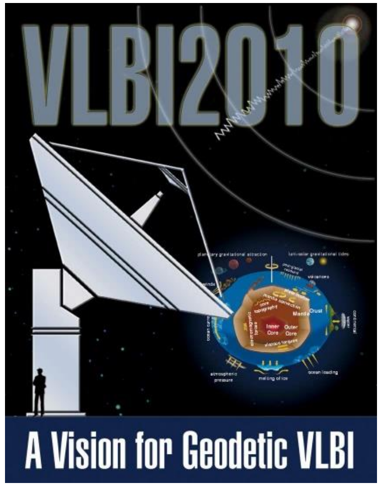
Realization Status of VGOS Infrastructure Buildout

Dirk Behrend

NVI, Inc./NASA GSFC, Greenbelt, MD, USA

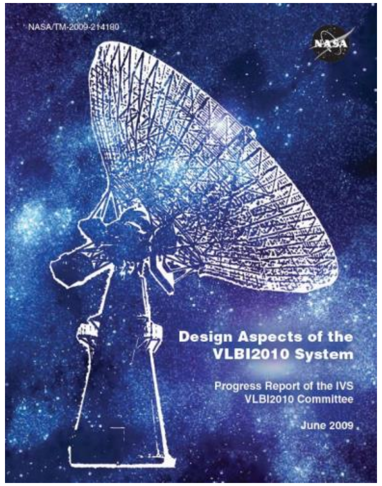
11th IVS Technical Operations Workshop
May 3–5, 2021

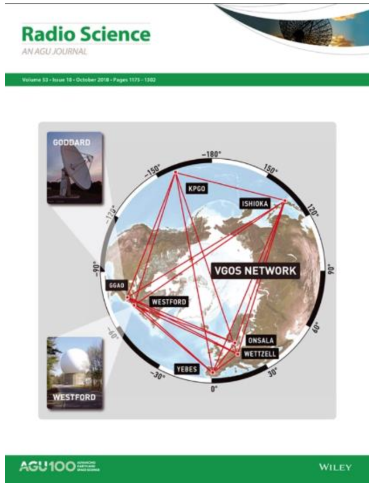
VLBI Global Observing System (VGOS): Some History



- IVS Working Group 3: Final Report
  - https://ivscc.gsfc.nasa.gov/about/wg/wg3/IVS_WG3_report_050916.pdf
  - September 2005
  - Vision document

- VGOS Technical Committee (VTC): Progress Report
  - https://ivscc.gsfc.nasa.gov/technology/vgos-docs/TM-2009-214180.pdf
  - June 2009
  - Definition of specifications





- Radio Science: Technical Report
  - https://doi.org/10.1029/2018RS006617
  - September 2018
  - Overview of VGOS system

What is the IVS?

The **International VLBI Service for Geodesy and Astrometry (IVS)** is an international collaboration of organizations which operate or support Very Long Baseline Interferometry (VLBI) components:

- IVS inauguration was on **1 March 1999**.
- 83 permanent components supported by 41 institutions in 21 countries.
- ~300 Associate Members.

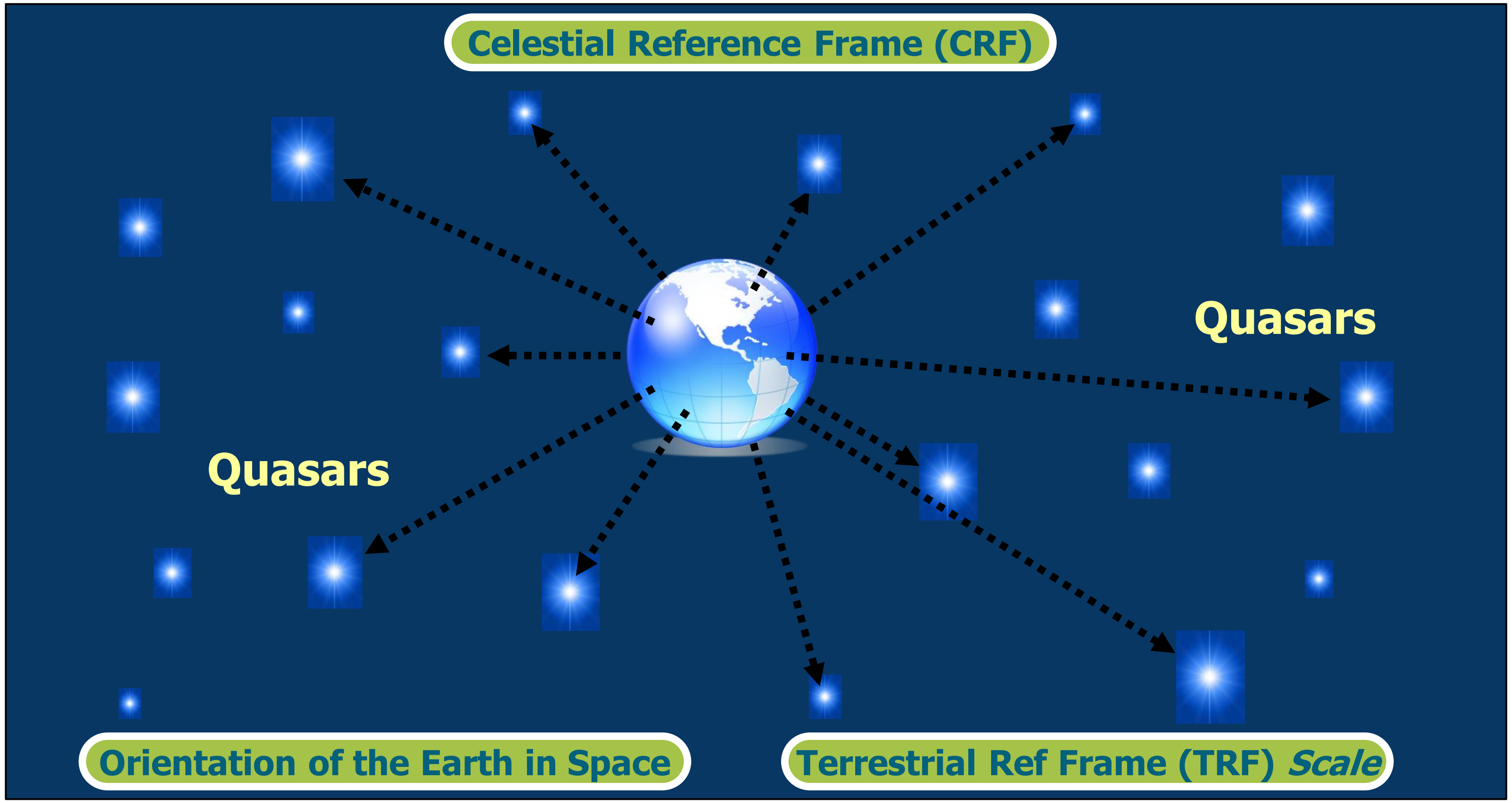
IVS is a recognized service of

- **IAG** – International Association of Geodesy
- **IAU** – International Astronomical Union
- **WDS** – ISC World Data System

IVS Products

- Earth Orientation Parameters (EOP):
  - 24-hour sessions (all EOP)
  - 1-hour Intensives (UT1–UTC)
- Terrestrial Reference Frame (TRF)
- Celestial Reference Frame (CRF)

- Daily EOP + station coordinates (SINEX files)
- Tropospheric Parameters
- Baseline Lengths



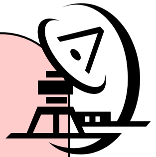
VGOS: Why a New System

Aging systems (now ~50 years old):

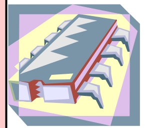
- Old antennas
- Obsolete electronics
- Costly operations
- RFI

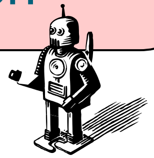
New system

New Technology:



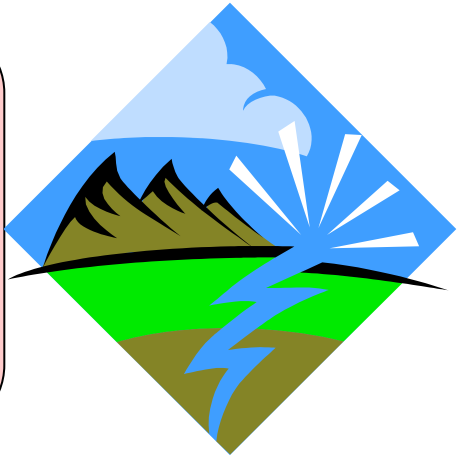
- Fast, affordable antennas
- Digital electronics
- Hi-speed networks
- Automation





New requirements:

- Sea level rise
- Earthquake processes
- 1-mm accuracy
- GGOS



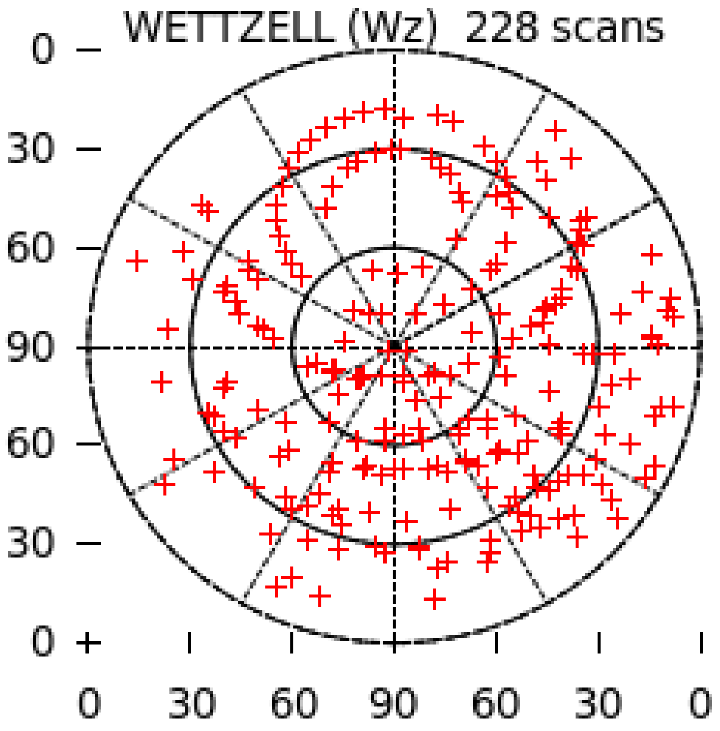
VGOS: Goals of the New System

VGOS Goals

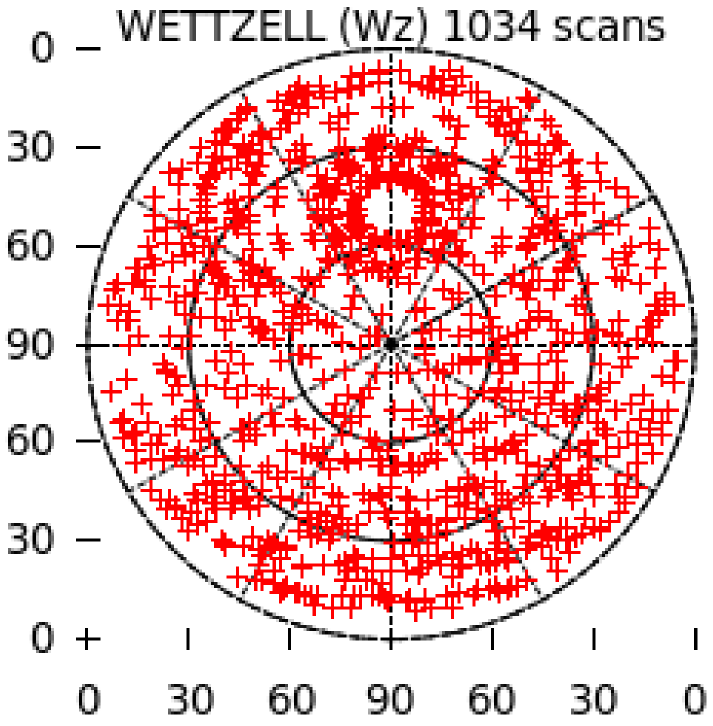
- **1-mm position accuracy *(based on a 24-hour observation)***
- **Continuous measurements of station position and EOP**
- **Turnaround time to initial products < 24-hrs**

VGOS: Increase in Number of Observations

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



Legacy S/X system

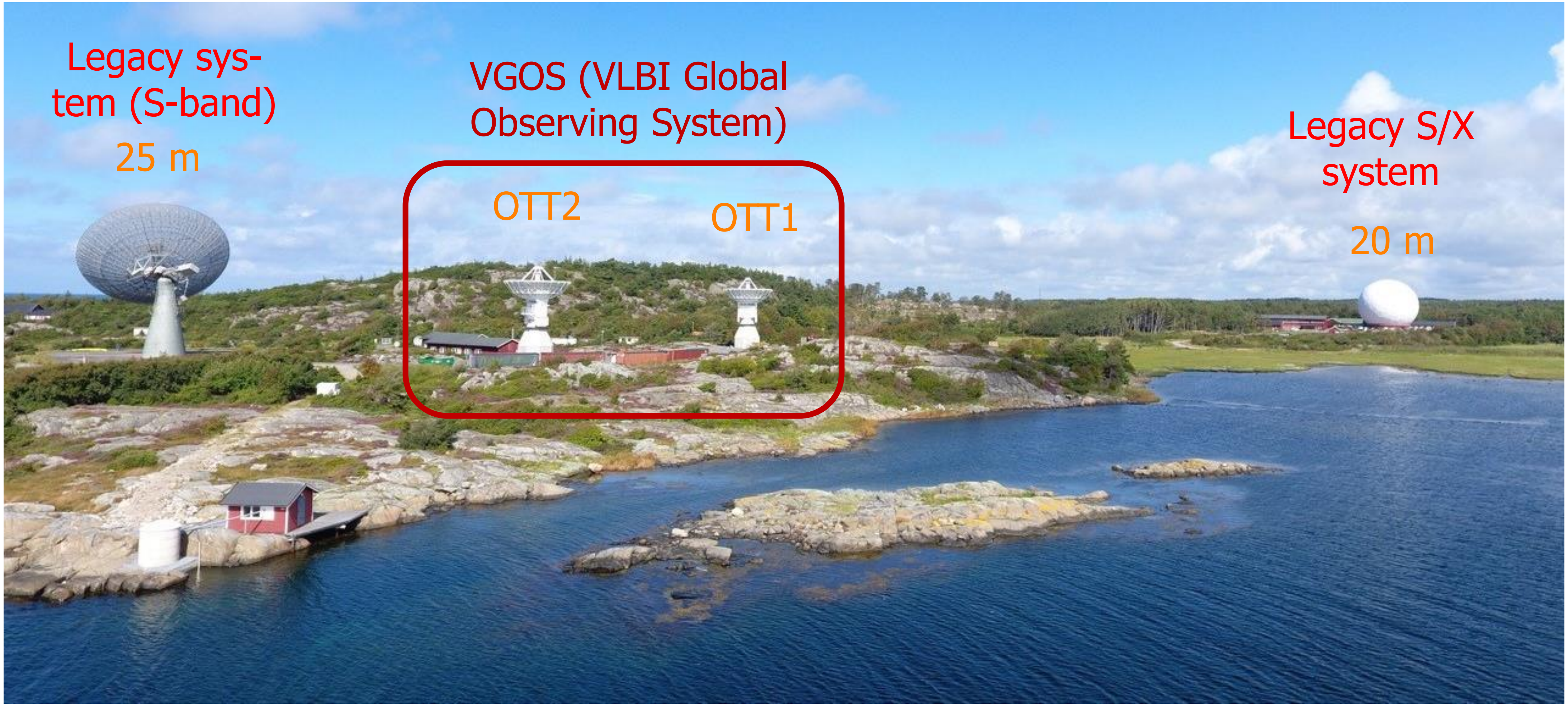


VGOS broadband system

VGOS vs. Legacy S/X: Comparison of Characteristics

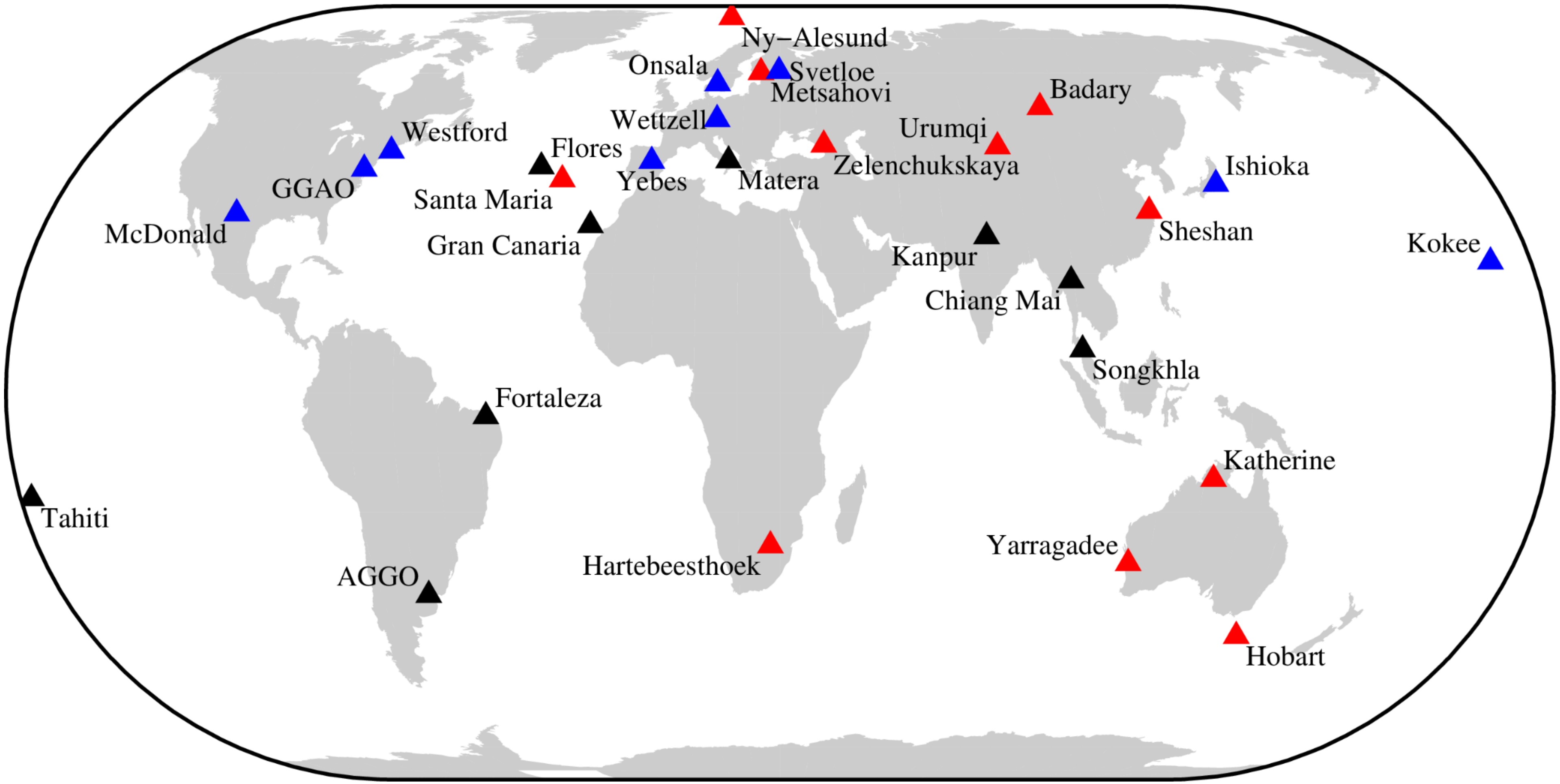
	Legacy S/X System	VGOS System	Benefit
Antenna size	5–100 m dish	12–13 m dish	reduced cost
Slew speed	~20–200 deg/min	≥ 360 deg/min	more observations for troposphere
Sensitivity	200–15,000 SEFD	≤ 2,500 SEFD	more homogeneous
Frequency range	S/X band [2 bands]	~2–14 GHz [1 broadband w/ 4 bands]	increased sensitivity, data precision
Recording rate	128, 256, 512 Mbps	8, 16, 32 Gbps	increased sensitivity
Data transfer	usually e-transfer, some ship disks	e-transfer, ship disks when required	
Signal processing	analog/digital	digital	stable instrumentation

Onsala Skyline



Courtesy R. Haas

Evolution of the VGOS Network



▲ operational ▲ antenna built, signal chain work
▲ in planning stage

VGOS Observing Sessions

VGOS observing in 2019:

- VGOS Test (VGOS-T) sessions
  - One 24-hour session every 2 weeks, correlation at MIT Haystack Observatory
  - Databases made available at IVS data centers (e.g., CDDIS)

VGOS observing in 2020:

- VGOS Operational (VGOS-O) sessions
  - One 24-hour session every 2 weeks, correlation at MIT Haystack Observatory
  - Officially operational sessions, databases at IVS data centers
- VGOS Intensive (V2) sessions
  - (Starting in late February) one 1-hour session every 2 weeks, alternating with VGOS-O sessions
  - Correlation at MIT Haystack Observatory, databases at IVS data centers

VGOS Correlation Verification

Developer:

- MIT Haystack Observatory
- Correlation and fringe fitting process based on DiFX software correlator

Knowledge transfer:

- Correlation workshop in May 2019
  - Transfer procedures, software versions, lessons learned to other centers to increase VGOS observing frequency
- Follow-up workshop in 2020 (postponed due to COVID-19)
- Correlation comparisons using bench-mark data sets (1-hour, 24-hour)

Verification of correlators:

- Bonn, Shanghai, USNO, and Vienna (plus Tsukuba and Onsala)
  - Each correlator has unique data transport challenges
  - Accepts disk modules, e-transfer only, limited network capacity
- Hands-on “blind-test” correlation with 1-hour VGOS Intensive session
  - Starting at raw data level
  - Verified that results agree within margin of errors
  - Needed iteration

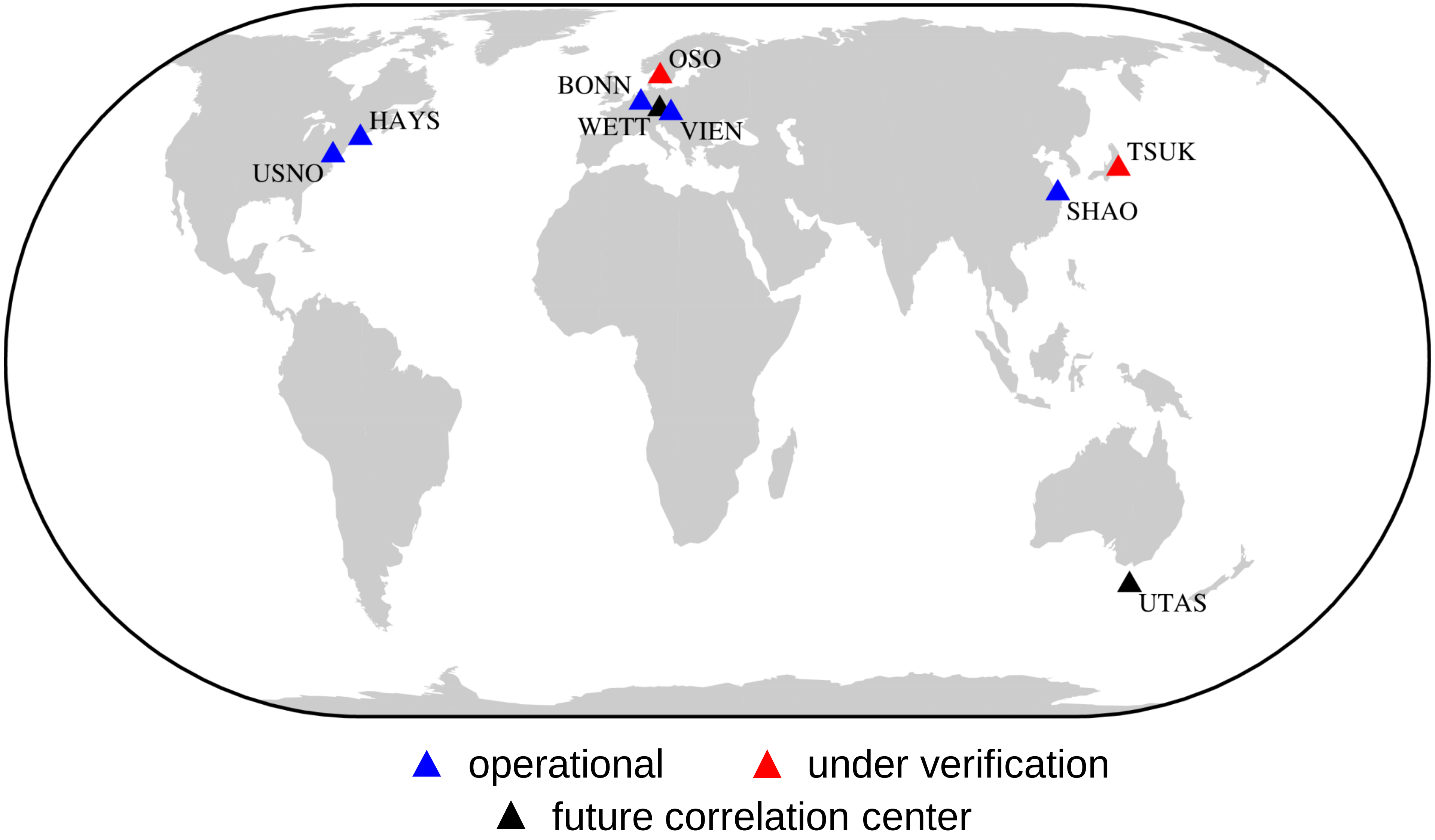
VGOS Correlation Verification

- Final verification w/ operational 24-hour VGOS session (VGOS-O: VO0009)
  - Bonn end-to-end from raw level
  - All other correlators start at post-correlation level (due to challenges w/ data transport of huge raw data)
  - Verified and validated VGOS corr-elation end-to-end process
  - Bonn, USNO started w/ operational sessions in 2020; VIEN, SHAO fol-lowed in 2021
- All verification results are published in Haystack memo series

"Mixed-mode" correlation:

- Simultaneous observing with VGOS and S/X stations in same network
- Important for tying the VGOS frame to the S/X frame
- Three R&D sessions observed in summer of 2020; two now correlated and contributed to ITRF2020
- Correlation VGOS-VGOS, S/X-S/X, and VGOS-S/X
- Mixed-mode correlator workshop directly following TOW2021

Rollout of VGOS Correlation Capabilities



Data Storage and Transport

Data storage requirements:

- Legacy S/X VLBI: ~2000 TB/year
- Typical 24-hour VGOS session (2020):
  - 8 stations
  - 50 TB/day/station of raw data
  - ~400 TB/day
- Network size to grow to 16–20 stations
  - for 20 stations: ~1000 TB/day
  - full year (24/7/365): ~360 PB/year

Data transport (electronic transfer):

- Required network data rates:
  - each site: 5.6 Gbps
  - correlator: 134 Gbps

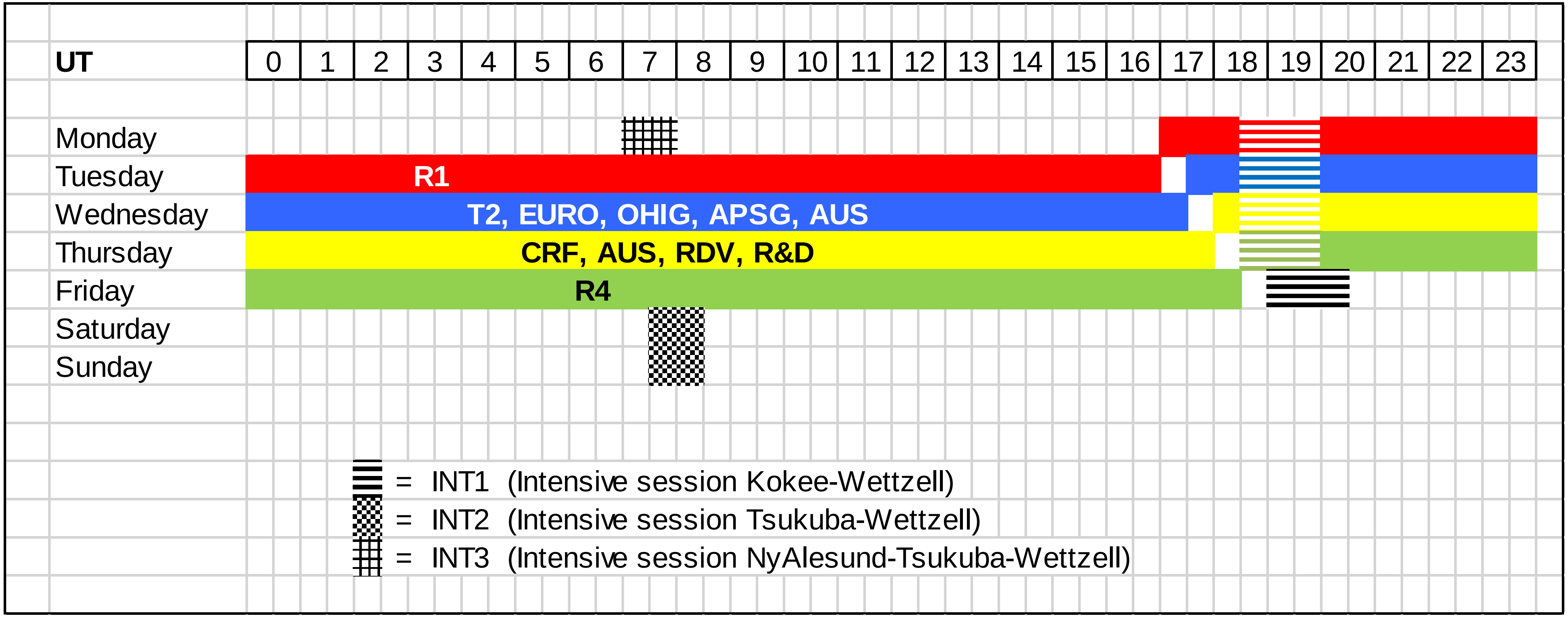
Station	Bandwidth now (sustained)	Transfer time for 50 TB of data
GGAO	1 Gbps	4.75 days
Westford	1 Gbps	4.75 days
Wettzell	4 Gbps	1.2 days
Yebes	5 Gbps	0.95 days
Ishioka	1 Gbps	4.75 days
Kokee Park	0.1 Gbps	47.50 days
Onsala	6 Gbps	0.8 days
McDonald	0.3 Gbps	15.8 days

Note:

Kokee was recently upgraded to 1 Gbps

IVS Observing Program: Legacy S/X System

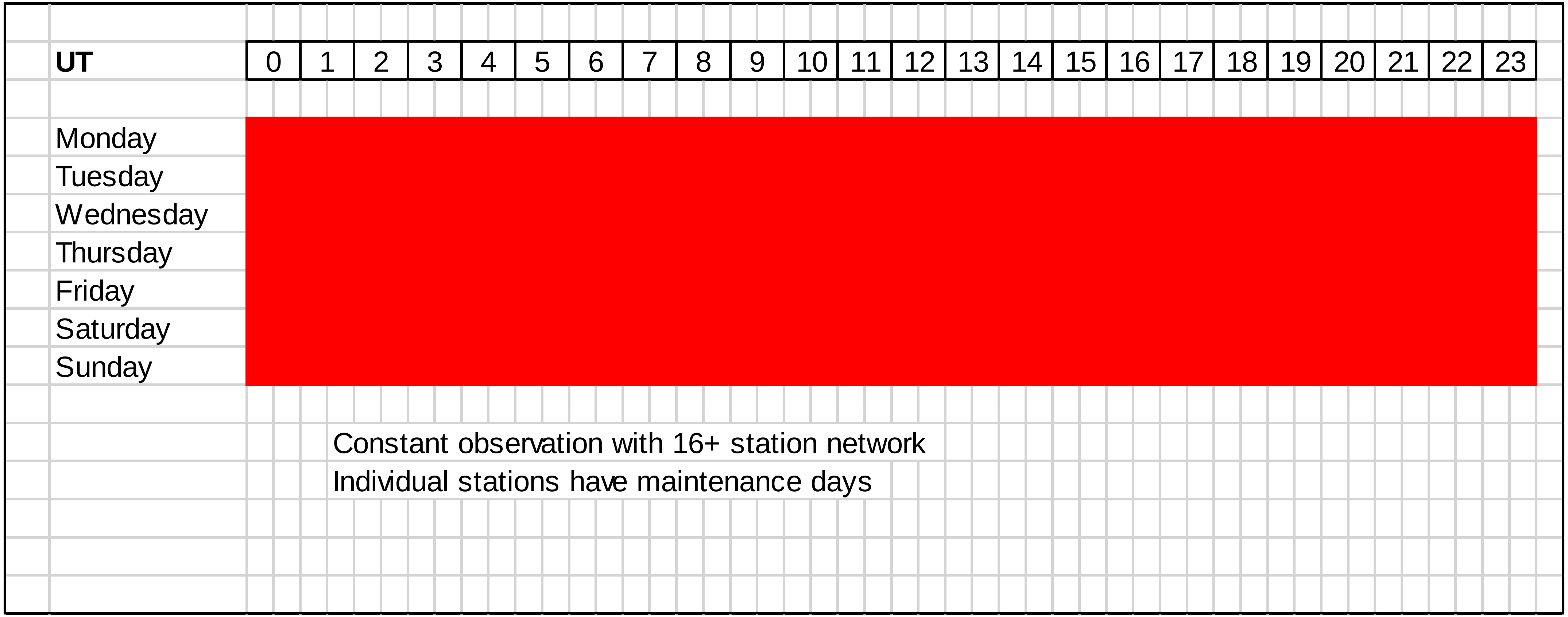
- Typical weekly layout for IVS observing sessions



- about 180 sessions per year, 3.5 sessions per week

IVS Observing Program: VGOS System

- Expected weekly observing coverage for VGOS (after 2020)



- 365 sessions per year, 7 sessions per week (24/7/365)

Analysis: VGOS Results for UT1−UTC

Comparison of VGOS Intensive and legacy S/X Intensive results w.r.t. IERS Bulletin B:

- The VGOS-B data show both the smallest uncertainties, a small bias, as well as the best agreement in terms of RMS and STD.
- Based on 11 sessions only, but very encouraging

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

From: Haas et al. Earth, Planets and Space (2021) 73:78

Future Steps

- VGOS network expansion to 24+ stations in next few years
- Use numerous correlators to go to higher cadence VGOS sessions
- Increase data storage and data transfer capacities at stations and correlation facilities
- Tie VGOS TRF to legacy S/X TRF using mixed-mode sessions (VGOS–S/X)
- Further avenues of improvement:
  - instrumentation development (e.g., bandwidth doubling)
  - atmosphere modeling
  - radio source structure
- Transition IVS production system from legacy VLBI to VGOS
- Eventual 24/7 observing

Ny Ålesund Twin Telescope

Inauguration event on 6 June 2018