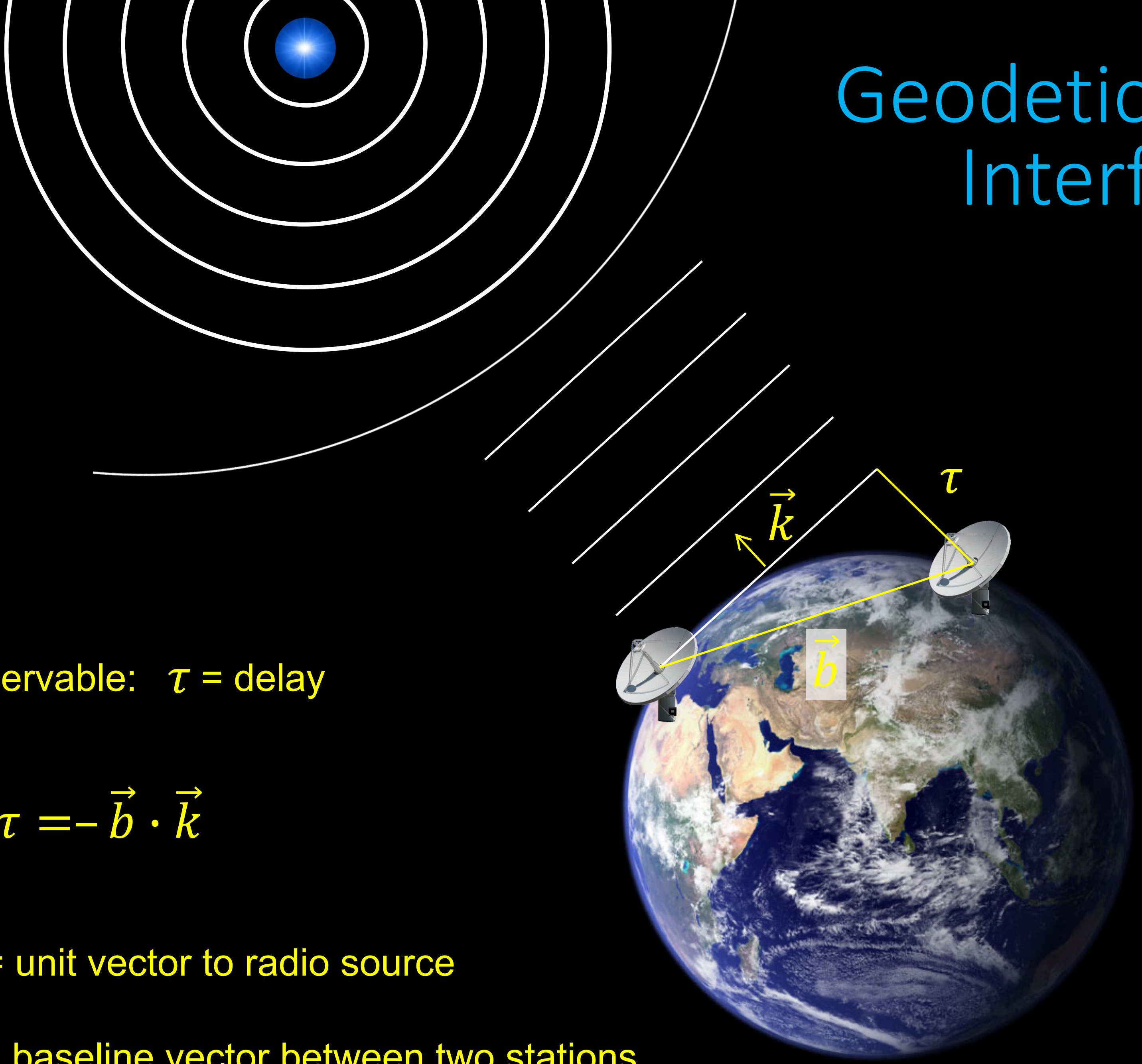
The International VLBI Service for Geodesy and Astrometry

– Status and Prospects –

22nd International Workshop on Laser Ranging
7–11 November 2022, Guadalajara, Spain

Rüdiger Haas

Geodetic Very Long Baseline Interferometry (VLBI)



observable: τ = delay

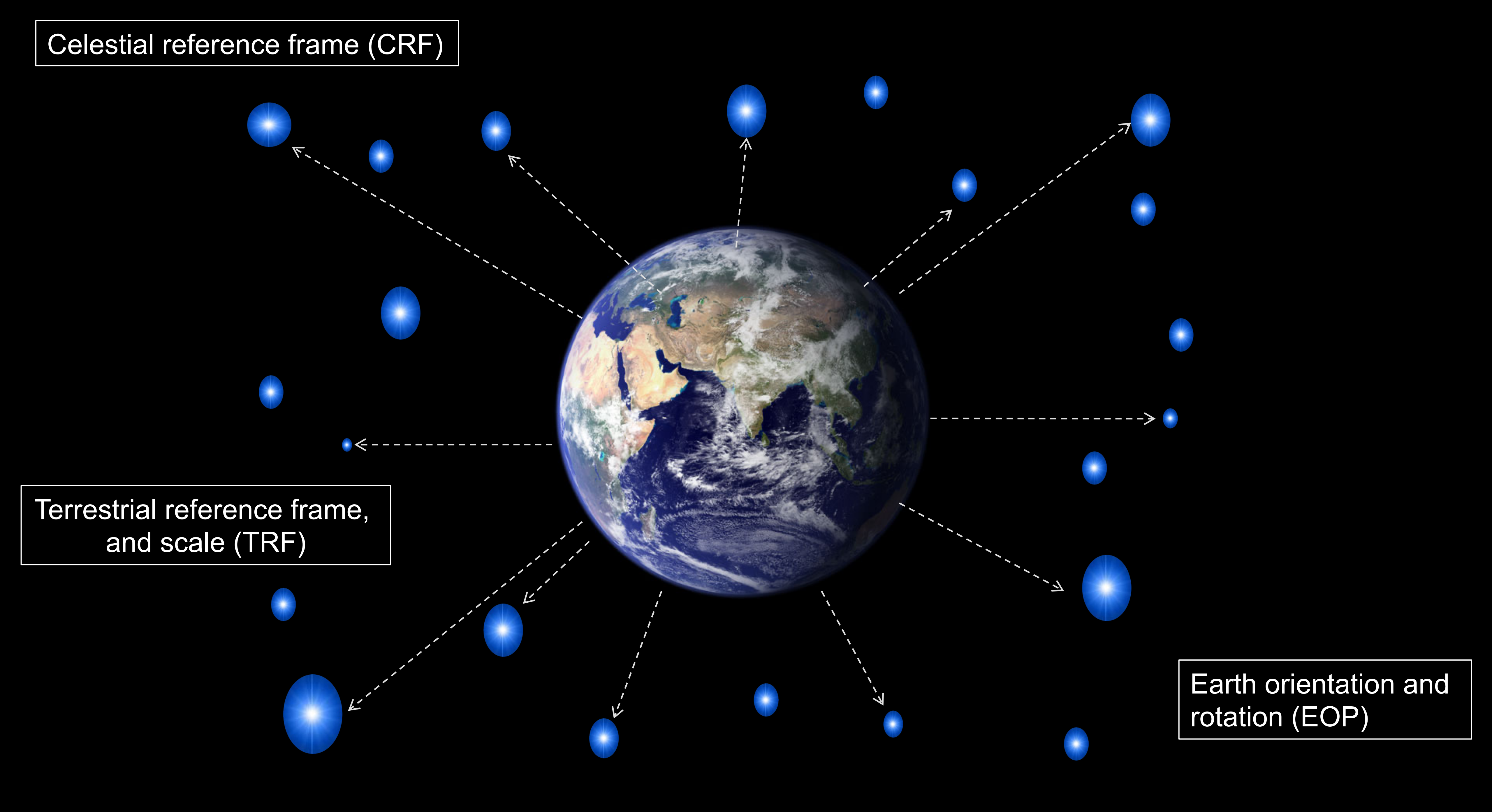
$$c \cdot \tau = - \vec{b} \cdot \vec{k}$$

$\vec{k}$ = unit vector to radio source

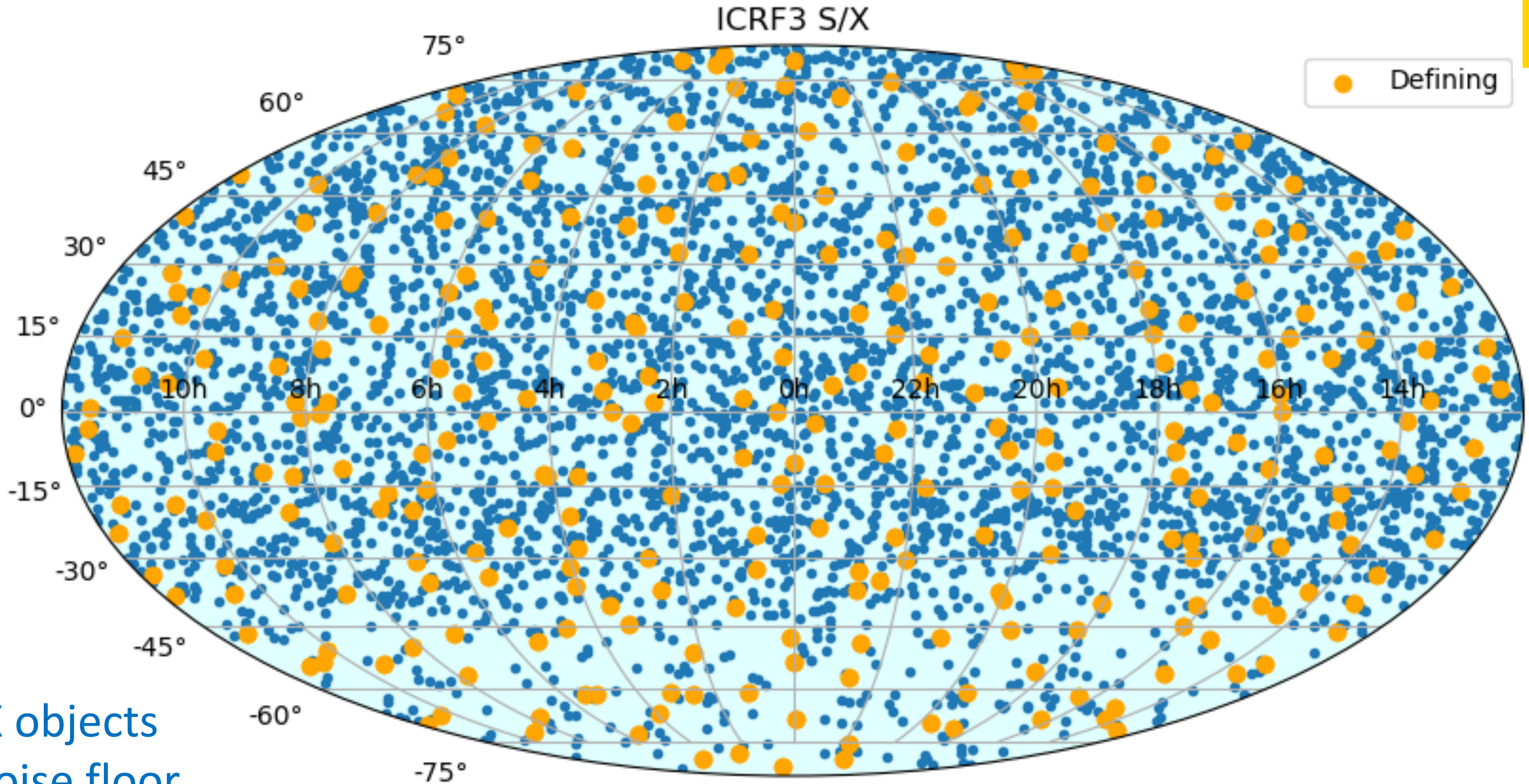
$\vec{b}$ = baseline vector between two stations

VLBI is unique:

- connects reference frames on the Earth with the background universe
- allows to determine all parameters that describe the orientation and rotation of the Earth
- relates via speed of light directly to SI-unit metre

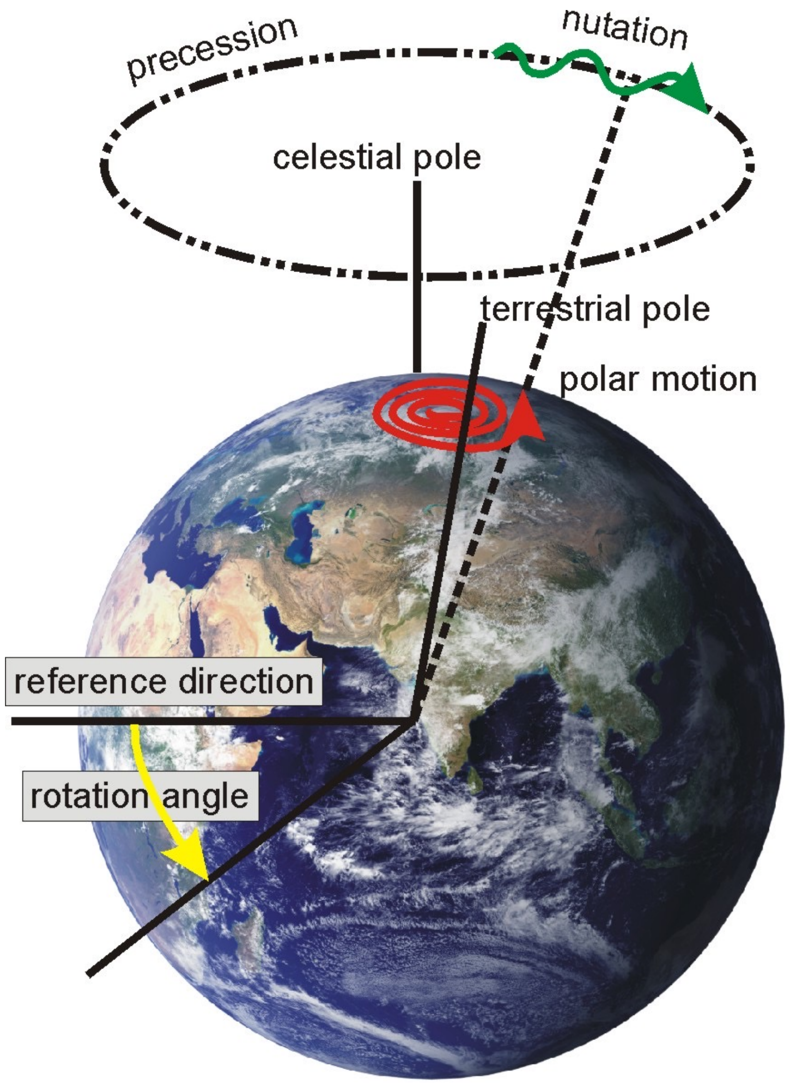

Celestial reference frame (CRF)
Terrestrial reference frame, and scale (TRF)
Earth orientation and rotation (EOP)

The celestial reference frame ICRF3

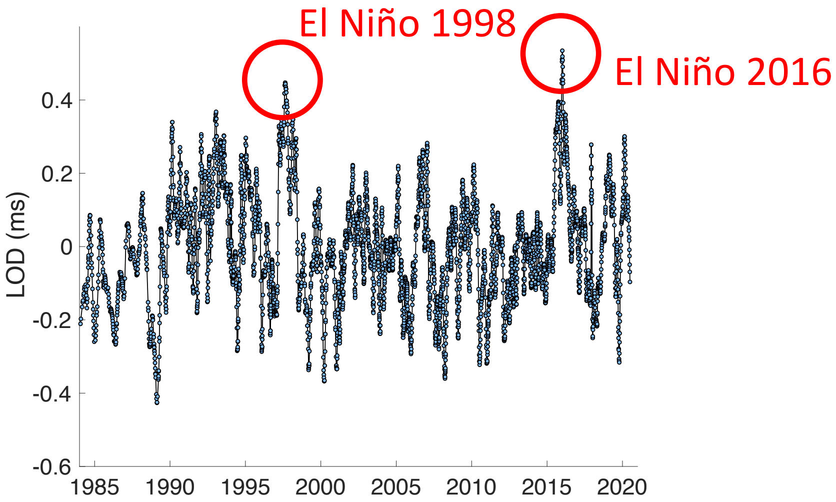


4536 S/X objects
30 µas noise floor

Earth orientation and rotation



- VLBI is sensitive to all earth orientation parameters (EOP)
  - Celestial pole offsets
  - UT1-UTC, and LOD
  - Polar motion, and polar motion rates
- Senses geodynamical phenomena, e.g. El Niño / Southern Oscillation



IVS – The International VLBI Service for Geodesy and Astrometry

- Founded in 1999 as an international collaboration of organizations which operate or support Very Long Baseline Interferometry (VLBI) components.
- Service for
  - IAG (International Association of Geodesy)
  - IAU (International Astronomical Union)
  - WDS (World Data System of the International Science Council)
- Objectives
  - support geodetic, geophysical, and astrometric research and operational activities
  - promote research and development activities in all aspects of the geodetic and astrometric VLBI technique
  - interact with the community of users of VLBI products and to integrate VLBI into a global Earth observing system

IVS service aspects

- IVS serves both outside users and the geodetic/astrometric community itself
- IVS serves both the contributors and the users of VLBI data
- IVS provides data and products for the scientific community
- The main IVS products are
  - a terrestrial reference frame (TRF)
  - the international celestial reference frame (ICRF)
  - Earth orientation parameters (EOP)

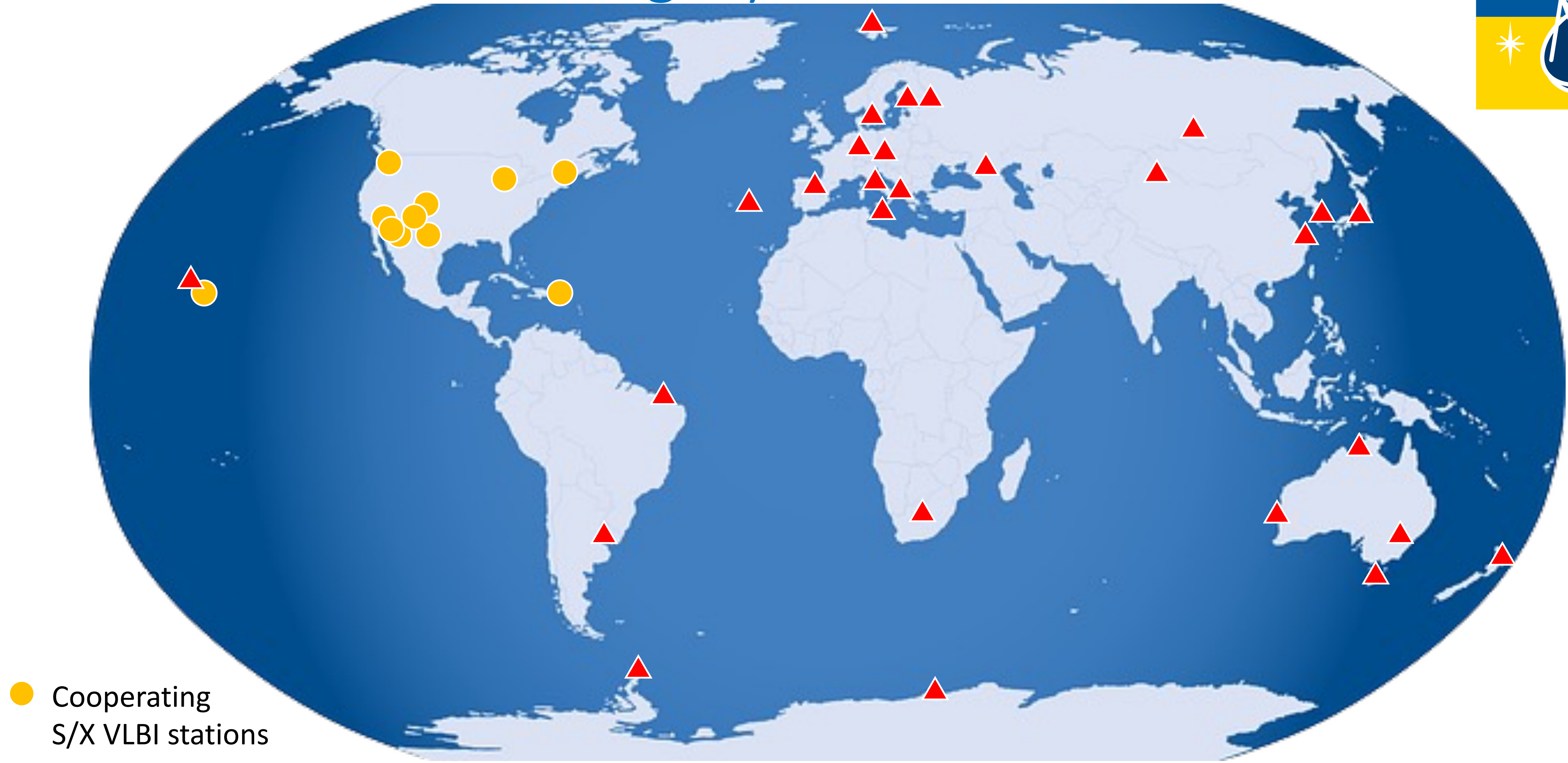
IVS organisational aspects

- A non-profit and best effort organisation
- 80+ permanent components
  - network stations – correlators – data centres – analysis centres – technology development centres – operation centres – coordinating centre
- 40+ institutions
  - Land survey agencies – space agencies – universities – research institutions
- 20+ countries
- In total ca. 350 associated members

Today's IVS observing plan: S/X legacy

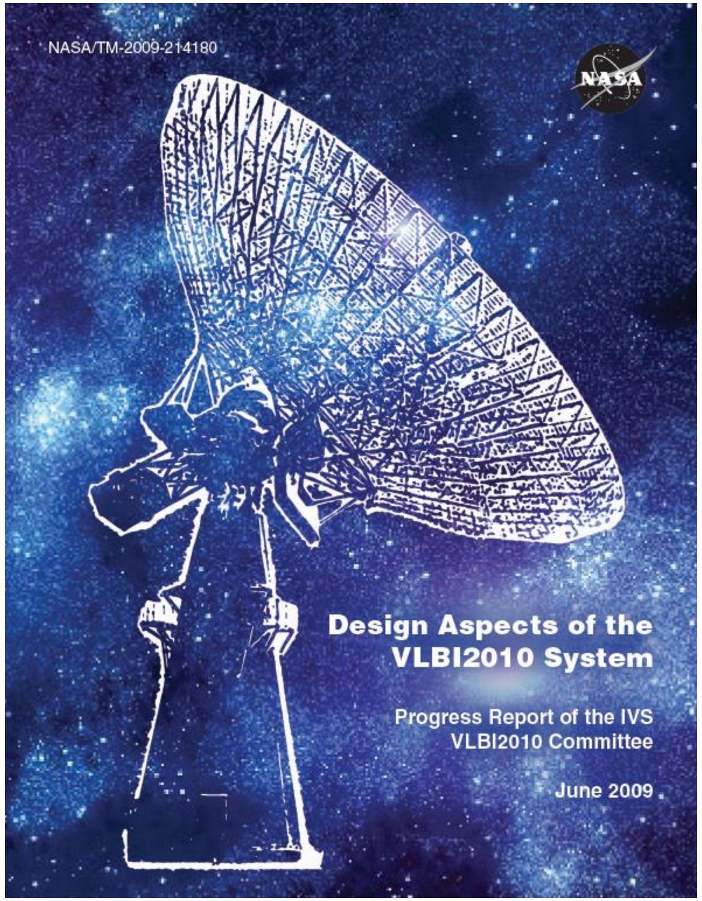
- S/X legacy observations, going back to 1979
- Today: ca. 40 S/X stations
- Large variety of radio telescopes
  - Diameter 6 m – 100 m
  - Many slow and deformable "astronomical" telescopes
- 24-h sessions (on average 3.5 sessions/week):
  - Two sessions per week for EOP: R1, R4
  - TRF, CRF and R&D sessions
- Daily 1-h sessions for UT1-UTC (Intensives):
  - INT1, INT2, INT3

IVS S/X legacy network in 2022



Today's IVS observing plan: VGOS

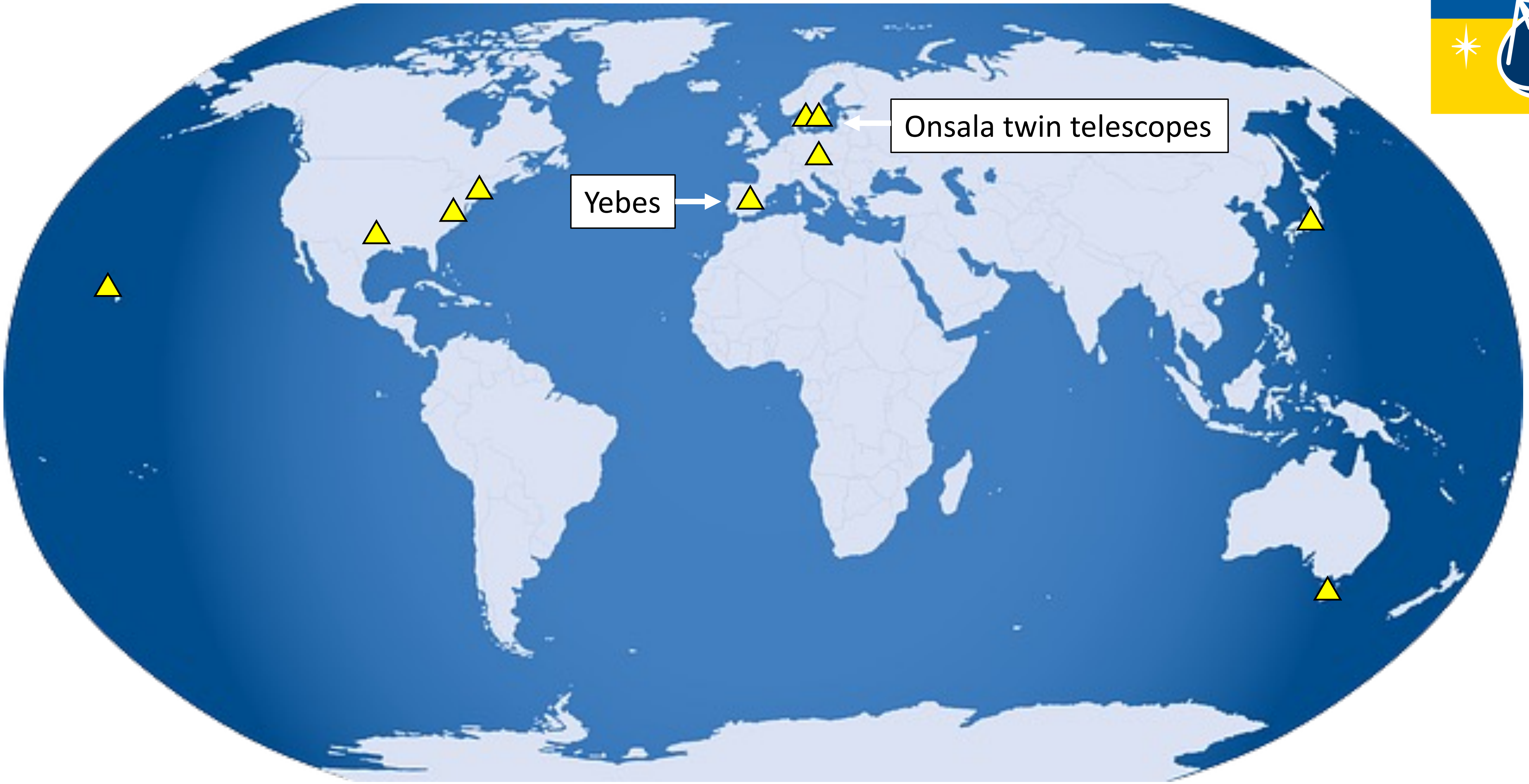
- VLBI Global Observing System (VGOS)
  - next generation VLBI system for Geodesy and Astrometry
- VGOS started in 2017, operational since 2020
- Today (2022): 10 operational VGOS stations
  - so far mainly northern hemisphere
- 24-h VGOS sessions:
  - One session per week / every 2nd week for EOP, TRF, CRF
- 1-h VGOS sessions for UT1-UTC (VGOS Intensives):
  - Several sessions per week (e.g., V2, S2, B2, C2)



The VGOS concept

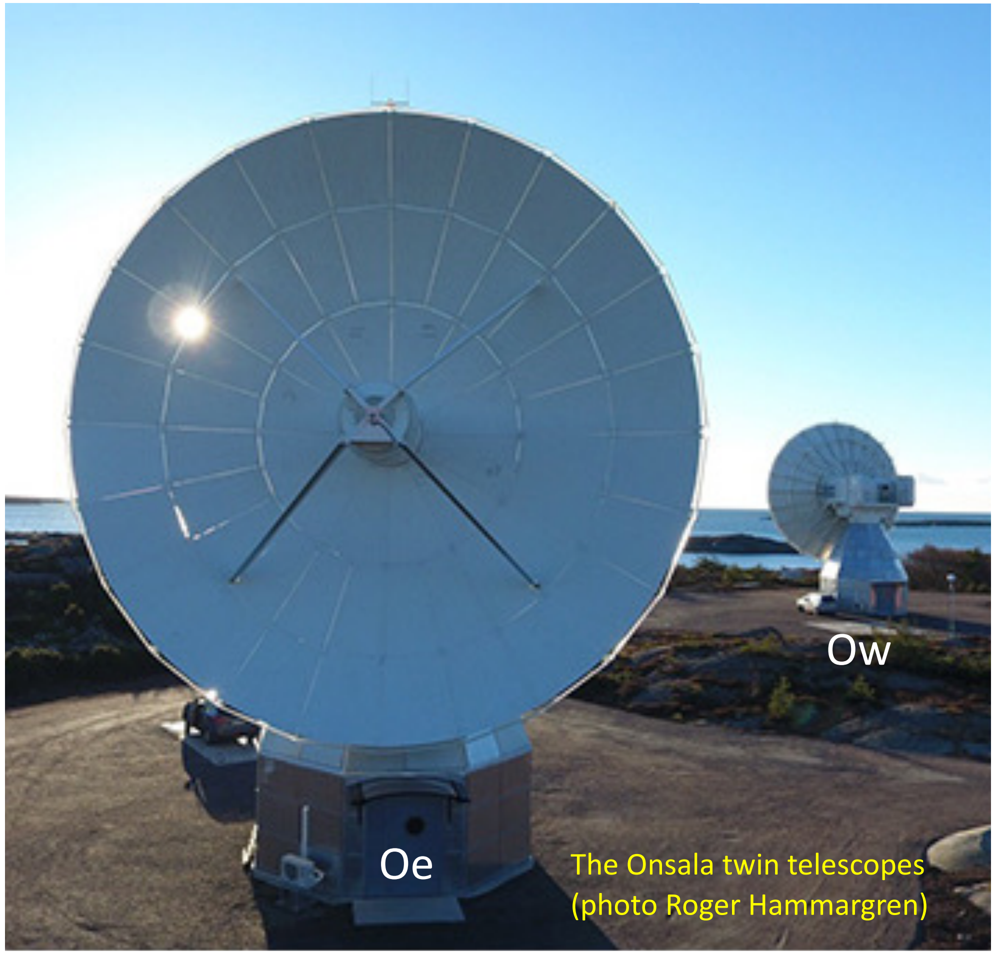
- Fast and stiff telescopes (12 °/s in azimuth, 6 °/s in elevation)
- Broadband receivers (2–14 GHz)
- Dual polarization
- Up to 2880 observations per day (ca. 6 times more than today)
- Electronic data transfer to the correlators (if possible)
- Expectation:
  - one order of magnitude improvement w.r.t. legacy S/X VLBI
- Twin telescopes, e.g. Onsala, Wettzell, Ny-Ålesund
  - Improved handling of atmospheric turbulence
  - Connect VLBI and satellite methods

IVS VGOS network in 2022



Example: The Onsala twin telescopes

- Two identical VGOS telescopes @ 75 m distance
- OHB/MTM, 13.2 m diameter, ring-focus design
  - Surface accuracy < 100 µm
  - Fast telescopes: 12 deg/s AZ, 6 deg/s EL
- Broadband receivers
  - Eleven-Feed on ONSA13SW (Ow), 2–14 GHz, H/V-pol
  - QRFH feed on ONSA13NE (Oe), 3–15 GHz, H/V-pol
- Phase- and cable-calibration systems
- DBBC3 digital backends, one each
  - Full-VGOS: 8 IF covering 16 GHz in 2 polarizations
  - Up to 128 Gb/s sampling capacity
- Flexbuff recorders (today 1 PB storage capacity)
- Fibre optics connections > 10 Gb/s

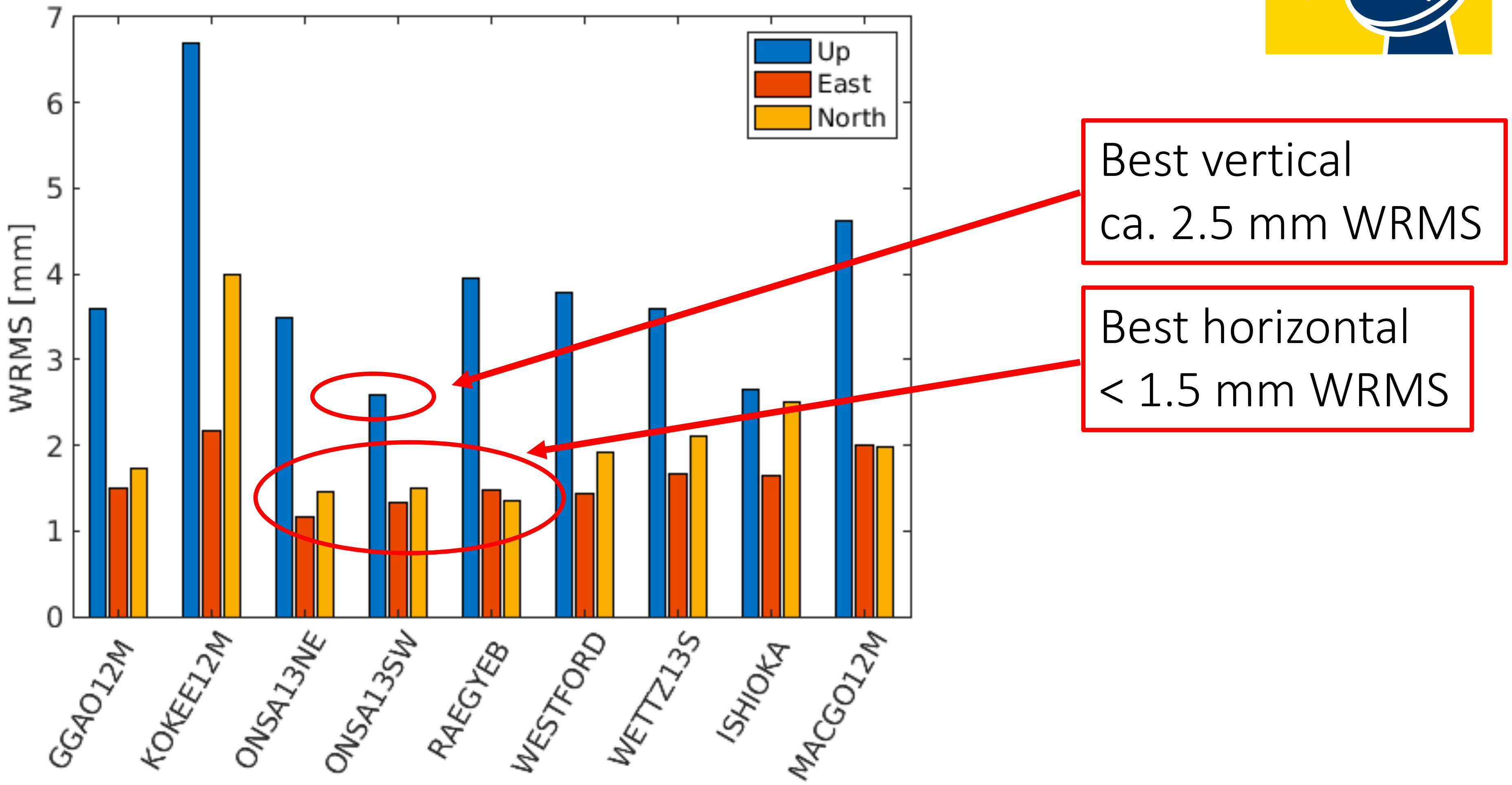


The Onsala twin telescopes
(photo Roger Hammargren)

Current VGOS performance

Station position WRMS from analysis of VGOS 2019–2021 data.

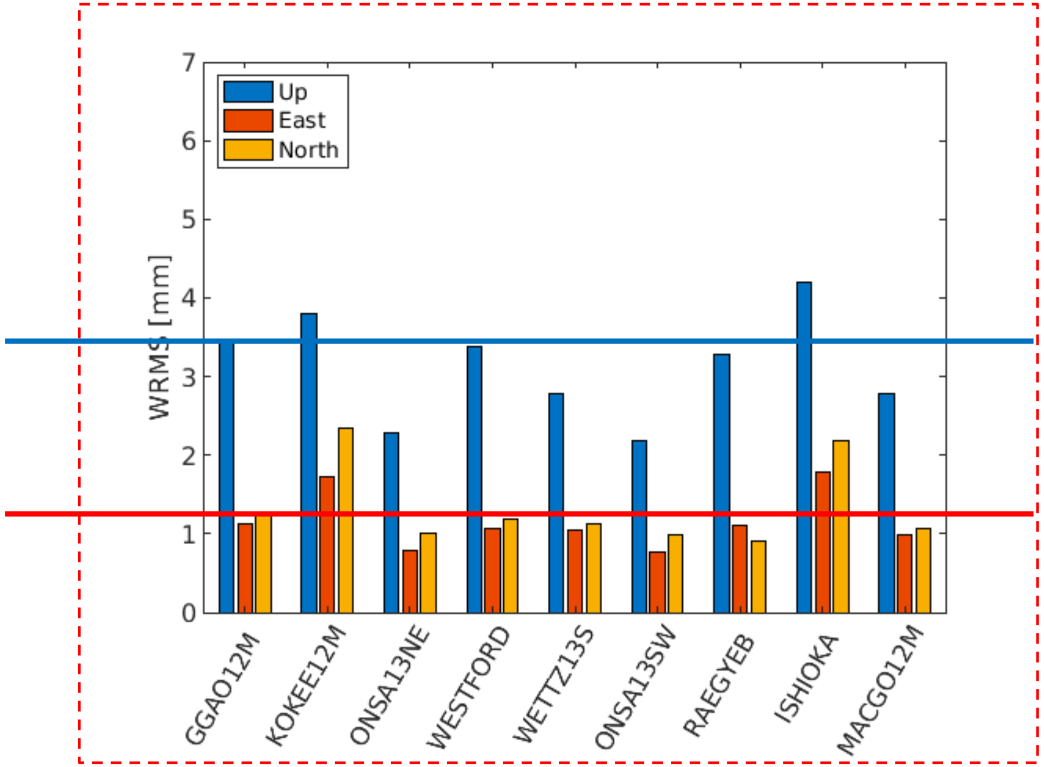
(Ref. Nilsson, Haas, Varenius, IVS GM 2022)



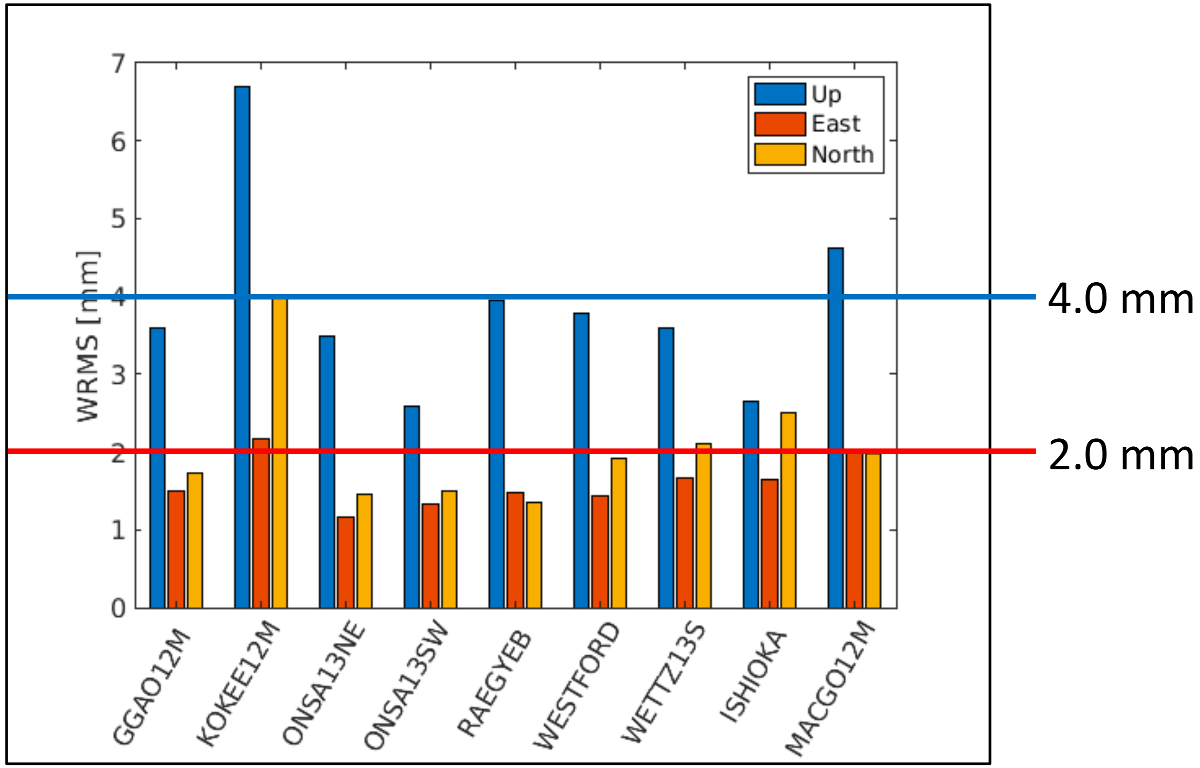
Station position repeatability, VGOS 2019–2021.

VGOS Simulations vs. VGOS Real Data

Analysis of simulated VGOS data 2019–2021
(Ref. Nilsson, Haas, Varenius, IVS GM 2022)



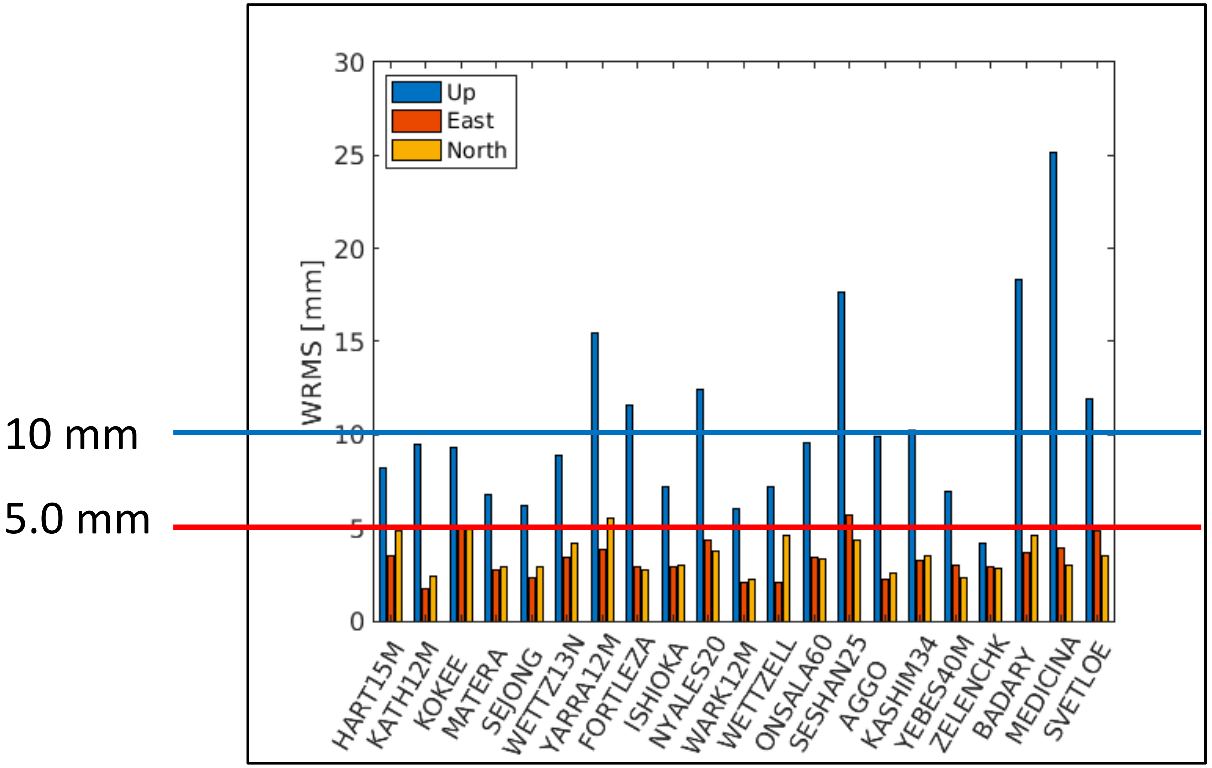
Analysis of real VGOS data 2019–2021
(Ref. Nilsson, Haas, Varenius, IVS GM 2022)



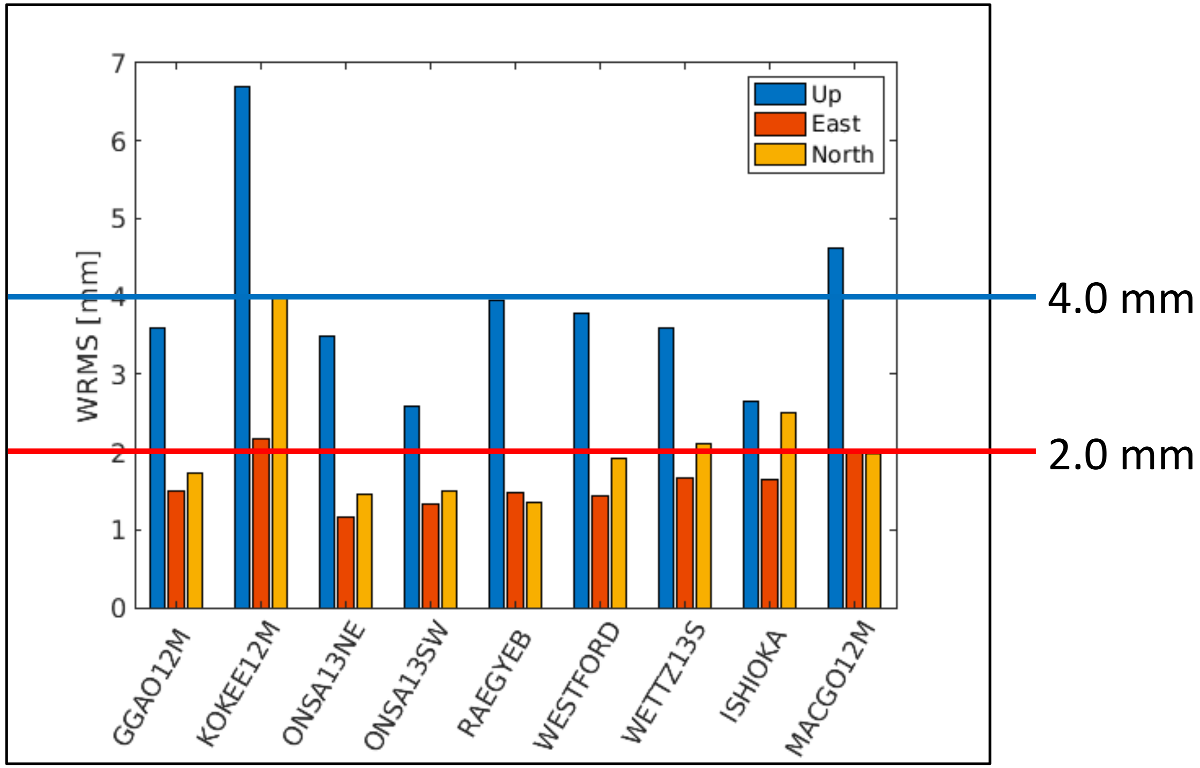
=> VGOS Real Data performance is only slightly worse than VGOS simulations.

Station positions: S/X legacy vs. VGOS

Analysis of S/X legacy data 2019–2021
(Ref. Nilsson, Haas, Varenius, IVS GM 2022)



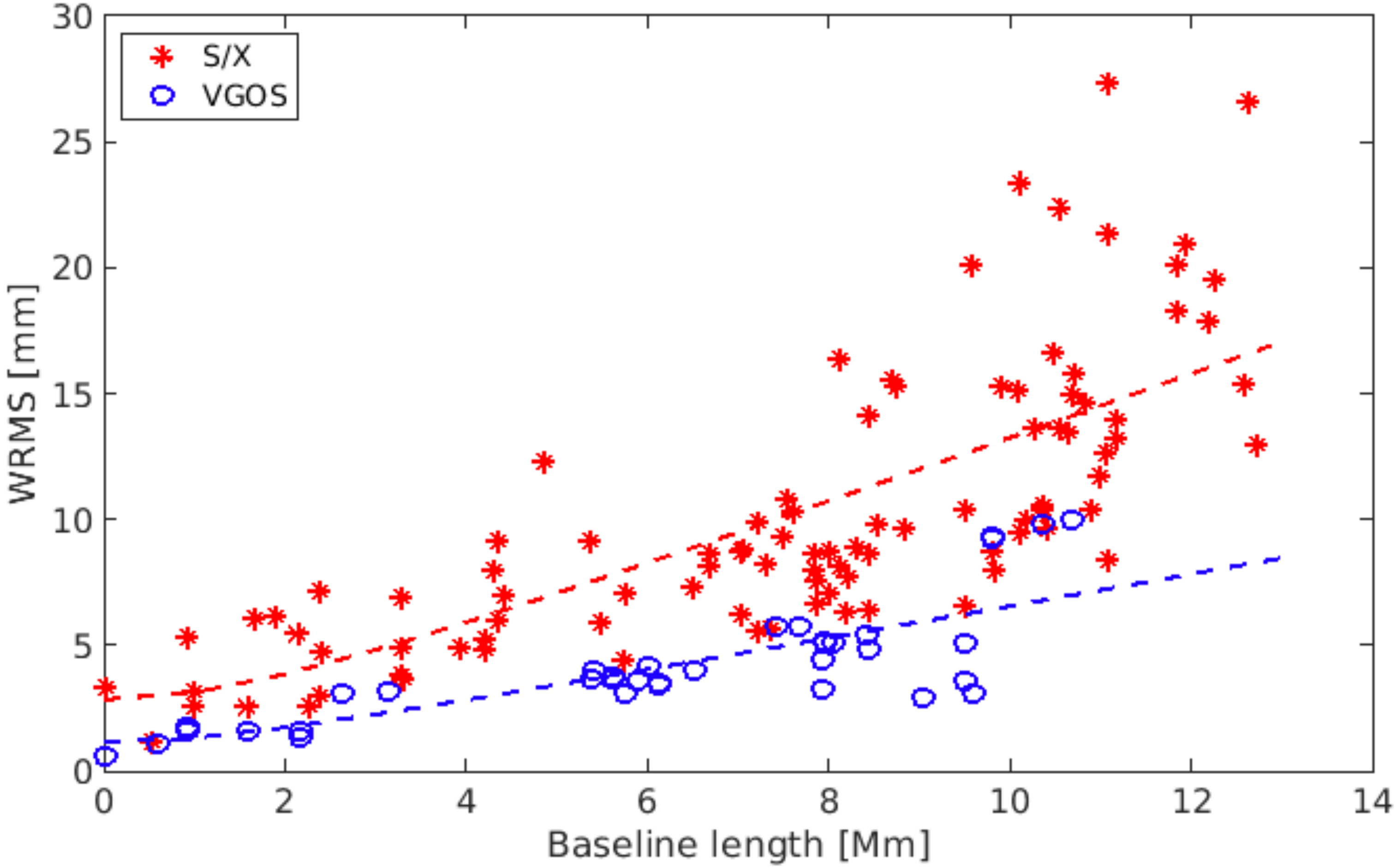
Analysis of VGOS data 2019–2021
(Ref. Nilsson, Haas, Varenius, IVS GM 2022)



=> Today's VGOS is about a factor of 2.5 better than legacy S/X .

Baseline repeatability: VGOS vs. S/X legacy

Baseline repeatability of simultaneous VGOS and R1/R4 sessions 2019–2021.



WRMS @ 6000 km:
- 4.0 mm (VGOS)
- 8.3 mm (S/X)

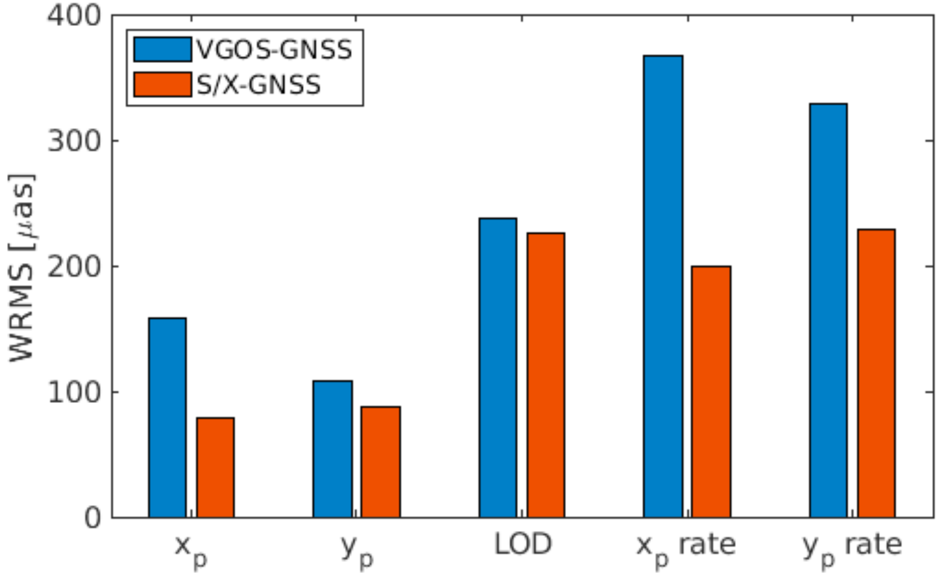
(Ref. Nilsson, Haas, Varenius, IVS GM 2022)

=> Today's VGOS is about a factor of > 2 better than legacy S/X .

EOP VGOS vs. S/X legacy

Series	σ_{mean}	σ_{median}	RMS	Bias	STD
All BKG INT1/INT2	14.8	14.2	32.9	14.3 ± 3.4	29.6
All GSF INT1/INT2	15.1	13.2	28.3	-2.0 ± 3.2	28.2
All USN INT1/INT2	14.6	12.9	28.4	8.5 ± 3.1	27.1
All GIS INT2	13.5	9.2	33.6	10.2 ± 6.7	32.0
All IAA INT1/INT2	15.0	12.2	27.8	5.0 ± 3.6	27.3
All OSO INT1/INT2	16.5	15.4	31.0	4.5 ± 3.6	30.6
OSO VGOS-B	4.5	4.2	23.2	-3.8 ± 7.2	22.9
Simultaneous OSO INT1	16.0	14.2	28.4	-0.8 ± 9.0	28.3
Simultaneous BKG INT1	17.3	16.1	32.9	8.4 ± 10.1	31.8
Simultaneous GSF INT1	18.8	16.8	24.2	-7.6 ± 7.3	23.0
Simultaneous USN INT1	14.3	14.4	27.9	5.4 ± 9.1	27.4

Comparison of UT1-UTC from simultaneously observed VGOS and S/X legacy Intensives.
(Ref. Haas *et al.*, EPS 2021)



Comparison of EOP from simultaneous VGOS and S/X legacy w.r.t. GNSS results.
(Ref. Nilsson, Haas, Varenius, IVS GM 2022)

=> VGOS is superior for UT1-UTC, but still slightly worse for polar motion.

VGOS Research and Development Sessions

- Goals are to further develop VGOS, e.g.:
  - Test new observation strategies, e.g. short scan length
  - Test frequency setups

- VGOS R&D in 2021/2022:
  - Short scans: e.g. VR2101 minimum and average scan length 7 s and 11 s, respectively
  - Many observations: e.g. VR2101 3397 scans, 23040 observations
  - Allows to resolve tropospheric parameters with 5 min temporal resolution (new!)

- All sites: co-located GNSS, often several ones
- Onsala: co-located GNSS and WVR

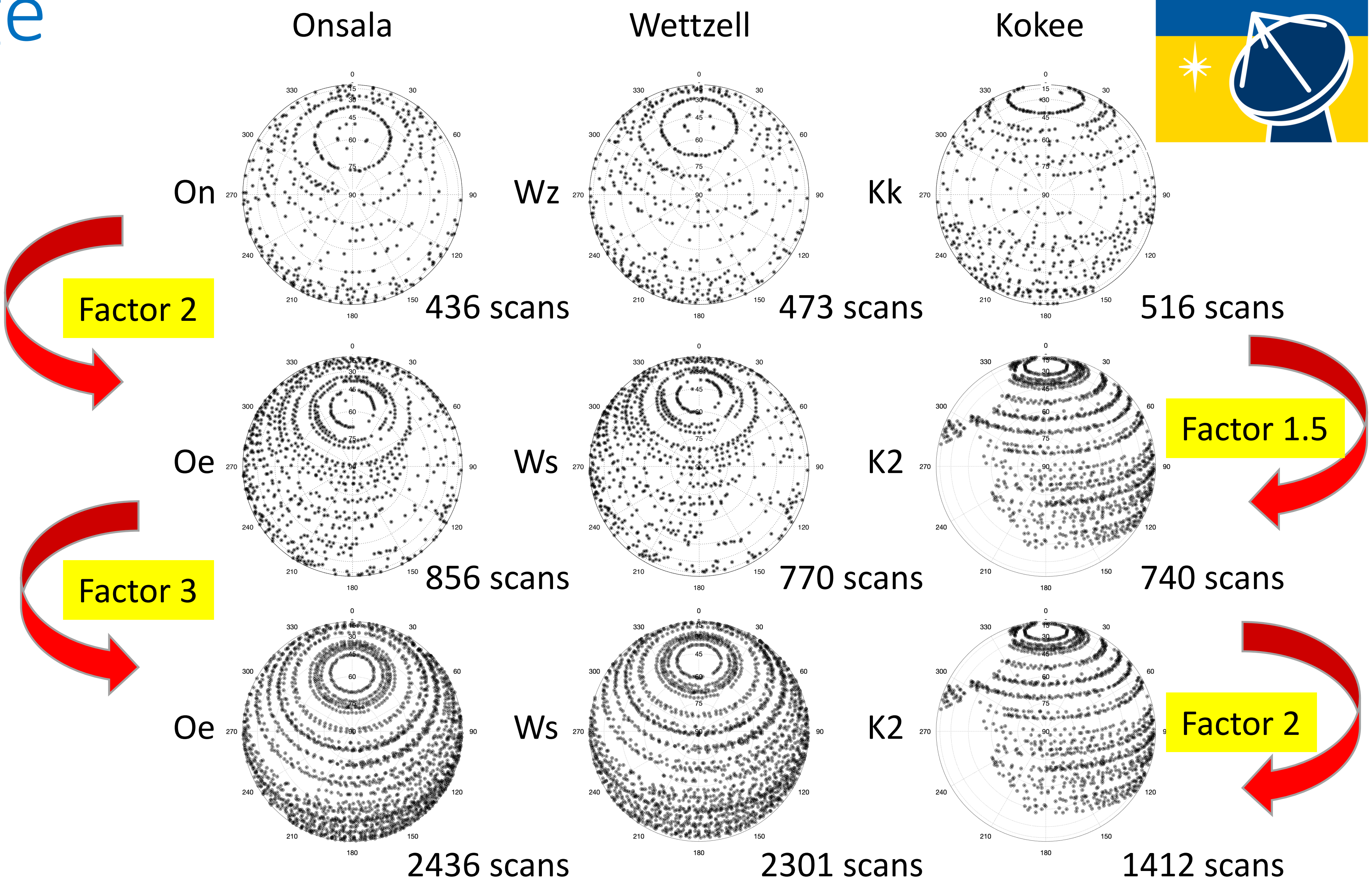
IVS

Sky coverage

Legacy S/X, R11101:
15 stations
1638 scans
Average scan length 75 s

VGOS, VO1203:
8 stations
1265 scans
Average scan length 30 s

VGOS, VR2101:
7 stations
3397 scans
Average scan length 11 s



Onsala: VGOS – GNSS – WVR

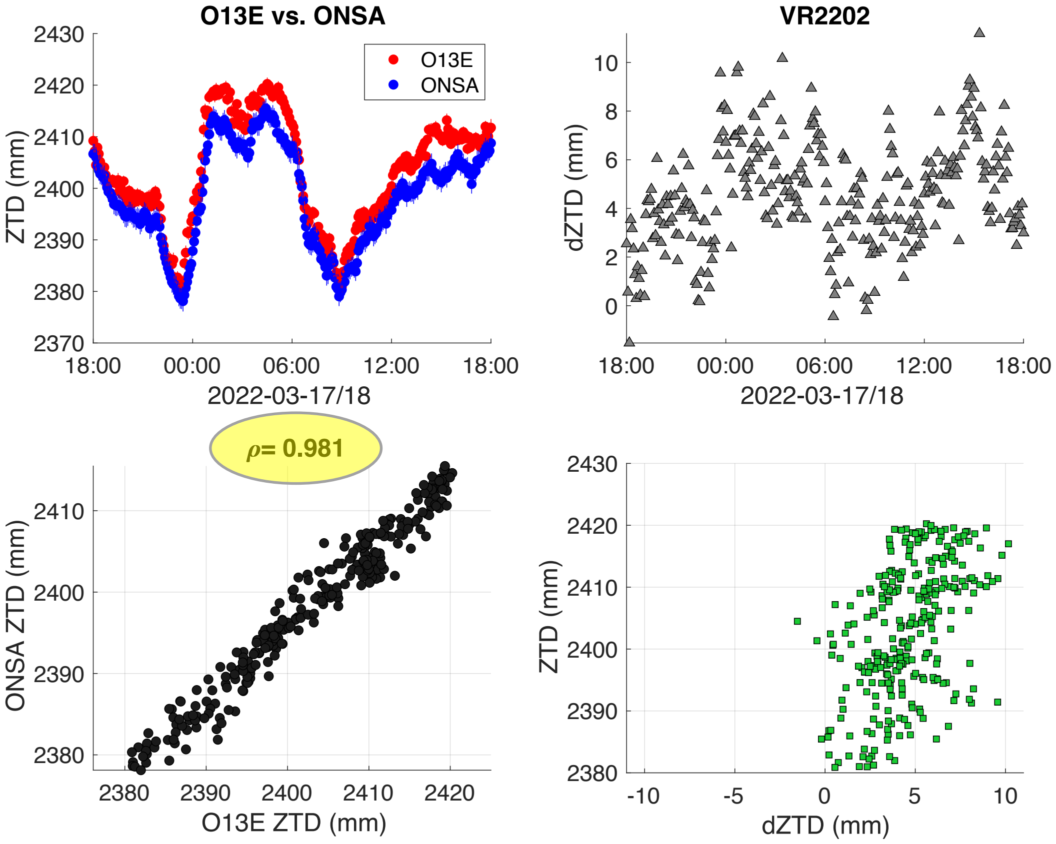
Onsala twin telescopes
Oe (O13E), Ow (O13W)

ONSA

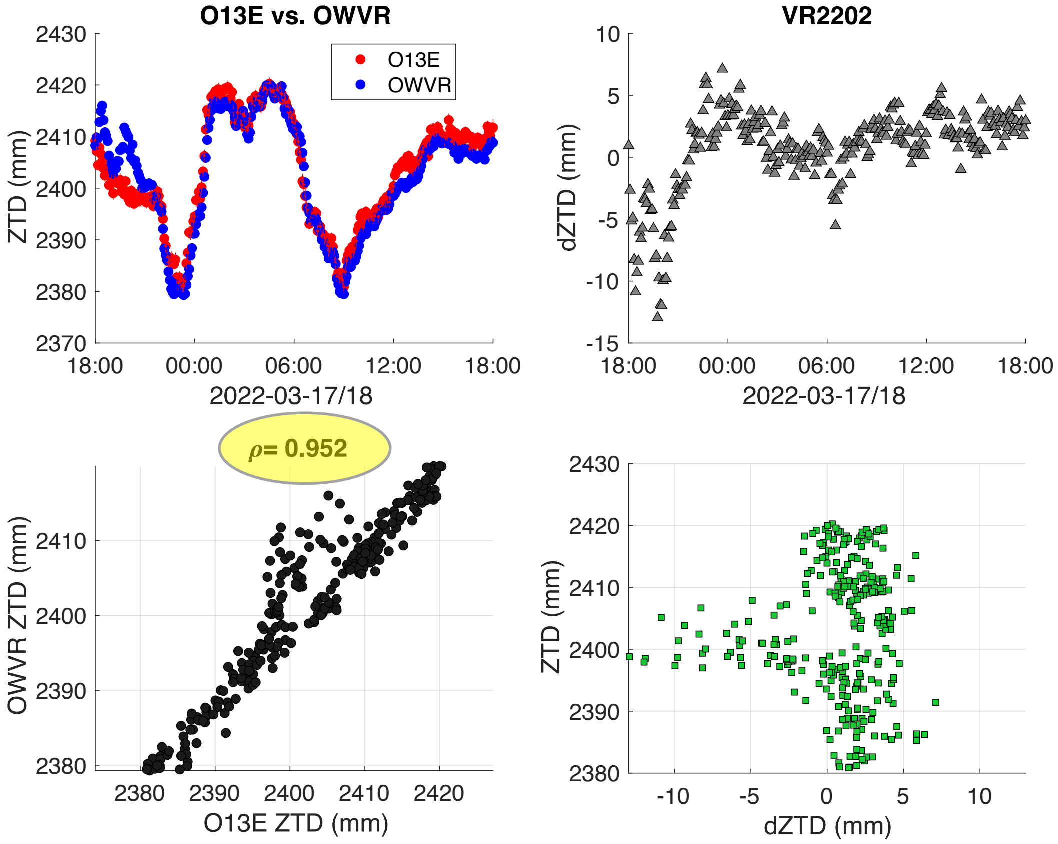
Konrad
(OWVR)

VR2202, Onsala ZTD: VGOS,GNSS, WVR

ZTD VGOS vs. GNSS

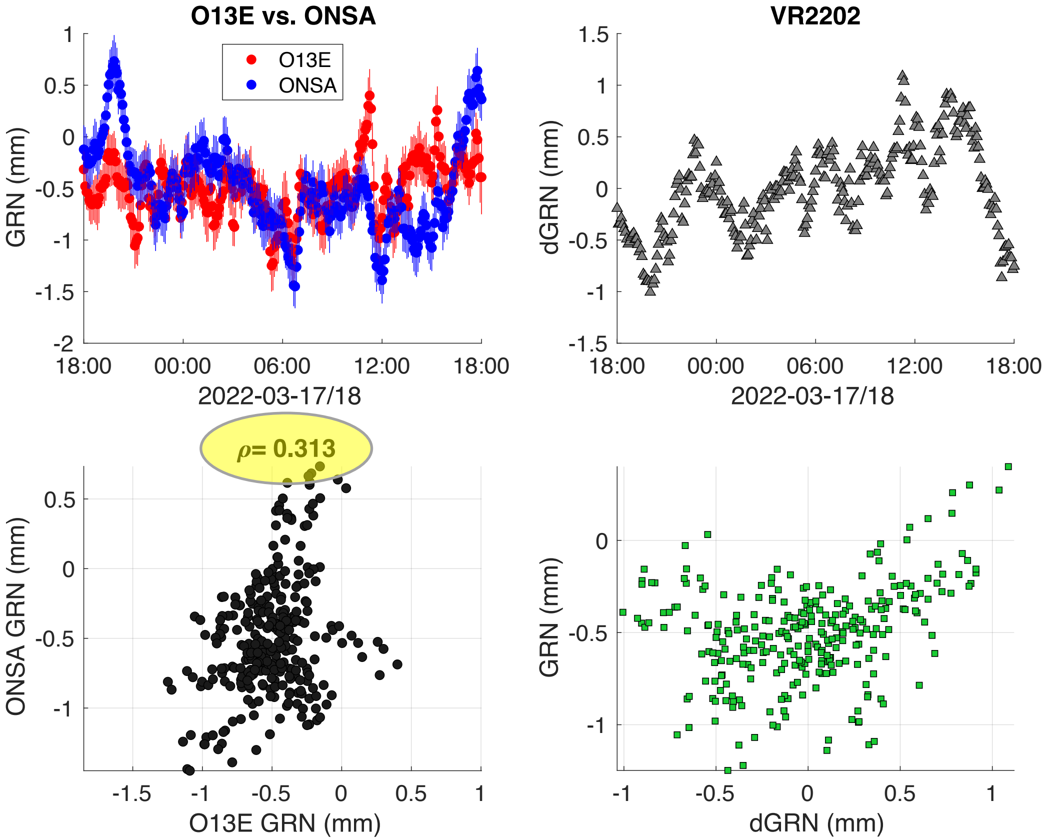


ZTD VGOS vs. WVR

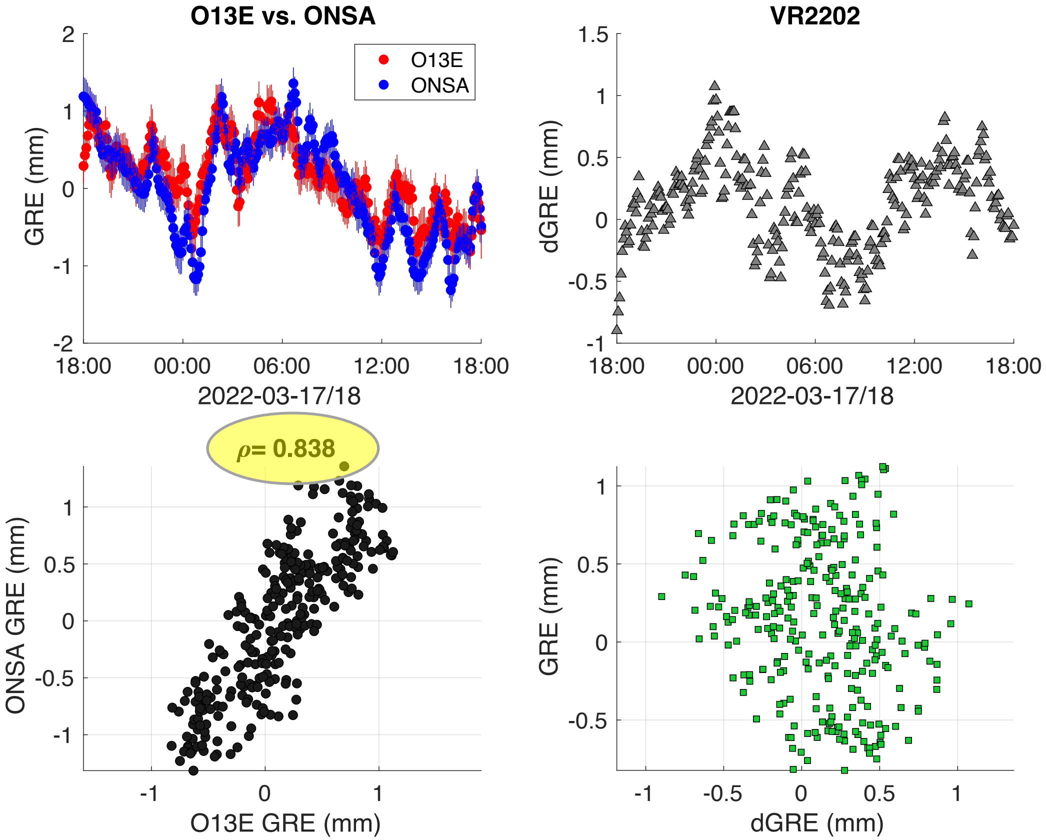


VR2202, Onsala GRAD: VGOS, GNSS

Gradient North VGOS vs GNSS

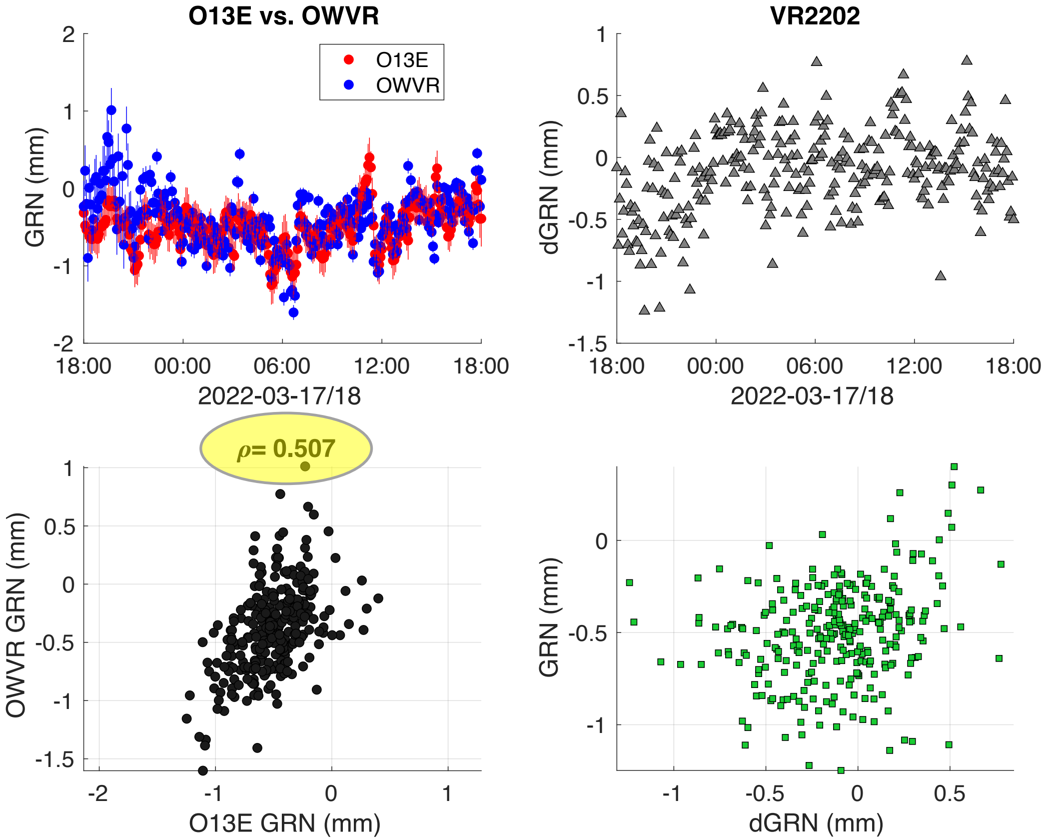


Gradient East, VGOS vs GNSS

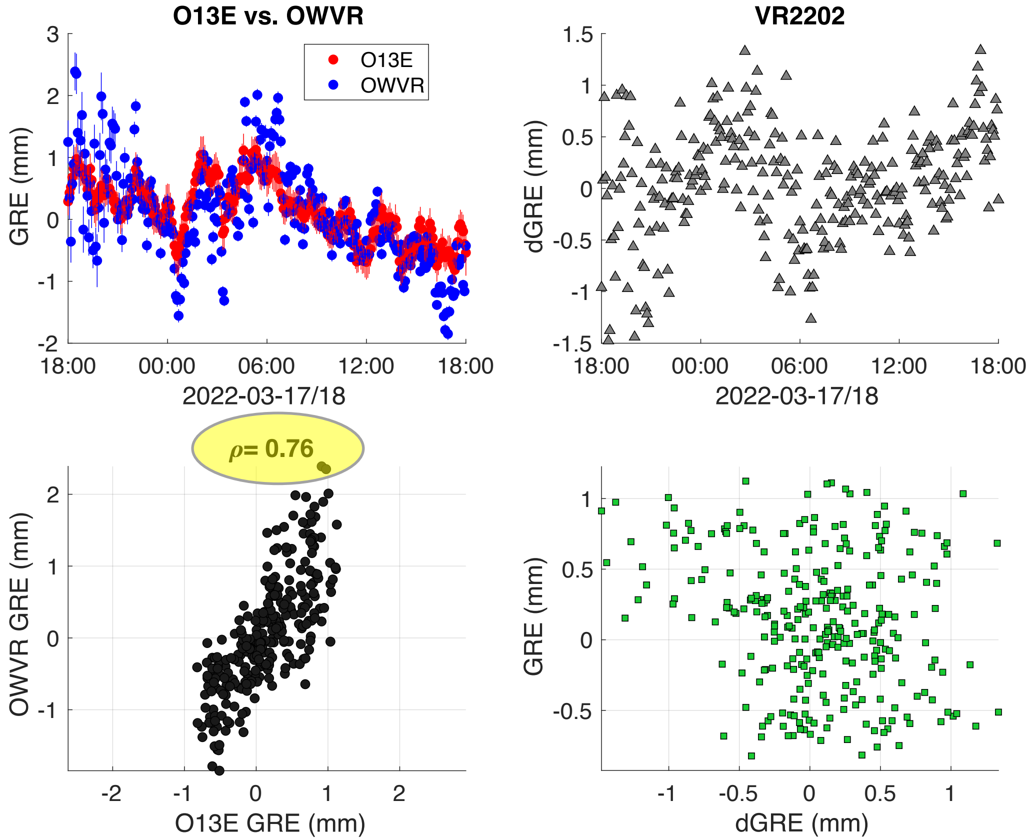


VR2202, Onsala GRAD: VGOS, WVR

Gradient North, VGOS vs. WVR

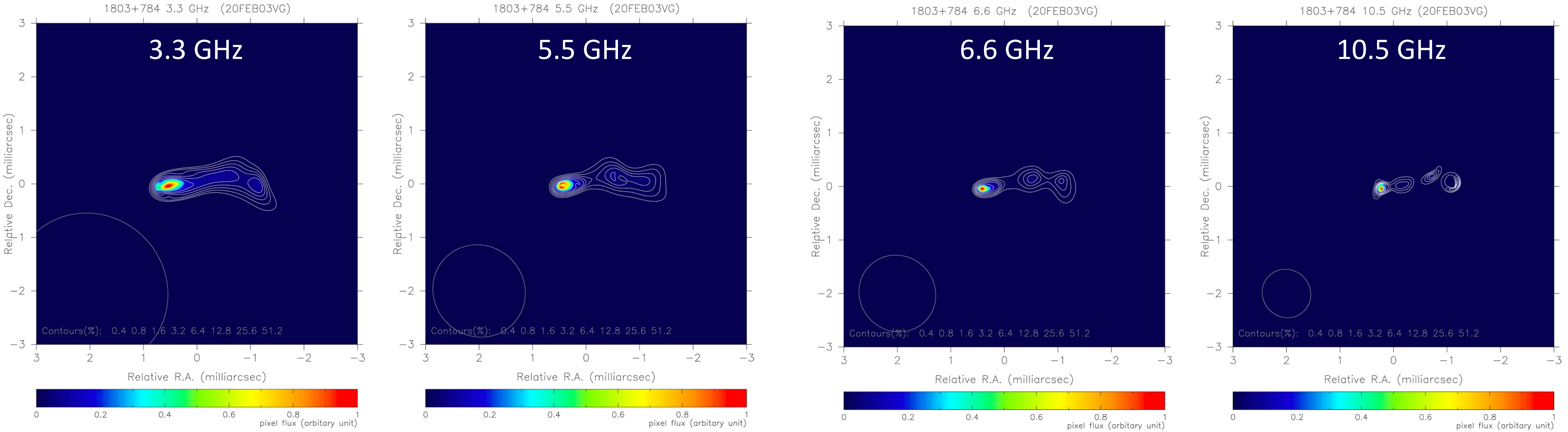


Gradient East, VGOS vs. WVR



VGOS radio source imaging

Example radio source 1803+784 (Ref. Xu et al., JGR 2021)



=> VGOS allows broadband imaging to investigate radio source structure.

VGOS flux density monitoring

Example:
Flux density obtained with the Onsala twin telescopes, 91 short (30 min) VSBI sessions
(Ref. Varenius et al., 2022)

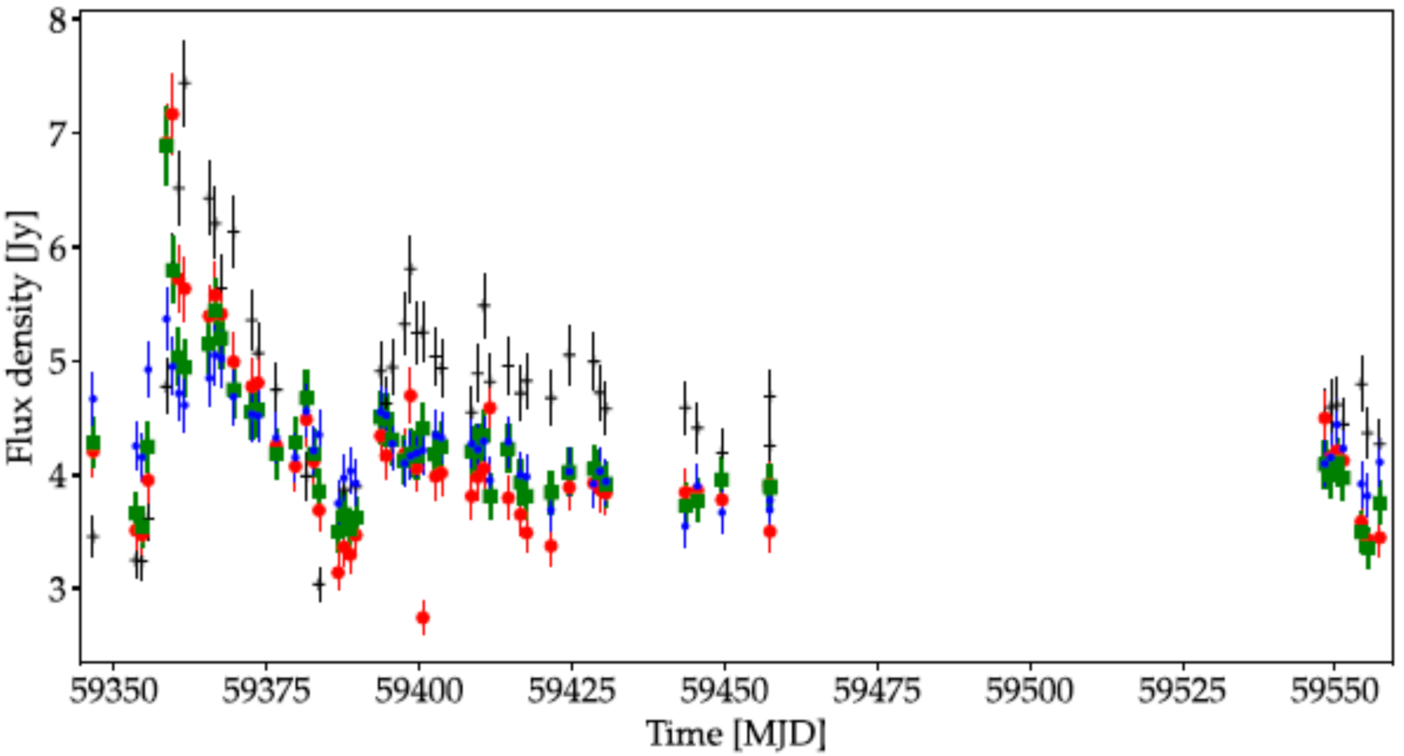


Fig. 3 The multi-frequency light curve of the source 0059+581, as observed in the FM-sessions, shown separately to appreciate the rich variability. Flux densities in the four VGOS bands 1, 2, 3 and 4 are shown with black crosses, red circles, green squares and blue dots respectively

=> Important to have correct flux density information for VGOS scheduling.

Summary

The IVS currently rolls-out a phantastic and very powerful new observing system: => VGOS

- It outperforms S/X legacy VLBI already today in terms of station positions, baseline repeatability, and UT1-UTC
- It is still slightly weaker for polar motion than S/X legacy VLBI due to worse network geometry (so far only 10 NH operational stations)
- It allows to address atmospheric turbulence
- It makes routine broadband radio source imaging possible
- It can derive ”real time” flux density from e.g. twin telescope observations

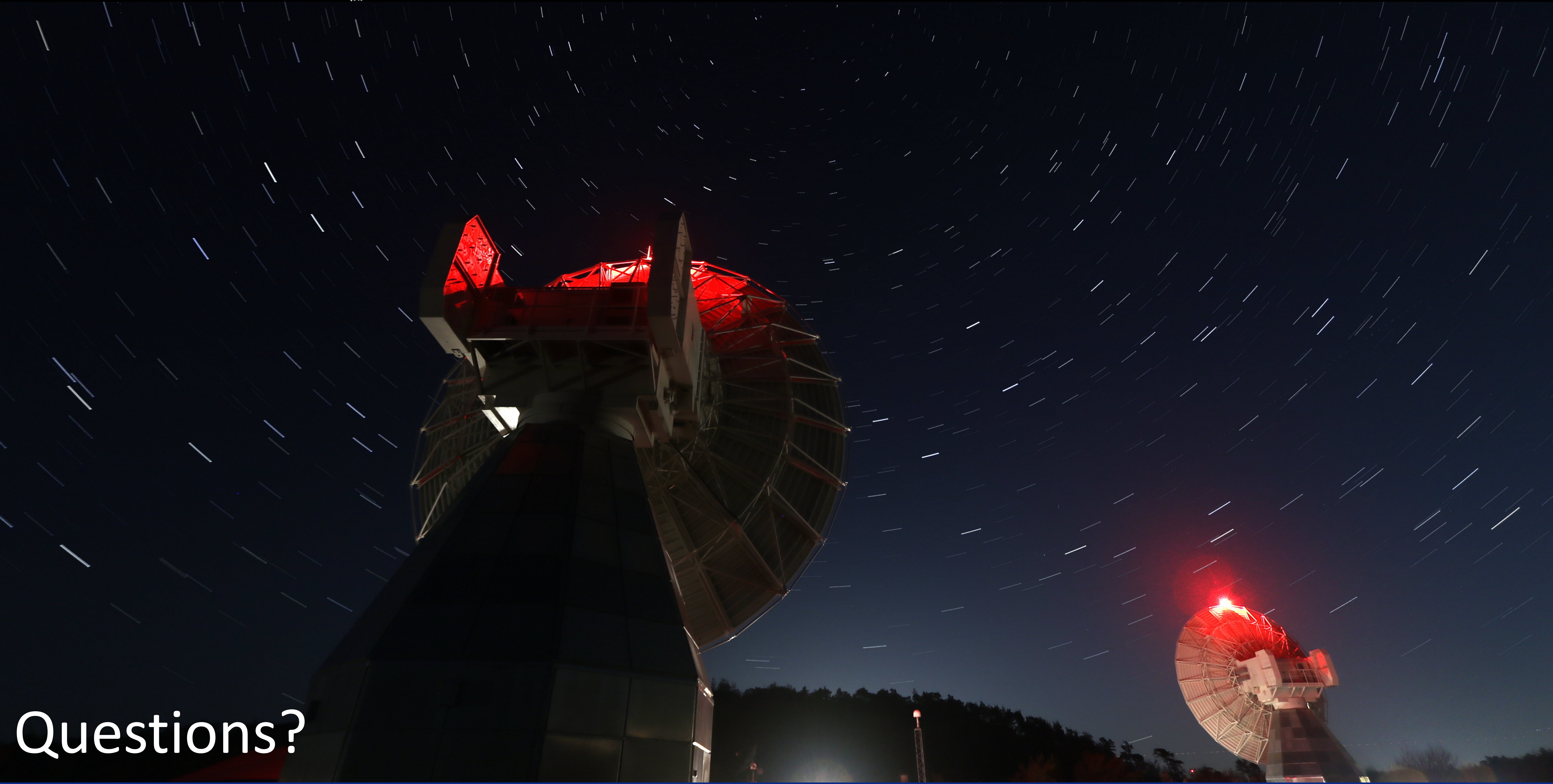
Outlook: IVS VGOS network in 5–10 years

Outlook: IVS plan for the next 10 years

- VGOS shall become “the work horse of the IVS”
  - Using VGOS for all IVS products, i.e. CRF, EOP TRF
  - Multi-frequency CRF: Continue S/X CRF and build up VGOS CRF
- IVS needs:
  - ca. 40 globally distributed VGOS
  - ca. 30 globally distributed legacy S/X stations
  - Sufficient number of correlator stations
- Future IVS observation plan
  - Twice daily VGOS UT1-UTC determination with low latency
  - Several 24-h VGOS sessions (12+ stations) per week for EOP/TRF
  - Several 24-h VGOS and S/X CRF sessions per year
  - Additional R&D sessions

Challenges for the IVS?

- IVS is a best effort and non-profit organisation
  - Relies solely on the IVS member institutions, no common money
- Establishing new VGOS stations is expensive and takes time
  - VGOS roll-out is slower than expected, but more stations to come in the next 2–5 years
  - Several stations have not yet reached ”full-VGOS” specifications
- Potential risk of increased RFI in VGOS bands, e.g. 5G, Starlink, …
  - Initiatives on IAU and IUGG level to protect VGOS bands
- VGOS produces huge amount of raw data
  - currently ca. 25 TB per station during 24 h (will increase to even 50 TB)
  - bottleneck problems at the correlator end
  - more IVS correlators are needed



Questions?