TECHNISCHE UNIVERSITÄT WIEN

Bologna VLBI
Life begins at 40!
MAY 22–26, 2023
BOLOGNA, ITALY

Celebrating 40 years of astrometric and geodetic VLBI data – a solid foundation for celestial and terrestrial reference frames

May 23, 2023

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www.vlbi.at

Outline

- IVS analysis center VIE
- Tasks of geodetic & astrometric VLBI
- Latest global Celestial and Terrestrial Reference Frames computed at TU Wien

IVS Analysis Center VIE

International Association of Geodesy (IAG)
a Constituent Association of IUGG (International Union of Geodesy and Geophysics)

International VLBI Service for Astrometry and Geodesy (IVS)

- Service of the IAG and of the IAU

- IVS provides a service which supports geodetic and astrometric work on reference systems, Earth science research, and operational activities.

IVS Analysis Center VIE (TU Wien + BEV)

International Astronomical Union (IAU)

Data Products of IVS

VLBI data products contribute uniquely to these important activities:

- defining and maintaining the celestial reference frame,
- monitoring universal time (UT1),
- monitoring the coordinates of the celestial pole (nutation and precession).

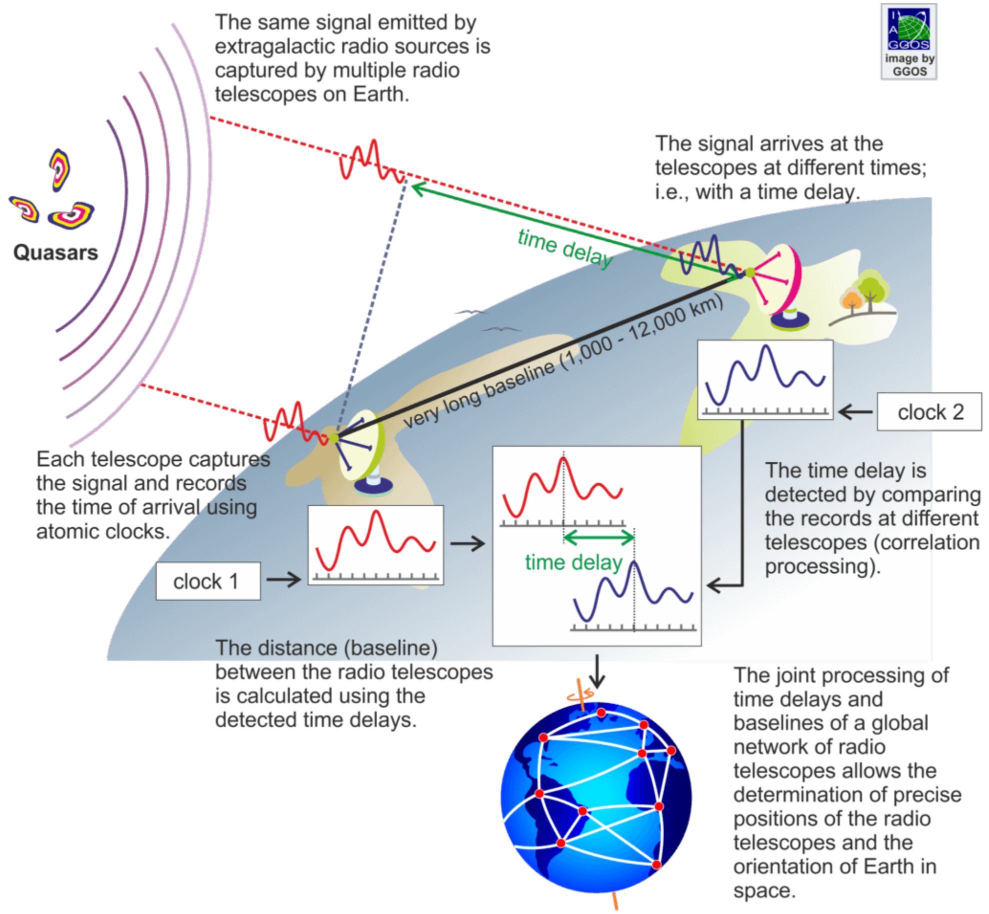
These results are the foundation of many scientific and practical applications requiring the use of an accurate quasi-inertial reference frame, such as high-precision positioning, navigation, and timing.

In addition IVS provides a variety of VLBI products with differing applications, timeliness, detail, and temporal resolution, such as:

- all components of Earth orientation parameters,
- terrestrial reference frame,
- baseline lengths,
- tropospheric parameters.

IVS Terms of Reference, May 24, 2019

VLBI principle (geodesy + astrometry)



https://ggos.org/item/vlbi/

Time delay τ

Primary observable of the geodetic VLBI

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

b baseline vector between two stations

k unit vector to radio source

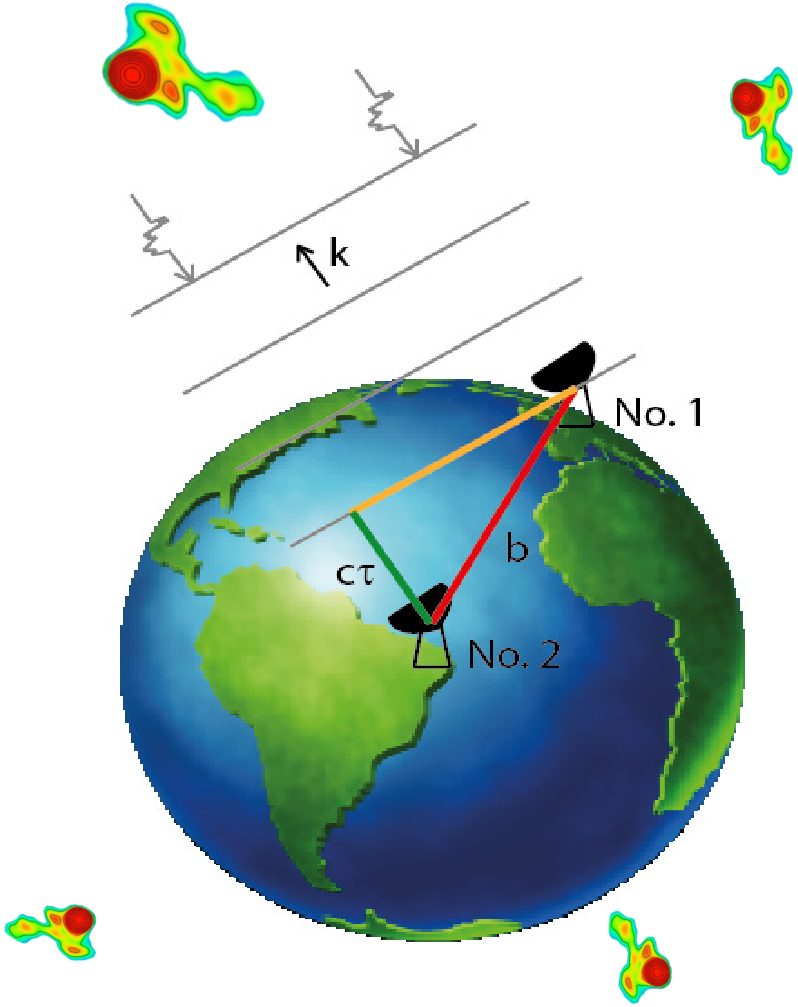
EOP $\left\{ \begin{array}{ll} W & \text{rotation matrix for polar motion} \\ S & \text{diurnal spin matrix} \\ Q & \text{precession-nutation matrix} \end{array} \right.$

Three Components of Space Geodesy

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 AGN which realize the **CRF**
- VLBI provides complete set of **EOP** and is unique for the determination of UT1-UTC and long-term nutation

  -> Earth rotation angle is of fundamental importance for any kind of positioning and navigation with the GNSS.
- VLBI provides precisely the length of intercontinental baselines, which strongly supports the realization and maintenance of the **TRF** with a stable scale



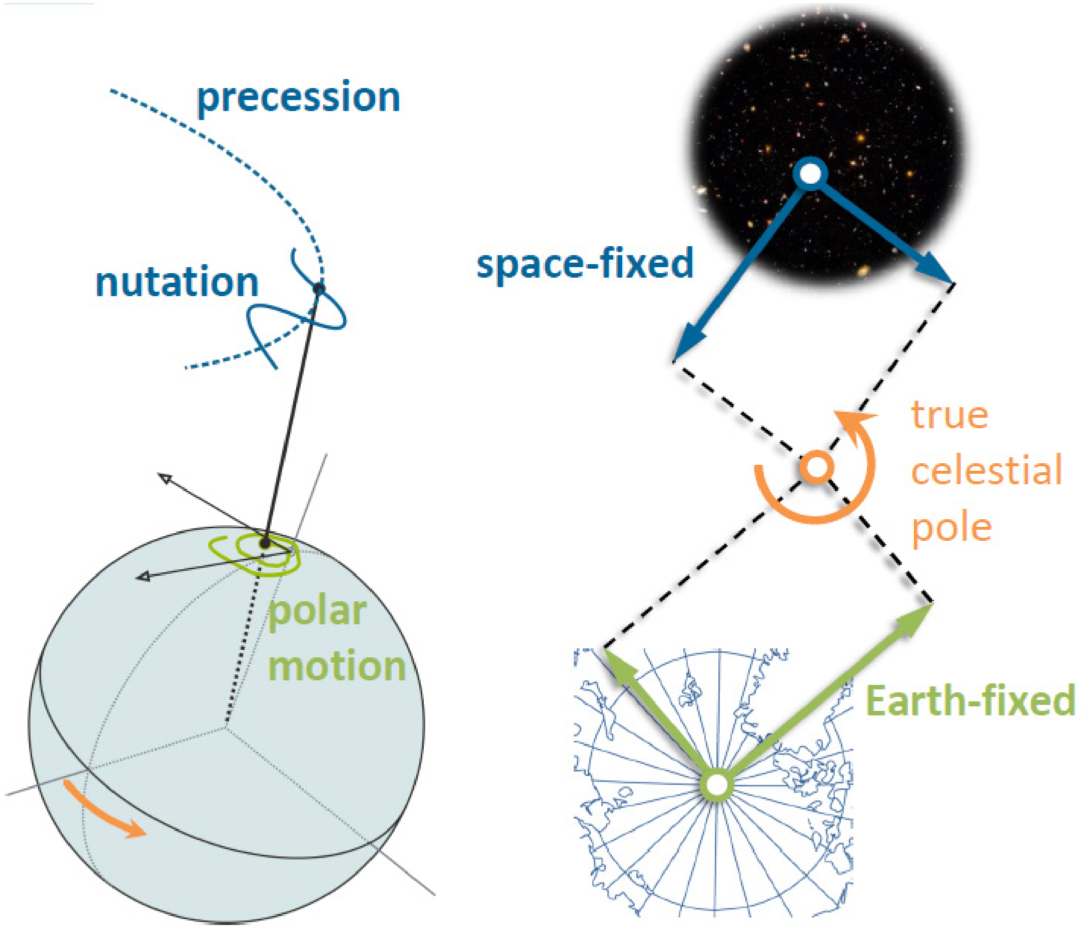
Earth rotation

- The Earth does not rotate with a constant velocity.
- The direction of the axis changes w.r.t. space.
- The solid Earth changes its position w.r.t. the Earth axis.
- Angular velocity and direction of the rotation axis exhibit periodic, irregular and secular variations.

courtesy of S. Böhm

Earth orientation parameters (EOP)

- **Precession-nutation**: orientation of the reference axis w.r.t. a space-fixed reference frame
- **Polar motion**: position of the reference axis w.r.t. an Earth-fixed reference frame
- **Earth spin**: rotational phase or rotation rate (length of day - LOD)

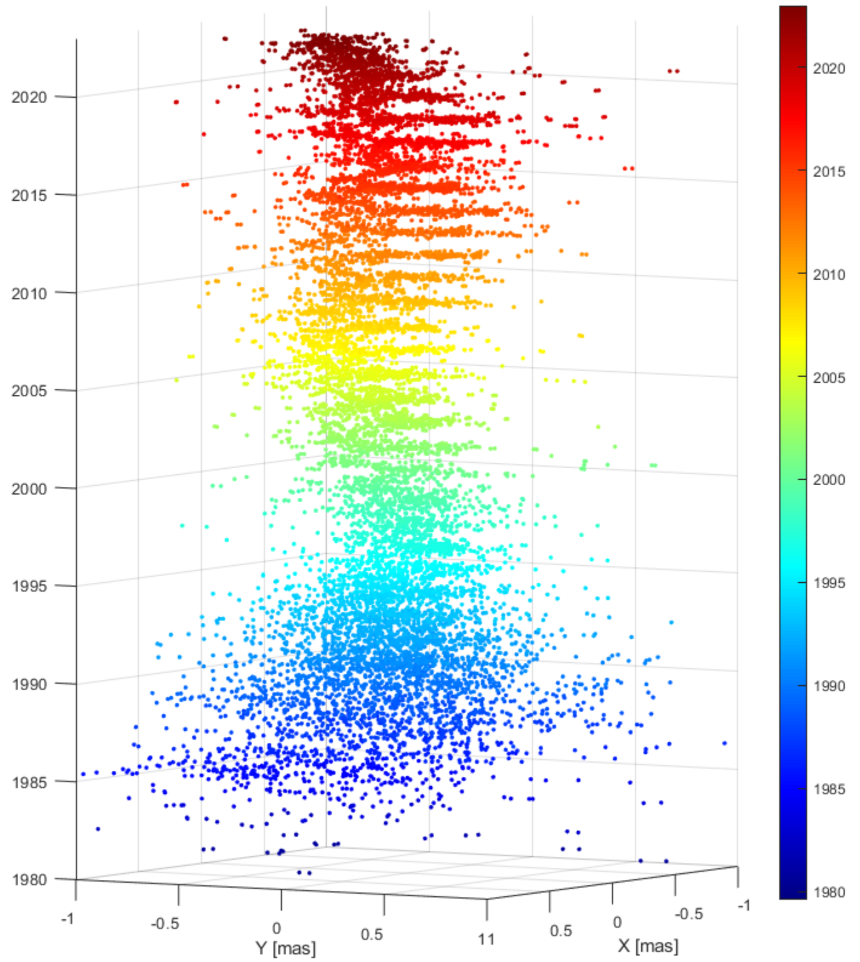


courtesy of S. Böhm

Precession / nutation

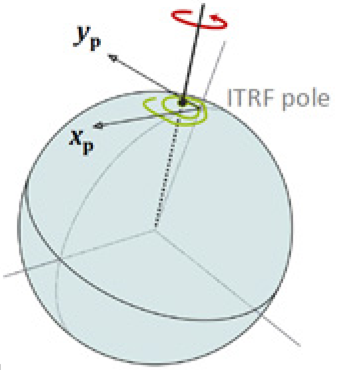
- Location of the rotation axis w.r.t. a space-fixed reference frame
  - Two components: X, Y
  - The main part is described using a model (currently IAU 2006/2000A)
  - The residuals (dX, dY) to the model are measured by means of geodetic VLBI
  - Residual signal mainly due to Free Core Nutation (FCN)

CPO from VIE2022 solution

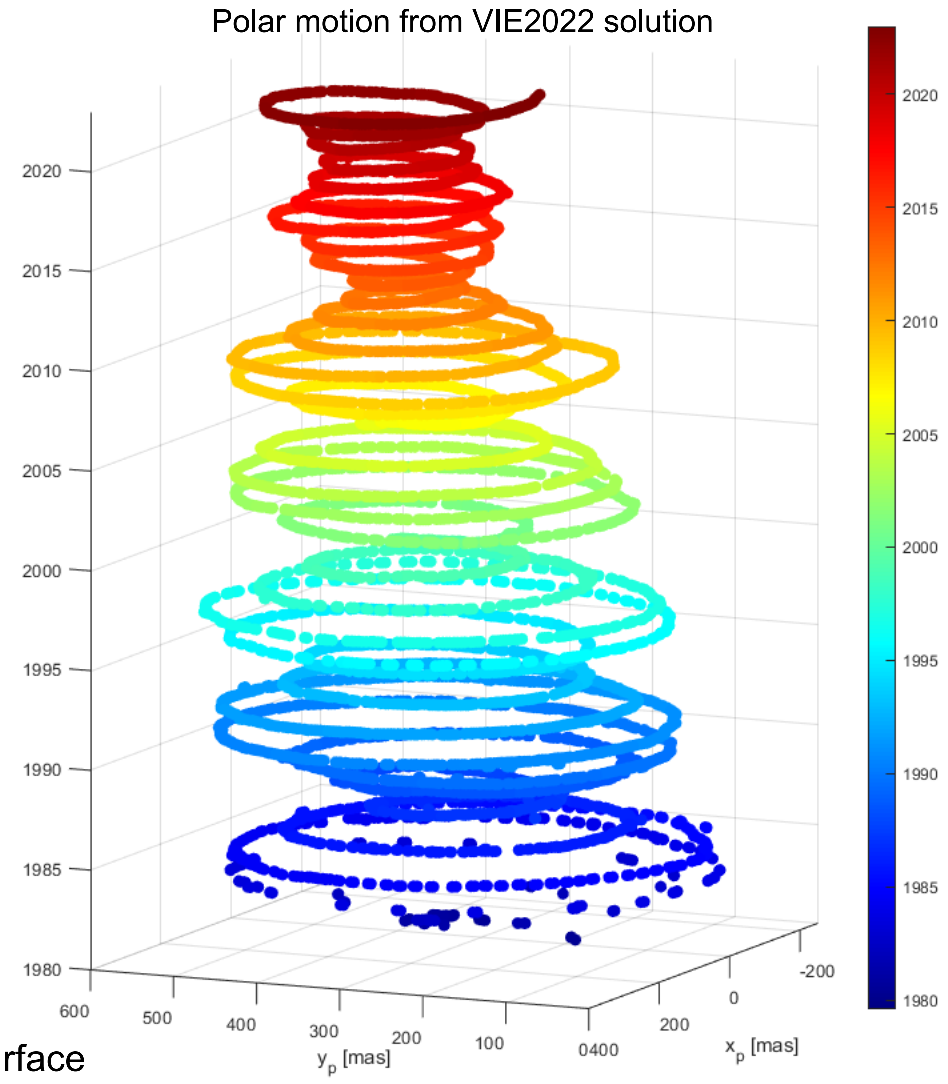


Polar motion

- Motion of the Earth rotation axis w.r.t. an Earth-fixed reference frame



- Main components
  - Chandler wobble: free oscillation of the Earth, period approx. 433 days
  - Annual wobble: caused by annual variations in atmospheric pressure
  - + unpredictable motions

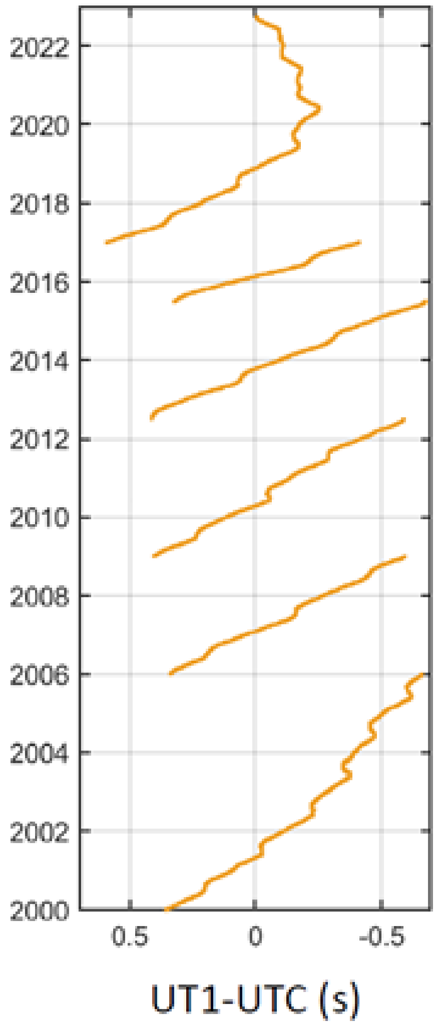


30 mas ≈ 1 m at the Earth surface

Earth spin

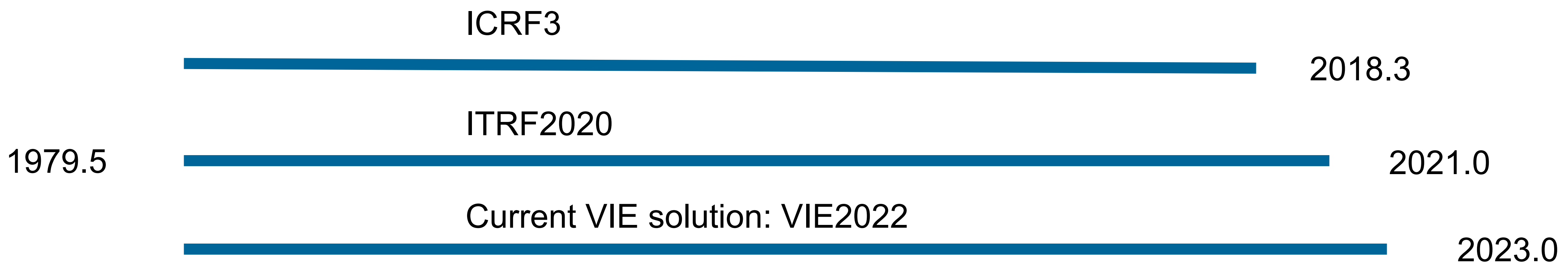
- Universal time UT1 – coordinated universal time UTC
  - UT1: the mean solar time relating to the Greenwich meridian
  - UTC: an atomic time scale adjusted to Earth rotation
  - UTC is adjusted to UT1 with leap seconds in such a way as to meet the condition

$$UT1 - UTC < 0.9 \text{ s}$$



courtesy of S. Böhm

VIE2022 solution (TRF + EOP + CRF)



VieVS – Vienna VLBI and Satellite Software

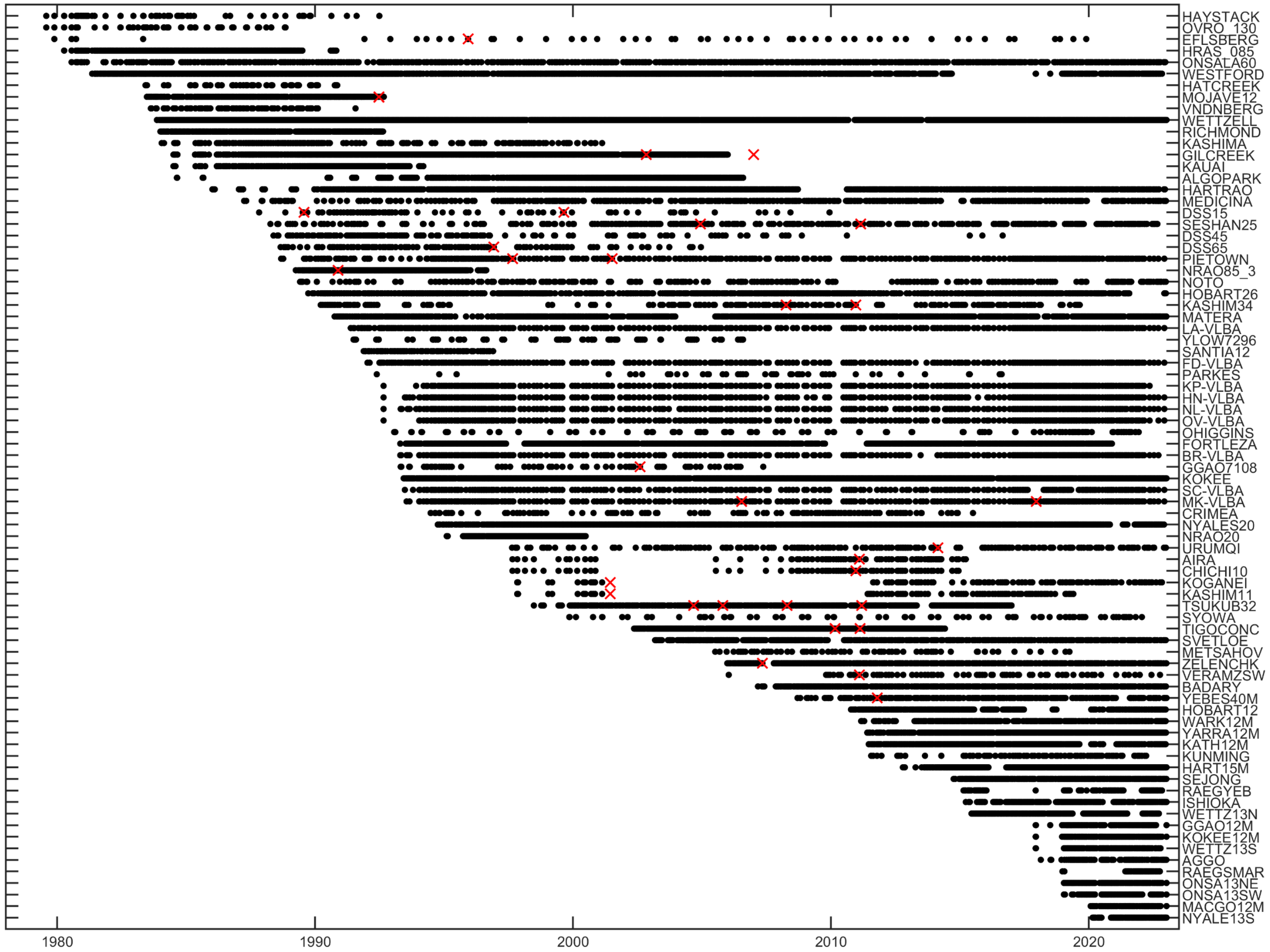
- VieVS-VLBI modul: geodetic VLBI analysis software package, open-source, available on GitHub https://github.com/TUW-VieVS
- Input: group delays provided in the IVS vgosDB format via IVS Data Centers

- Theoretical delay is modelled following the latest IERS Conventions 2010 (+ updates)
- Adjustment of data is done with the Least Squares Method

Global
Terrestrial Reference Frame
VIE2022

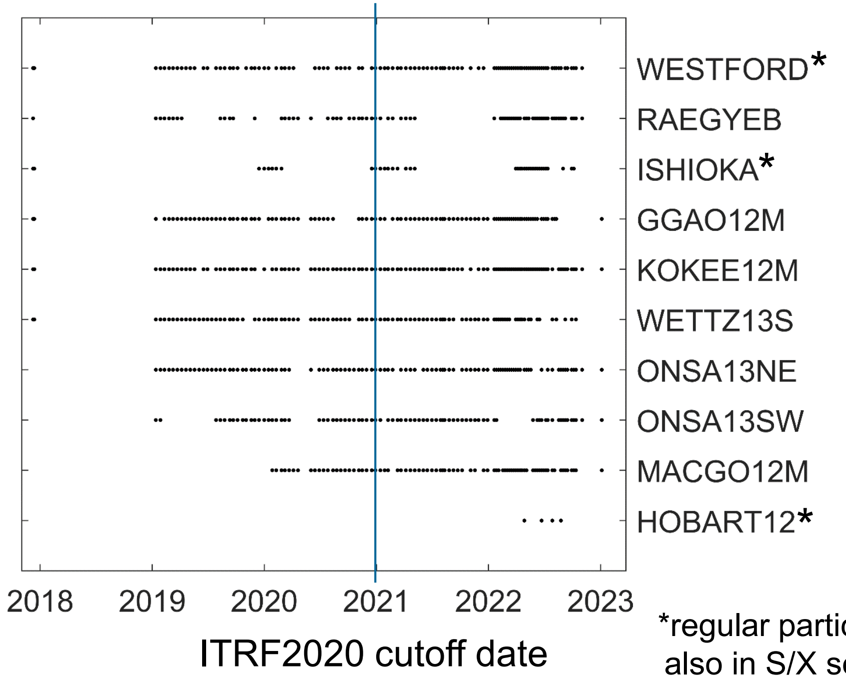
TRF-VIE2022

Antennas participating in > 50 sessions in VIE2022



- 7300 24-h IVS sessions (S/X + VGOS)
- 123 VGOS sessions
  - first session in December 2017
  - regular observations since 2019

VGOS sessions



*regular participation also in S/X sessions

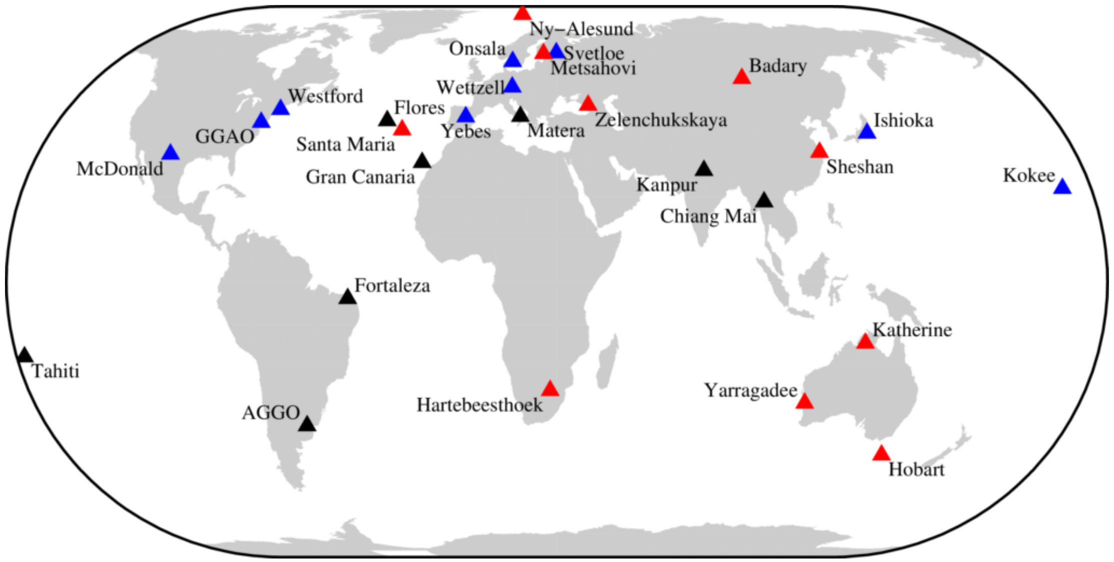
VGOS: The New VLBI Component of GGOS

- Science requirements established by Global Geodetic Observing System (GGOS)
  - accuracy of 1 mm in station position and 0.1 mm/year in station velocity on global scales

- The IVS contribution to GGOS is the VLBI Global Observing System (VGOS)
- Upgrade of the VLBI system to meet the required level of accuracy

VGOS system

- based on the broadband delay (four frequency bands in the range from 2.5 GHz to 14 GHz)
- fast-slewing, 12-m class antennas with a high data rate of 8 Gbps
- planned to replace the currently employed legacy S/X system as its operational system for geodetic product creation over the next few years



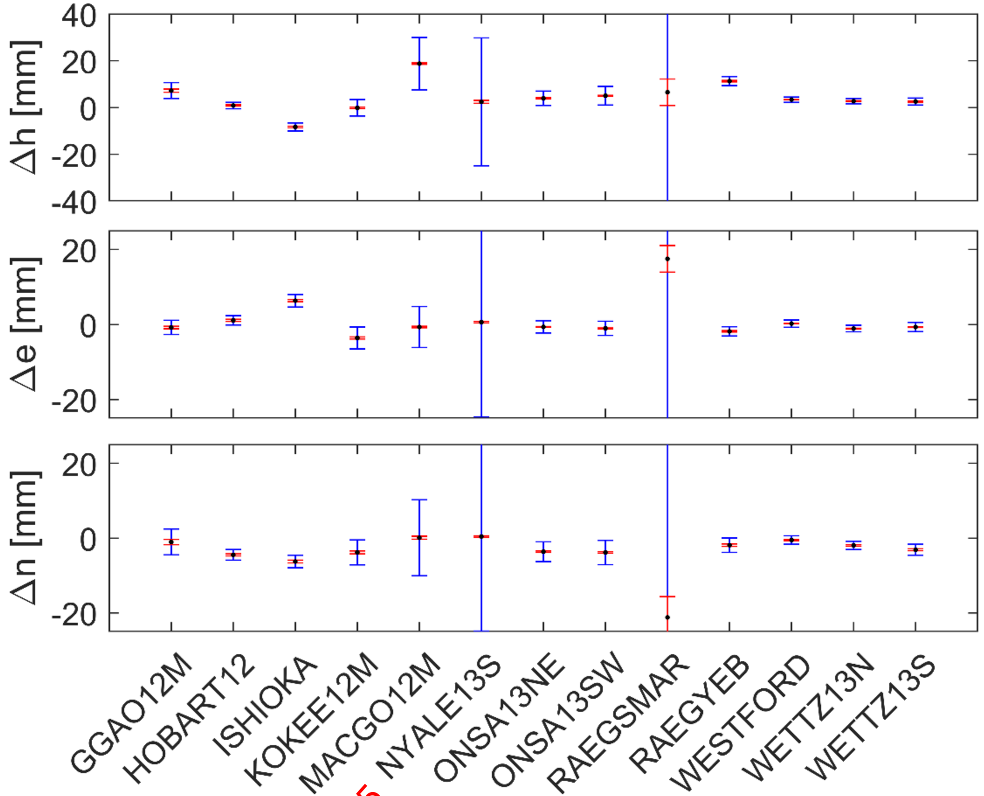
projected VGOS network, status 09/2020

https://ggos.org/item/ivs/

VIE2022 w.r.t. ITRF2020

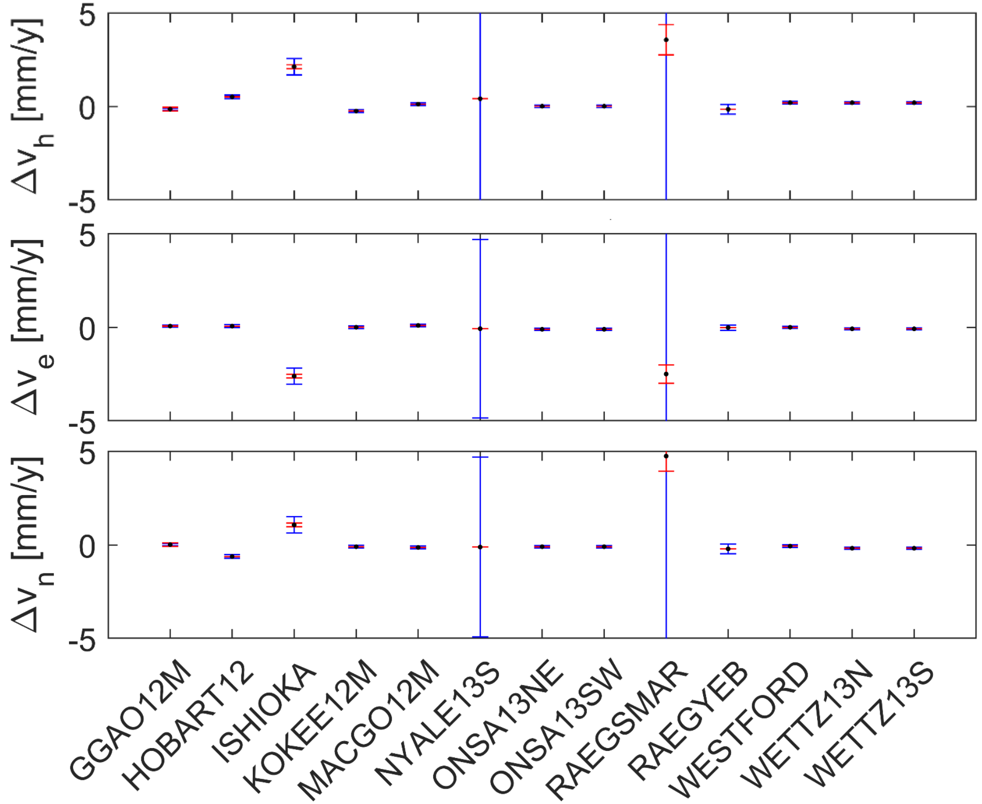
VGOS telescopes (some of them participate in S/X sessions)

Difference in **position** (at epoch 2015.0)



formal errors
ITRF2020
VIE2022

Difference in **velocity**



sessions: 7/83 25/245 3/106

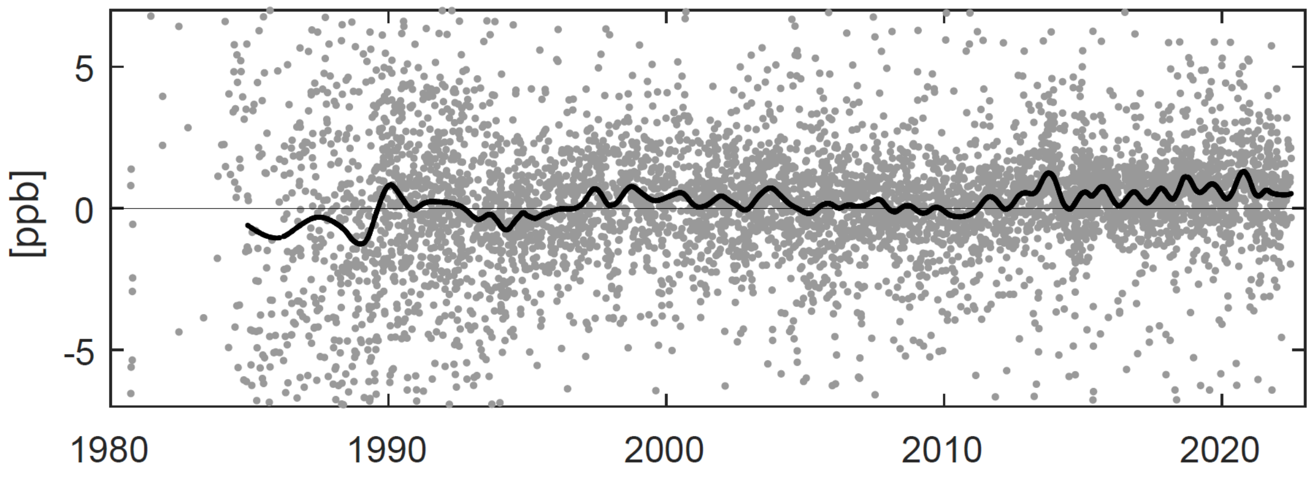
Transformation parameters

at epoch 2015 from ITRF2020 to VIE2022

Tx [mm]	Ty [mm]	Tz [mm]	Rx [µas]	Ry [µas]	Rz [µas]	Scale [mm]
2.1 ± 0.8	-1.3 ± 0.8	-2.1 ± 0.8	38 ± 30	46 ± 30	17 ± 24	2.9 ± 0.7

Tx‘ [mm/y]	Ty‘ [mm/y]	Tz‘ [mm/y]	Rx‘ [µas/y]	Ry‘ [µas/y]	Rz‘ [µas/y]	Scale‘ [mm/y]
0.15 ± 0.02	-0.14 ± 0.02	-0.17 ± 0.02	4.3 ± 0.7	2.7 ± 0.7	1.6 ± 0.6	0.17 ± 0.02

scale factor computed from each session separately (VIE2022b w.r.t. ITRF2020)

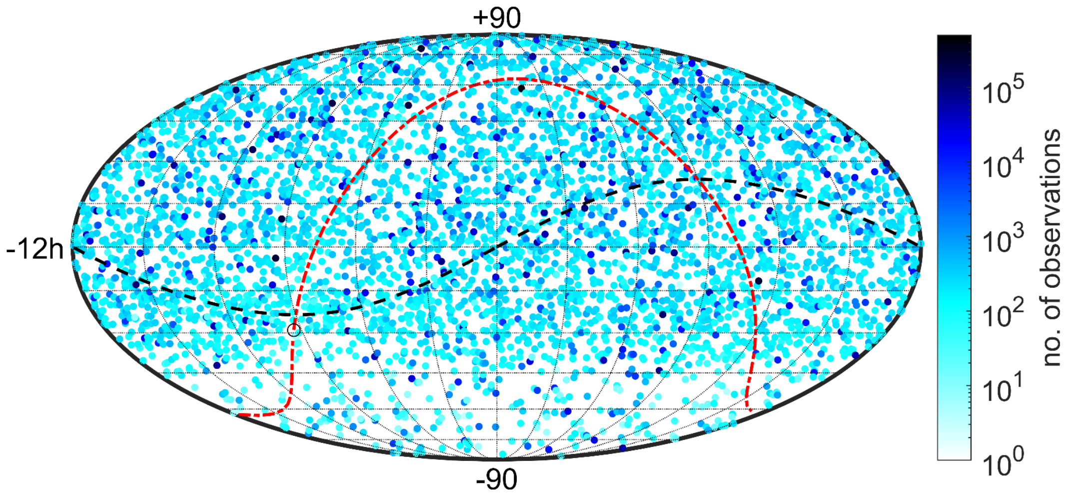


ITRF2020 scale relies on

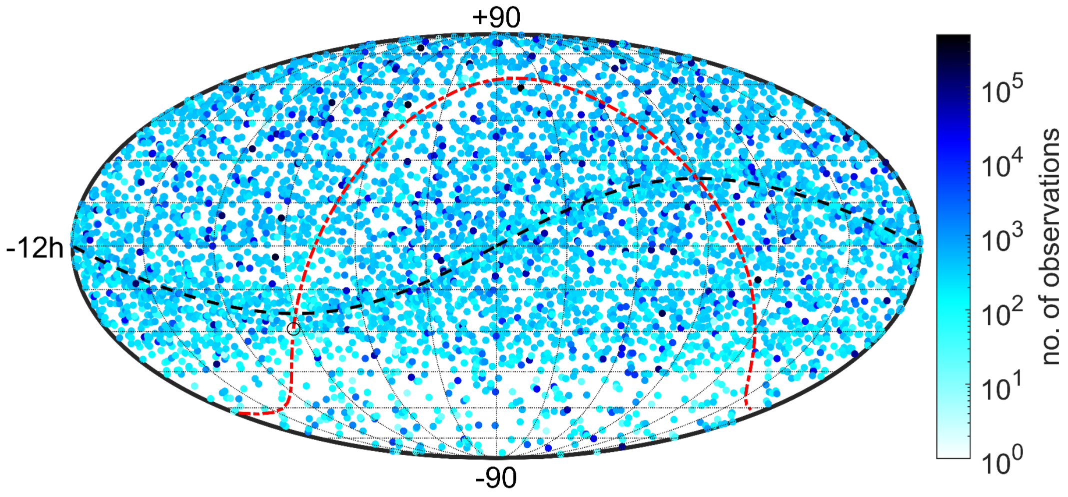
- VLBI (selected sessions until 2013.75)
- SLR

Global
Celestial Reference Frame
VIE2022sx

VIE2022sx versus ICRF3sx

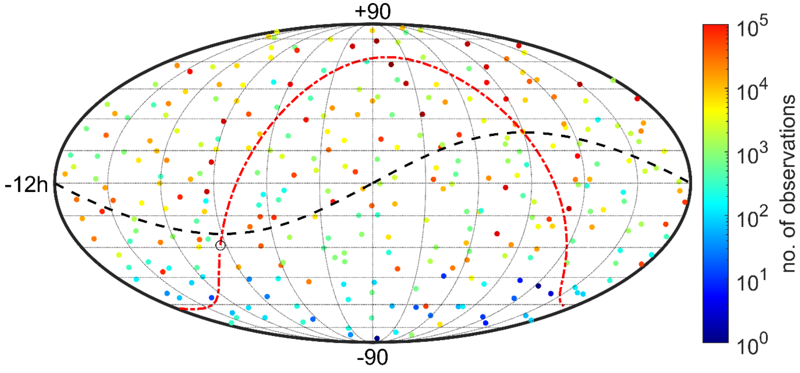


ICRF3sx		# sources	# obs.	median obs. per sou.
all sources	<0°, 90°>	2615	9.8e+06	254
	<-45°, 0°>	1665	3.1e+06	186
	<-90°, -45°>	256	2.7e+05	58

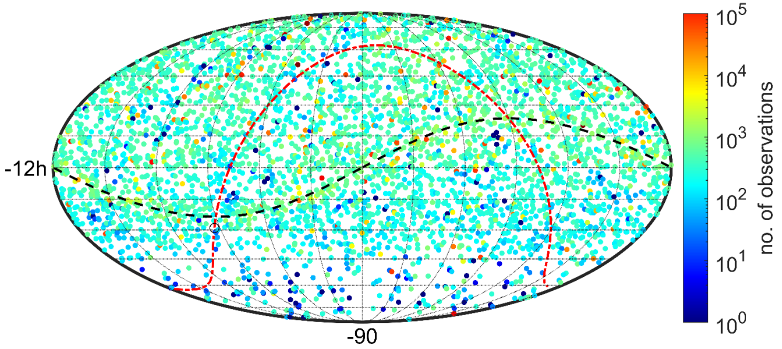


VIE2022sx		# sources	# obs.	median obs. per sou.
all sources	<0°, 90°>	3125	1.3e+07	426
	<-45°, 0°>	2038	4.5e+06	303
	<-90°, -45°>	268	4.0e+05	148

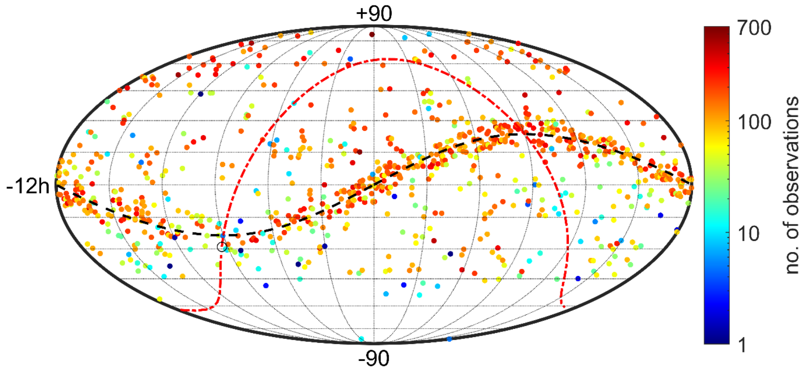
Observations in VIE2022sx after ICRF3sx cutoff date



303 defining ICRF3sx



4234 non-defining ICRF3sx



894 non ICRF3sx

ICRF3sx		# sources	# obs.	median obs. per sou.
def	<0°, 90°>	149	1.7e+06	3548
	<-45°, 0°>	105	8.4e+05	2140
	<-90°, -45°>	49	5.7e+04	277
non-def	<0°, 90°>	2467	1.6e+06	199
	<-45°, 0°>	1561	5.0e+05	126
	<-90°, -45°>	206	7.1e+04	63
new	<0°, 90°>	510	1.0e+05	197
	<-45°, 0°>	373	5.8e+04	141
	<-90°, -45°>	12	5.6e+02	29

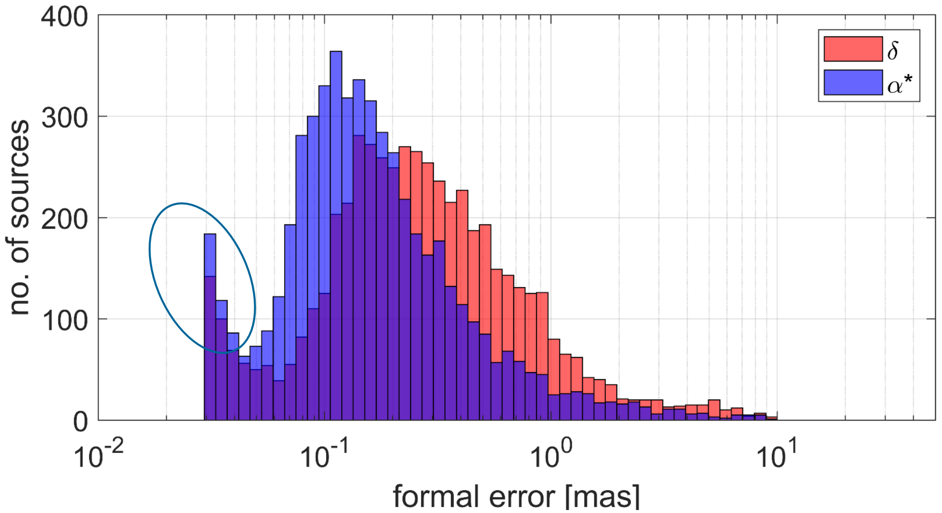
Defining sources in ICRF3

- Defining sources are needed for rotational alignment with the underlying CRF
- For ICRF3 a new set of defining sources was selected

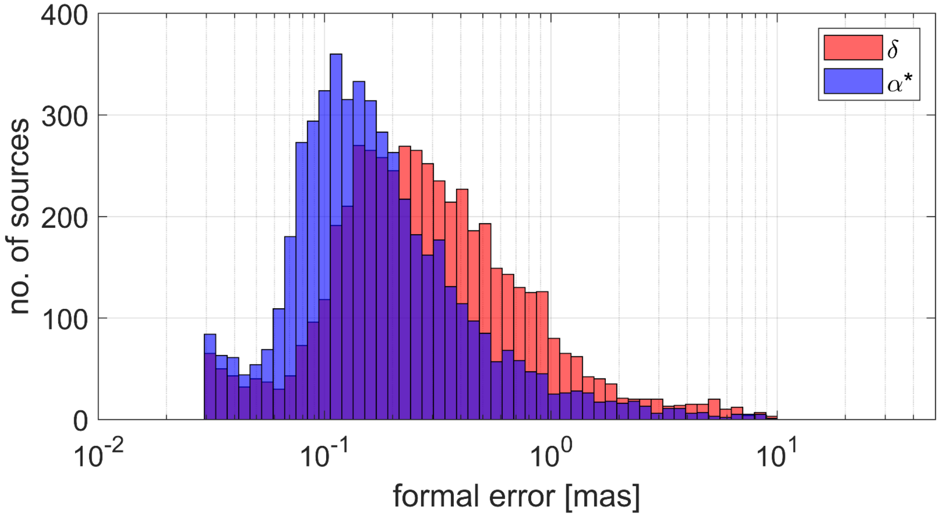
- Selection criteria
  - overall sky distribution of the defining sources
  - position stability of the individual sources
  - compactness of their structure

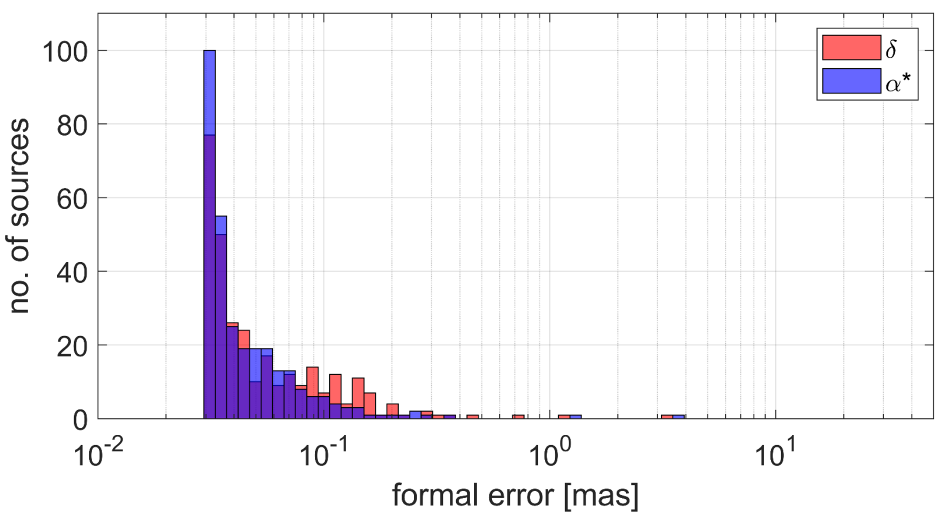
- In VIE2022 we apply unweighted no-net-rotation condition

Distribution of formal errors in VIE2022sx

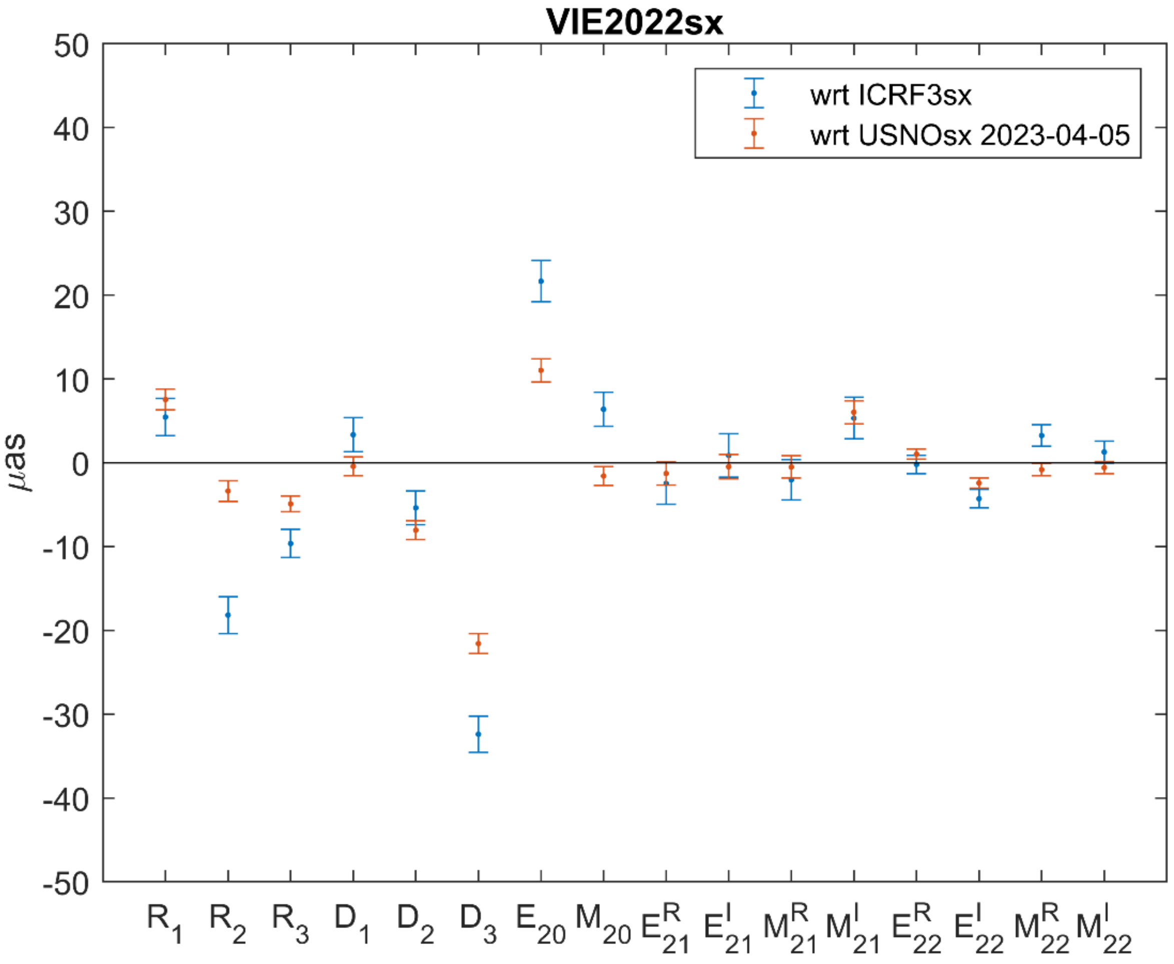


median formal error	α* [µas]	δ [µas]
all sources in VIE2022sx	143	249
non-defining	151	265
defining	37	41





VSH parameters up to degree 2



Vector spherical harmonics decomposition (VSH, Mignard & Klioner, 2012; Titov & Lambert, 2013)

- Rotation (R_1, R_2, R_3)
- Dipole (D_1, D_2, D_3)
- Coefficients for quadrupole harmonics

- 35 AGN removed as outliers
  angular separation to ICRF3 > 10 mas

Global
Celestial Reference Frame at K-band
VIE2022b-k

K-band CRF

- K-band Working Group (PI: Aletha de Witt)

- Krásná H., Gordon D., de Witt A., Jacobs C.S. (2023)
  The K-band (24 GHz) CRF determined from VLBI sessions conducted over the past 20 years, IAGS Series

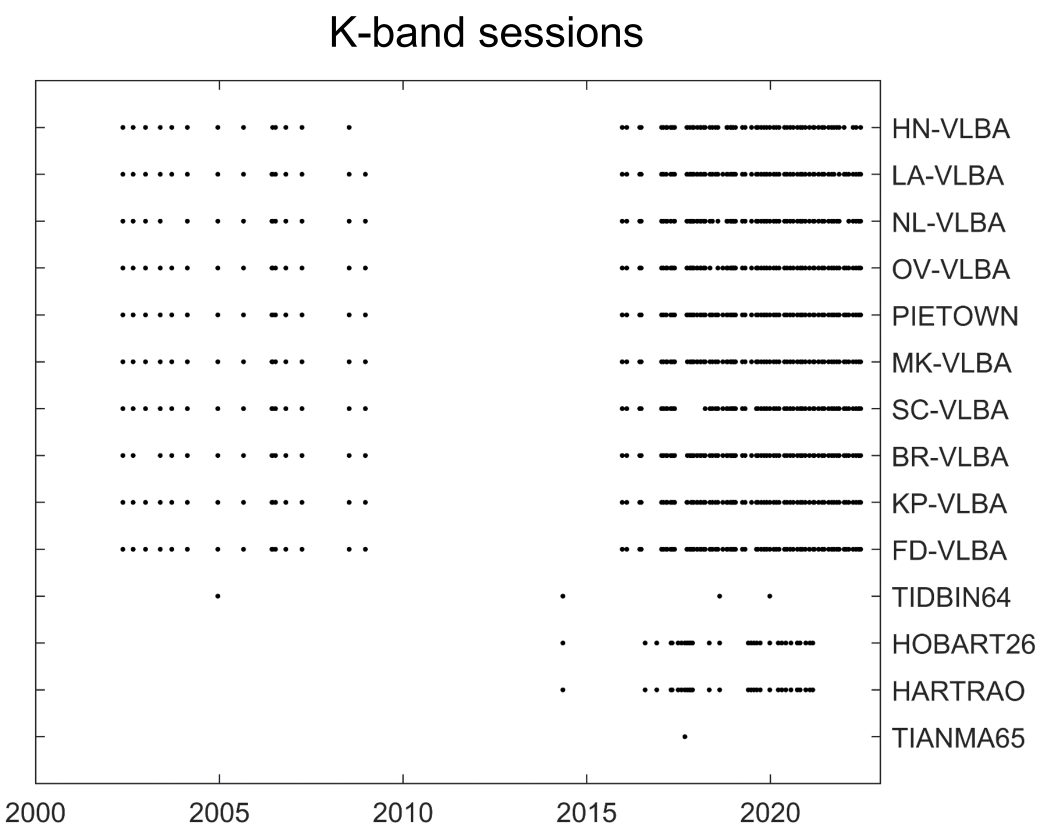
  - Comparison and assessment of systematic differences between K-band solutions
  - K-band VLBI sessions 2002.5 – 2022.5

  - Two main challenges in K-CRF computation
    - Observations at a single frequency require an external ionospheric calibration
    - 99% of observations come from VLBA causing a globally non-optimal observation geometry

  - Solutions
    - USNO-K-2022July05, David Gordon, Calc/Solve
    - VIE-K-2022b, VieVS

K-band sessions VIE2022b-k

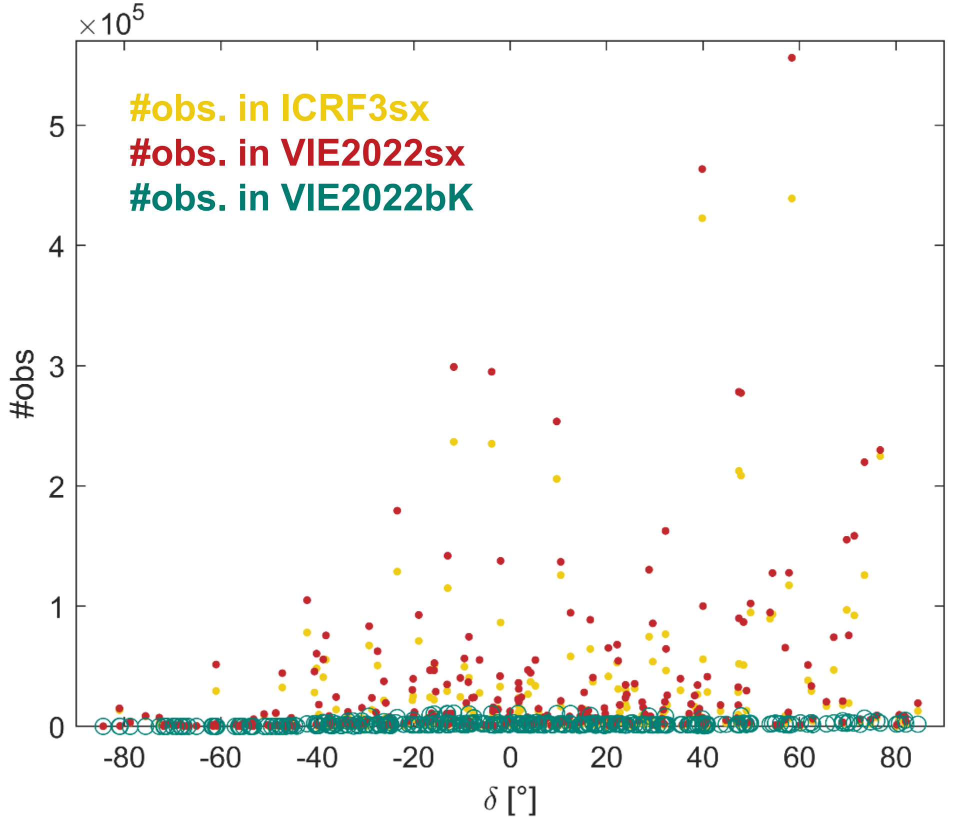
time span	session code	data rate [Mbps]
	Northern (VLBA) sessions	
05/2002 - 12/2008	BR079a-c, BL115a-c, BL122a-d, BL151a-b	128
06/2006 - 10/2006	BP125a-c	256
12/2015 - 10/2019	BJ083a-d, UD001a-x, UD009a-o	2048
11/2019 - 06/2022	UD009p-z, UD009aa-ah, UD015a-l	4096
	Southern sessions	
05/2014 - 07/2016	KS1401, KS1601	1024
11/2016 - 02/2021	KS1603, KS1702-KS2102	2048

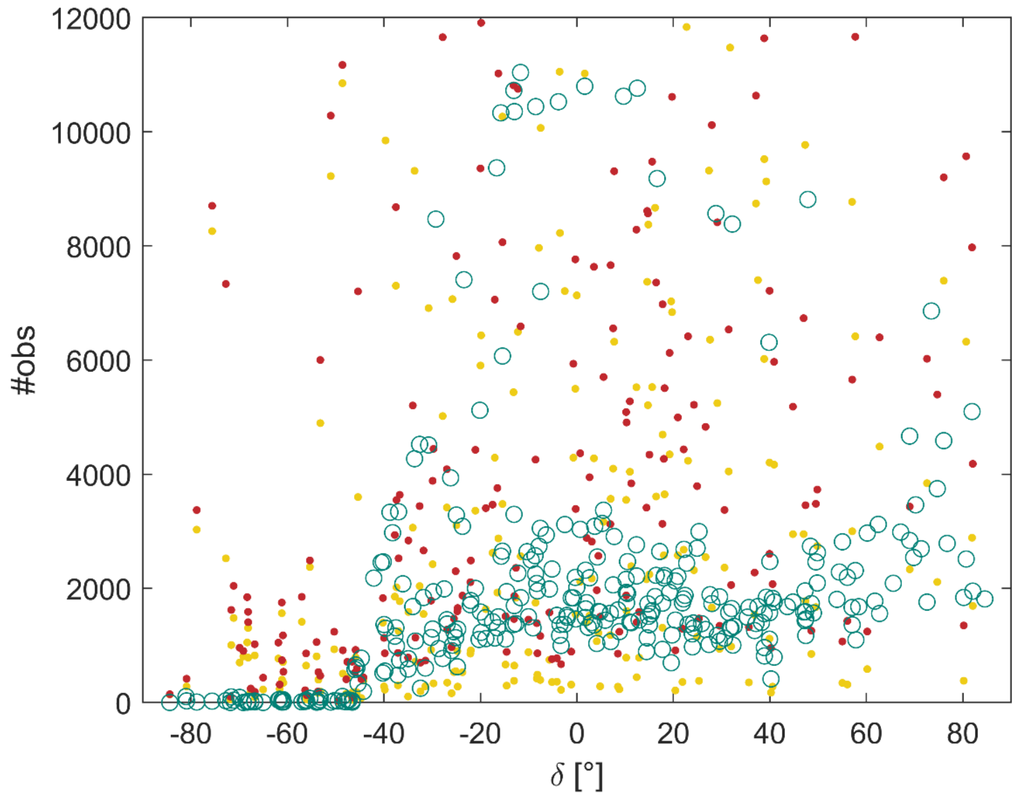


Defining sources in ICRF3

299 (out of 303) ICRF3sx defining sources
are observed at K-band (VIE2022bK cutoff date June 2022)

more observations at K-band have:
73 sources (24%) compared to ICRF3sx
33 sources (11%) compared to VIE2022sx





Investigation on ionospheric mf

Ionospheric mapping function
(Schaer, 1999; recently discussed in Petrov, 2023)

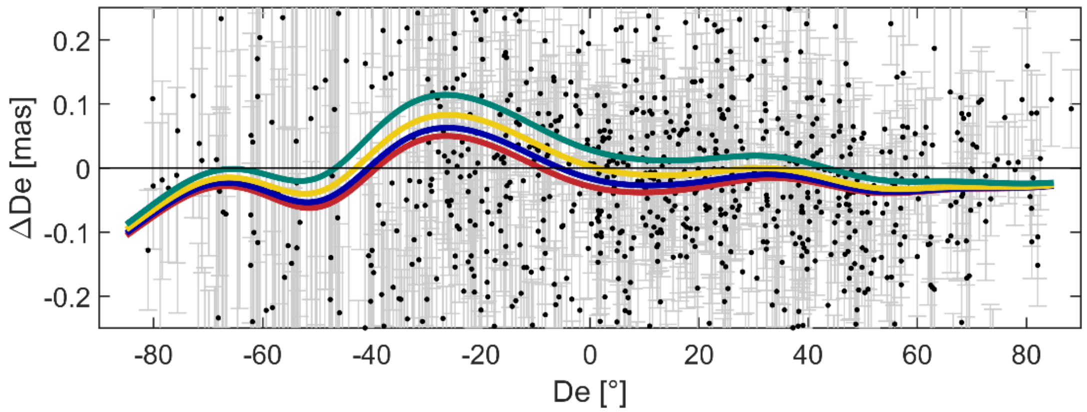
$$M(\epsilon) = k \cdot \frac{1}{\sqrt{1 - \left(\frac{R_E}{R_E + H_i + \Delta H}\right)^2 \cdot \cos^2 \alpha\epsilon}},$$

Table 4 Parameters of the ionospheric mapping function and the resulting VSH parameters D_3 and $a^e_{2,0}$.

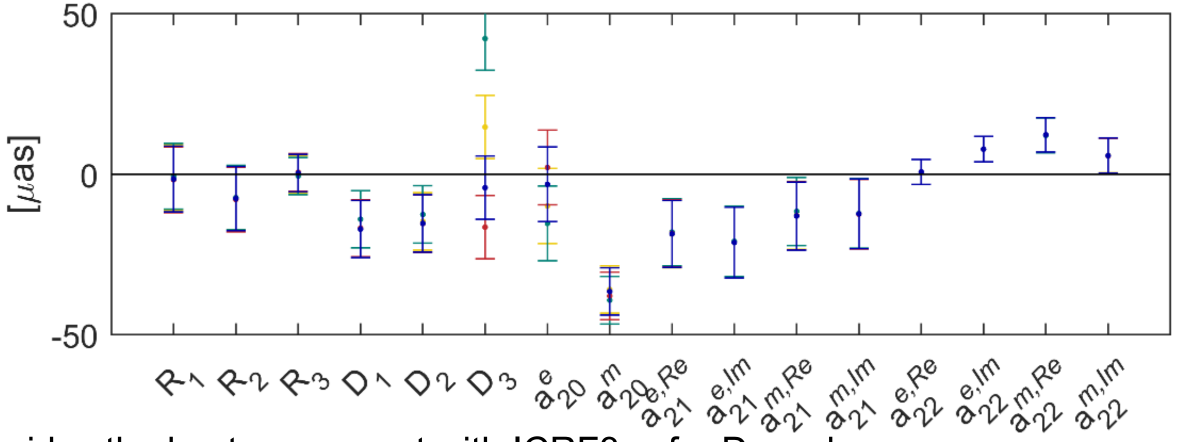
	k [-]	ΔH [km]	α [-]	D_3 [µas]	$a^e_{2,0}$ [µas]
MSLM	1	56.7	0.9782	-4 ± 10	-3 ± 12
SLM	1	0	1	-17 ± 10	$+2 \pm 12$
iono3	1	150.0	0.9782	15 ± 10	-10 ± 12
iono4	0.85	56.7	0.9782	42 ± 10	-15 ± 12

VIE-K-2022b →

VIE-k w.r.t. ICRF3sx



VIE-k w.r.t. ICRF3sx



Modified Single-Layer Model mf provides the best agreement with ICRF3sx for D_3 and $e_{2,0}$

Thank you for your attention!

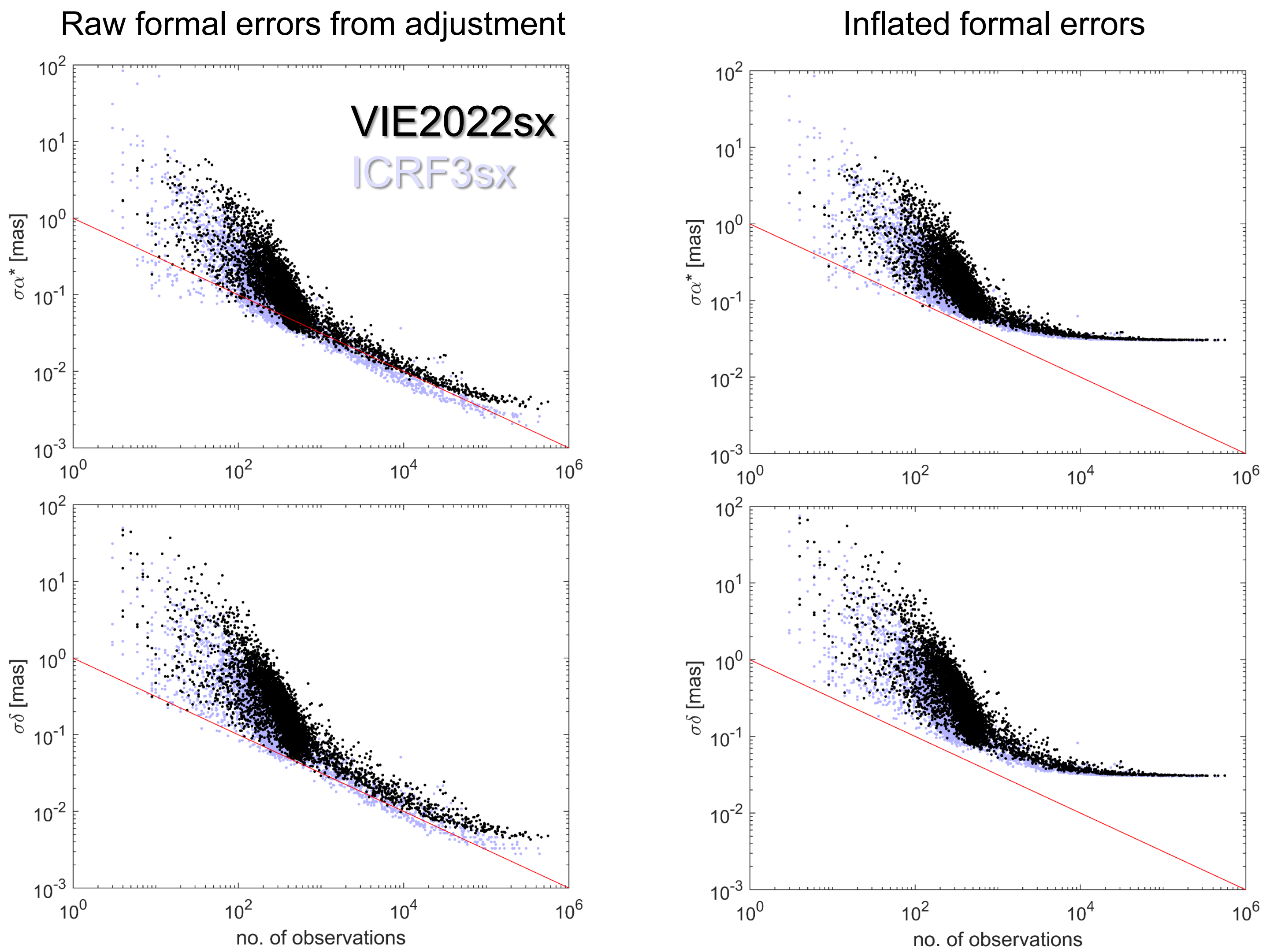
Celebrating 40 years of astrometric and geodetic VLBI data

–

a solid foundation for celestial and terrestrial reference frames

Backup

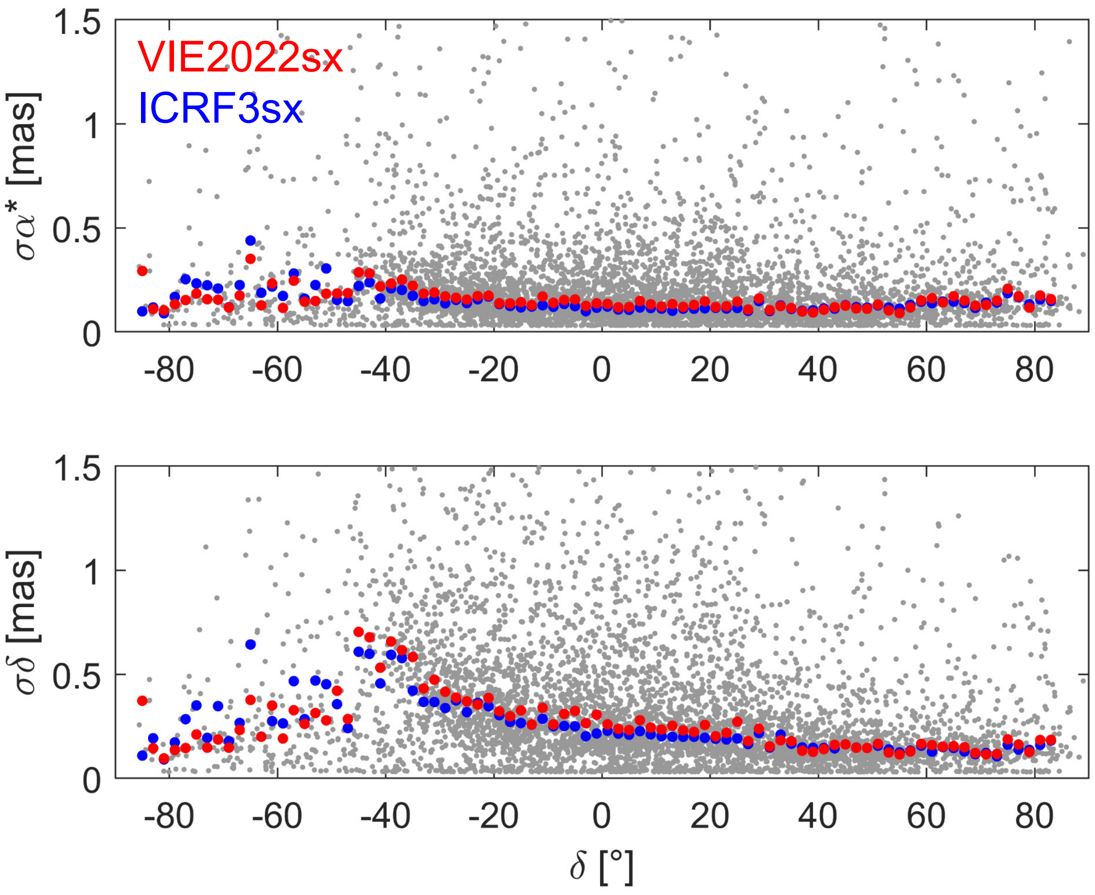
Formal errors w.r.t. #observations (VIE2022sx)



- In theory, formal errors decrease with $\sqrt{\#obs}$ (Gaussian errors)
- General assumption of LSM – observations are uncorrelated
  - in the real word, e.g., spatial and temporal correlations due to troposphere, or the same observation set up at a station for all observations
  - accounting of the elevation-dependent weighting in VIE2022sx
- Inflation of formal errors in ICRF3 and VIE2022sx
  - scaling factor of 1.5 (determined firstly by Ryan et al. 1993)
  - noise floor of 30 µas determined for ICRF3

Formal errors w.r.t. declination

Inflated formal errors from VIE2022sx



median errors computed over 2° declination

Uncertainties in declination

- a growth starting at 30° declination (median σ_{De} = 150 µas) which accelerates until −45° declination (median σ_{De} = 700 µas).
- Further south, the formal errors jump back to values around 250 µas.

The majority of sources was observed in campaigns of VLBA Calibrator Survey

- based on its location, observes the southern sources under rather low elevation angles.
- This means that the path of the signal in the atmosphere is longer, which leads to larger formal errors of the estimated position of the emitting radio sources.

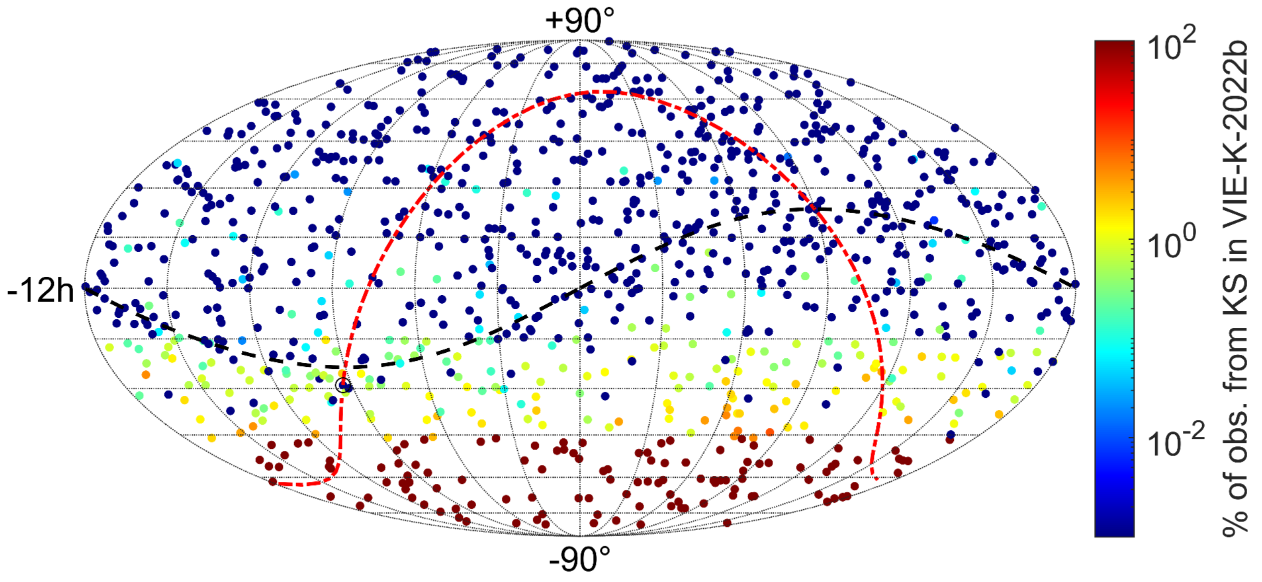
.

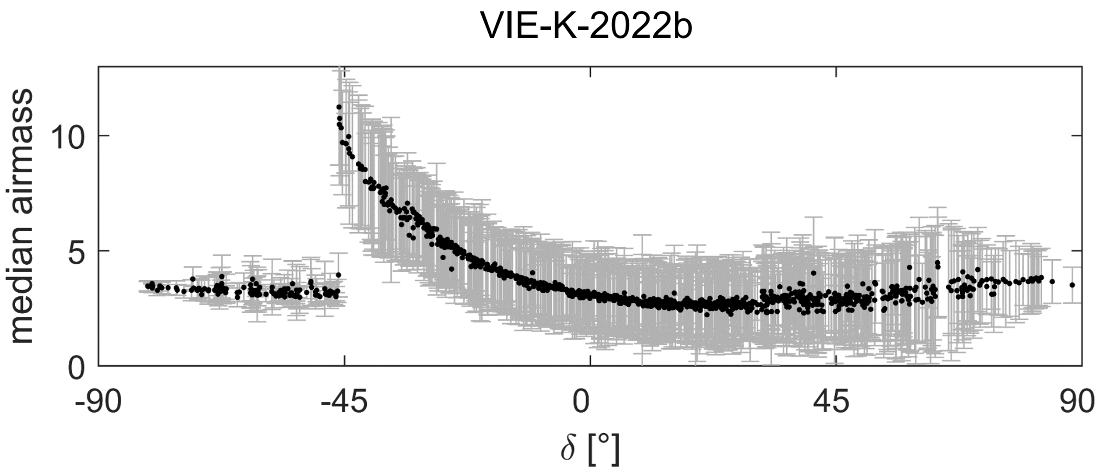
Systematic in elevation angles (VIE2022b-k)

<u>airmass</u> – parameter quantifying the path length through the troposphere for each sources

$$\text{airmass} = \frac{1}{\sin(\varepsilon_1)} + \frac{1}{\sin(\varepsilon_2)}$$

ε – elevation angle





Elevation weighting of observations (Gipson et al., 2008) accounts partly for the overweighting of the low elevation scans from VLBA (which observe low declination sources in the declination area between approx. -10° to -45°).