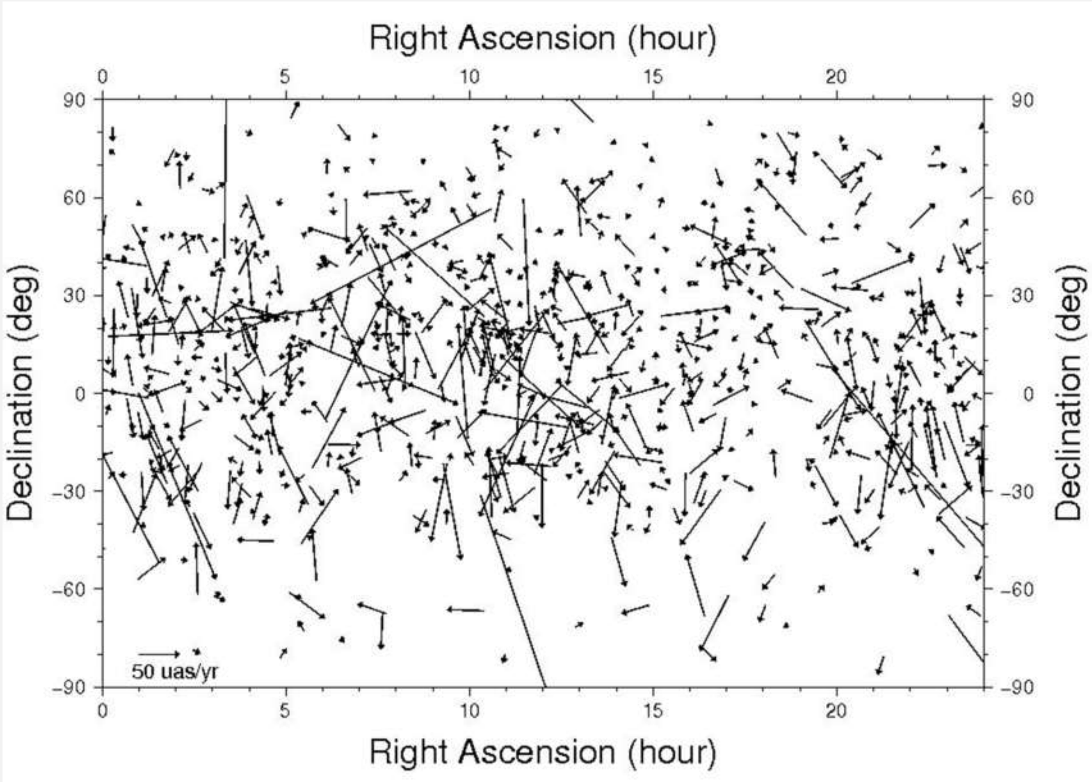
Galactic center (RA=266°,Dec=-29°)

Aberration proper motion (Titov and Lambert, 2013)

Aberration constant = V^2/Rc (maximum proper motion)

In the source direction projected on plane of the sky:
Aberration proper motion $\Delta\mu = (V^2/Rc) \sin\theta$

Observed Proper Motions



Proper motion field computed from site position time series (RA and DEC uncertainties < 50 µas/yr)

- Observed proper motions: - as large as a few hundred µas/yr
  - mainly caused by source structure.
- Systematic galactic aberration proper motions < 6 µas/yr

WG Charter

1. Determine an a priori secular aberration drift model for analysis

- Aberration systematic significant relative to the CRF noise floor (40 µas for ICRF2)
- Systematic drift of ~5 µas/yr => 100 µas after 20 years
- Aberration estimates from both geodetic VLBI and astrometric VLBI galactic measurements are available

WG Charter

2. Investigate significance of the non-galactic center components of the geodetically estimated aberration acceleration vector A

- Non-galactic center components < 25% of amplitude of A
- Investigated dependence on: 1) sessions used, 2) sources included, 3) parametrization of solutions
- Further investigation of possible physical means of producing non-galactic center acceleration is needed

WG Charter

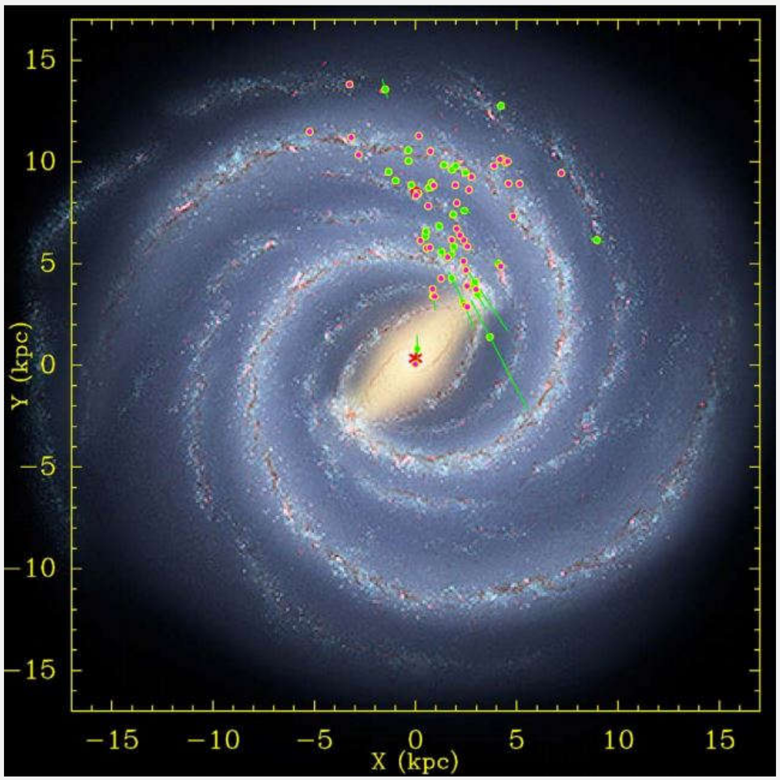
3. Consider redefinition of the ICRS to account for aberration

- Not possible for IVS – this would have to be done of IAU
- Not necessary – simply apply aberration correction as other models are applied in analysis (e.g., annual aberration, precession)

Aberration from Galactic Astronomy

Galactic Astronomy using VLBI observations of Galactic masers

VLBI measurements:
- VLBA, EVN, VERA networks => 136 masers (2016), 18 masers (2009)
- Masers in high-mass star-forming regions
- Trigonometric parallaxes and proper motions are measured



Aberration from Galactic Astonomy

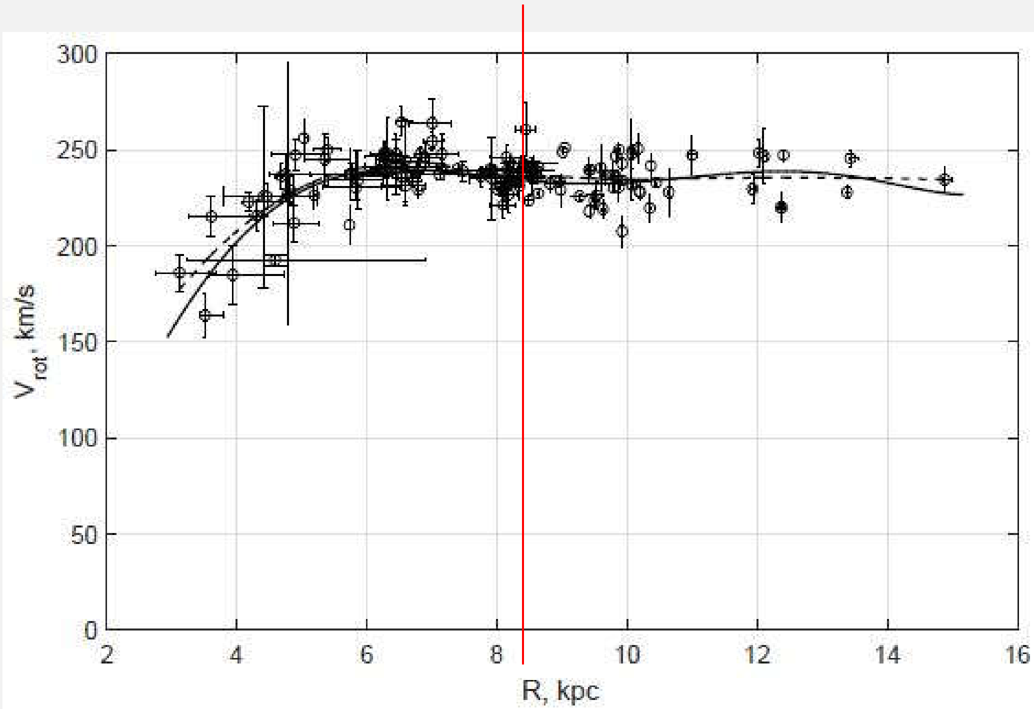


Figure 1. Rotation curve of the Galactic disk. Measure maser values of V and R are also plotted. (Rastorguev et al., 2016)

Modeling of the Galaxy:
Parameters include
R = radial distance (kpc) to the Galactic center
V = circular rotation speed (km/s)

At Solar system barycenter
R=8.30 kpc
V=246 km/s

Aberration constant
$A = V^2/Rc$

=> A = 4.8 μas/yr

Estimates Based on Astrometry

	A_G	σ	V	σ	R	σ	# masers
	µas/yr		km/s		kpc		
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 (2016)	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

Aberration from Geodetic VLBI

Source proper motion

$$\boldsymbol{s} = \frac{\boldsymbol{s}_0 \times (\boldsymbol{A}\;\; t \times \boldsymbol{s}_0)}{c} = \frac{[\boldsymbol{A}\;\; t \qquad (\boldsymbol{s}_0 \cdot \boldsymbol{A}\;\; t)\boldsymbol{s}_0]}{c}$$

Δt ≡ t-tref

$$\tau = \frac{\boldsymbol{B} \cdot \;\; \boldsymbol{s}}{c}$$

Delay Contribution

$$\tau = \quad \frac{\boldsymbol{B} \cdot \mathbf{A}\;\; t}{c^2} \qquad \frac{F \;\;\; t\boldsymbol{B} \cdot \boldsymbol{s}}{c} \qquad F(\mathrm{RA}, \mathrm{Dec}) \equiv \frac{(\boldsymbol{A} \cdot \boldsymbol{s})}{c}$$

Scale term

1) Global estimation of aberration vector (effect on source positions) [MacMillan, Xu et al.]

2) Estimation of proper motions from source position time series + Estimation of A from proper motions [Titov and Lambert]

3) Global estimation of scale factors F for each source + Estimation of A from scale factors F [Titov and Krasna]

Estimates from Geodetic VLBI

NVI, INC.

		A_G	σ	|A|	σ	RA	σ	DEC	σ	
		μas/yr		μas/yr		deg		deg		
Titov&Lambert (2011)	1990-2010	6.3	1.4	6.3	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 (2017)	1979-2016	6.0	0.3	6.1	0.3	260	2	-18	4	VieVS, global
Titov&Krásná(2017)	1993-2016	5.4	0.6	5.4	0.6	273	4	-27	8	VieVS, global
Titov&Krásná (2017)	1979-2016	5.1	0.3	5.2	0.3	281	3	-35	3	VieVS, global/scale

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

Recommendation

Possible Options:

1) Geodetic VLBI weighted mean
2) Galactic astronomy weighted mean
3) Average of 1 and 2

Self-consistency => Geodetic VLBI value of should be used

Recommended value A_G = 5.6 μas/yr
for geodetic analysis and specifically for the ICRF3 solution

Aside:
1) The IAU (1985) recommended values of R = 8.5 kpc and V= 220 km/s need to be revised. Inconsistent with recent galactic astronomy
2) => a value of A_G = 4.0 μas/yr inconsistent with geodetic VLBI.

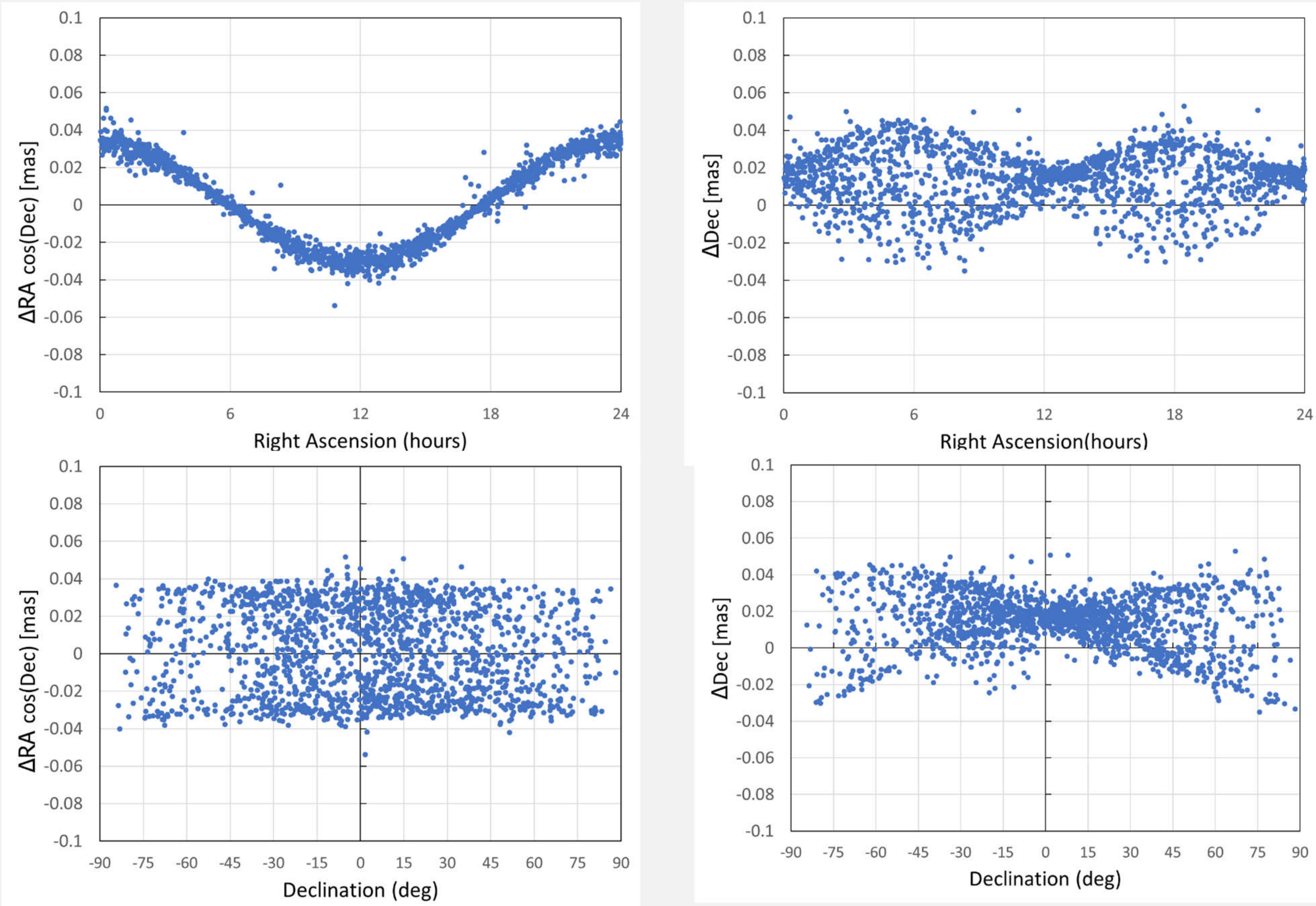
Aberration Effect on EOP

Effect of Applying aberration (5 µas/yr) on EOP

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

Aberration Effect on Source Positions



Summary and Conclusions

1. Recommended an aberration constant should be consistent with geodetic VLBI solutions (specifically for the ICRF3 solution)

   => weighted mean of 5.6 ± 0.2 µas/yr of geodetic VLBI estimates

2. ICRF3 working group will use a value close to this value

3. Analysis software should be modified to apply a Galactic aberration correction

4. Recommended value is fairly close to the Galactic astronomy weighted mean (recent values) = 4.9 ± 0.2 µas/yr

5. Non-galactic center part of the aberration vector estimates have relatively small components < 25% of |A|

   => Requires further work to determine possible causes

6. Working group final report is done