L01 – Why do we do it?
A motivation for (and an overview of) VLBI for Geodesy and Geosciences

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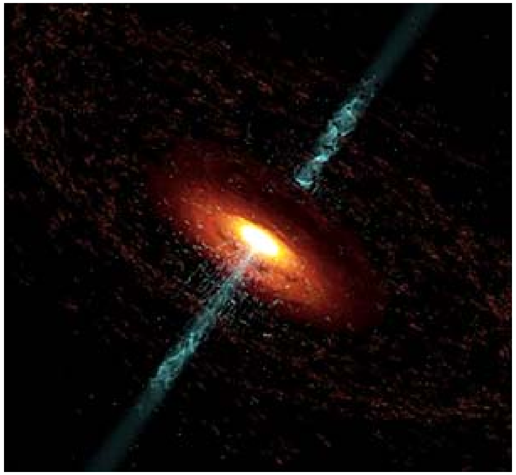
Outline

- Geodetic VLBI principles
  - Radio sources and radio telescopes
  - Data flow and analysis
  - Correlation and fringe fitting
  - Bandwidth synthesis
- International VLBI Service for Geodesy and Astrometry
  - Observing network and operations
  - Operational products
  - Further results
- VLBI Global Observing System (VGOS)
- Global Geodetic Observing System (GGOS)

Radio sources



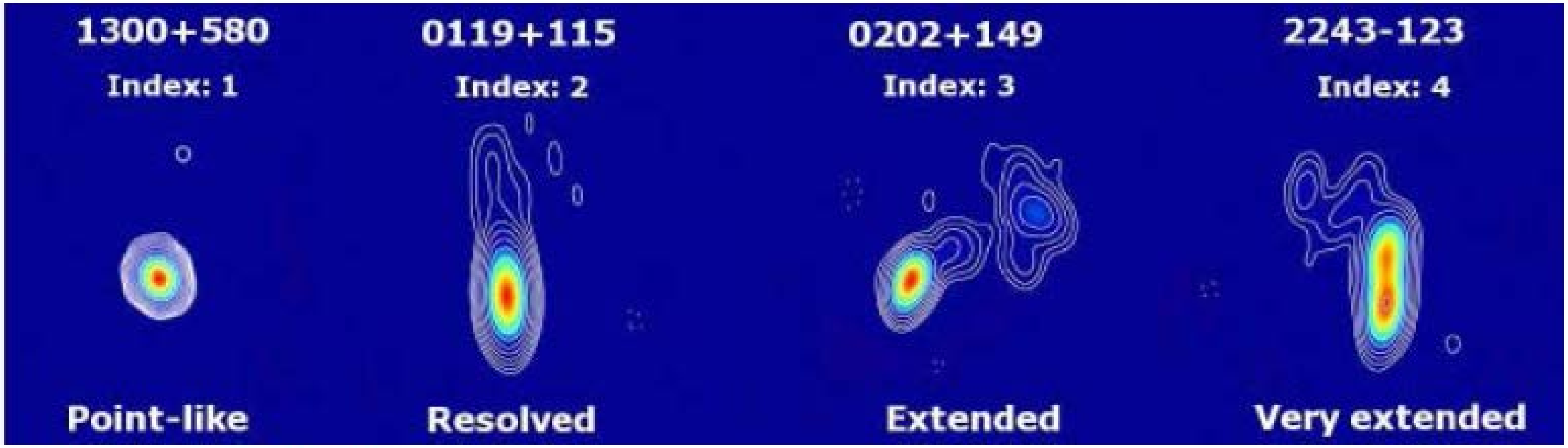
Active galactic nuclei, galaxies, quasars

Distance 2 – 8 billion light years

Point sources

No proper motions

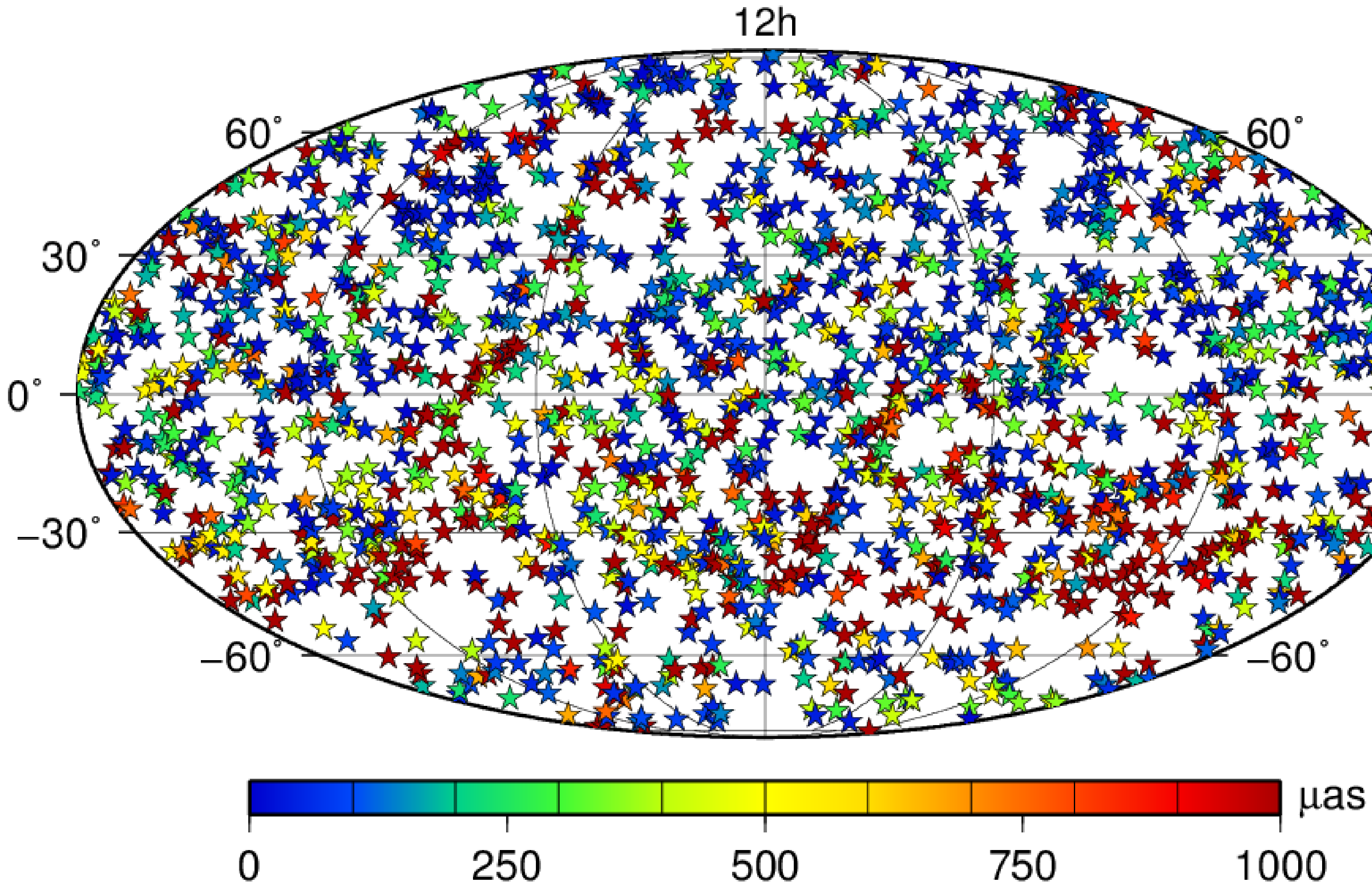
→quasi-inertial reference system



Collioud and Charlot (2009)

ICRF-2

International Celestial Reference Frame (ICRF)



Radio telescopes

Wettzell, Germany

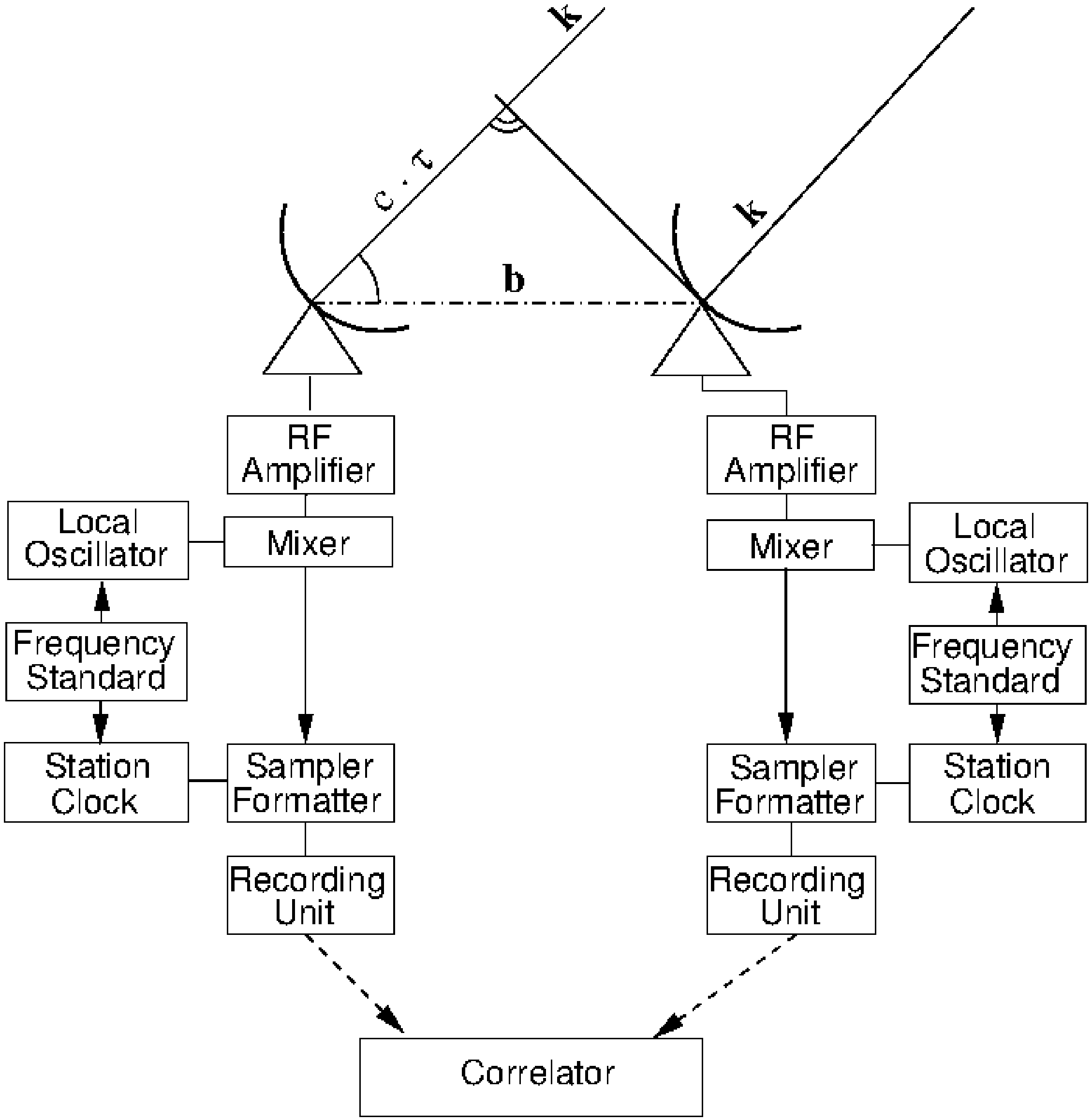
O,Higgins, Antarctica

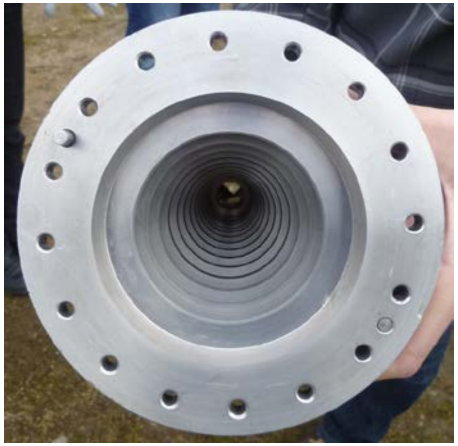
© BKG

Urumqi, China

Effelsberg, Germany

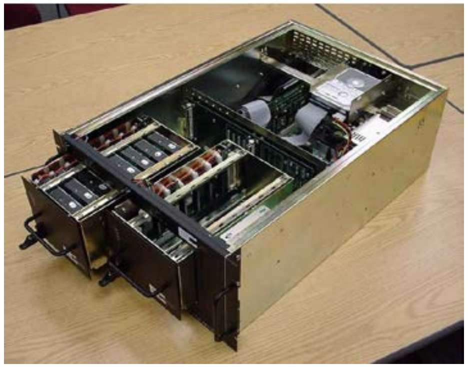
VLBI principles I



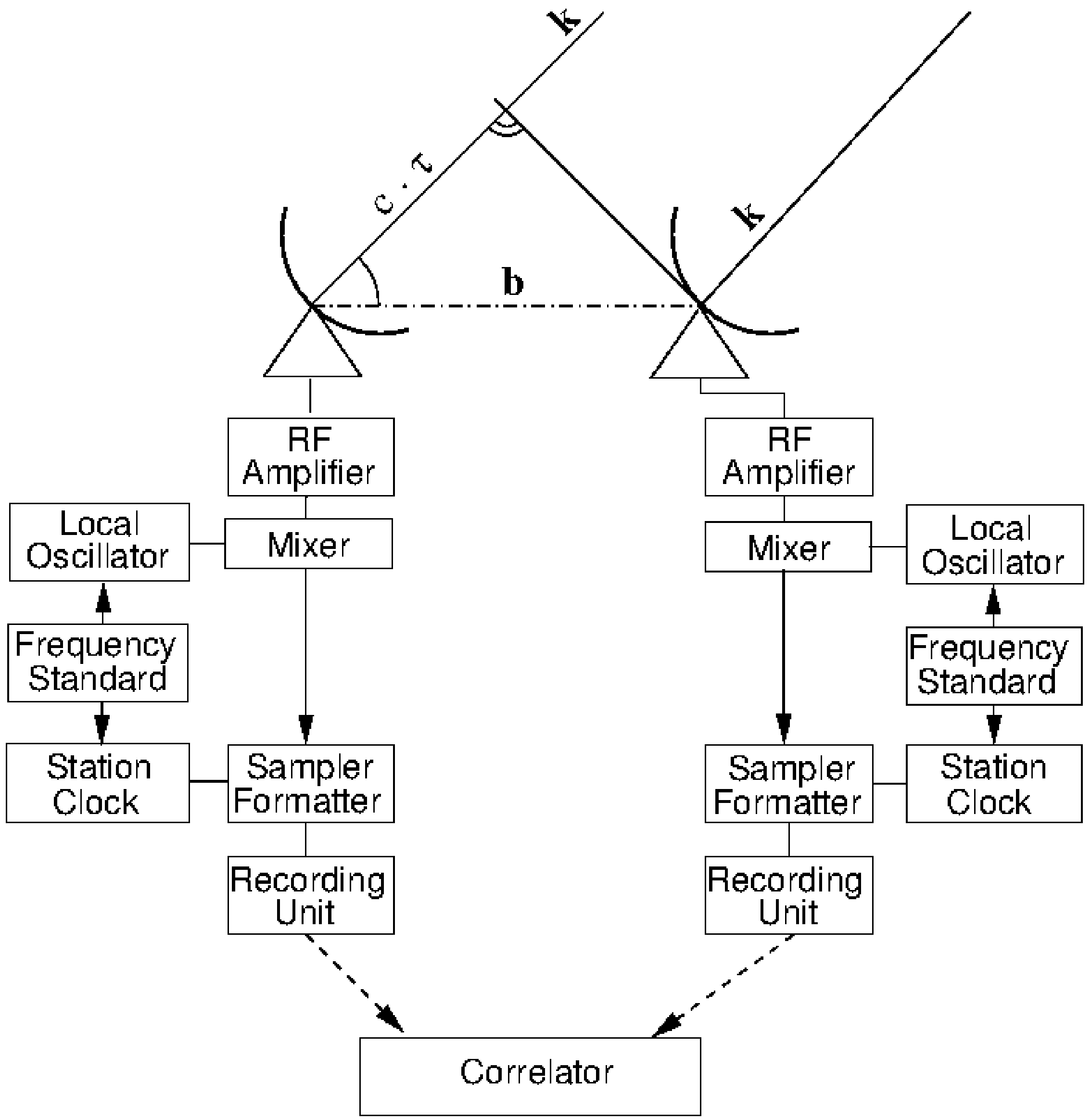


Flat-spectrum noise

720 / 130 MHz
X/S band

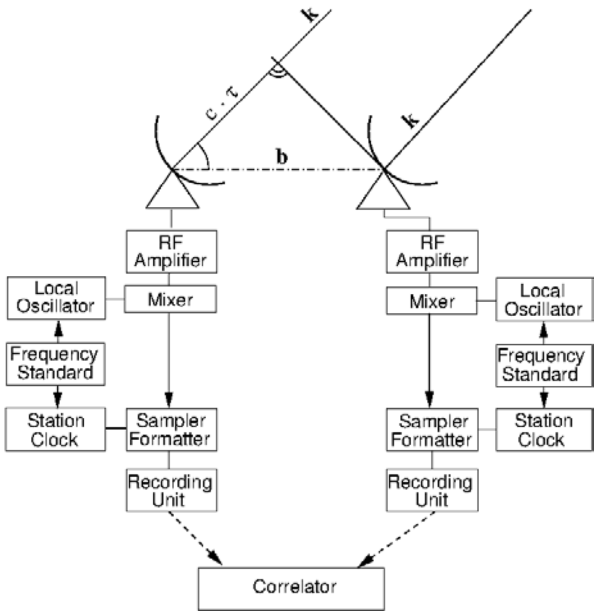


VLBI principles I

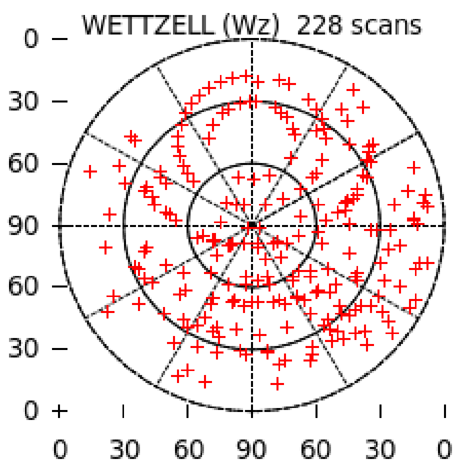


- Number of correlated bits determine accuracy
  → large bandwidth
- Data volume of several TeraByte per day
- Data transfer to correlator
  - By network links
  - By disk units

VLBI principles II

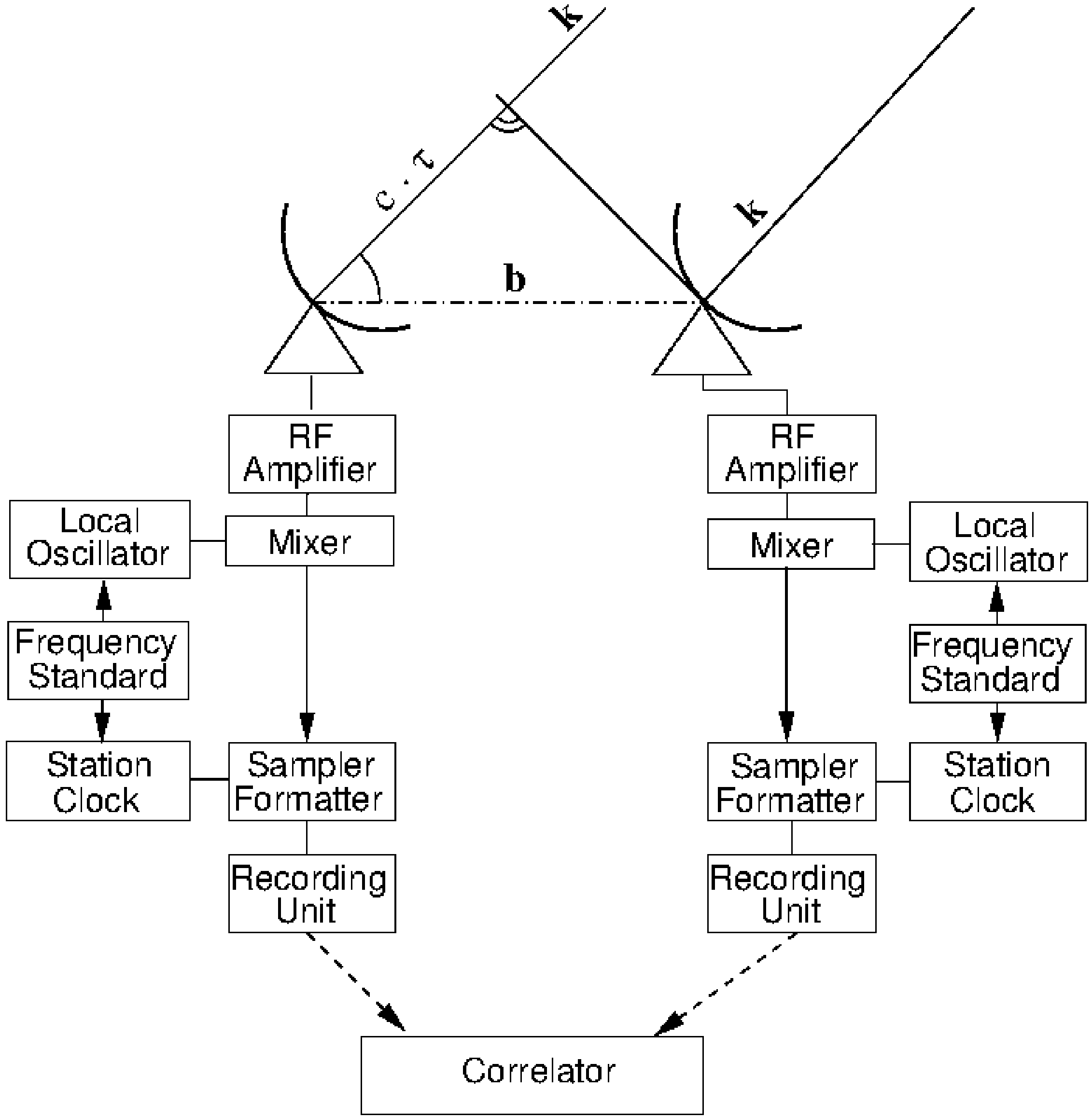


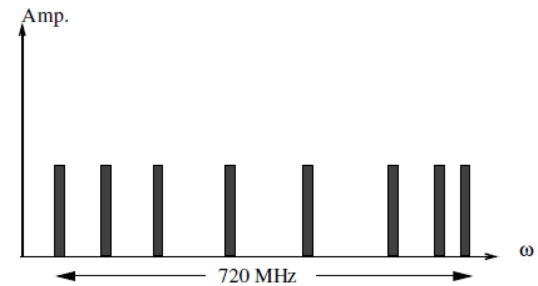
- Recording time 20 – 200 s (= 1 scan) (Integration time for signal-to-noise)
- Earth rotates
- Geometry not stationary
- Makes group delay determination complicated
- 1 scan produces one group delay/delay rate

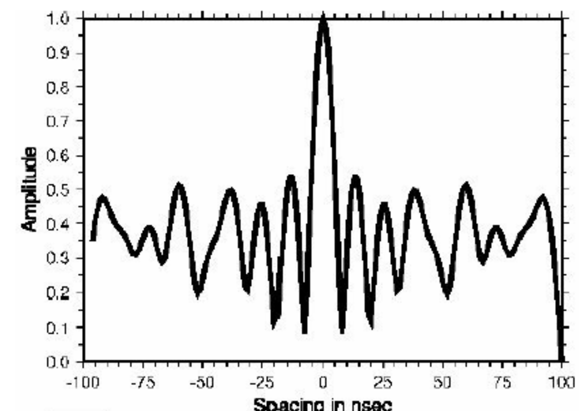


- Multiple scans in one observing session (1hr or 24 hour duration)
- Intermediate step: Correlation

VLBI principles II

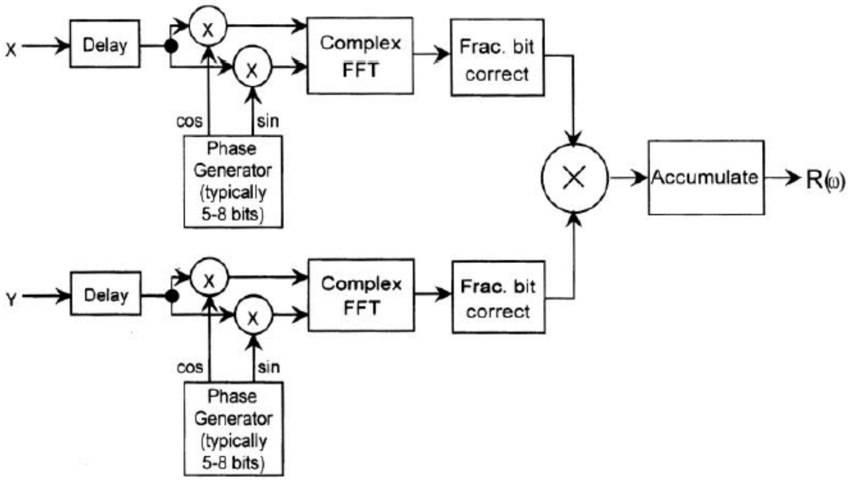




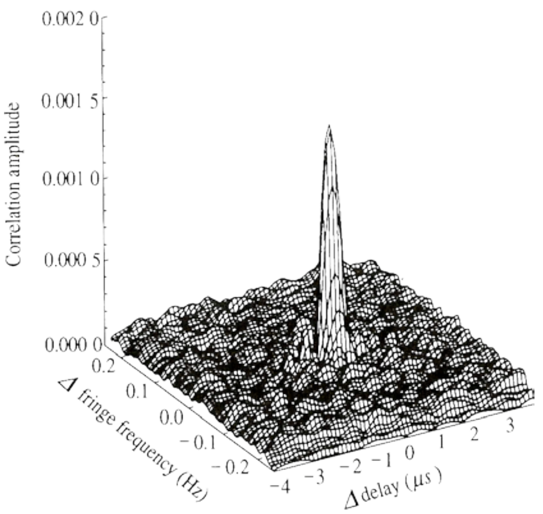


Correlation

FX cross correlation process



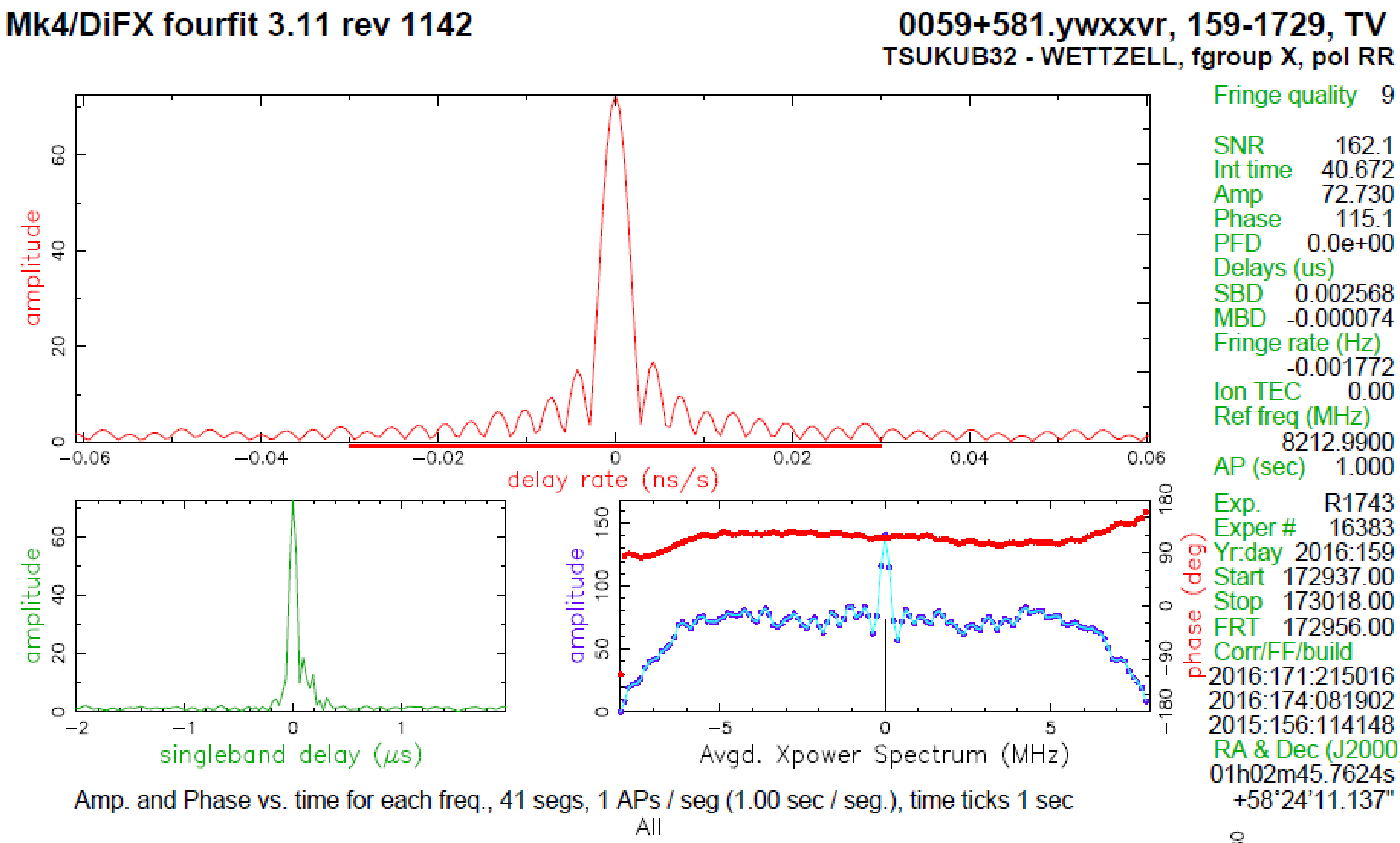
Correlation makes extensive use of a priori information (geometry, clocks, atmosphere) to limit trial regions



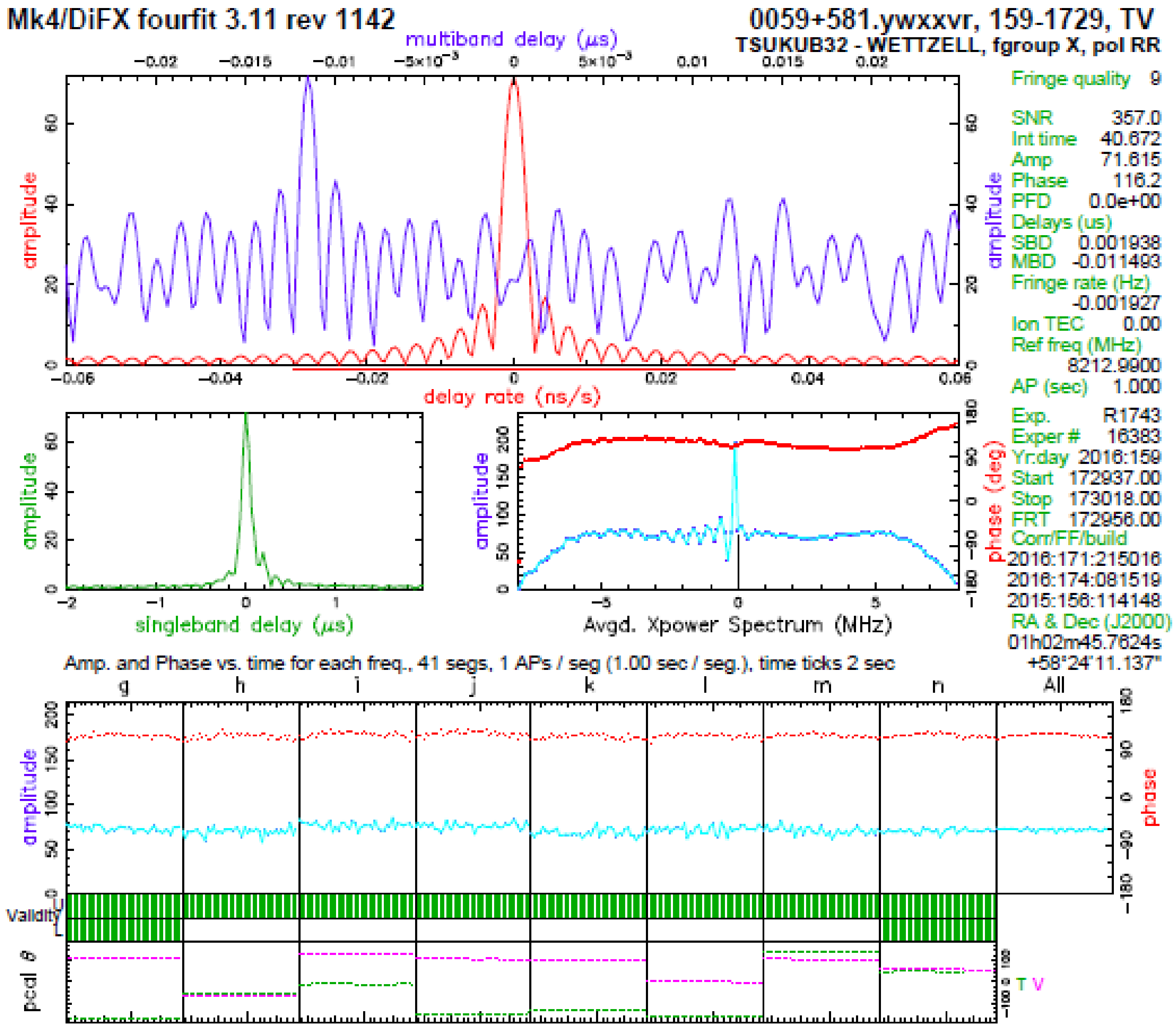
Fringe fitting = Search for max. correlation amplitude (time lag and fringe rate)

[always near zero]

Single band delay



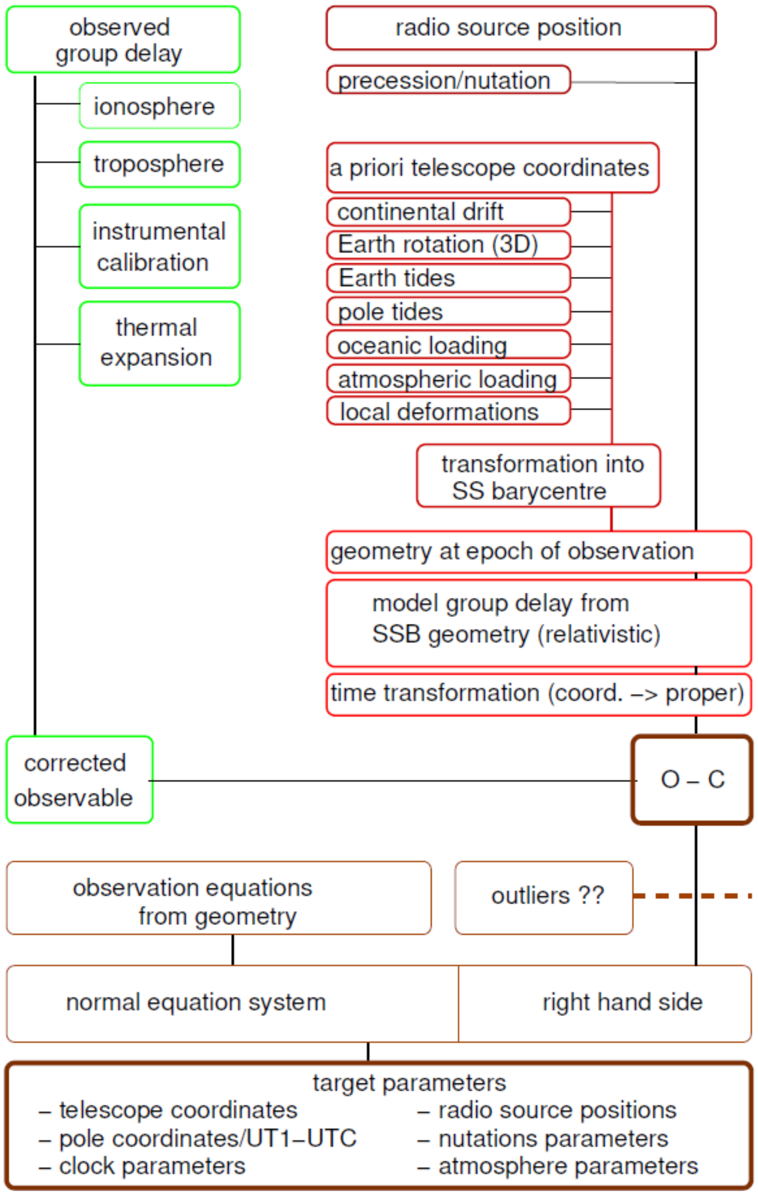
8-channel multiband delay



Overall goals

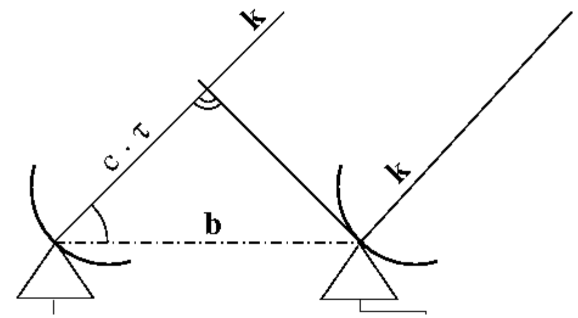
- **Reference frames and their kinematics**
  - **Celestial**
    - Quasars and other compact radio sources
    - Pulsars
    - Spacecraft tracking
    - Planetary investigations
  - **Terrestrial**
    - Positions and velocities (higher order phenomena)
    - Links to other techniques
- **Earth Orientation Parameters**
  - **Nutation, daily rotation, polar motion (time derivatives)**
- **Atmosphere/Troposphere (Climatology)**

Data analysis



Input 200 – 400 group delays per baseline per 24 hours

$$\tau = -\frac{1}{c}\vec{b} \cdot R(t) \cdot \vec{k}$$



Least-squares adjustment builds on well known a priori geometry → **O – C**

Many geometric and geophysical effects are applied and corrections may be estimated

Fundamental equation with corrections

$$\tau_{geo} = -\frac{1}{c} b_{i.6} \cdot W_{ij.} \cdot S_{ij.} \cdot Q_{ij.} \cdot k_{i.2}$$

$$\tau_{obs} = \tau_{geo} - \tau_{geo}\left(\frac{(v_{i.}+v^b_{i.})\cdot k_{i.}}{c} + \frac{(v_{i.}\cdot k_{i.})^2+2(v_{i.}\cdot k_{i.})(v^b_{i.}\cdot k_{i.})}{c^2} + \frac{(b_{i.}\cdot v_{i.})(v^b_{i.}\cdot k_{i.})}{c^3} + \frac{(b_{i.}\cdot v_{i.})(v_{i.}\cdot k_{i.})}{2c^3}\right) + \text{corrections} + \text{e}$$

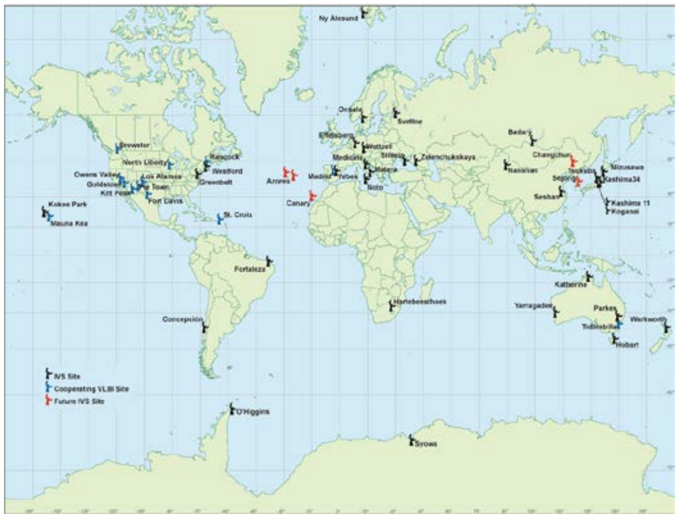
$$\tau_{obs} = -\frac{1}{c}\begin{pmatrix} x_{a.6} - x_{b.6} \\ y_{a.6} - y_{b.6} \\ z_{a.6} - z_{b.6} \end{pmatrix} \cdot W_{ij.}(xp, yp) \cdot S_{ij.}(UT1) \cdot Q_{ij.}(X, Y) \cdot \begin{pmatrix} \cos\delta_{.2} \cdot \cos\alpha_{.2} \\ \cos\delta_{.2} \cdot \sin\alpha_{.2} \\ \sin\delta_{.2} \end{pmatrix} \cdot \left(1 - F(v_{i.}, v^b_{i.})\right) + \text{corrections} + \text{e}$$

$b_{i.6}$	Baseline components in Earth-fixed system with	F	Abberation terms
$x_{*.}, y_{*.}, z_{*.}$	components of telescope coordinates		
$W_{ij.}$	Rotation matrix for polar motion	v	Velocity of geocentre
$S_{ij.}$	Rotation matrix for daily spin	v^b	Velocity of telescope 2 w.r.t. geocentre
$Q_{ij.}$	Rotationsmatrix for precession/nutation	$\alpha_{i.}$	Right Ascension
$k_{i.2}$	Unit vector in source directions in sky-fixed system	$\delta_{i.}$	Declination
	with $\alpha_{i.}$, $\delta_{i.}$	e	Observation deviations

IVS

International VLBI Service for Geodesy and Astrometry

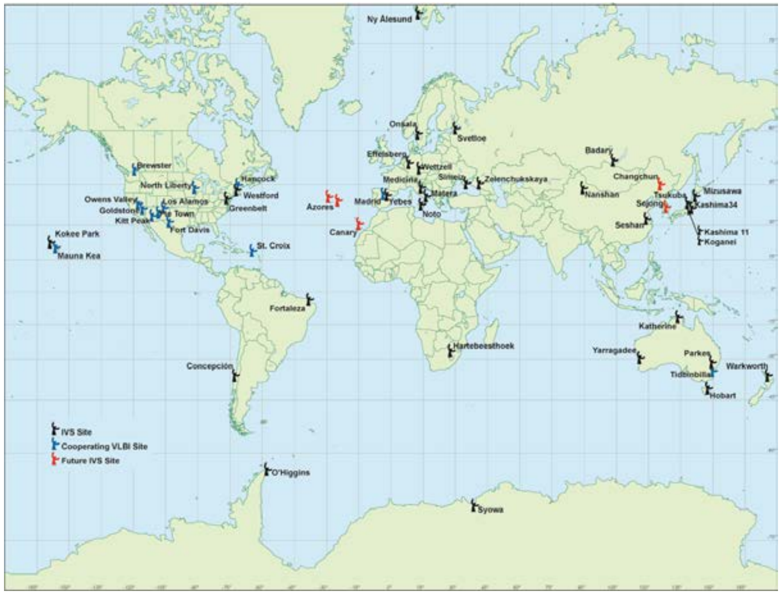
The IVS is an international collaboration of organizations which operate or support VLBI components

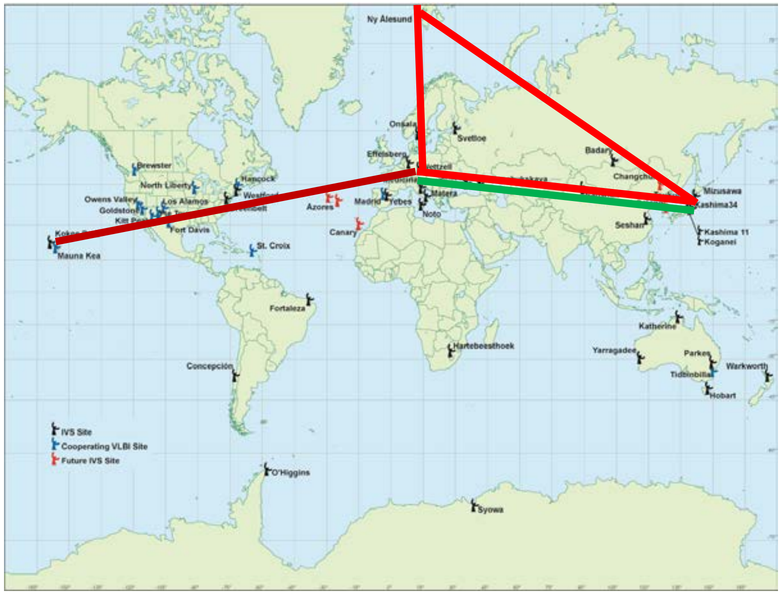


IVS Observing Sessions

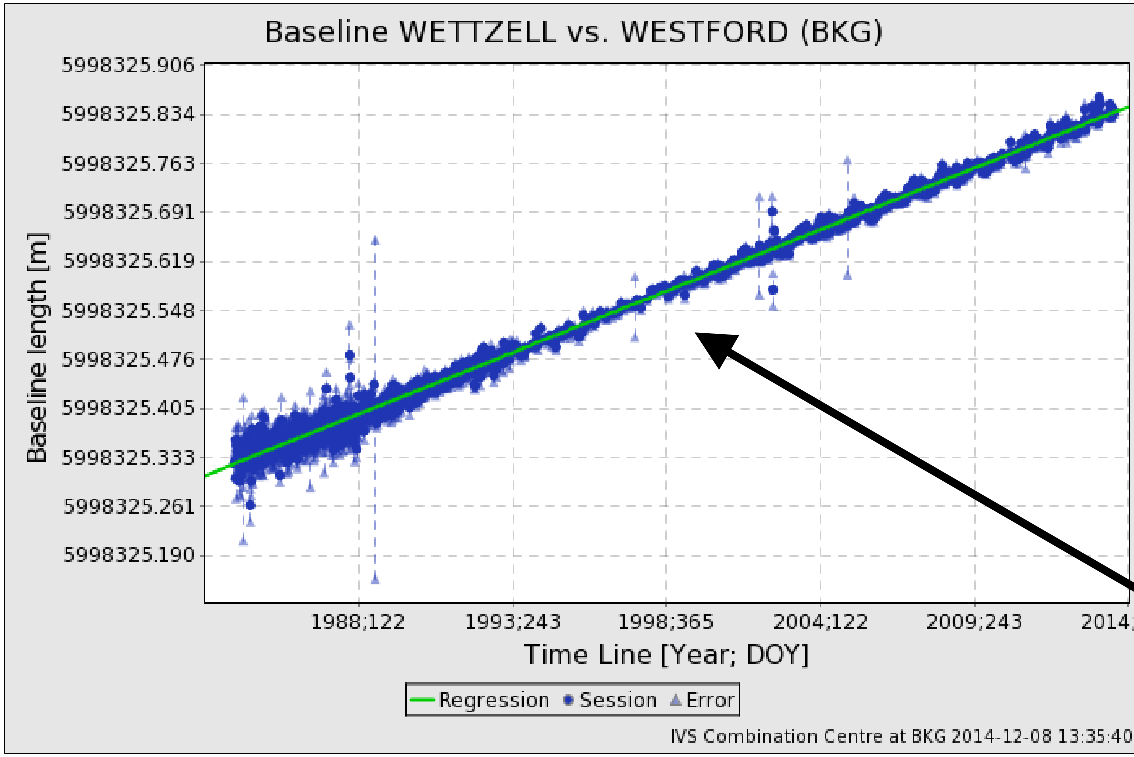
- Network sessions (24 hr duration)
  - R1, R4 for regular Earth orientation parameter determinations
    (8 – 10 telescopes)
  - T2, OHIG, EUROPE, AOV, for telescope coordinate determinations (up to 18 telescopes)
  - CRF for celestial reference frame (4 – 7 telescopes)

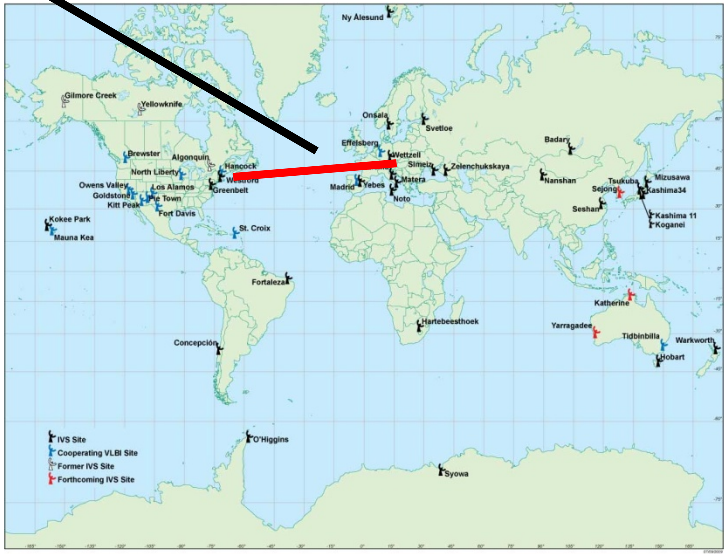
- Single baseline/triangle sessions (1 hr duration)
  - Daily sessions for the determination of UT1-UTC



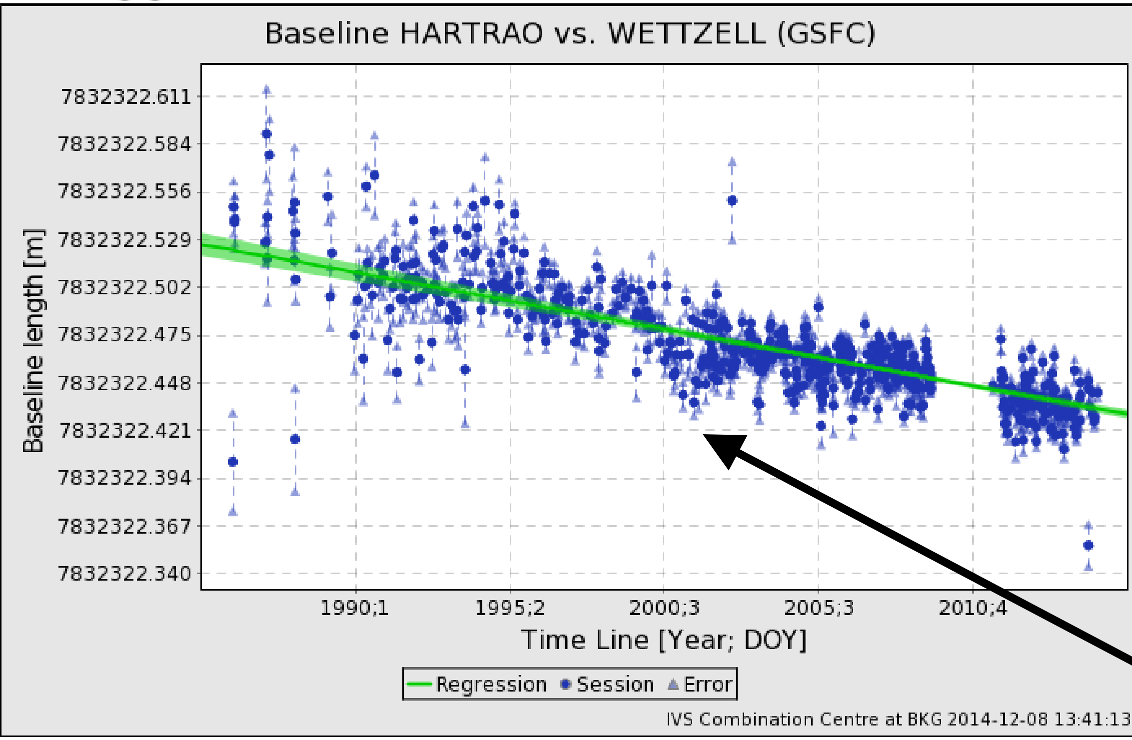


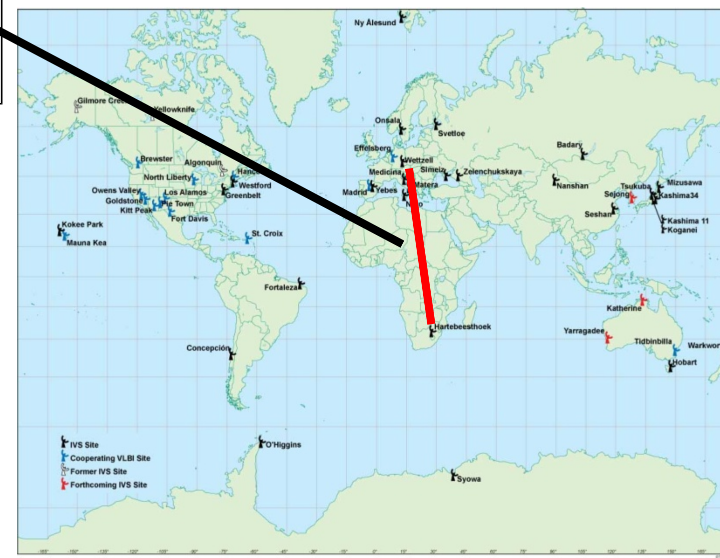
Westford - Wettzell



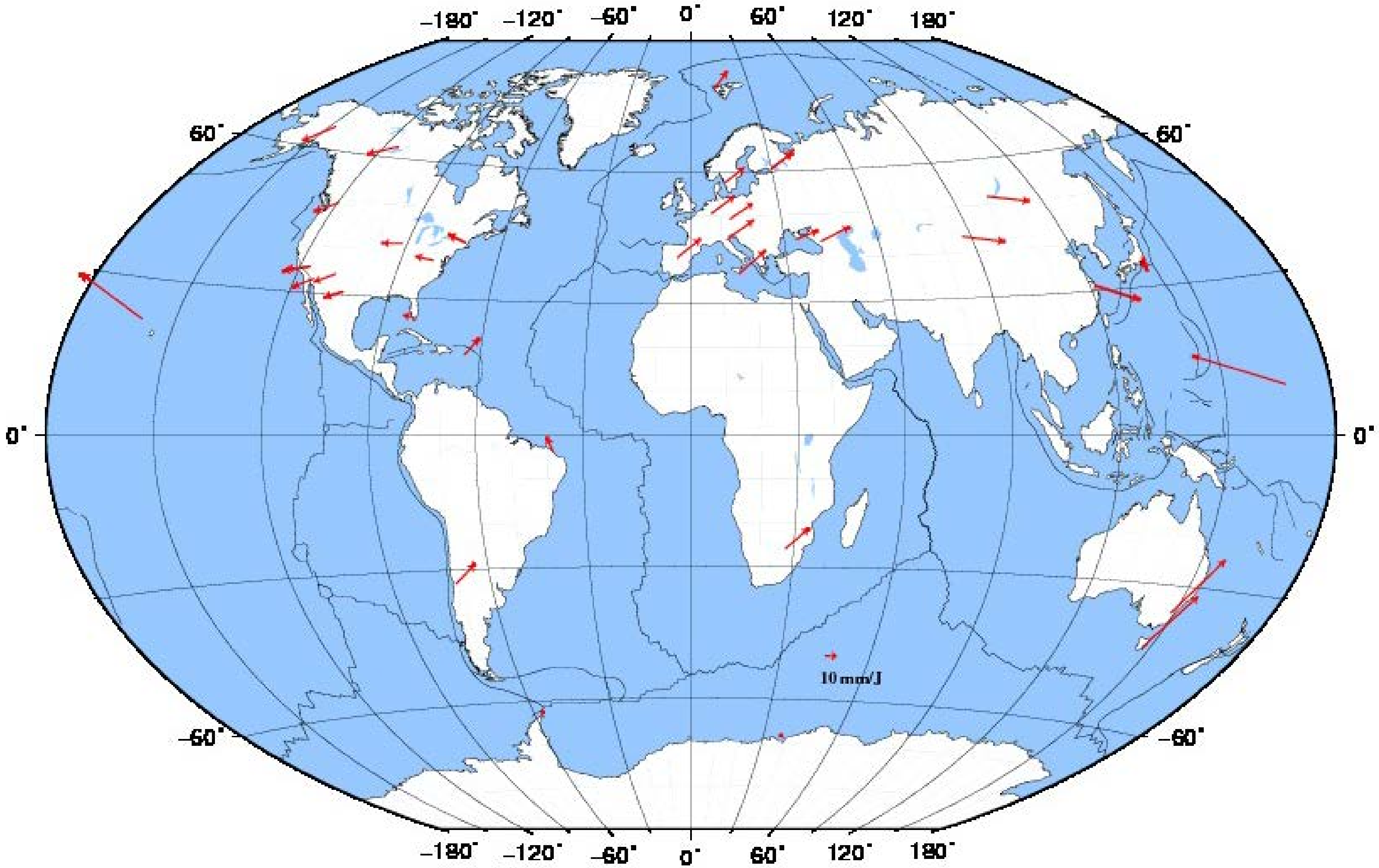


Europe – South Africa

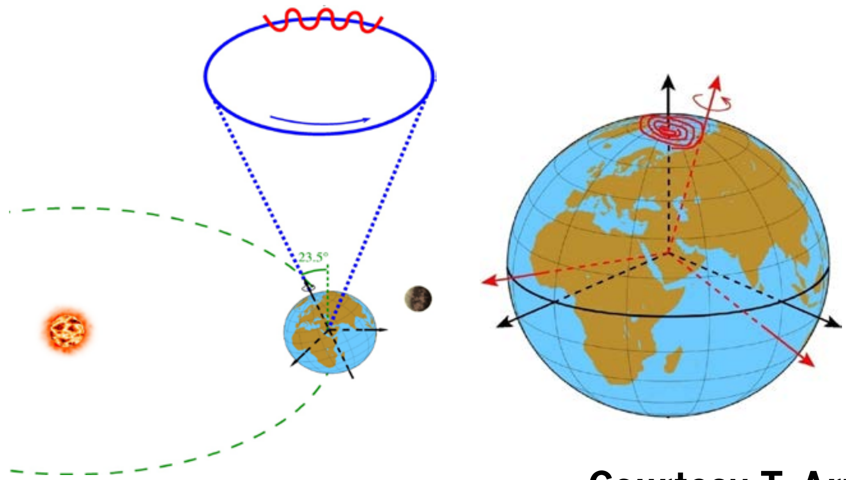




Positions and velocities



VLBI and SLR define the scale of ITRF2014



Courtesy T. Artz.

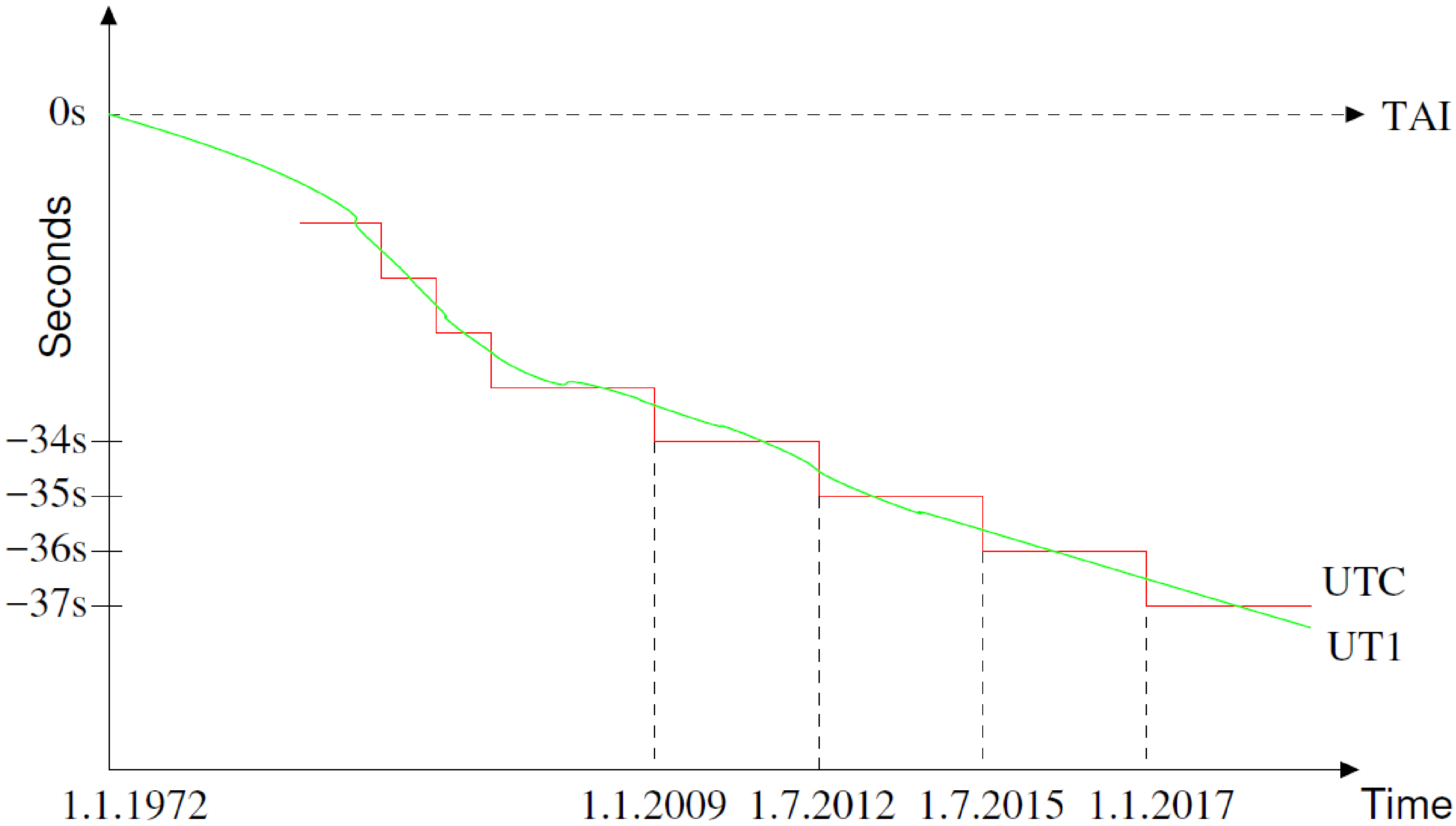
Telescope coordinates (time series)

Quasar positions (ICRF2 → ICRF3)

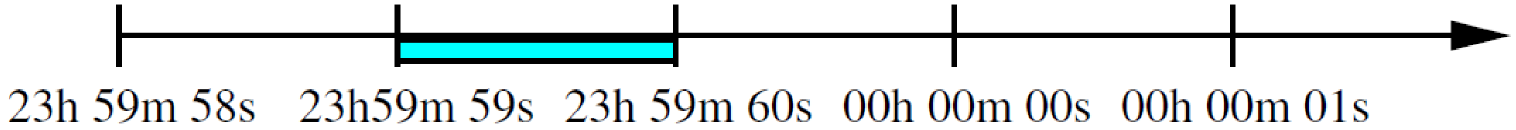
Earth Orientation Parameters

Polar motion	~2-3x /week	latency 10 – 14 days
Nutation offsets	~2-3x / week	latency 10 – 14 days
UT1-UTC	7x /week	2x ~3.5 µs, latency 10 – 14 days 6x ~15 µs, latency 1 – 2 days

UT1-UTC

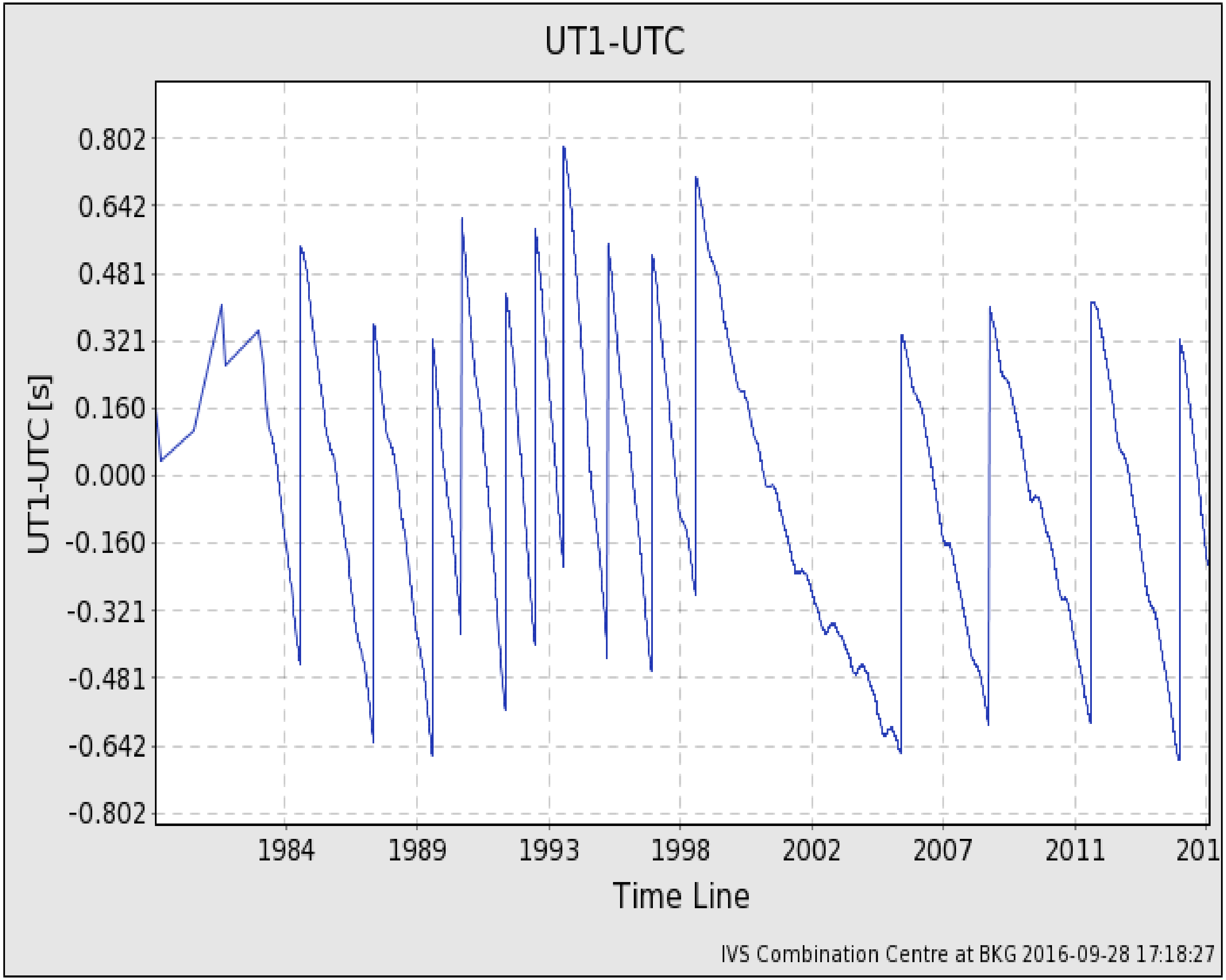


0s
TAI
Seconds
−34s
−35s
−36s
−37s
UTC
UT1
1.1.1972
1.1.2009
1.7.2012
1.7.2015
1.1.2017
Time

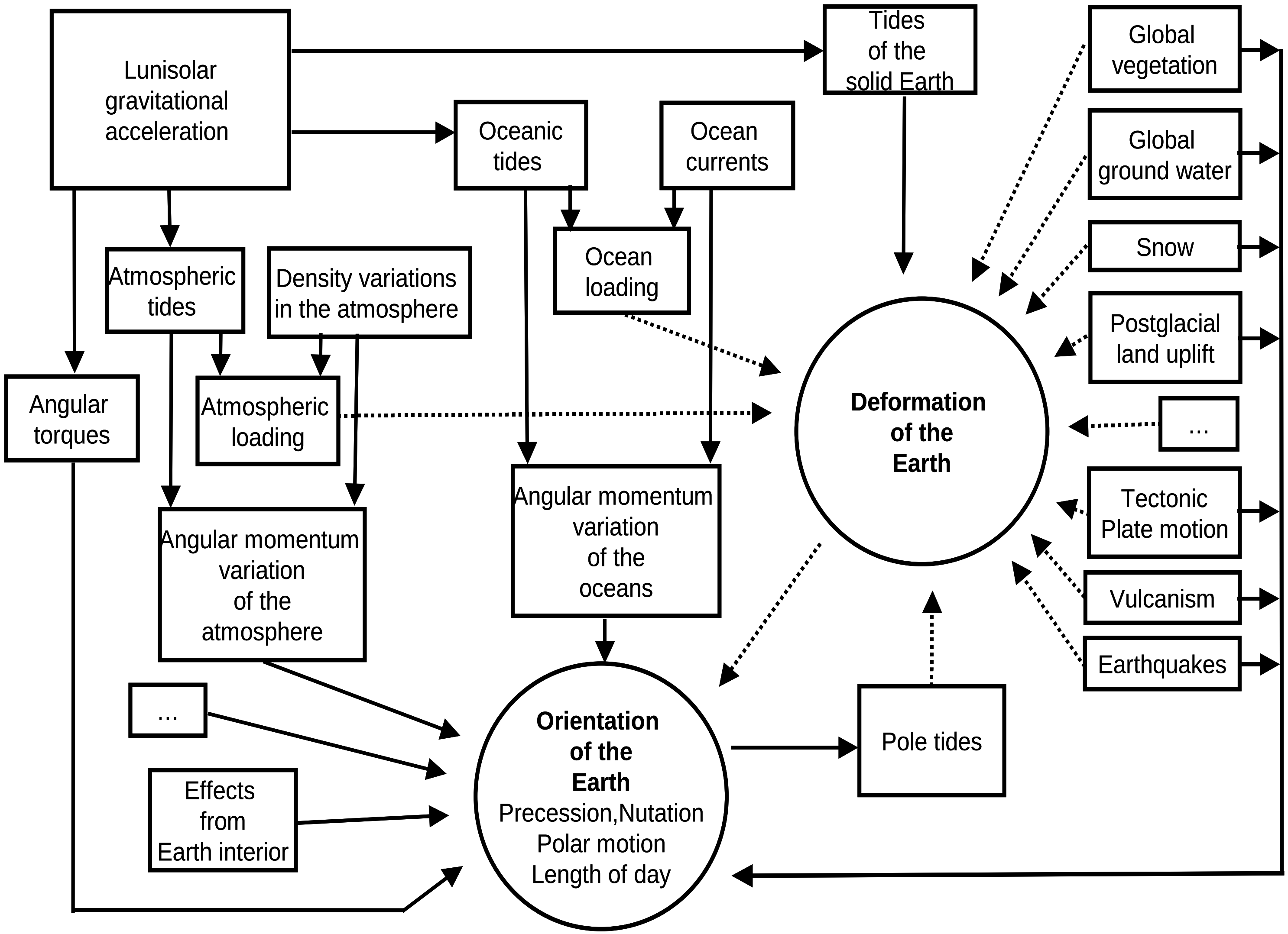


23h 59m 58s
23h59m 59s
23h 59m 60s
00h 00m 00s
00h 00m 01s

Phase of daily rotation



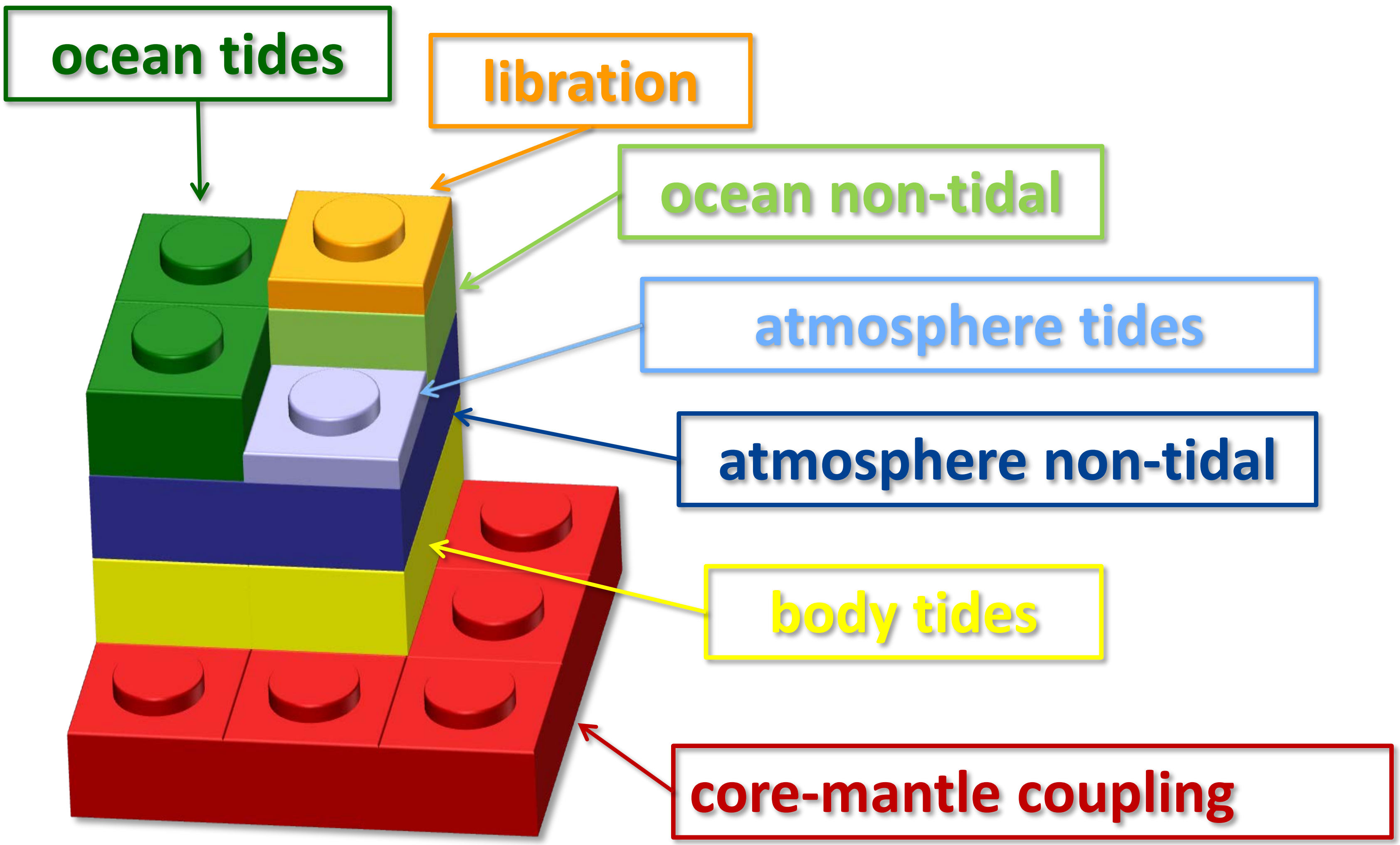
Interactions of System Earth



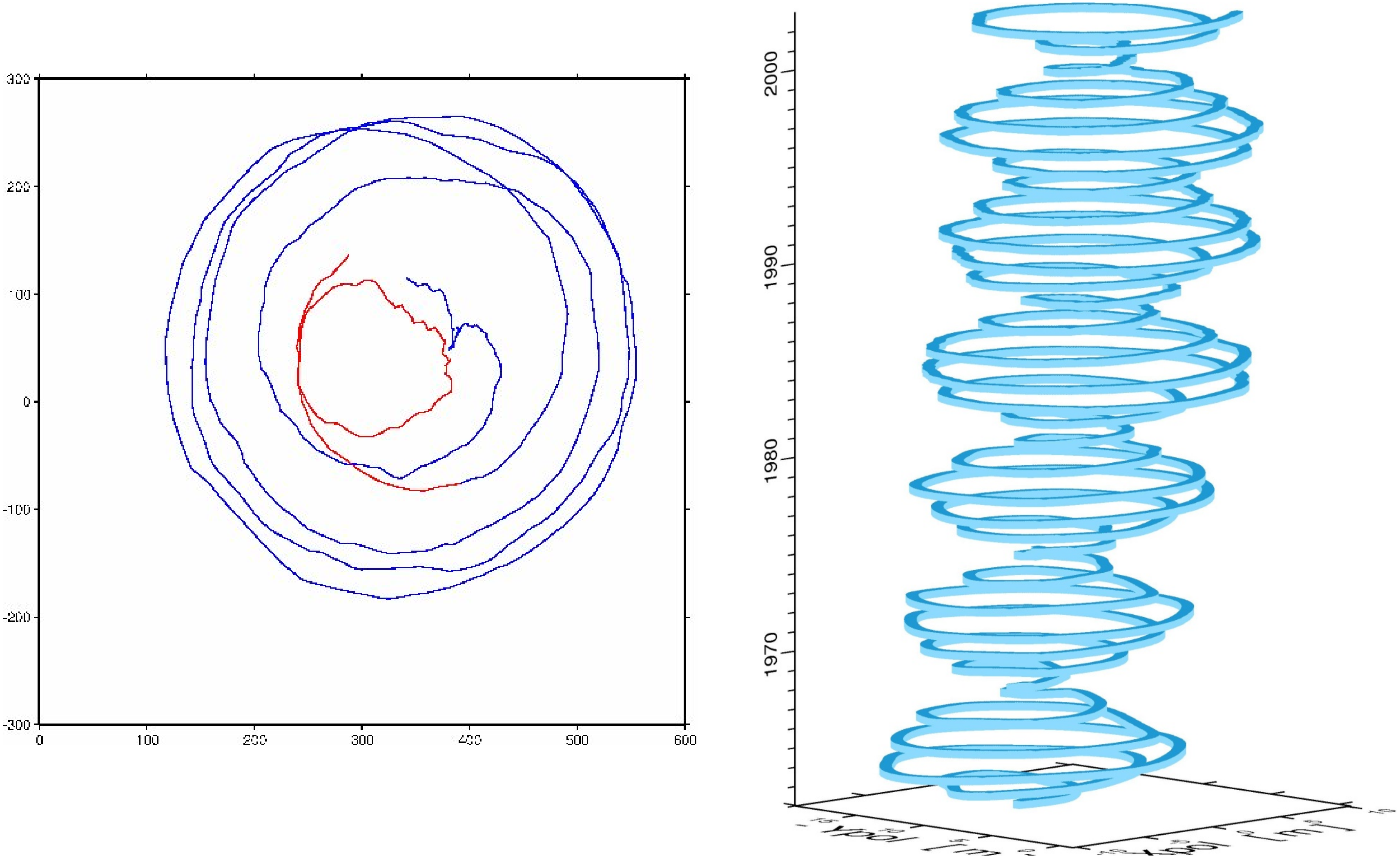
According to Schuh and Haas, 1995 (modified)

Periodic LOD – composition

Courtesy Sigrid Böhm, TU Vienna

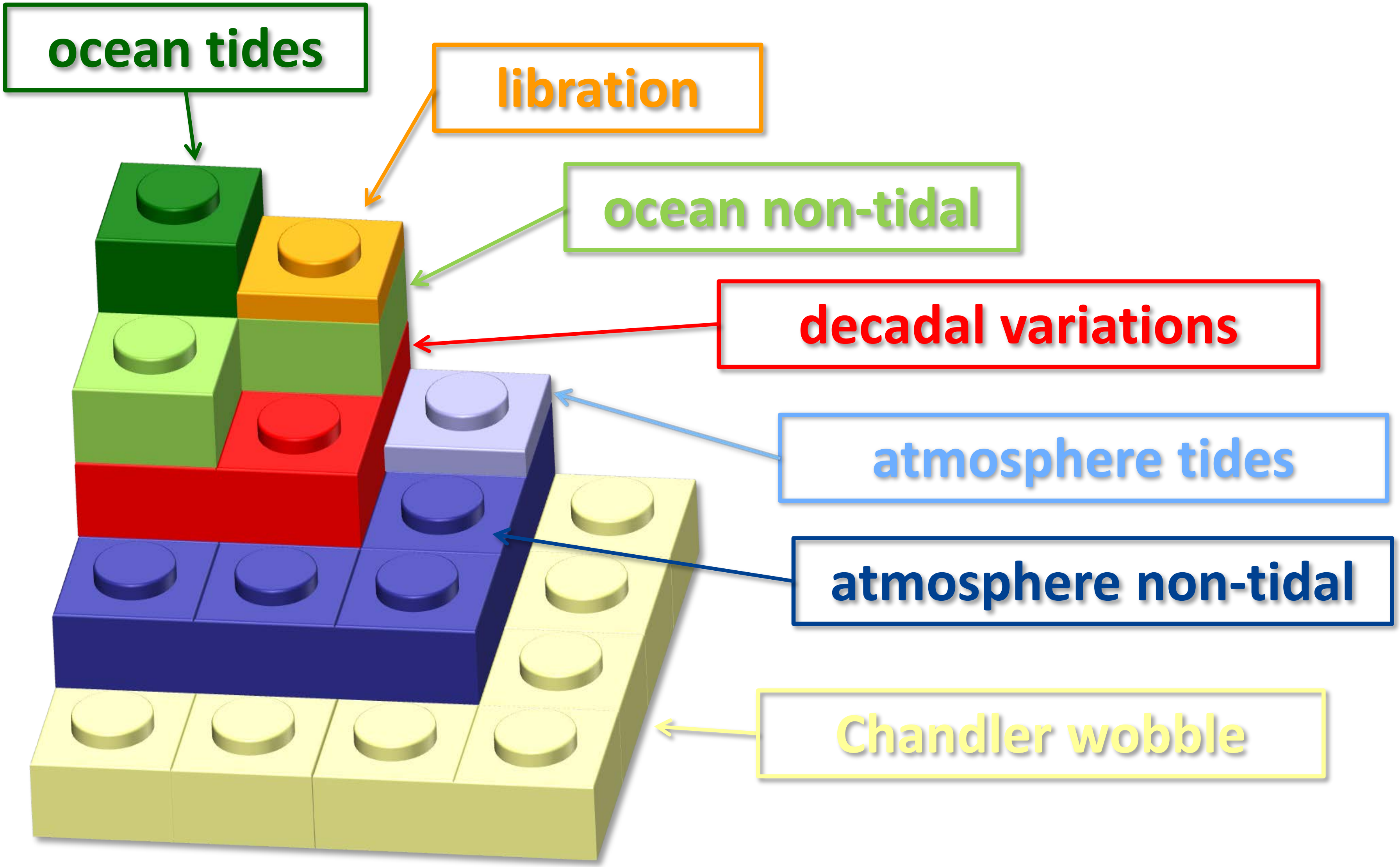


Polar motion

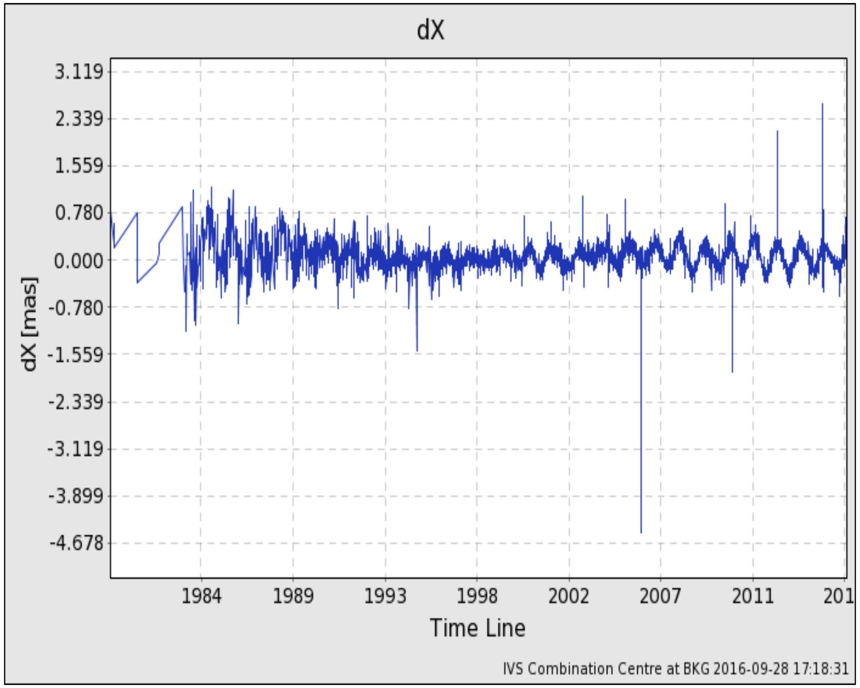


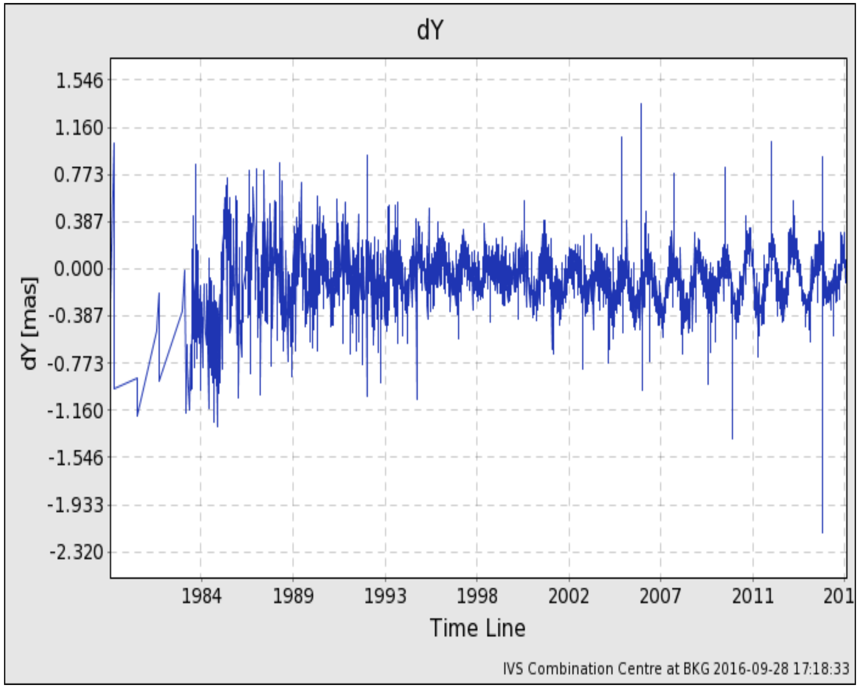
Periodic polar motion – composition

Courtesy Sigrid Böhm, TU Vienna



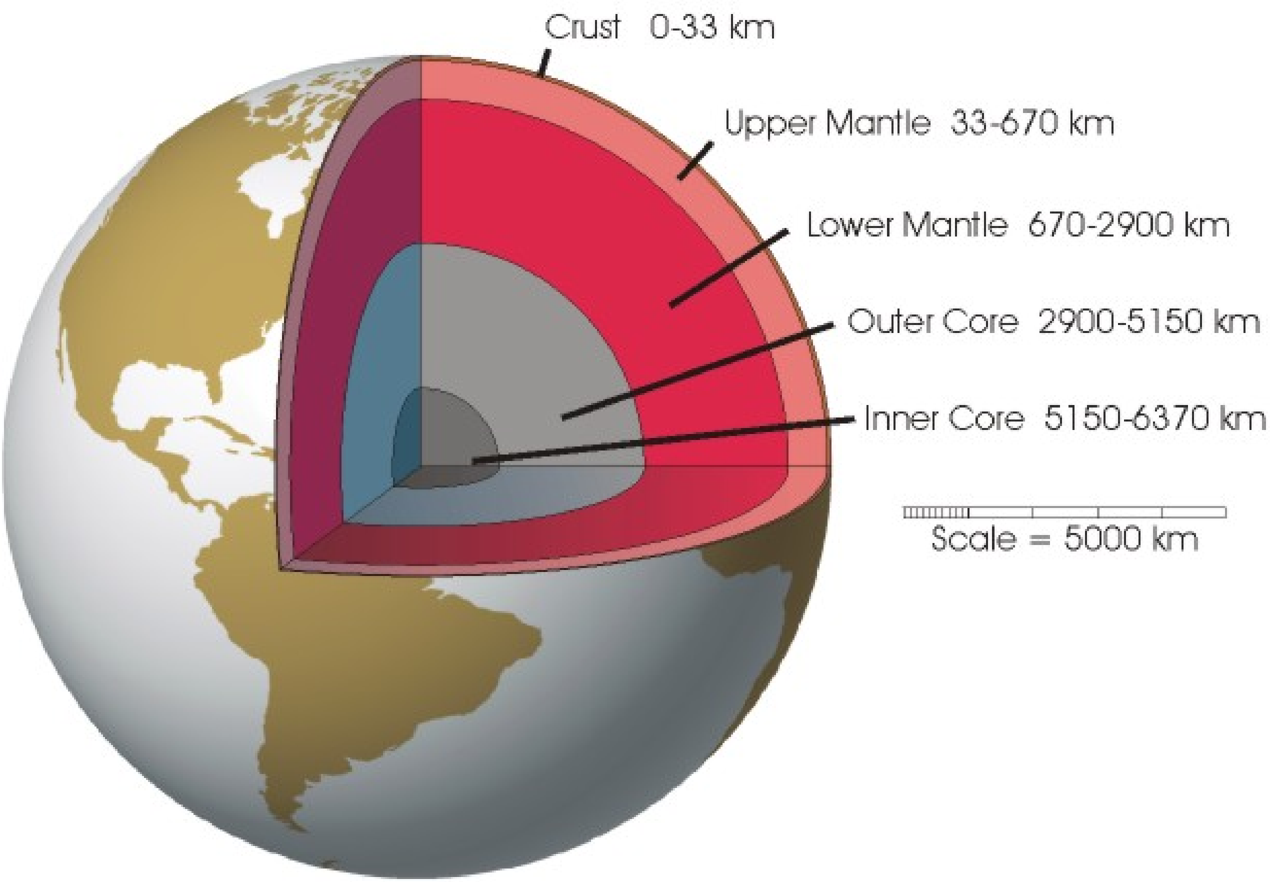
Time series of nutation parameters





Residuals of IAU2000/2006 precession and nutation model

Free Core Nutation

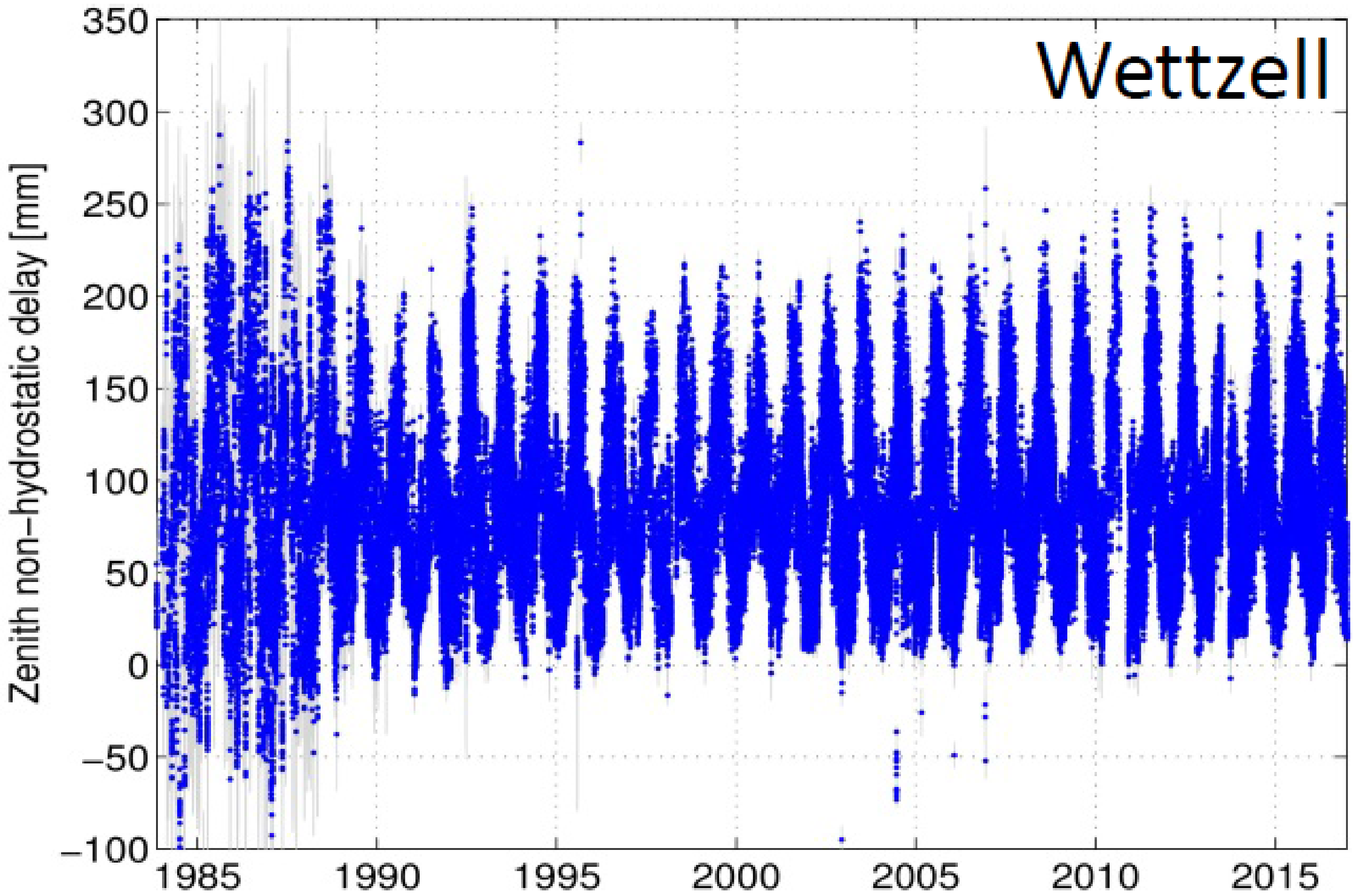


http://facweb.bhc.edu

FCN = Free core nutation

FICN = Free inner core nutation

Water vapor content



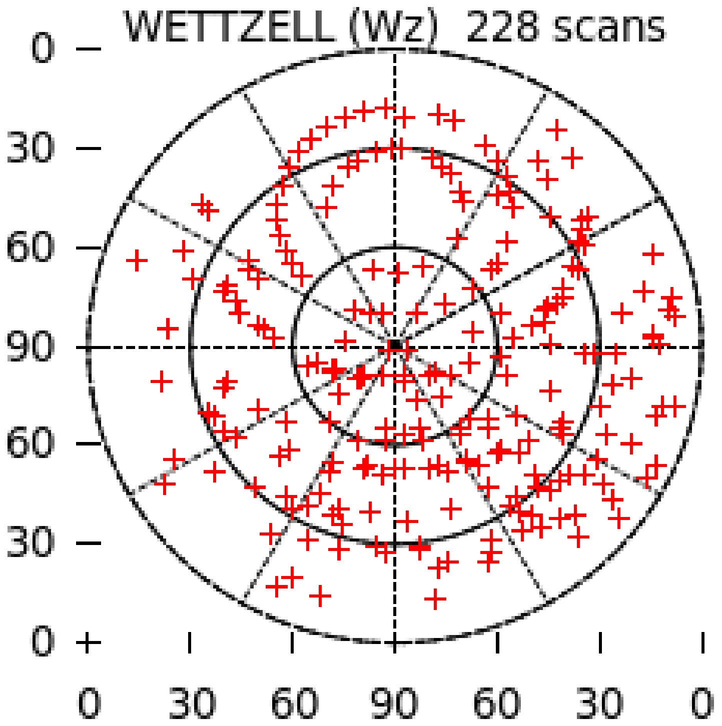
Zenith refraction delay (wet component) as proxy for water vapor content

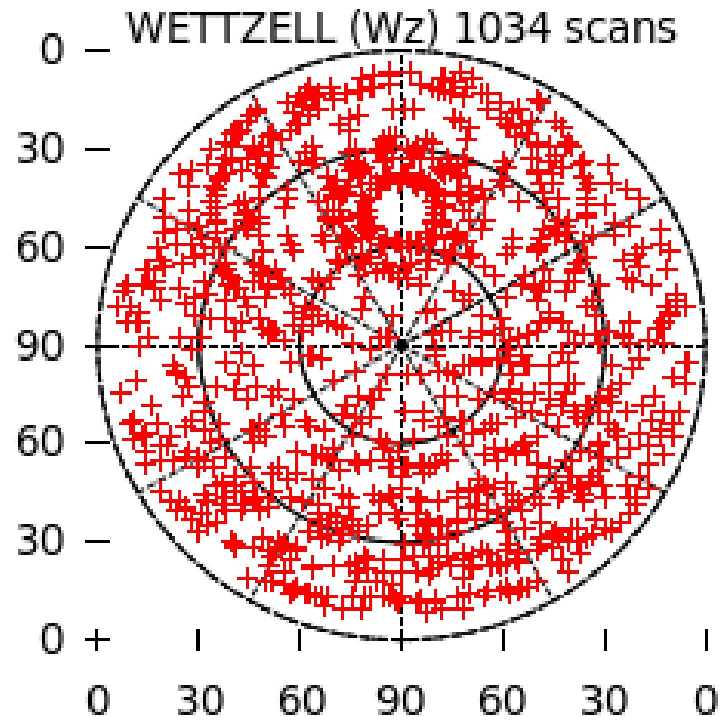
Courtesy R. Heinkelmann, GFZ

- **New generation VLBI infrastructure**

  simulations

  → dense sampling of local sky
  for optimal estimation of atmosphere parameters





Concept of VGOS

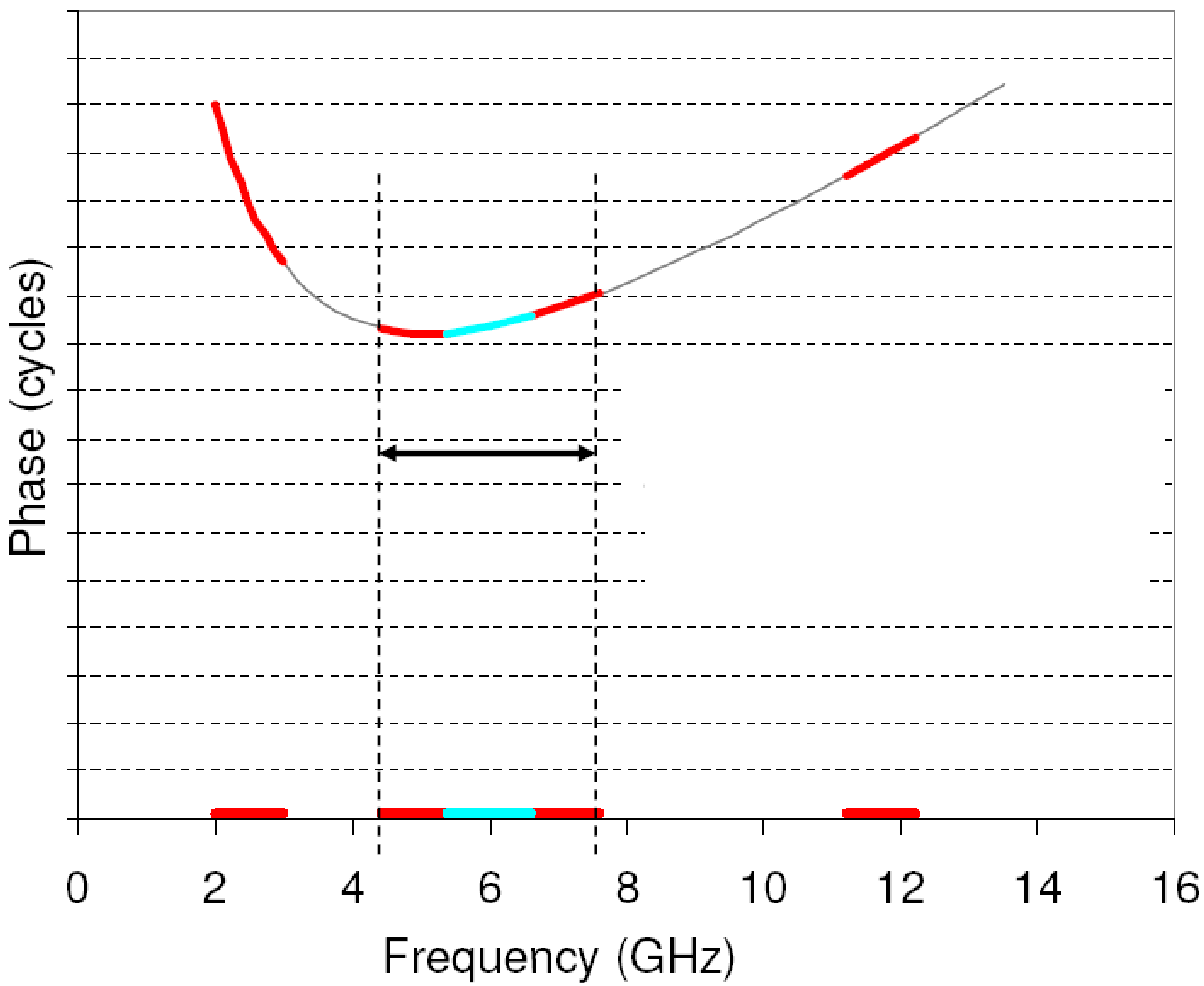
- **New generation VLBI infrastructure**
  - **dense sampling of atmosphere**
  - **agile telescopes**
    → small (12 – 13 m) 12º/sec
  - **up to 2 observations per minute (2880/day)**

$$\sigma_\tau \propto \sqrt{\frac{1}{A_1 A_2 \cdot B}}$$

=> Large bandwidth needed

- **wide band receivers (2 – 14 GHz [3 - 18])**
- **Flexible frequency allocation**
- **Dual linear polarization**

VGOS Frequencies



Courtesy B. Petrachenko

VGOS Telecopes

Wettzell (DE)

Zelenchukskaya (RU)

Courtesy
A. Ipatov

Ishioka (JP)Courtesy Y. Fukuzaki

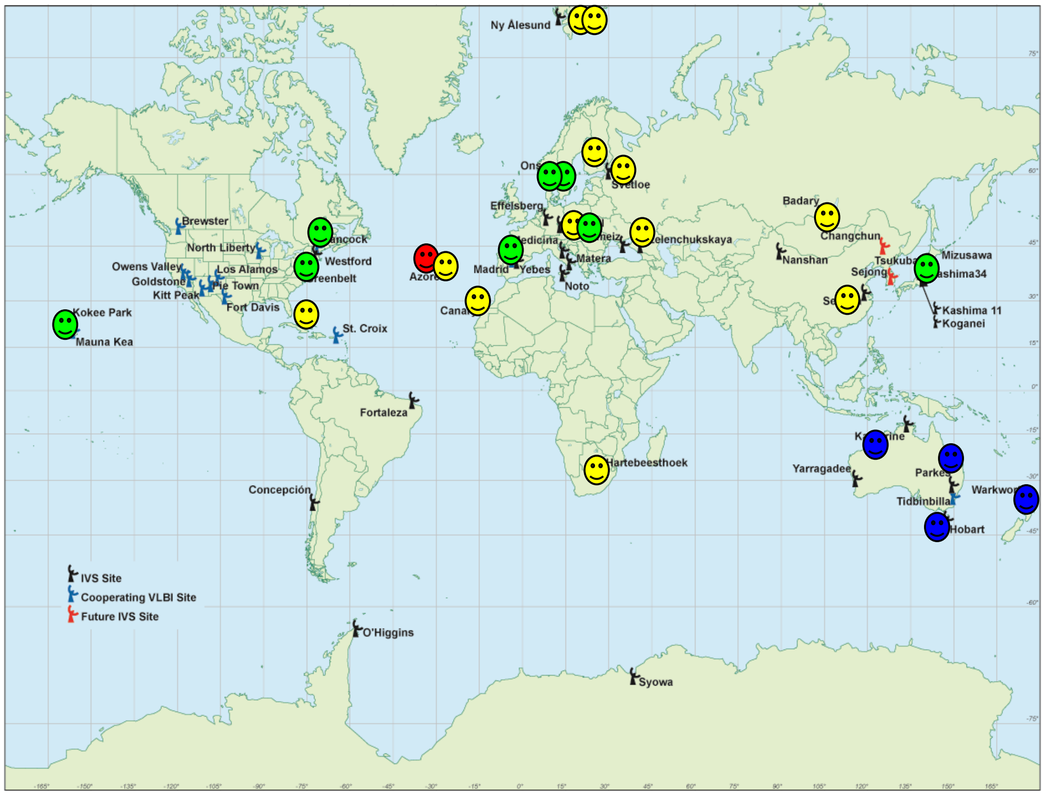
GGAO (US)

Courtesy A. Niell

Badary (RU)

Courtesy
A. Ipatov

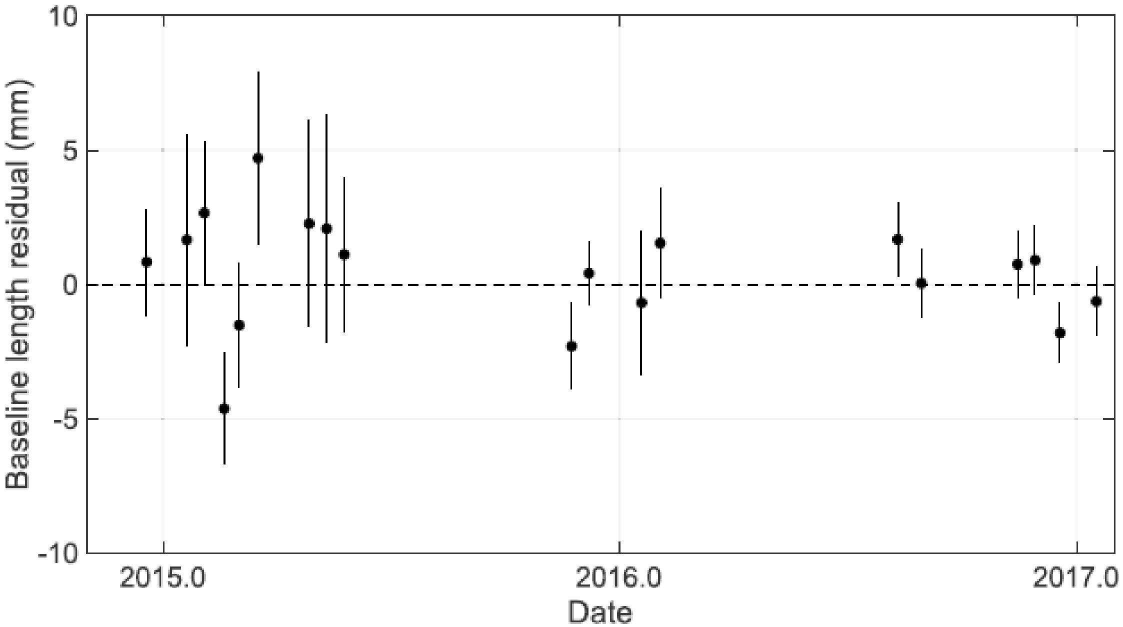
VGOS World



- **Commissioning/operational**
- **under construction**
- **funded**
- **upgrade phase**

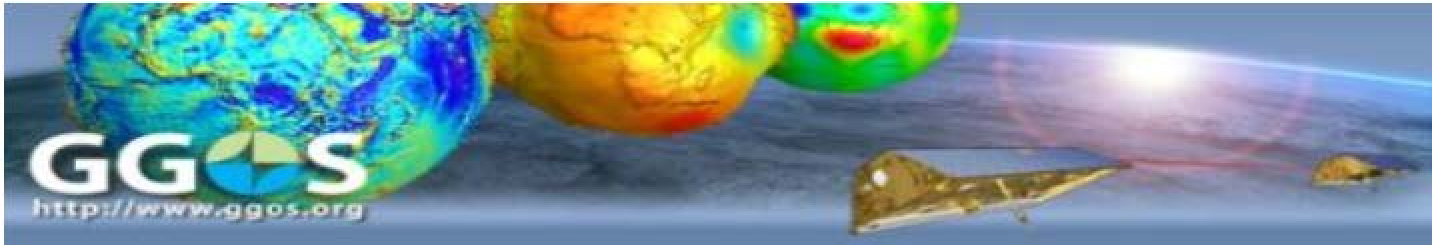
Courtesy H.Hase/VPEG,
based on available information
December 2018

Accuracy evaluation from first observations



Niell et al. (2018)
WRMS residual of 1.6 mm

Global Geodetic Observing System



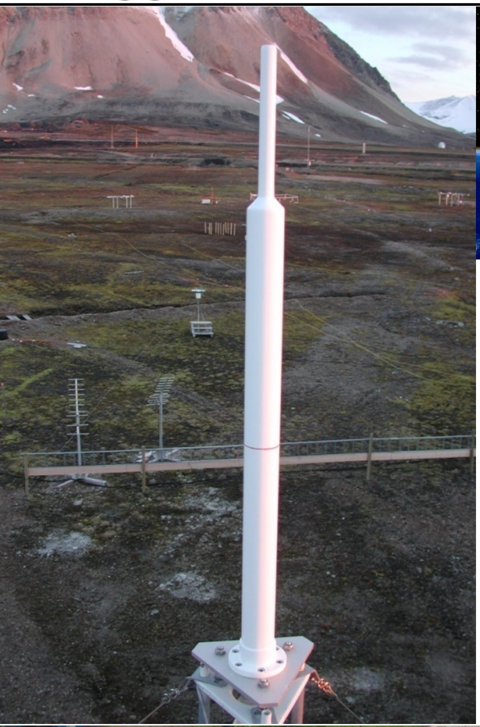
IVS → VGOS → GGOS

Global Geodetic Observing System
of the International Association of Geodesy (IAG)

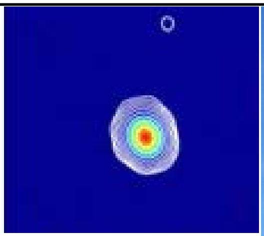
Contribution to GGOS

- Global distribution → Well-designed network
- Continuous → Economic operations
- Stable over decades → Monitoring of telescopes and local ties
- 1 mm/0.1 mm/y → Improved technology, better modeling

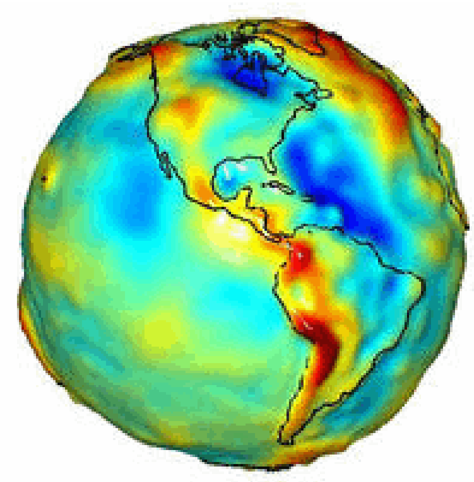
Global Geodetic Observing System



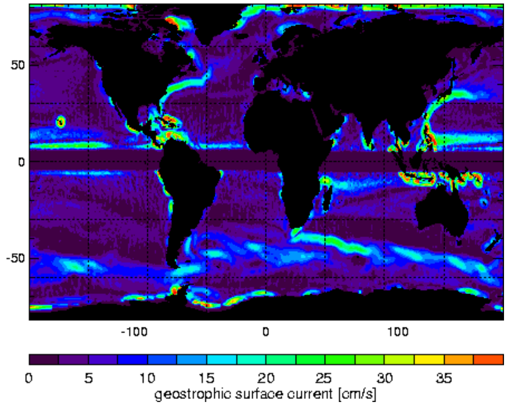
DORIS



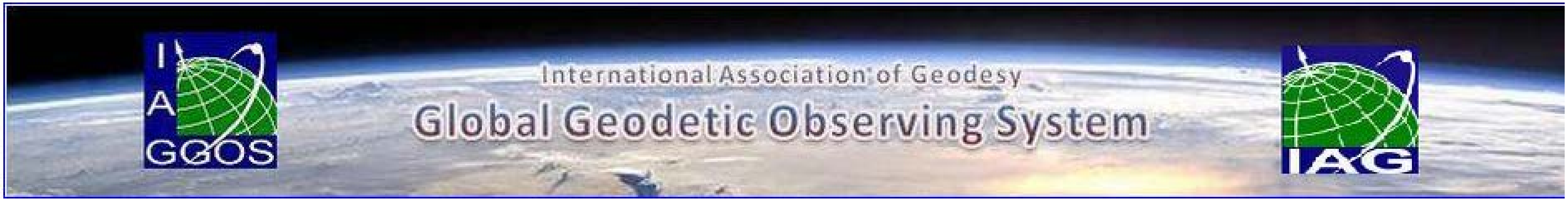
VLBI



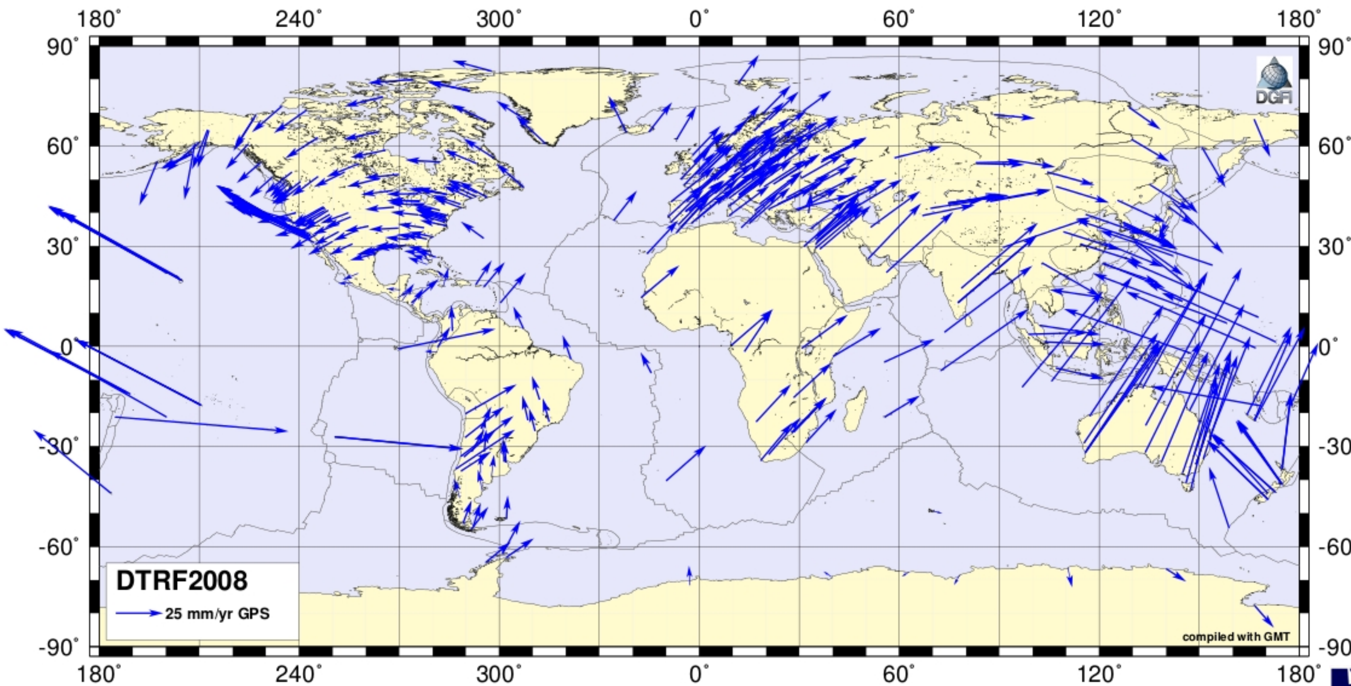
GPS



SLR



VGOS is part of GGOS



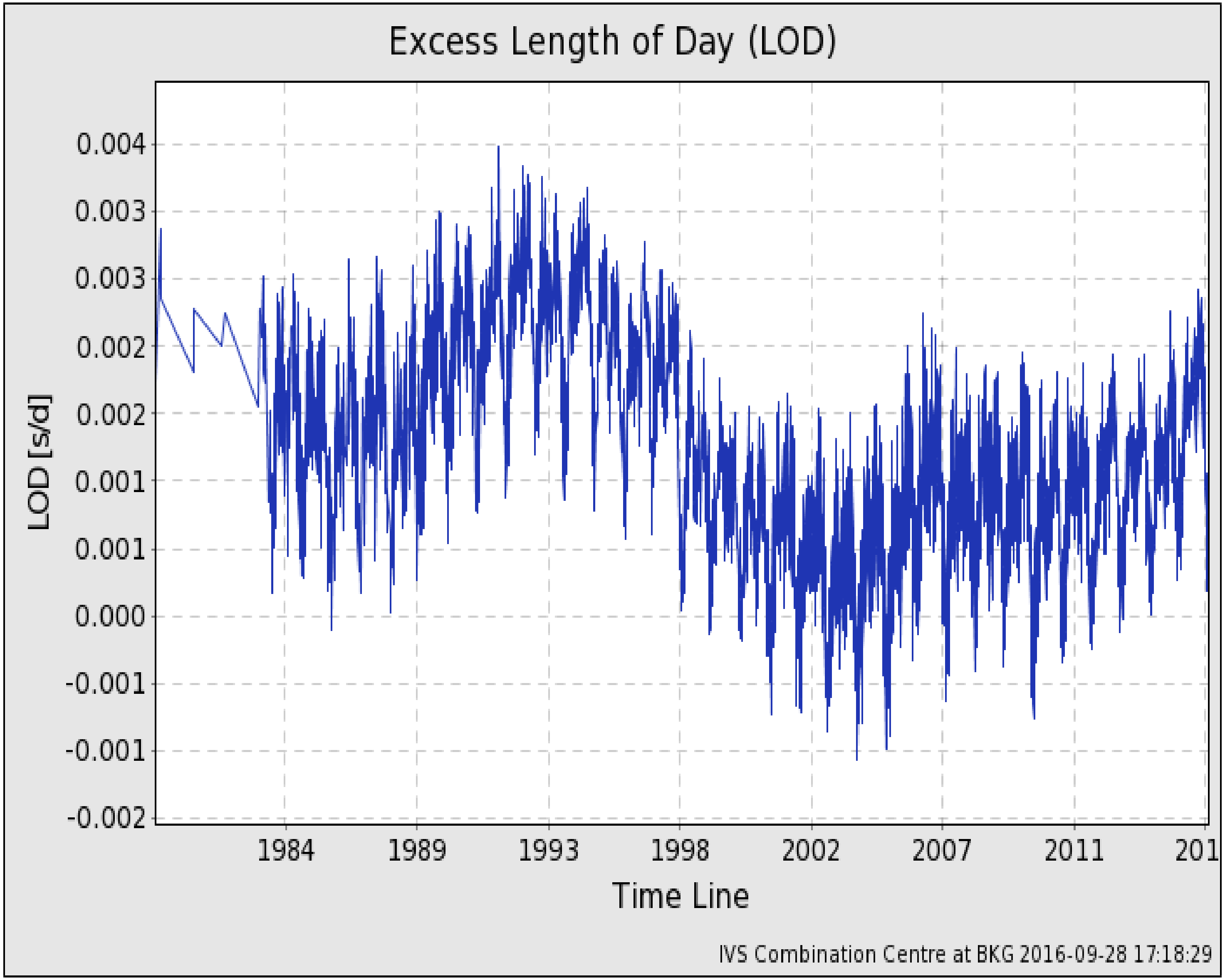
IAG
150 years
International Association of Geodesy

Geodetic Observatory Wettzell

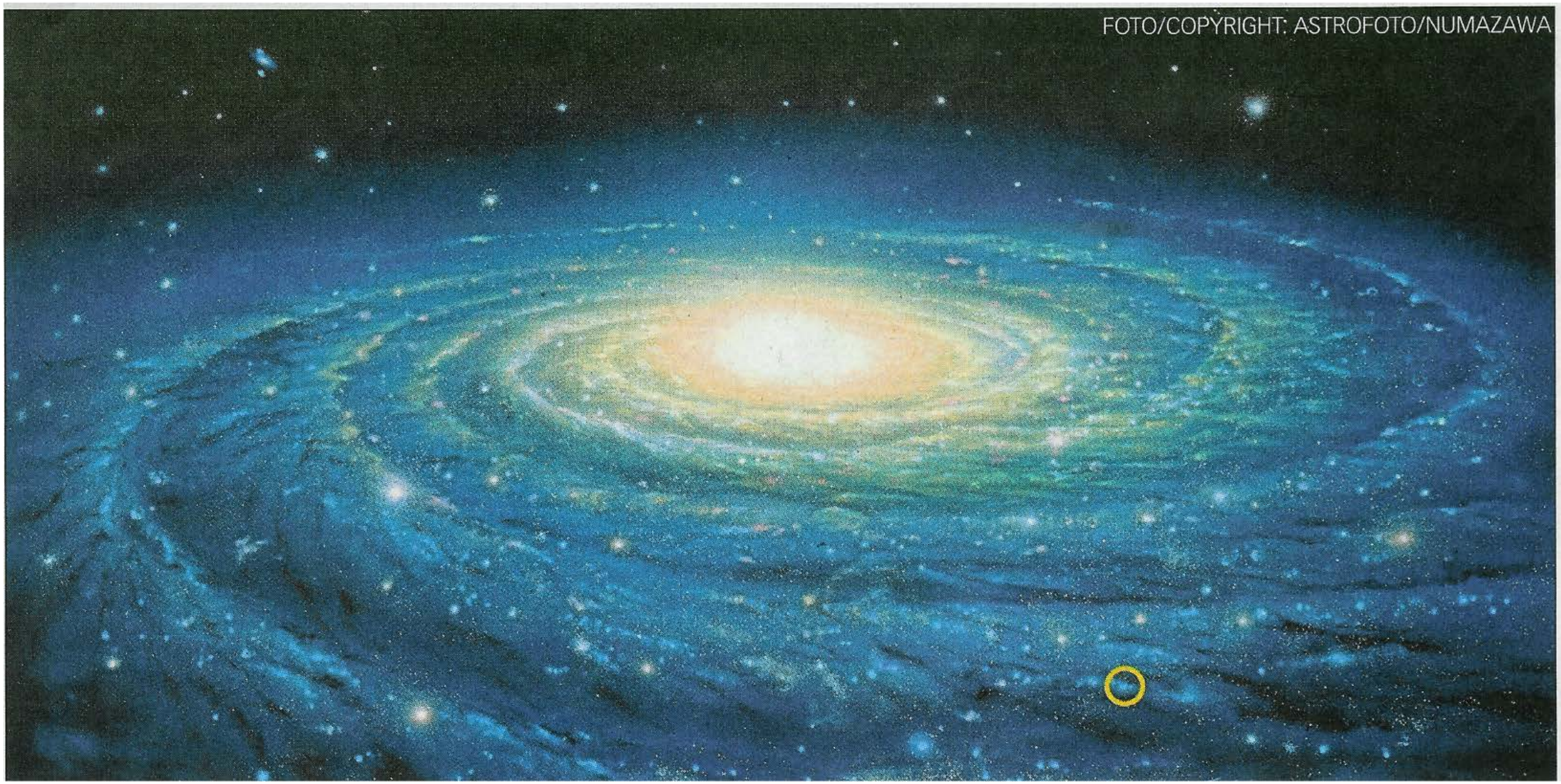
Courtesy T. Schüler (2016)

Backup

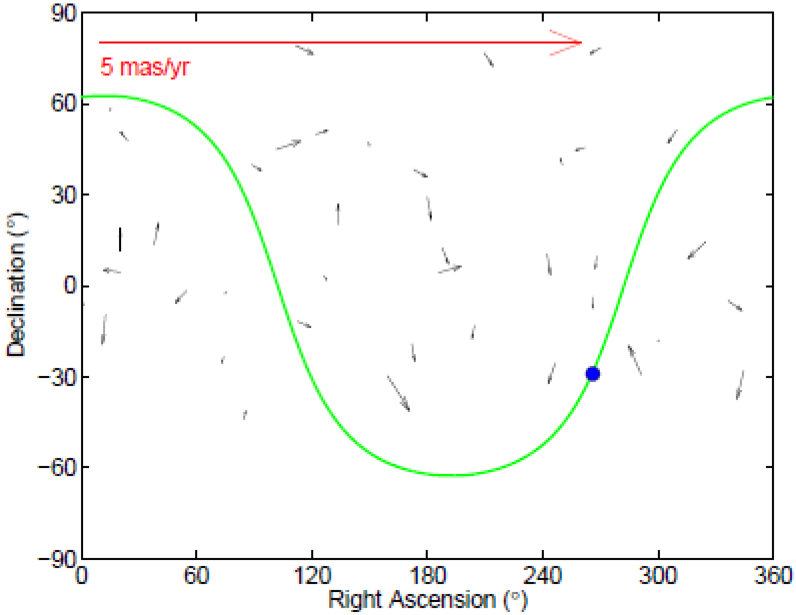
Time derivative of rotation phase

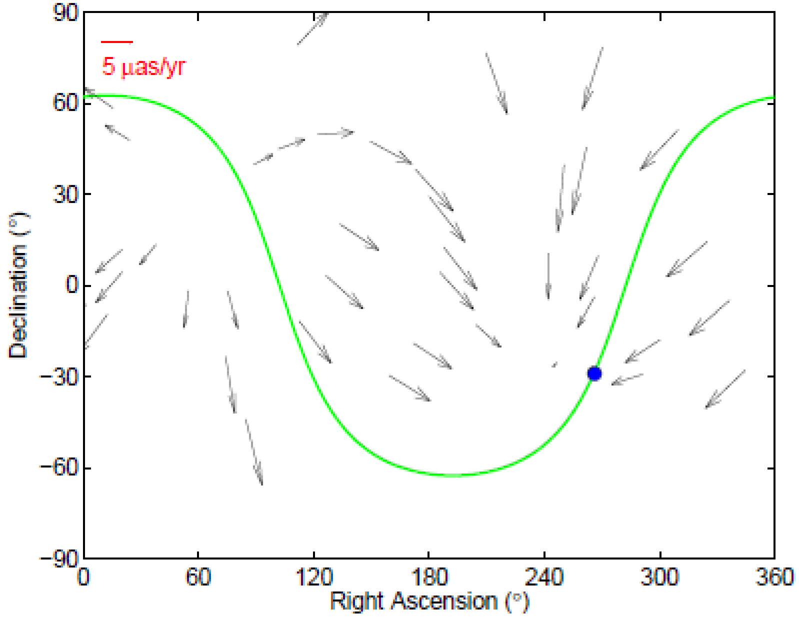


Galactic abberation



Galactic abberation





1) Geodetic VLBI: range of 6 estimates: [5.2 - 6.4] µas/yr

mean = 5.7 µas/yr ; Standard deviation of estimates = 0.47

2) Stellar astronomy: range of 6 estimates: [4.8 - 5.4] µas/yr

mean = 5.0 µas/yr ; Standard deviation of estimates = 0.21

Annual signal in station heights