Seminar of the Astronomical Institute CAS, May 09, 2018, Prague, Czech Republic

Galactic aberration estimated from VLBI geodetic data & other current topics

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Outline

VLBI telescope in Onsala, Sweden. May 2017

- Introduction to geodetic VLBI and VieVS
- Galactic Aberration
  - estimation of the GA vector from geodetic VLBI
  - impact of the omitted GA on the TRF & CRF
- Other topics in progress (related to the Hertha Firnberg project “Galactic VLBI” funded by the Austrian science fund FWF)
  - Source structure investigation
  - K-band data analysis
    - Imaging of radio sources
    - Estimation of Earth orientation parameters
  - Kalman filtering as a novel approach to determine CRF
  - Geodetic VLBI, Earth rotation and the Sagnac effect

Very Long Baseline Interferometry

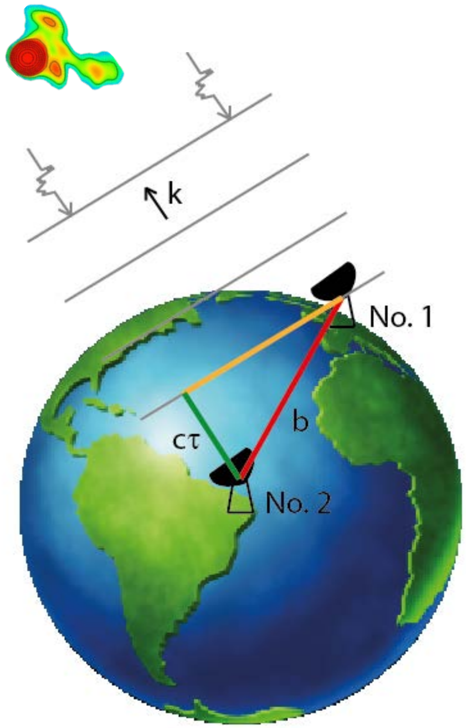
- Principle of VLBI:

  Extragalactic microwave signals from quasars are received at at least two Earth-fixed antennas simultaneously.

$$\tau = -\frac{1}{c}\vec{\boldsymbol{b}}\cdot \boldsymbol{WSQ}\cdot\vec{\boldsymbol{k}}$$

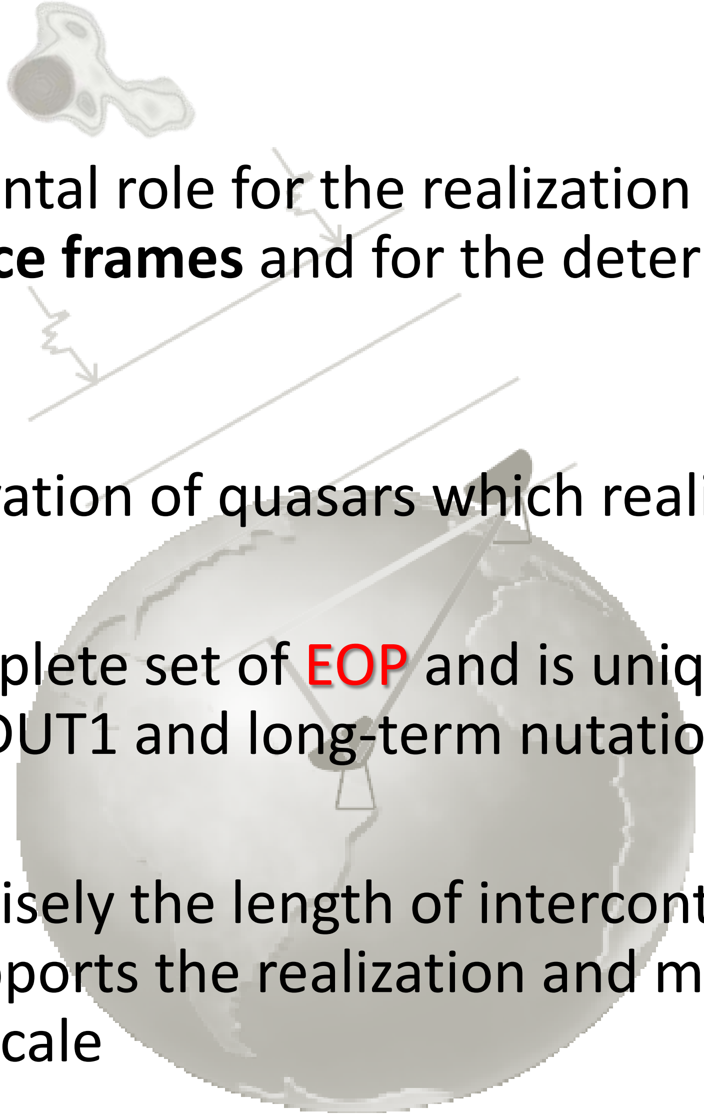
- Primary observable of the VLBI technique

  Time delay τ – the difference between the reception times of the signal at stations No.1 and No.2



	b	baseline vector between two stations
	k	unit vector to radio source
Earth Orientation Parameters	W	rotation matrix for polar motion
	S	diurnal spin matrix
	Q	precession-nutation matrix

Strengths of geodetic VLBI



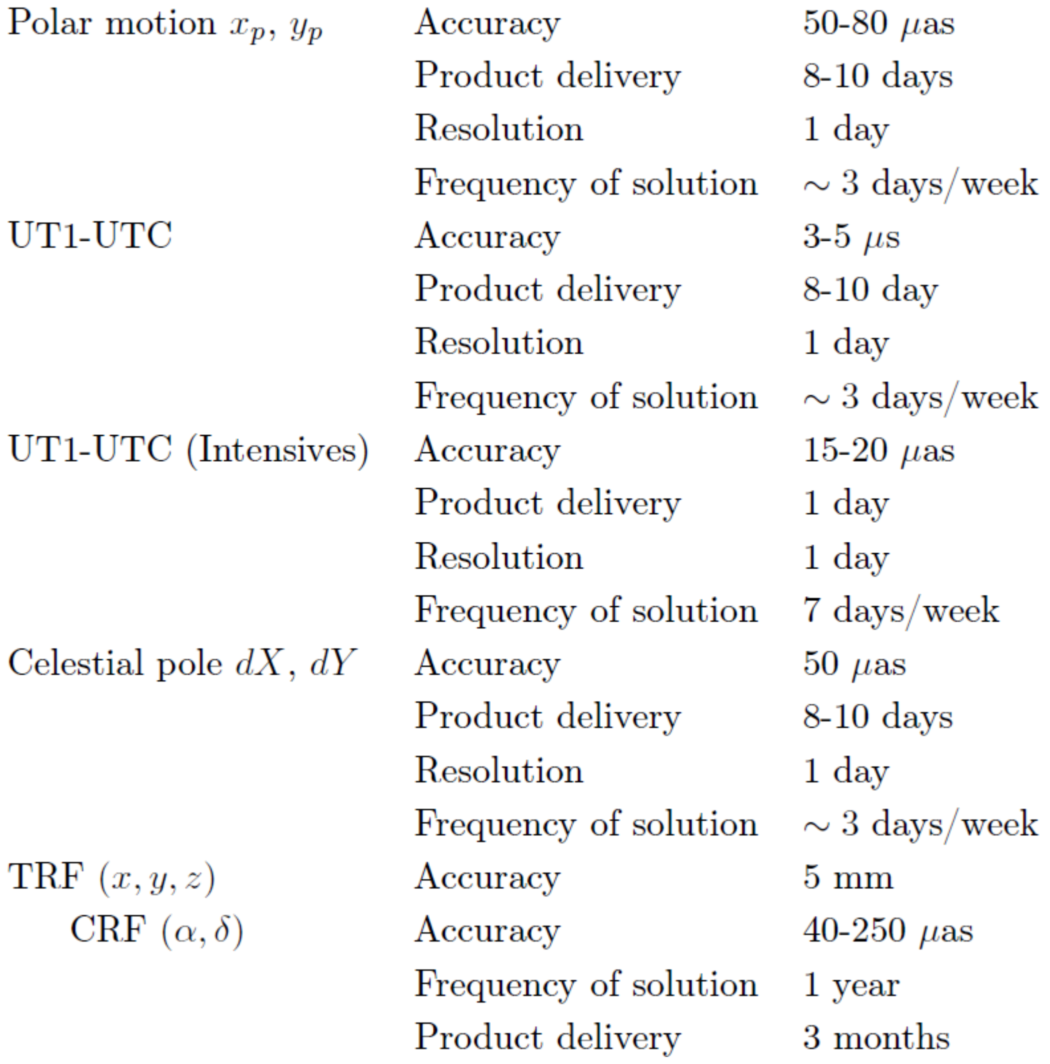
VLBI plays a fundamental role for the realization and maintenance of the **global reference frames** and for the determination of the **EOP**:

- VLBI allows observation of quasars which realize the CRF
- VLBI provides complete set of EOP and is unique for the determination of DUT1 and long-term nutation
- VLBI provides precisely the length of intercontinental baselines, which strongly supports the realization and maintenance of the TRF with a stable scale

Results from geodetic VLBI and the IVS

(International VLBI Service for Geodesy & Astrometry)

Status 2010 of IVS main products with their current accuracies
(Schlüter and Behrend 2007)



Polar motion x_p, y_p	Accuracy	50-80 μas
	Product delivery	8-10 days
	Resolution	1 day
	Frequency of solution	$\sim$ 3 days/week
UT1-UTC	Accuracy	3-5 μs
	Product delivery	8-10 day
	Resolution	1 day
	Frequency of solution	$\sim$ 3 days/week
UT1-UTC (Intensives)	Accuracy	15-20 μas
	Product delivery	1 day
	Resolution	1 day
	Frequency of solution	7 days/week
Celestial pole dX, dY	Accuracy	50 μas
	Product delivery	8-10 days
	Resolution	1 day
	Frequency of solution	$\sim$ 3 days/week
TRF (x, y, z)	Accuracy	5 mm
CRF (α, δ)	Accuracy	40-250 μas
	Frequency of solution	1 year
	Product delivery	3 months

What is VieVS?

- VieVS = **Vie**nna **V**LBI and **S**atellite software
- A state of the art, geodetic VLBI data analysis software package
- Written in Matlab
- Since 2008 it is developed at the Department of Geodesy and Geoinformation (Research Group Advanced Geodesy), Technische Universität Wien
- Close cooperation with former colleagues (University of Tasmania, Hacettepe University in Turkey, Shanghai Astronomical Observatory)

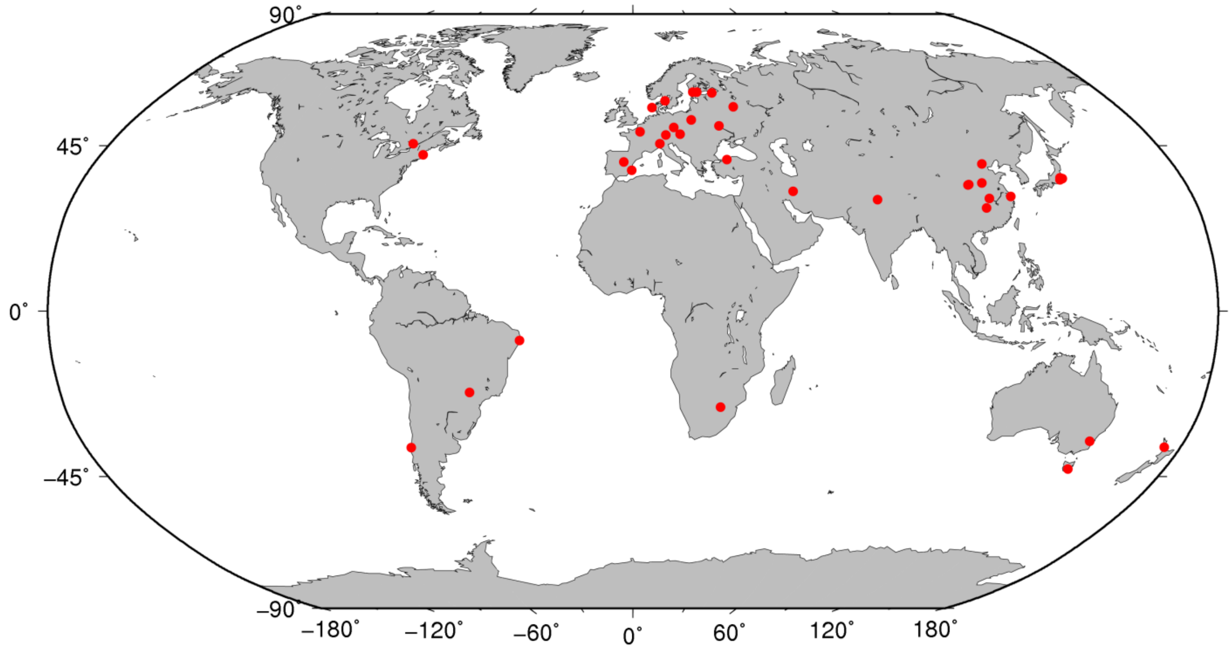
- Important that there exist several different types of VLBI analysis software
- Different software packages can validate each other. Helps identifying bugs etc.
- Analysts have a choice of what to use

- Current reference:

Böhm J., S. Böhm, J. Boisits, A. Girdiuk, J. Gruber, A. Hellerschmied, H. Krásná, D. Landskron, M. Madzak, D. Mayer, J. McCallum, L. McCallum, M. Schartner, K. Teke (2018). *Vienna VLBI and Satellite Software (VieVS) for Geodesy and Astrometry*. Publications of the Astronomical Society of the Pacific 130/986. pp.1-6.

VieVS development

- Development started in 2008
- First version released in the end of 2009 (In the first version many parts were based on OCCAM. Now almost every subroutine is written from scratch)
- Current Version 3.0 was released in June 2017
- Freely available to registered users: http://vievswiki.geo.tuwien.ac.at
- Currently registered users from about ~50 institutions worldwide

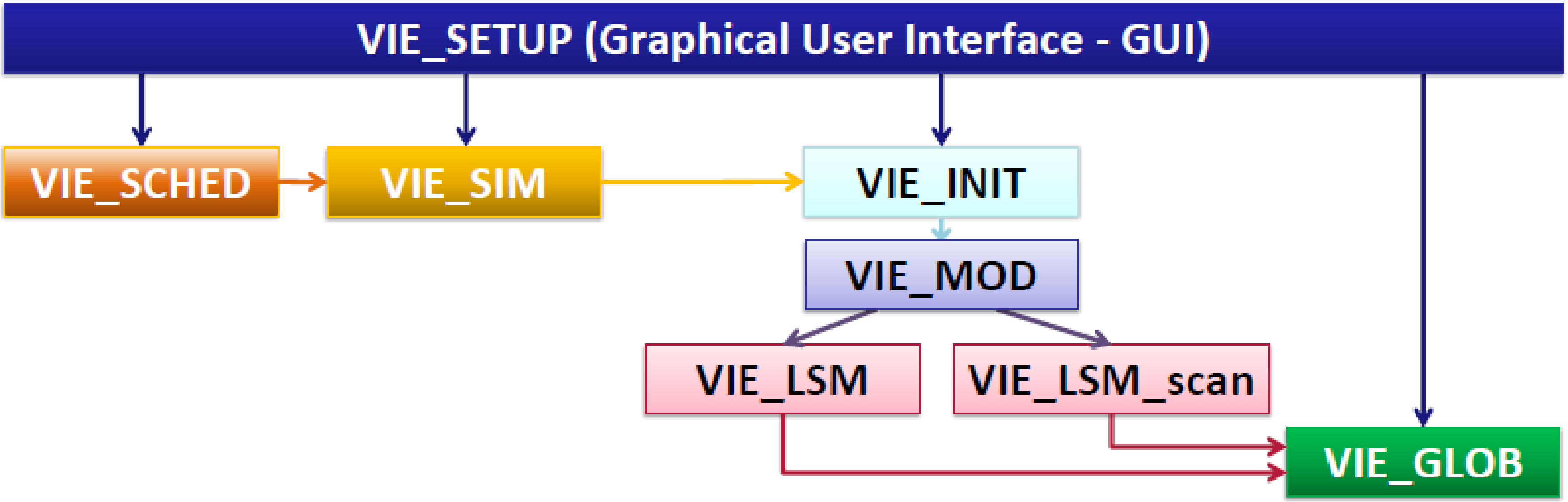


Who develops VieVS?

- **current members** of the VieVS group at the Technische Universität Wien:

- **former members** of the VLBI group at the TU Wien
- contributions from **external partners** from international universities worldwide

VieVS Structure


VIE_SETUP (Graphical User Interface - GUI)

VIE_SCHED

VIE_SIM

VIE_INIT

VIE_MOD

VIE_LSM

VIE_LSM_scan

VIE_GLOB

- One common GUI, including plotting tools
- Separate batch mode to be used after the setup

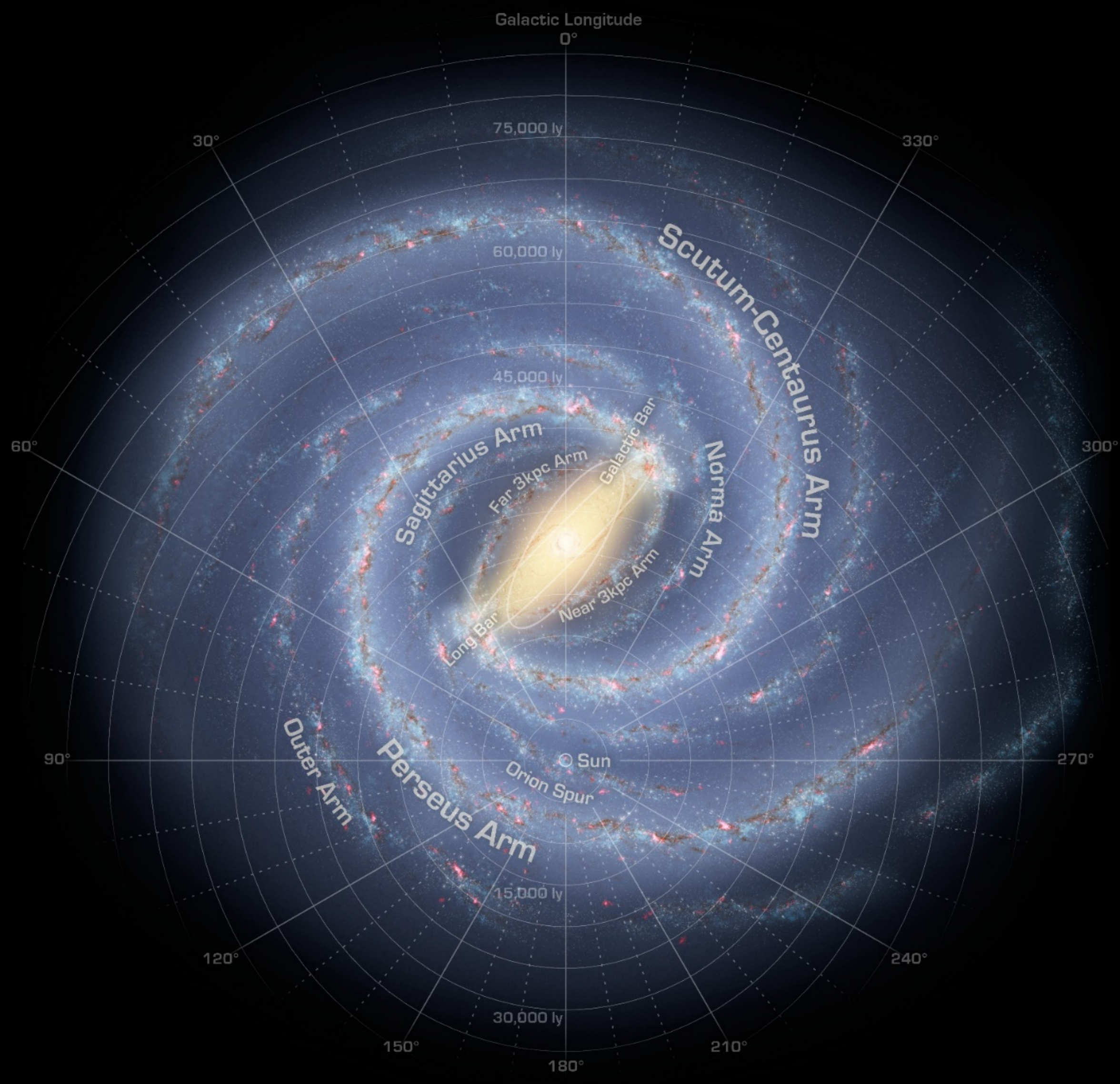
VieVS User Workshops

Galactic Aberration

The IVS Working Group on Galactic Aberration (WG8) was established by the IVS Directing Board in November 2015

- Purpose: investigation of the issues related to incorporating the effect of galactic aberration in the geodetic VLBI analysis
- Based on these studies, the WG was tasked to formulate a recommendation for an aberration correction model to be provided to the ICRF3 working group
- Group 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, Australia
    - [9] Shanghai Astronomical Observatory, Shanghai, PR China

Galactocentric acceleration

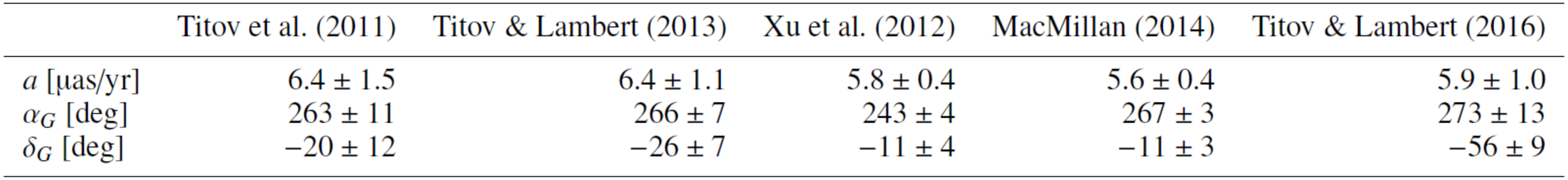


- raises through the relative motion of the SSB around the **Galactic centre** on a quasi circular orbit
  - rotation speed ~250 km/s
  - rotation period ~200 Myr
- the acceleration of the SSB is directed **towards the centre** of the Galaxy
- this effect is **omitted in the a priori** modelling of the VLBI observable so far, which results in a systematic dipole proper motion (Secular Aberration Drift, SAD) of extragalactic radio sources
- the acceleration vector can be **estimated from the VLBI** measurements

This artist's concept depicts the most up-to-date information about the shape of our own Milky Way galaxy. Credits: NASA/JPL-Caltech/R. Hurt (SSC/Caltech)

GA vector from the geodetic VLBI analysis

Recent estimates of the GA vector from the geodetic VLBI analysis



	Titov et al. (2011)	Titov & Lambert (2013)	Xu et al. (2012)	MacMillan (2014)	Titov & Lambert (2016)
a [μas/yr]	6.4 ± 1.5	6.4 ± 1.1	5.8 ± 0.4	5.6 ± 0.4	5.9 ± 1.0
α_G [deg]	263 ± 11	266 ± 7	243 ± 4	267 ± 3	273 ± 13
δ_G [deg]	−20 ± 12	−26 ± 7	−11 ± 4	−11 ± 3	−56 ± 9

- Fitting of the radio source proper motion field (Calc/Solve, OCCAM)
  - Titov et al. (2011)
  - Titov and Lambert (2013)
  - Titov and Lambert (2016)
- GA as global parameter (Calc/Solve)
  - Xu et al. (2012)
  - MacMillan (2014)

- Astrometric measurements of proper motions and parallaxes of masers in the Milky Way Galaxy
  - Amplitude 4.8 – 5.5 μas/y
  - RA = 266 deg
  - De = -29 deg

GA vector as a global parameter

- ~5800 observing sessions from 1979.7 until 2016.5 provided by the IVS
- Following Titov et al. (2011) the conventional equation for the group delay model (Petit and Luzum, 2010) was extended by the GA vector.

$$\frac{\partial\tau_{group}}{\partial a} = \frac{\Delta t}{c^2}\left((bs)s - b\right) - \frac{\Delta t}{c^3}\left(b\left(s(V + w_2)\right) + \frac{b(Vs)}{2} - (bV)s\right)$$

b - baseline vector,
s – barycentric unit vector of the radio source
V - barycentric velocity of the geocentre
w_2 - geocentric velocity of the second station

Parameters in the global solution:

- TRF (position + linear velocity)
- CRF (positon)
- GA vector

	Most of the available IVS sessions 1979.7 – 2016.5, (~5800 sessions)	**NEOS-A, IVS-R1, IVS-R4 and all CONT 1993.0 – 2016.5 (~2000 sessions)**
Ampl [µas/y]	6.1 ± 0.2	5.4 ± 0.4
RA_{GC}[deg]	260 ± 2	273 ± 4
De_{GC} [deg]	-18 ± 4	-27 ± 8

Estimation of the GA vector from the VLBI scale

new method

- Simplified group delay model including only the main aberration effect:

$$\tau = -\frac{b \cdot s}{\mathrm{c}} + \frac{b(s(s \cdot V) - V)}{\mathrm{c}^2} = -\frac{b \cdot s}{\mathrm{c}} + \frac{b \cdot \Delta s}{\mathrm{c}^2}$$

b - baseline vector,
s – barycentric unit vector of the radio source
V - barycentric velocity of the geocentre

- The standard correction for the annual aberration: $\Delta s = (s \times (s \times V))$

Corresponding correction for the aberration effect if the GA vector a is added to the group delay model (Δt is the time since a reference epoch):

$$\tau_{aberr} = \frac{b\big(s\big(s(V + a\Delta t)\big) - (V + a\Delta t)\big)}{\mathrm{c}^2} =$$

$$= \frac{b(s(sV) - V)}{\mathrm{c}^2} + \left(\frac{bs}{\mathrm{c}} \frac{(sa)\Delta t}{\mathrm{c}} - \frac{(ba)\Delta t}{\mathrm{c}^2}\right) = \tau_{aberr1} + \tau_{aberr2}$$

- The effect of the proper motion on the source coordinates is $\tau' = -\frac{b \cdot \mu \Delta t}{\mathrm{c}}$

- Finally after some rearrangement: $\tau_{aberr2} + \tau' = \frac{(b \cdot s)(s \cdot a)\Delta t}{\mathrm{c}^2} - \frac{(b(a + \mathrm{c}\mu))\Delta t}{\mathrm{c}^2}$

Term sensitive to the Galactocentric acceleration

Term with the individual proper motions of the sources

Estimation of the GA vector from the VLBI scale

- For a perfect model, the scale factor F is equal to unity for all observations:

$$F = \frac{d\tau_{group}}{d\tau_{geom}} \equiv 1$$

- When the unmodelled delays $(\tau_{aberr2} + \tau')$ are contained in the group delay,

the scale factor is given by

$$\boxed{F = 1 + \frac{a \cdot s}{\mathrm{c}} \Delta t}$$

and **manifests itself as a variable parameter** depending on

- GA
- radio source position
- the time since a reference epoch.

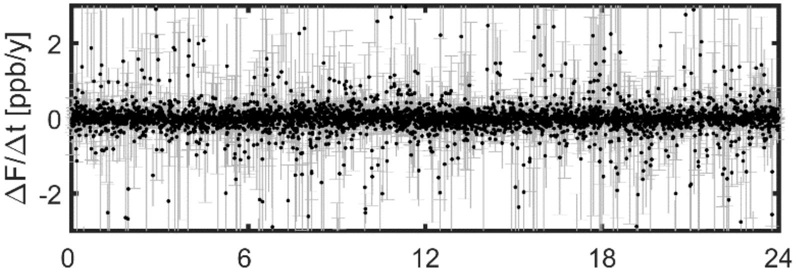
Scale factor corrections [ppb/y] as a function of equatorial coordinates

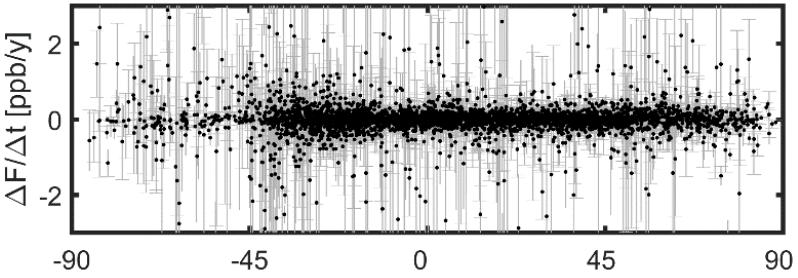
- 5825 observing sessions from 1979.7 until 2016.5 provided by the IVS
- **Solution 1** – Standard solution, IERS2010

- Parameters in the global solution:
  - TRF (position + linear velocity)
  - CRF (positon)
  - Individual scale factor for each source

GA as a time-independent effect

Partial derivative: $\frac{\partial \tau_{group}}{\partial\left(\frac{F}{\Delta t}\right)} = -\frac{b \cdot s}{\mathrm{c}} \cdot \Delta t$



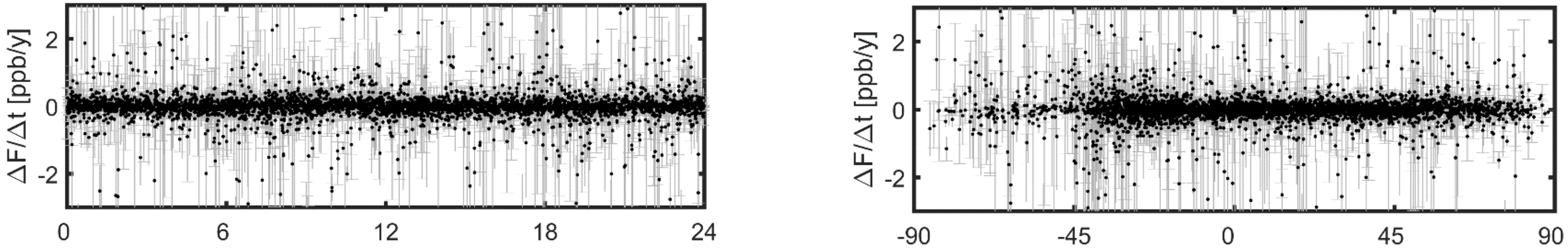


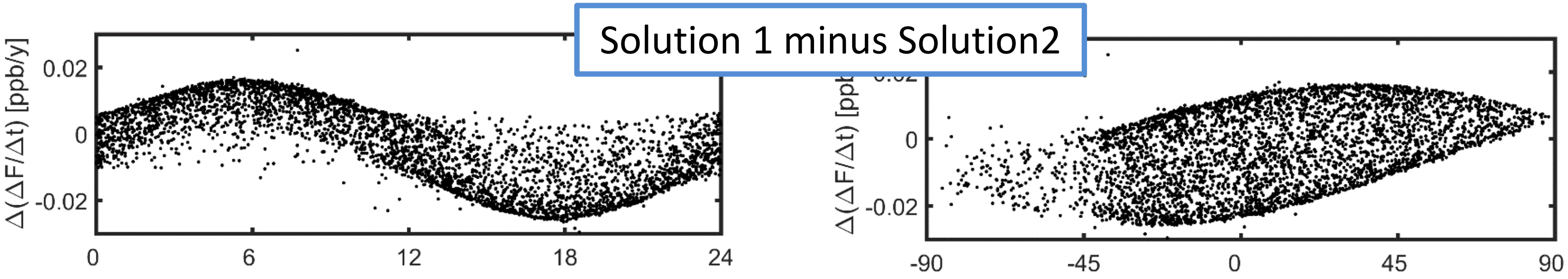
Scale factor corrections [ppb/y] as a function of equatorial coordinates

- 5825 observing sessions from 1979.7 until 2016.5 provided by the IVS
- **Solution 1** – Standard solution, IERS2010
- **Solution 2** – as Sol1 but the GA vector was added in the a priori group delay model
- Parameters in the global solution:
  - TRF (position + linear velocity)
  - CRF (positon)
  - Individual scale factor for each source

GA as a time-independent effect: plotted diff $\frac{a \cdot s}{c}$

Partial derivative: $\frac{\partial \tau_{group}}{\partial\left(\frac{F}{\Delta t}\right)} = -\frac{b \cdot s}{c} \cdot \Delta t$



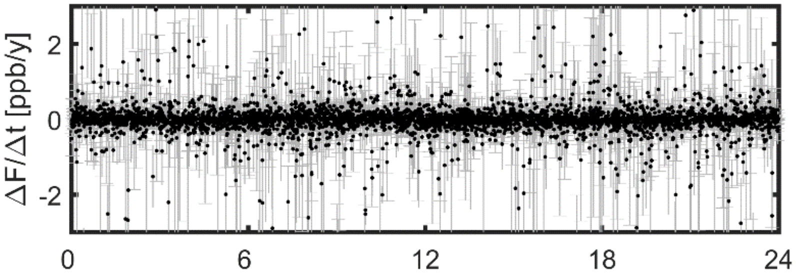

Solution 1 minus Solution2

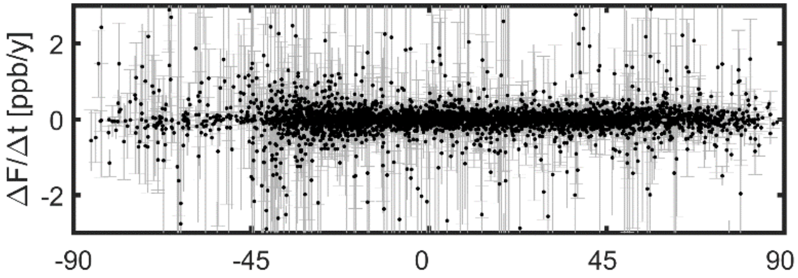
An annual effect on the scale (~0.02 ppb/year) which grows proportional to Δ*t* reaching ~0.2 ppb if the mean Δ*t* is about 10 years.

Estimates of the dipole components (GA vector)

GA as a time-independent effect

Partial derivative: $\frac{\partial \tau_{group}}{\partial\left(\frac{F}{\Delta t}\right)} = -\frac{b\cdot s}{c}\cdot \Delta t$





The components of the GA vector (a_1, a_2, a_3) are estimated by fitting the individual scale factor corrections by the following model:

$$\Delta F = a_1 \cos\alpha \cos\delta + a_2 \sin\alpha \cos\delta + a_3 \sin\delta$$

$$a_1 = A \cos RA_{GC} \cos De_{GC}$$
$$a_2 = A \sin RA_{GC} \cos De_{GC}$$
$$a_3 = A \sin De_{GC}$$

$$A = \sqrt{a_1^2 + a_2^2 + a_3^2} \quad RA_{GC} = \arctan\left(\frac{a_2}{a_1}\right) \quad DeGC = \arctan\left(\frac{a_3}{\sqrt{(a_1^2 + a_2^2)}}\right)$$

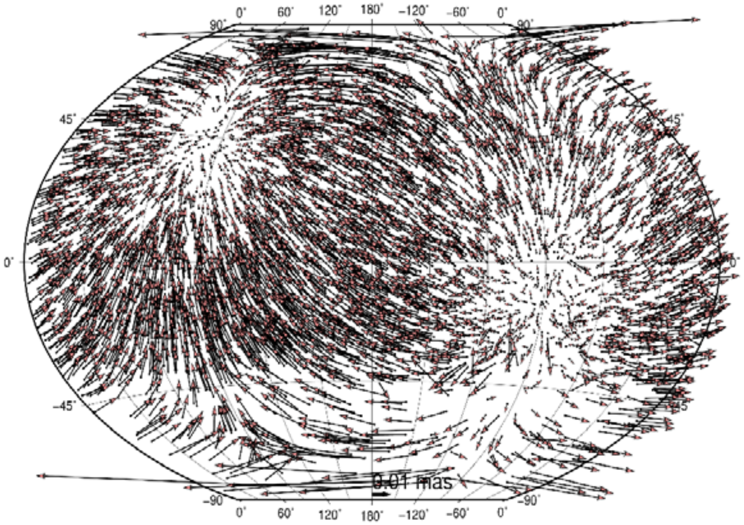
Num. of observations	> 4	> 10	> 50	> 500	> 1 000	> 10 000	>20 000	> 50 000
Num. of sources	4062	4001	3414	573	476	133	87	43
A [µas/y]	7.1 ± 0.2	8.2 ± 0.3	5.2 ± 0.2	5.1 ± 0.3	5.0 ± 0.3	4.8 ± 0.4	5.3 ± 0.5	4.6 ± 0.7
RA_{GC} [deg]	281 ± 3	281 ± 3	281 ± 3	281 ± 4	280 ± 5	280 ± 7	281 ± 7	290 ± 13
De_{GC} [deg]	-51 ± 2	-55 ± 2	-35 ± 3	-34 ± 3	-32 ± 4	-28 ± 5	-34 ± 5	-24 ± 8

Estimates of the dipole components (GA vector) a posteriori from ΔF/Δt (Solution 1).
Different cut-off thresholds for number of radio source observations (N) applied.

Changes in the CRF

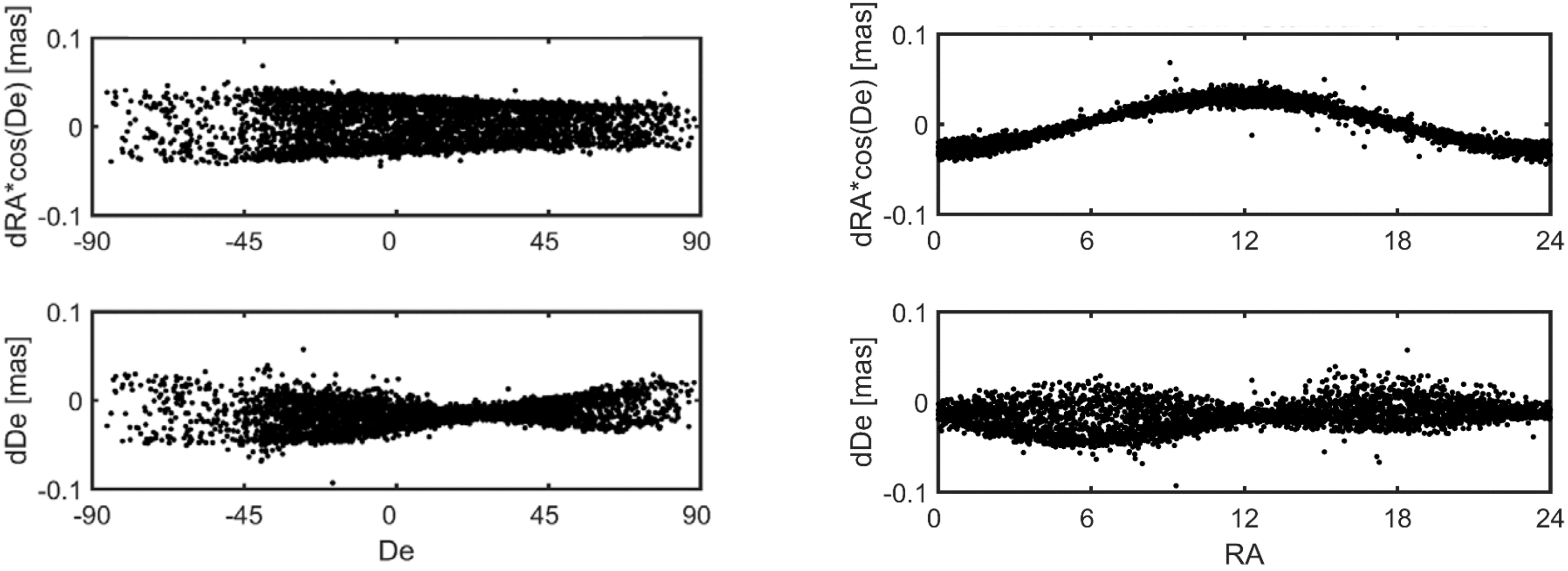
due to the omitted GA effect

Solution 1 – Solution 2



Solution 1 – Standard solution, IERS2010
Solution 2 – same as Solution 1,
but GA vector (A = 5 µas/y)
was added to the conventional equation

Systematic difference in the De and RA with an amplitude of ~50 µas.



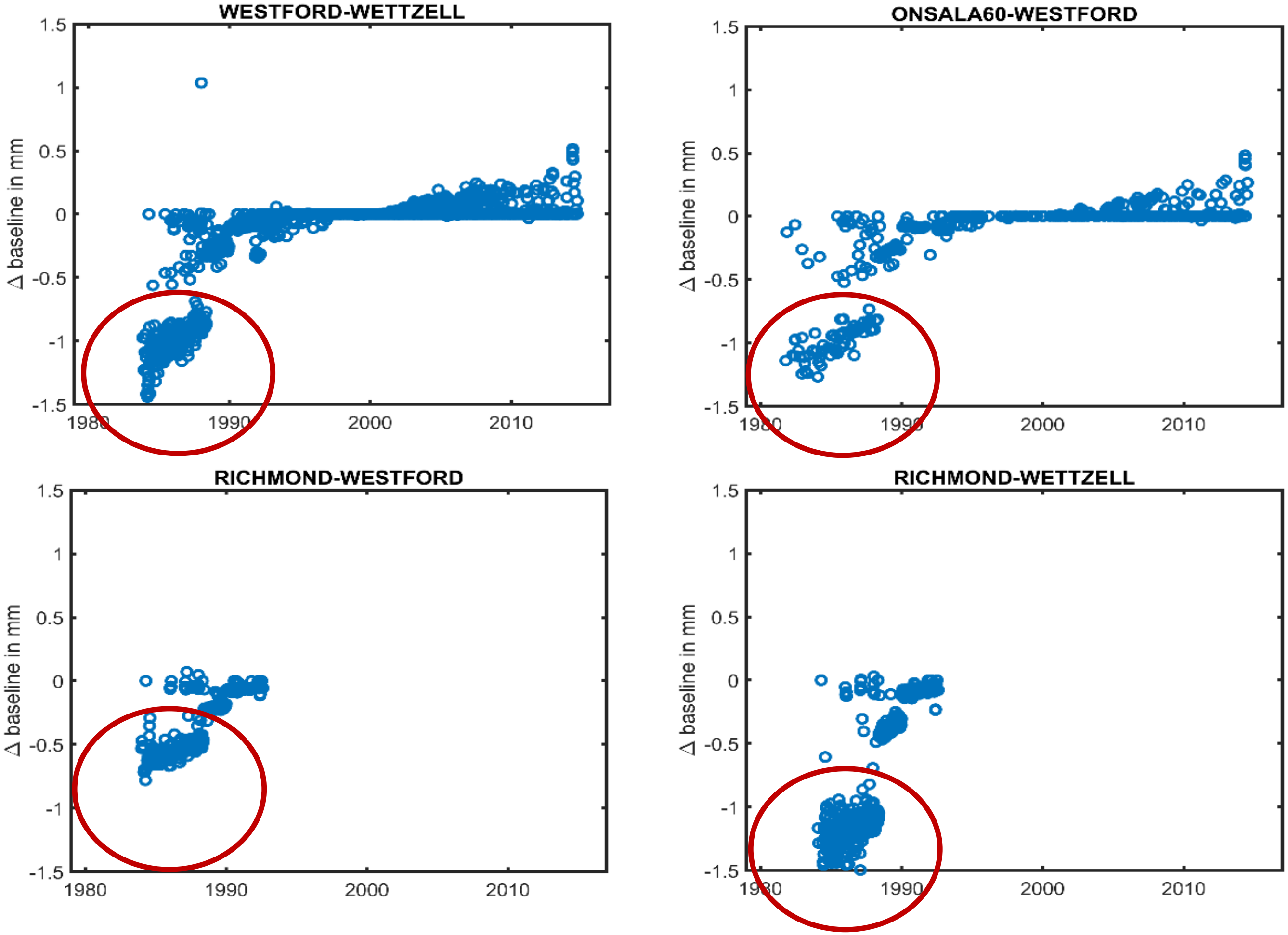
Changes in the baseline length

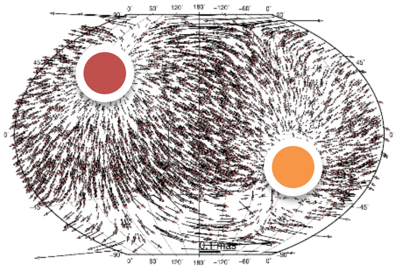
due to the omitted GA effect

Solution 1 – Standard solution, IERS2010

Solution 2 – same as Solution 1, but GA vector was added to the conventional equation

Solution 1 minus Solution 2





Radio sources located near the Galactic centre/anticentre cause a strong systematic effect on the **baseline length exceeding 1 mm.**

After 1990 the scheduling strategy was changed and the influence of the individual sources was mitigated.

Changes in the baseline length

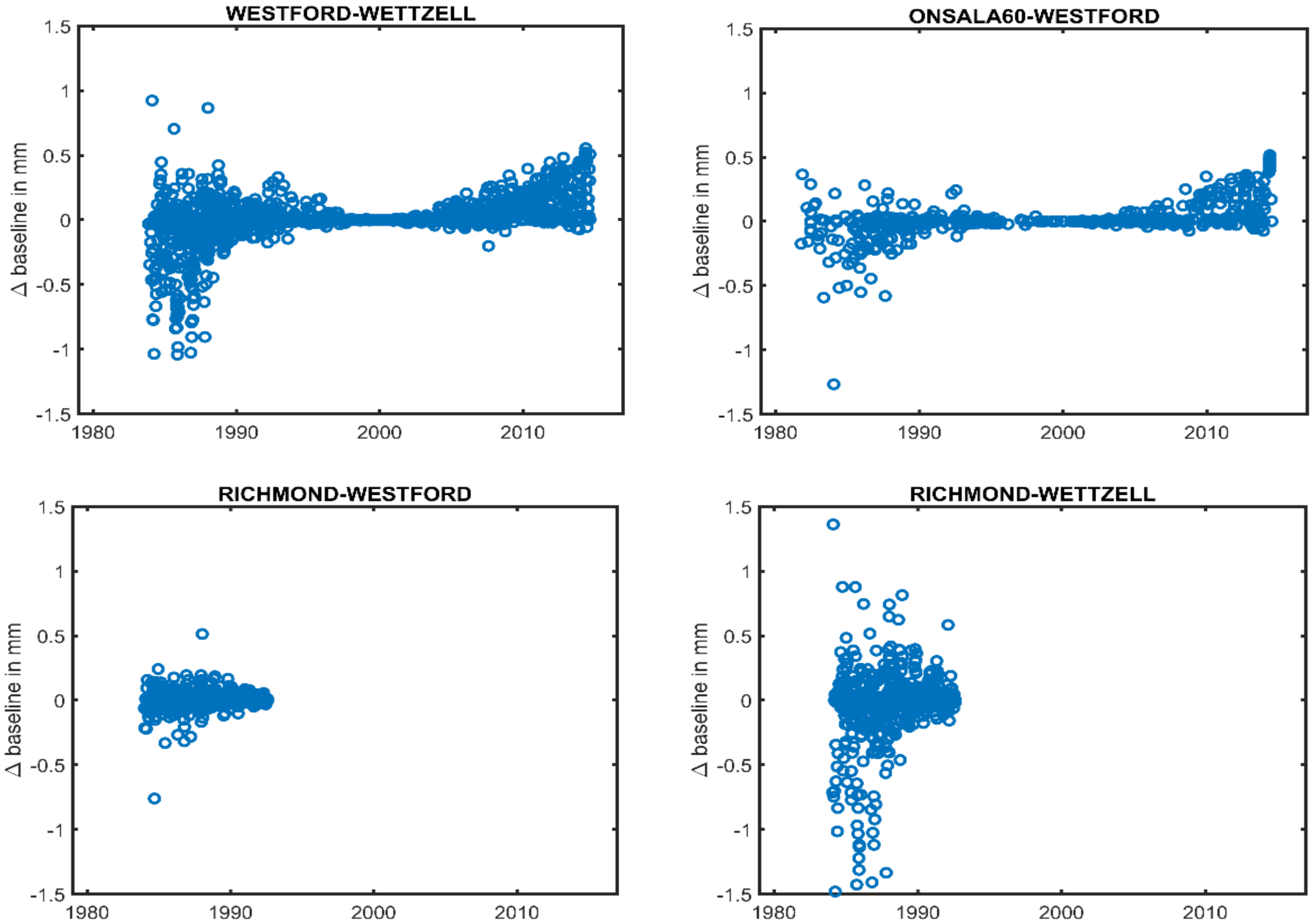
due to the omitted GA effect

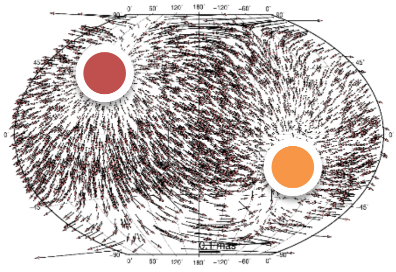
Solution 1 – Standard solution, IERS2010

Solution 2 – same as Solution 1, but GA vector was added to the conventional equation

Solution 3 – same as Solution 2, but the **GA correction was omitted** for the source **0552+389**

Solution 1 minus Solution 3





Radio sources located near the Galactic centre/anticentre cause a strong systematic effect on the **baseline length exceeding 1 mm**, especially, in early VLBI years.

Conclusions - GA

- We introduce **a new method** for estimation of the **galactic acceleration** (secular aberration drift) **vector** from VLBI measurements.

- The GA vector is obtained by **fitting the scale factor corrections** estimated for each source individually **within a global solution**.

- From fitting the individual scale factor corrections of sources with more than 50 observations during 1979.7 – 2016.5 we got the GA vector with the **amplitude of 5.2 ± 0.2 µas/y**, and the direction **RA = 281 ± 3 deg** and **De = -35 ± 3 deg**.

- We estimated the GA vector also directly within a global adjustment of the VLBI data. This procedure seems to be sensitive to the inclusion of weak networks. GA vector determined from selected IVS sessions after 1993 (**Ampl = 5.4 ± 0.4 µas/y**, **RA = 273 ± 4 deg**, **De = -27 ± 8 deg**) is closer to its theoretical value than the estimate from the entire VLBI history.

- **Neglecting the galactic acceleration** in the a priori VLBI observation model causes errors in the estimated **baseline length** which can exceed **1 mm** especially in the early VLBI years, and systematic errors in the determined **celestial reference frame** (up to **0.05 mas**).

- Titov O., H. Krásná (2018). *Measurement of the solar system acceleration using the Earth scale factor.* Astronomy & Astrophysics 610, A36.

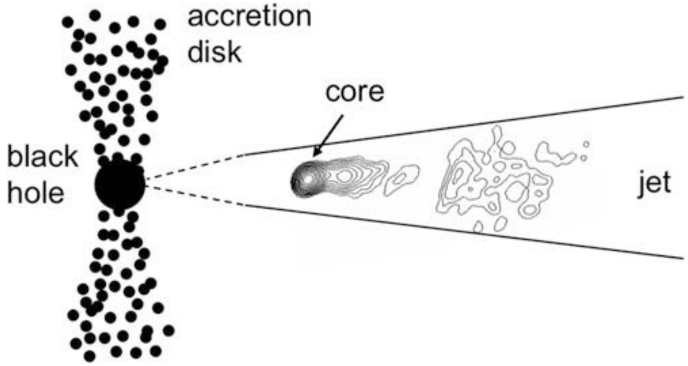
Investigation of source structure

in cooperation with Leonid Petrov

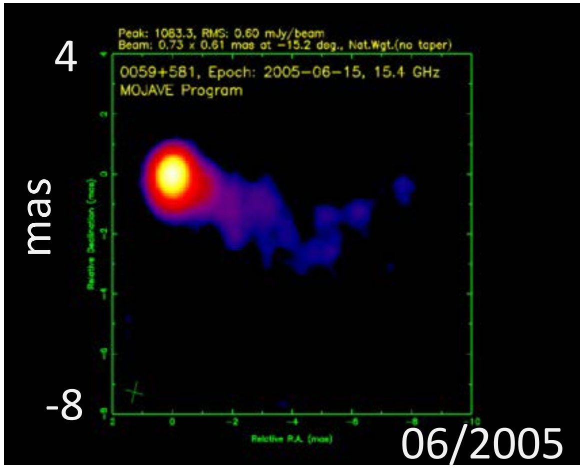
(ADNET Systems Inc./NASA GSFC, USA)

CRF is built up with the radio-loud quasars

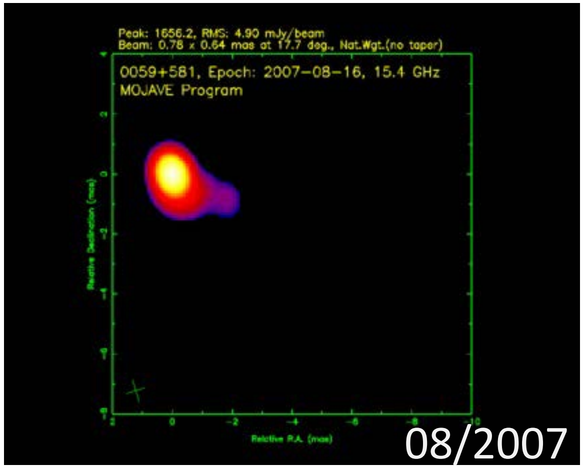
- Geodesists want to have
  - Bright point sources
  - Fixed in space and time
- In reality they are
  - Supermasive black holes
  - With jets – structure
  - Changing on time scales of months and years



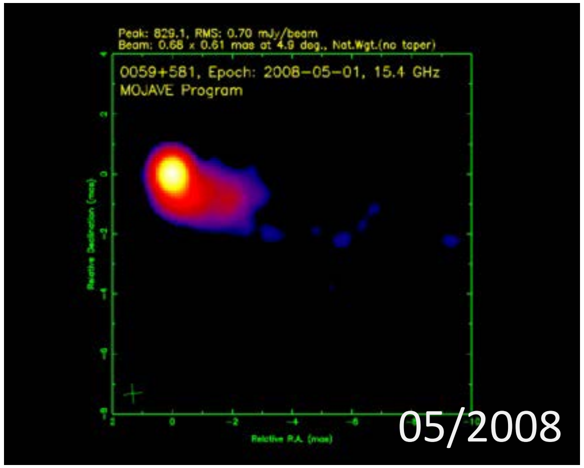
Shabala et al. (2015). Model of a quasar.
Radio emission is associated with the jet of synchrotron-emitting plasma. The location of the peak in radio emission (the "core") is frequency-dependent due to synchrotron self-absorption, and always in some distance from the black hole.



06/2005



08/2007



05/2008

Lister et al. (2009), Shabala et al. (2014)

Investigation of source structure

in cooperation with Leonid Petrov
(ADNET Systems Inc./NASA GSFC, USA)

- Many sources show significant proper motion presented as a linear change of source positions in time - for many sources it is greater than the 5 μas/yr due to the Galactic aberration

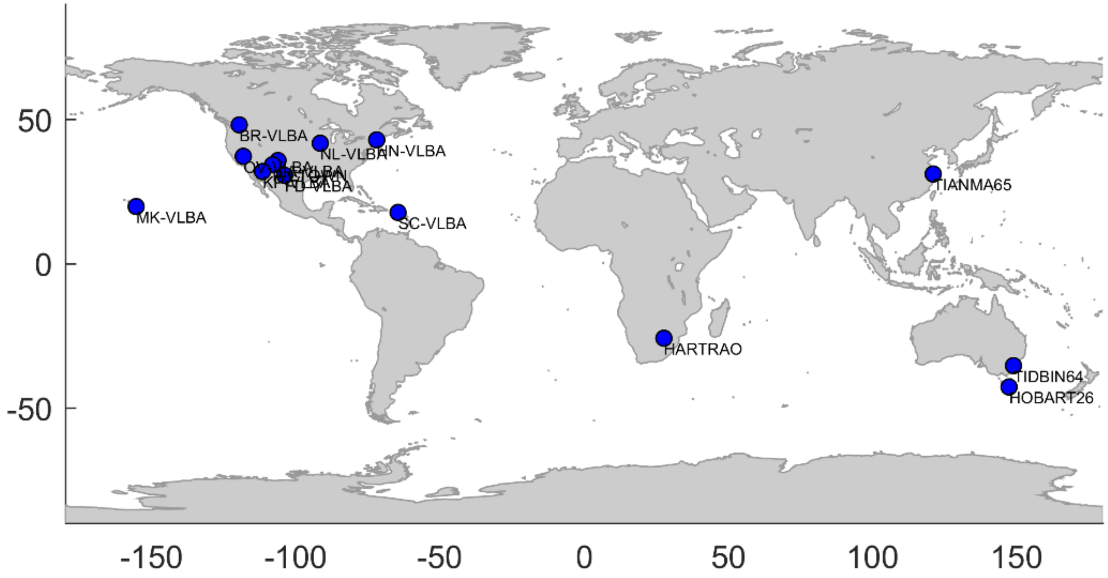
- Further progress in the GA study can be achieved by reducing systematic errors, such as the source structure

- The testbed is the MOJAVE (Monitoring Of Jets in Active galactic nuclei with VLBA Experiments) database
  - VLBA experiments at a wavelength of 2 cm / Ku radio band at 15 GHz
  - analysis of the MOJAVE dataset with and without source structure, correlation of source structure contribution with source kinematics

K-Band Project - Imaging

- Members:
  - Aletha de Witt (HartRAO)
  - Christopher Jacobs (NASA/JPL)
  - Hana Krásná (TU Wien/Astronomical Institute CAS)
  - Cristina García Miró (SKA)
  - Michael Bietenholz (HartRAO/York University)

- Observations at 24 GHz (1.2 cm)
- VLBA telescopes on the U.S. territory + South Africa – Australia baseline



K-Band Project - Imaging

CRF related topic:

- Produce images of all sources to determine their suitability for K-band CRF and show that sources become more compact at higher frequencies
- AIPS software

- Spatial resolution - few parsecs
- Temporal resolution from a 0.5 to 2 months’ cadence of observation for a given radio source

- Parameters to be calculated: e.g. structure indices, number of components, jet directions, source size, flux density.

K-Band Project

EOP related topic:

- The EOP are regularly estimated by VLBI. Until now, published VLBI estimates of EOP were based solely on observations from the S/X frequency band.

- For the first time, we present VLBI estimates of EOP from an observing frequency which is independent of the traditional SX-band using Very Long Baseline Array (VLBA) measurements at K-band (24 GHz, 1.2 cm).

  By June 2018, we will have about 1.5 years of regular VLBA experiments conducted with telescopes located in U.S. territory. We investigate the potential of K-band VLBI to produce more accurate EOP because of its reduced source structure effects relative to SX-band. We will compare our K-band EOP S/X VLBA results and the IERS C04 data.

- Poster presentation

  Krásná H., Jacobs C.S., de Witt A., Gordon D., Bertarini A. (2018). **Earth Orientation Parameters estimated from K-band VLBA measurements.** COSPAR Scientific Assembly. Pasadena, CA, USA, July 14 - 22, 2018.

Other topics

Kalman filtering as a novel approach to determine celestial reference frames

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- The conventional approach to determine celestial reference frames (CRF) is by estimating constant radio source coordinates in a least-squares adjustment.
- However, several radio sources exhibit coordinate variations that go beyond the traditional constant coordinate model considering nowadays' growing accuracy requirements.
- Since it is currently very difficult to correct for the effects causing such variations (e.g., source structure) on the observational level, we have decided to use a time series representation of the radio source coordinates that constitute our CRF solutions.
- We treat radio source coordinates as stochastic processes and estimate them in a Kalman filter.
- The selection of the process noise model, which regulates the temporal variations of the resulting time series, is essential in the application of Kalman filtering.
- We test different approaches to derive the process noise model, for example based on the variability of the source flux and the jet direction. We compare the Kalman filter CRF solutions with traditional ones by assessing their performance in the VLBI data analysis, in particular concerning the estimated source coordinates and nutation parameters.

<u>Poster</u>:

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Other topics

Geodetic VLBI, Earth rotation and the Sagnac effect

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- Geodetic VLBI measures the group delay and phase delay rate in the barycentric reference frame. These both observables are sensitive to the geocentric motion of the telescopes.
- This results in a non-zero closure delay and closure delay rate (as a sum of the three values around the closed triangle of baselines).
- The group delay equation includes a term consistent to the Sagnac effect (usually applied to the ring laser interferometer technique or GNSS modeling) and, therefore, could be used to estimate the instantaneous vector of the Earth angular velocity.
- However, the delay rate suggests more effective way to do this job because it manifests as the Sagnac effect in the primary term of the model.
- The instantaneous vector of the Earth angular velocity is estimated with accuracy of 10^{-12} - 10^{-13} 1/sec with a small set of modern geodetic VLBI data. This provides an opportunity to detect the Thomas (geodetic) precession, Lense-Thirring effect (frame-dragging) and even the angular rotation of the Galaxy using the full 40-year set of geodetic VLBI observations.

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Thank you for your attention!

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