Realization Status of the VLBI Global Observing System

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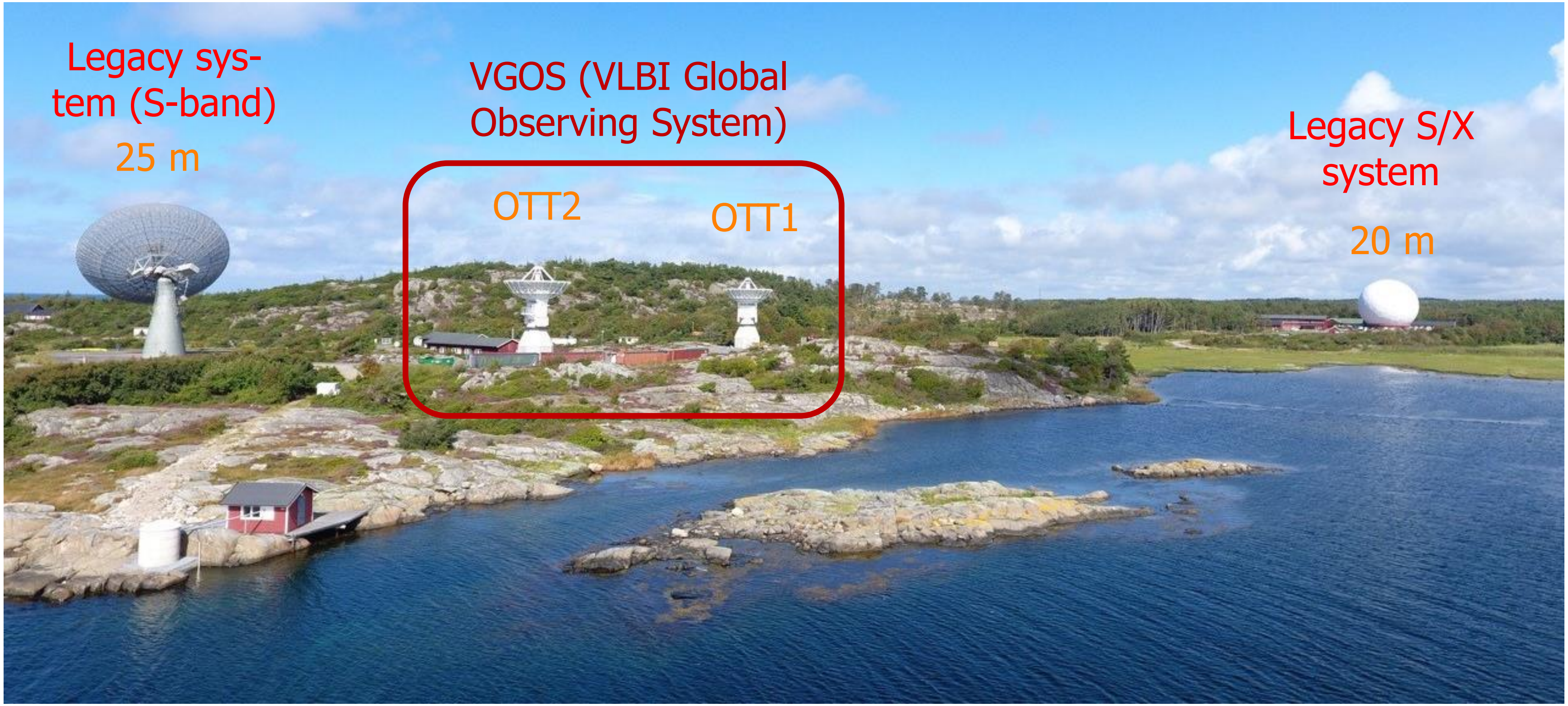
AGU 2020 Fall Meeting

VLBI Site: E.g., Onsala Space Observatory, Sweden

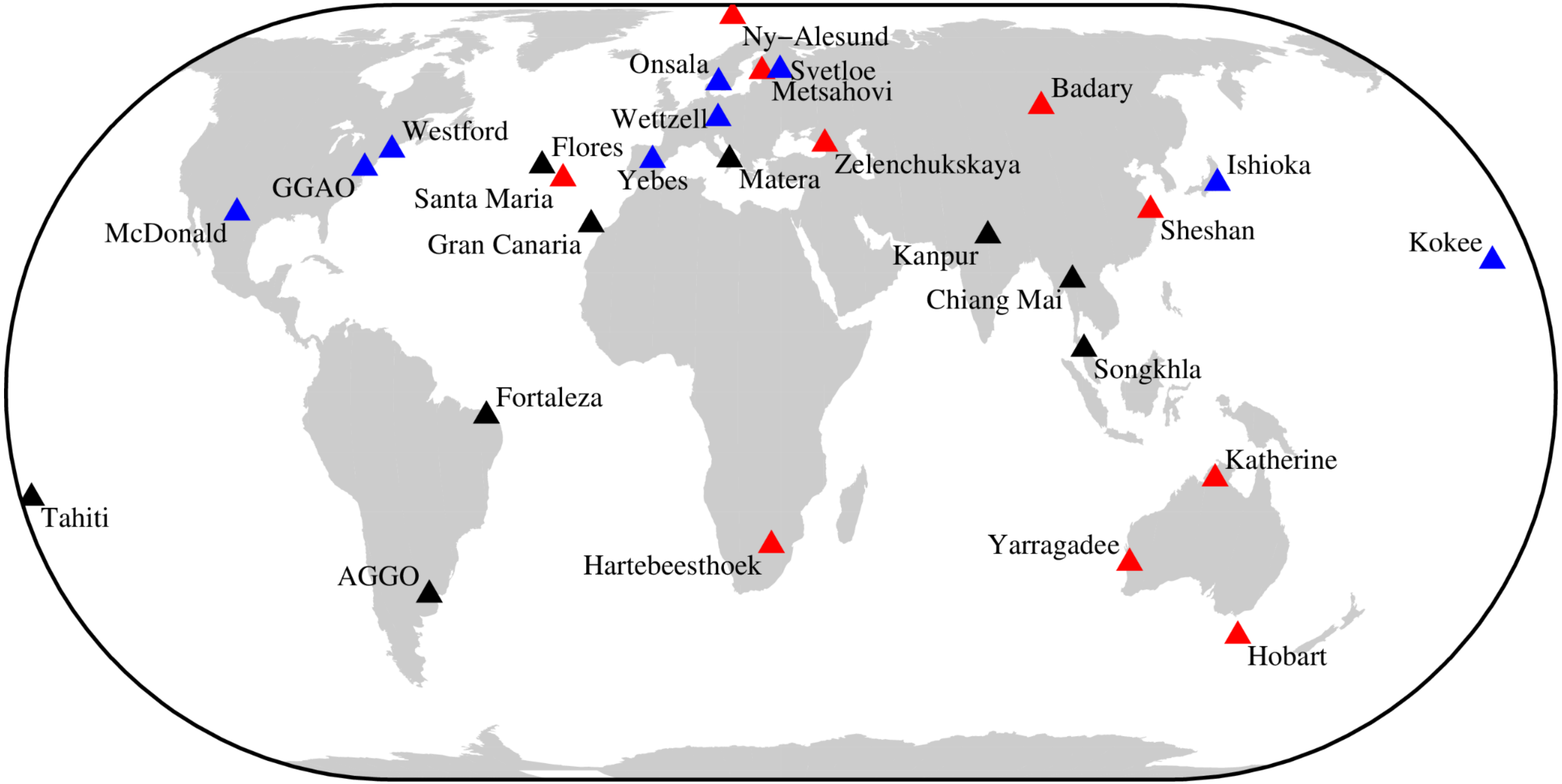


Courtesy R. Haas

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

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

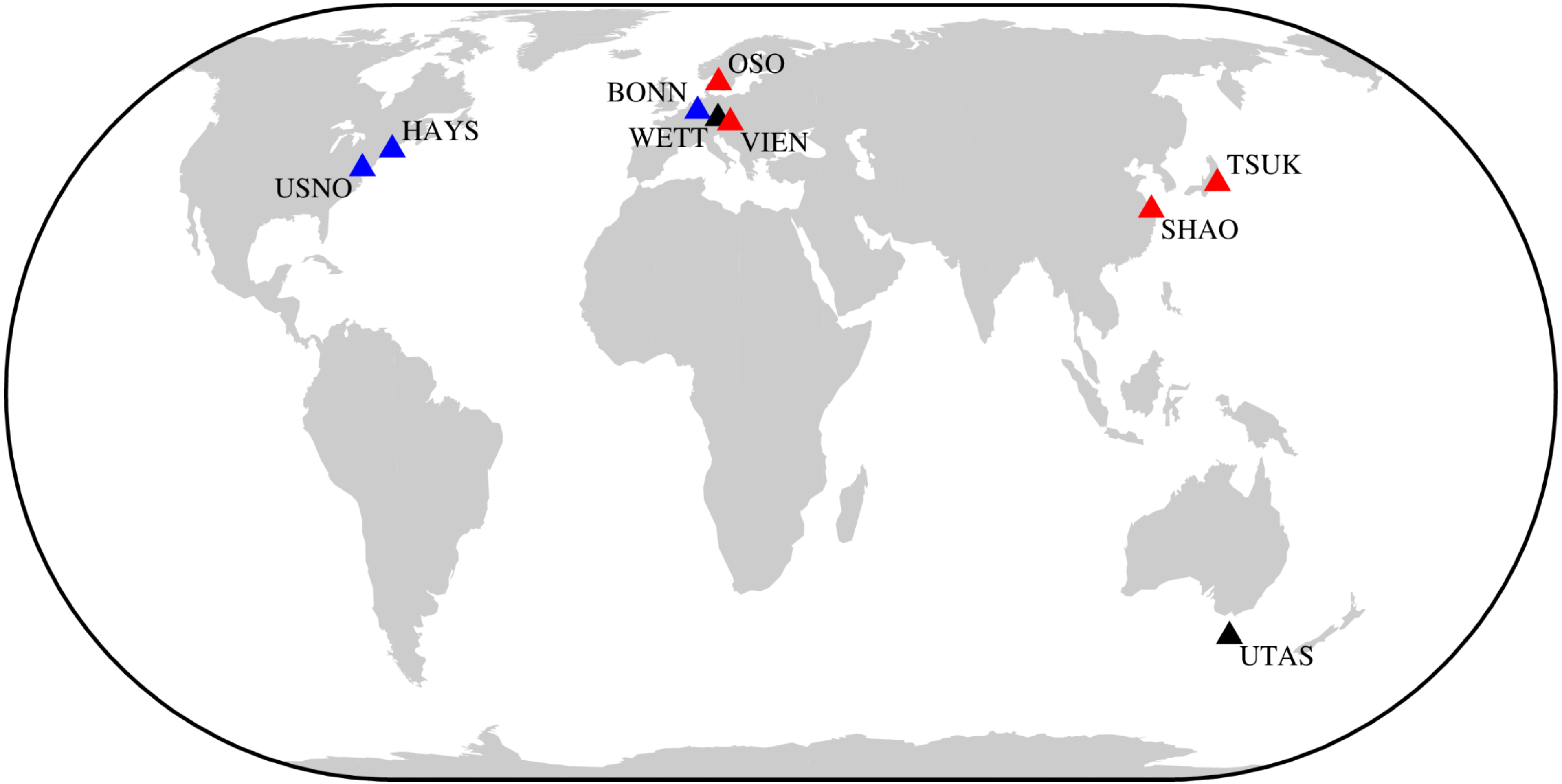
VGOS Correlation Verification

- 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; other centers will follow 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; currently being correlated at Haystack
- Correlation VGOS-VGOS, S/X-S/X, and VGOS-S/X
- Mixed-mode workshop planned for May 2021 (format dependent on COVID-19 evolution)

Rollout of VGOS Correlation Capabilities



▲ operational ▲ under verification

▲ future correlation center

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 storage types (fixed vs portable):
  - RAID: needed at station & correlator
  - Recording module: physical shipment

Data transport (electronic transfer):

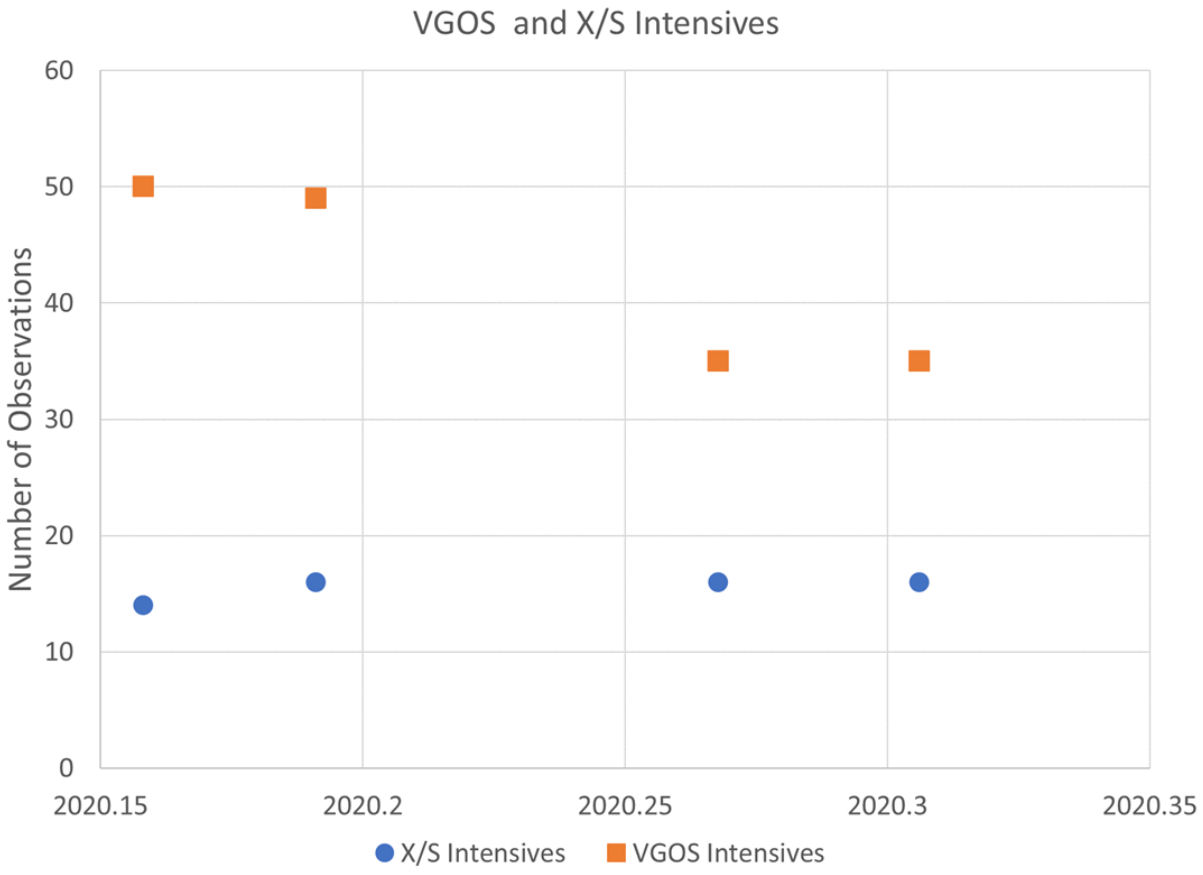
- Required network data rates:
  - each site: 5.6 Gbps
  - correlator: 134 Gbps

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

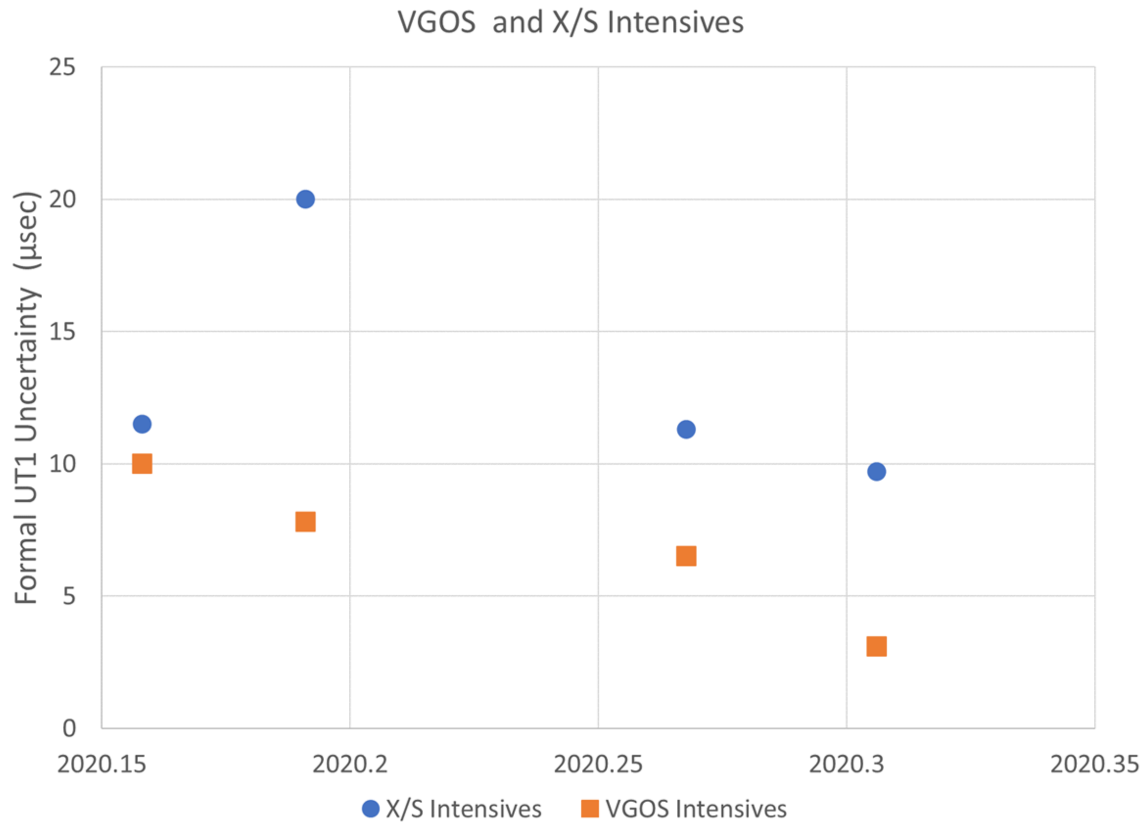
Analysis: UT1 Comparison VGOS vs. S/X

UT1-UTC comparison:

- Four 1-hour Intensive sessions
- Simultaneous VGOS and S/X baselines between Kokee and Wettzell (K2-Ws, Kk-Wz)
- Standard Intensive *Solve* solution



Analysis: UT1 Comparison VGOS vs. S/X



Results:

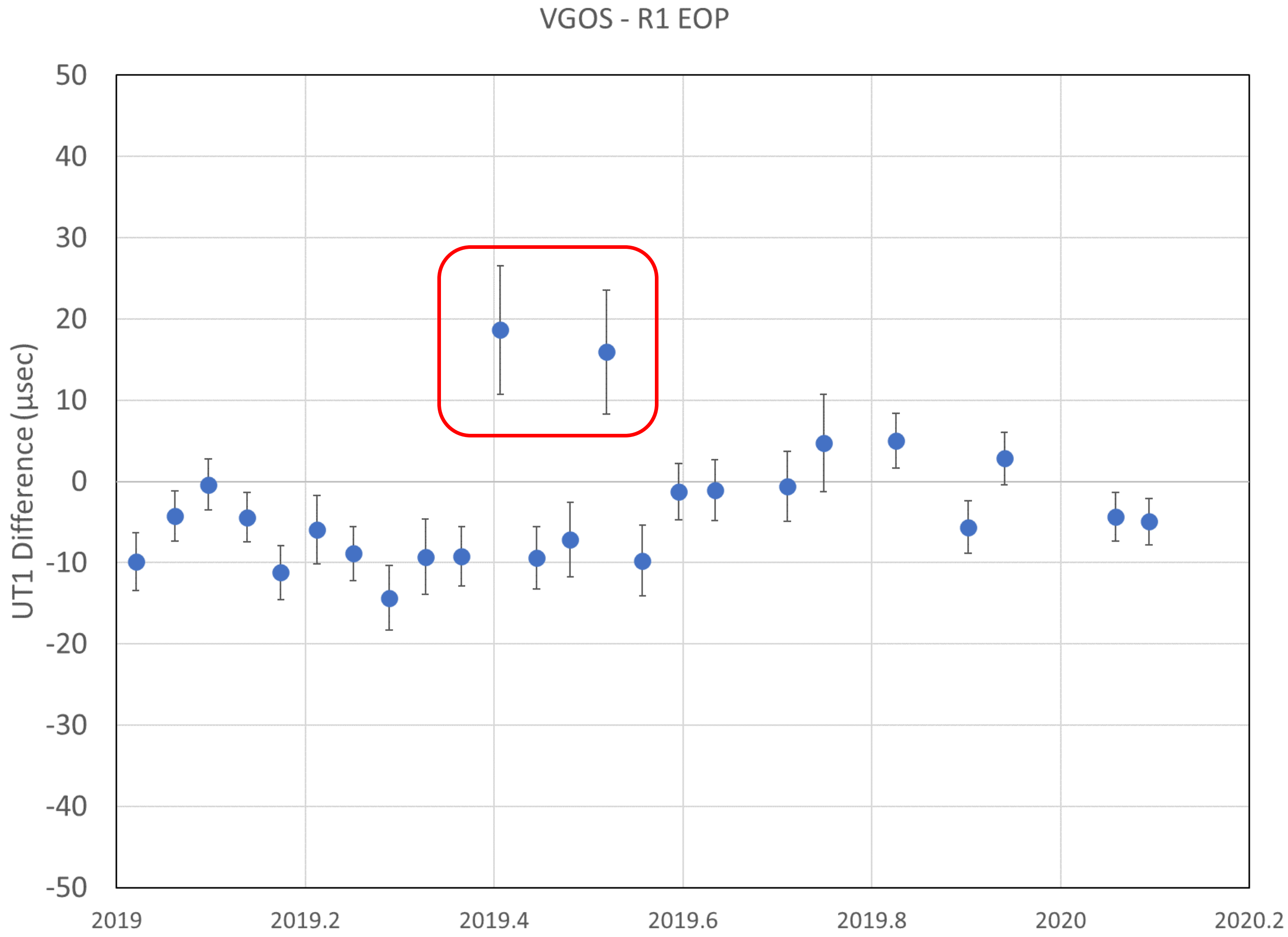
- VGOS has 2–3 times more observations
- VGOS has lower formal errors:
  - VGOS UT1 formal error factor ~2 smaller than S/X
- General agreement between VGOS and S/X results:
  - UT1 differences between VGOS and S/X within 1–2 sigma (not shown)

Simultaneous VGOS and S/X 24-hour Sessions

		Stations	Num Obs	Soln Fit (ps)
2019.02	$19JAN07VG	GsK2OeOwWfWsYj	7043	18.75
2019.06	$19JAN22VG	K2OeOwWfWsYj	5372	15.59
2019.10	$19FEB04VG	GsK2OeWfWsYj	4397	16.475
2019.14	$19FEB19VG	GsK2OeWfWsYj	7291	14.817
2019.17	$19MAR04VG	GsK2OeWfWsYj	7275	17.842
2019.21	$19MAR18VG	GsK2OeWfWsYj	5336	17.777
2019.25	$19APR01VG	GsK2OeWfWsYj	7190	16.944
2019.29	$19APR15VG	GsK2OeWfWs	4849	17.193
2019.33	$19APR29VG	GsK2OeWfWs	4764	22.635
2019.37	$19MAY13VG	GsK2OeWfWs	3951	19.564
2019.41	$19MAY28VG	GsOeWs	1377	22.31
2019.44	$19JUN11VG	GsK2OeWfWs	4656	28.605
2019.48	$19JUN24VG	GsK2OeWfWs	4759	28.161
2019.52	$19JUL08VG	GsOeWs	1780	19.208
2019.56	$19JUL22VG	GsK2OeOwWfWs	5812	23.39
2019.60	$19AUG05VG	GsK2OeOwWfWsYj	10879	29.707
2019.63	$19AUG19VG	GsK2OeOwWfWsYj	11108	34.302
2019.71	$19SEP16VG	GsK2OeOwWfWsYj	11767	27.126
2019.75	$19SEP30VG	GsK2OeOwWfWs	6713	25.121
2019.83	$19OCT28VG	GsK2OeOwWf	4930	18.012
2019.90	$19NOV25VG	GsK2OeOwWfWsYj	10204	17.868
2019.94	$19DEC09VG	GsIsOeOwWfWs	8173	18.83
2020.06	$20JAN21VG	GsIsK2MgOeOwWs	7766	19.868
2020.09	$20FEB03VG	GsIsK2MgOeOwWfWs	13284	22.945

		Stations	Num Obs	Soln Fit (ps)
2019.02	$19JAN07XA	HtKeKkKvMaWnYg	3151	41.905
2019.06	$19JAN22XA	FtHtIsKkKvNyWnWwWzYg	5633	33.129
2019.10	$19FEB04XA	FtHtIsKeKkNyOnWnWzYg	6524	30.806
2019.14	$19FEB19XA	FtHtKeKkKvNyOnShWnWzYg	7378	28.283
2019.17	$19MAR04XA	IsKeKkKvNyWzYg	4081	35.612
2019.21	$19MAR18XA	HtIsKeKkKvNyShYg	4790	33.276
2019.25	$19APR01XA	FtHtIsKeKkKvNyOnWnWzYg	6483	32.003
2019.29	$19APR15XA	AgFtHtIsKeKkKvNyWnWzYg	4606	34.577
2019.33	$19APR29XA	AgFtHtIsKeKkKvWnYg	4086	44.843
2019.37	$19MAY13XA	AgFtHtIsKeKkKvMaNyWzYg	5561	38.168
2019.41	$19MAY28XA	AgHtIsKeKkMaNyWz	3704	34.409
2019.44	$19JUN11XA	AgHtIsKeKkKvMaNyWzYg	5549	34.672
2019.48	$19JUN24XA	AgHtIsKeKkKvMaYg	4035	42.892
2019.52	$19JUL08XA	HtKbKeKvMaShYg	3783	31.221
2019.56	$19JUL22XA	FtHtIsKeMaNyShWzYg	5423	31.689
2019.60	$19AUG05XA	AgHtIsKbKeKkMaNyShWzYg	6890	36.414
2019.63	$19AUG19XA	IsKbKkKvOnShWzYgYs	6546	49.568
2019.71	$19SEP16XA	AgHtIsKkKvMaNyShWwWzYg	6181	41.494
2019.75	$19SEP30XA	AgFtHtKkKvMaYg	1807	62.91
2019.83	$19OCT28XA	AgHtIsKkKvMaNyWnWzYg	5924	31.626
2019.90	$19NOV25XA	AgHtIsKkKvWnWwYg	3533	46.681
2019.94	$19DEC09XA	HtKkNyOnWnWwYg	2725	30.77
2020.06	$20JAN21XA	BdFtHoHtKkKvMaNySvWzYgZc	7809	31.162
2020.09	$20FEB03XA	AgBdFtHtKkKvMaNyOnSvWwWzYgZc	10372	31.367

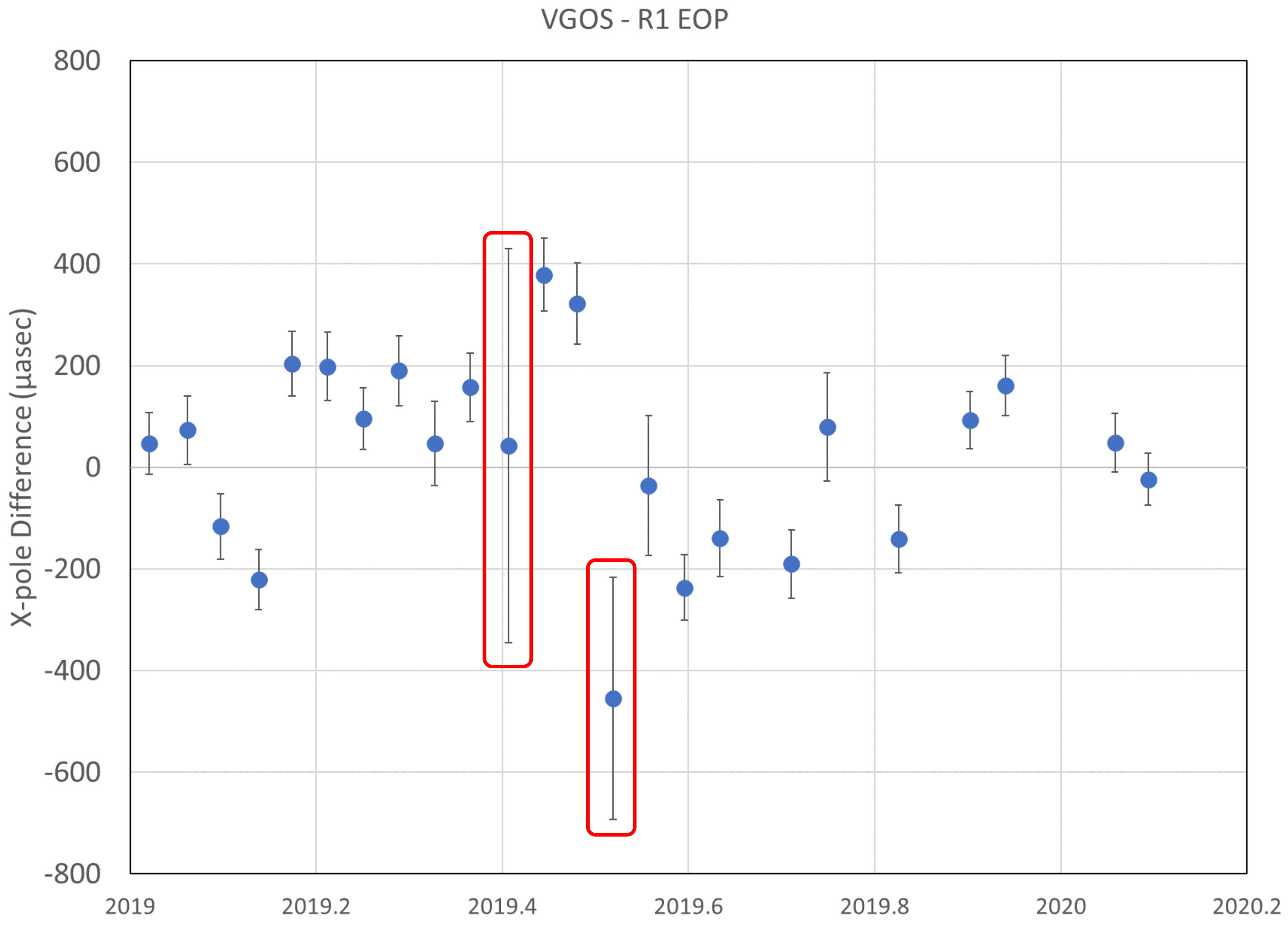
Analysis: EOP Comparison VGOS vs. S/X



UT1 difference (VGOS−S/X):

- Bias: −4.4 ± 0.82 µs
- Stdev: 5.6 µs
- Avg Sigma: 4.1 µs

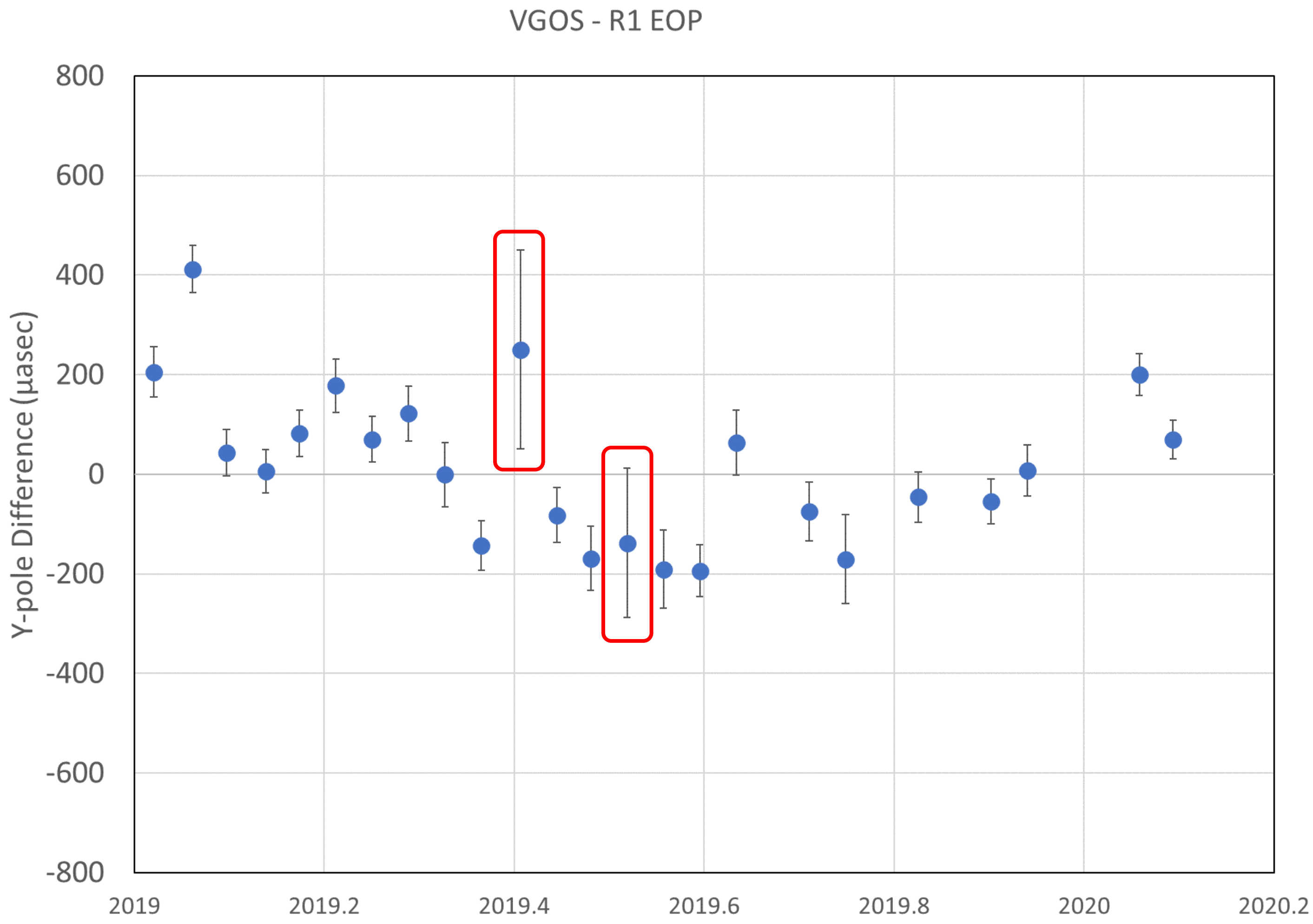
Analysis: EOP Comparison VGOS vs. S/X



X-p difference (VGOS−S/X):

- Bias: 38 ± 19 μas
- Stdev: 164 μas
- Avg Sigma: 90 μas

Analysis: EOP Comparison VGOS vs. S/X



Y-p difference (VGOS−S/X):

- Bias: 15 ± 13 µas
- Stdev: 127 µas
- Avg Sigma: 64 µas

- ❖ **VGOS and S/X results are consistent.**
- ❖ **VGOS has the potential to be more accurate.**

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
- Use mixed-mode sessions (VGOS–S/X) to tie VGOS TRF to legacy VLBI TRF
- Further avenues of improvement:
  - instrumentation development (e.g., ongoing bandwidth doubling)
  - atmosphere modeling
  - radio source structure imaging
- Transition IVS production system from legacy VLBI to VGOS
- Eventual 24/7 observing

Ny Ålesund Twin Telescope

Inauguration event on 6 June 2018