VLBI tie between the legacy and VGOS geodetic antennas at Kokee Park Geophysical Observatory, Hawaii

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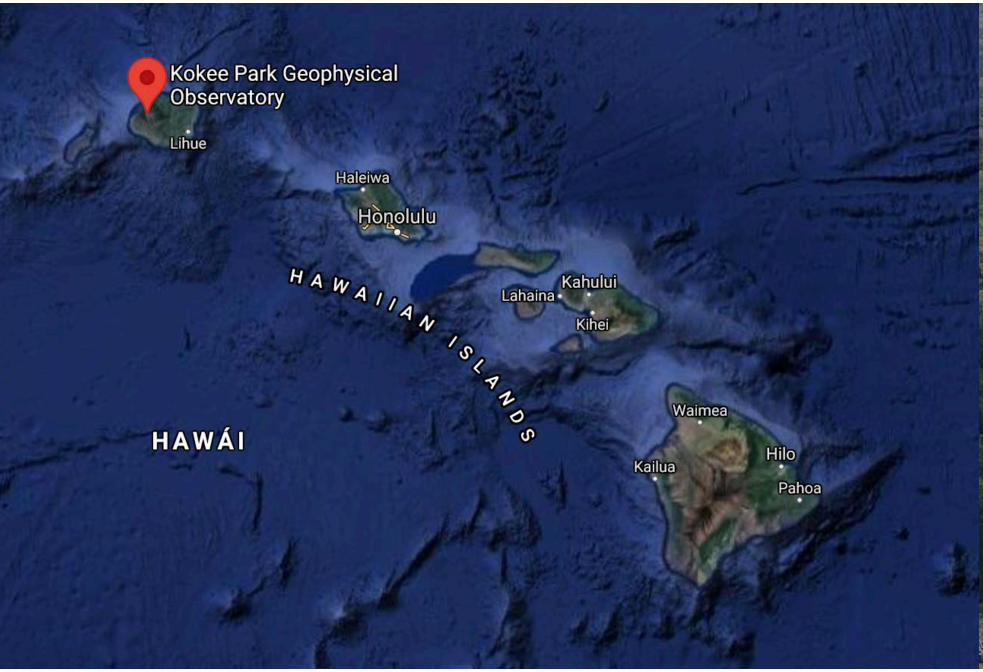

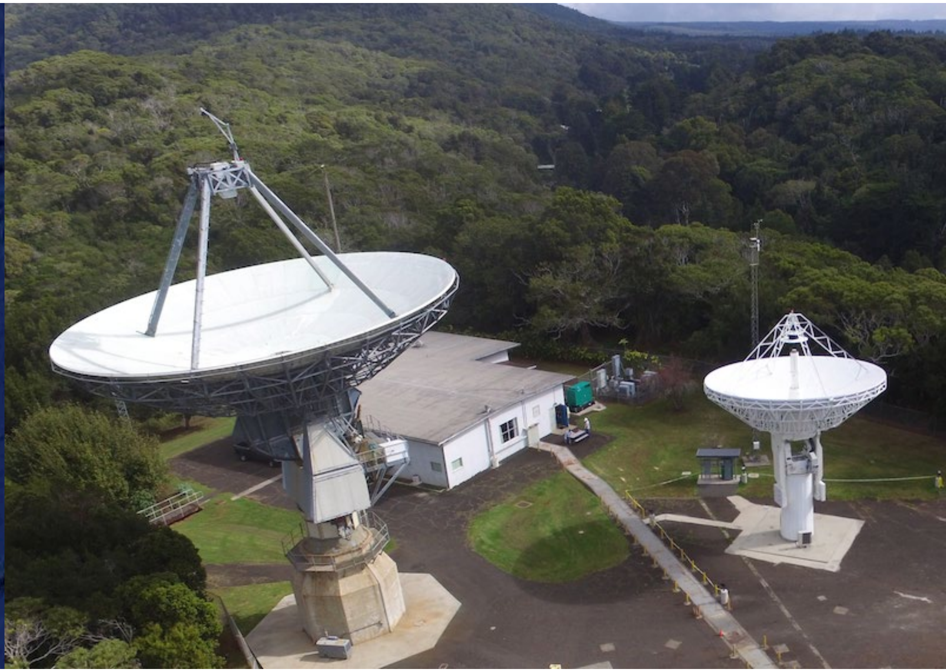

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Outline

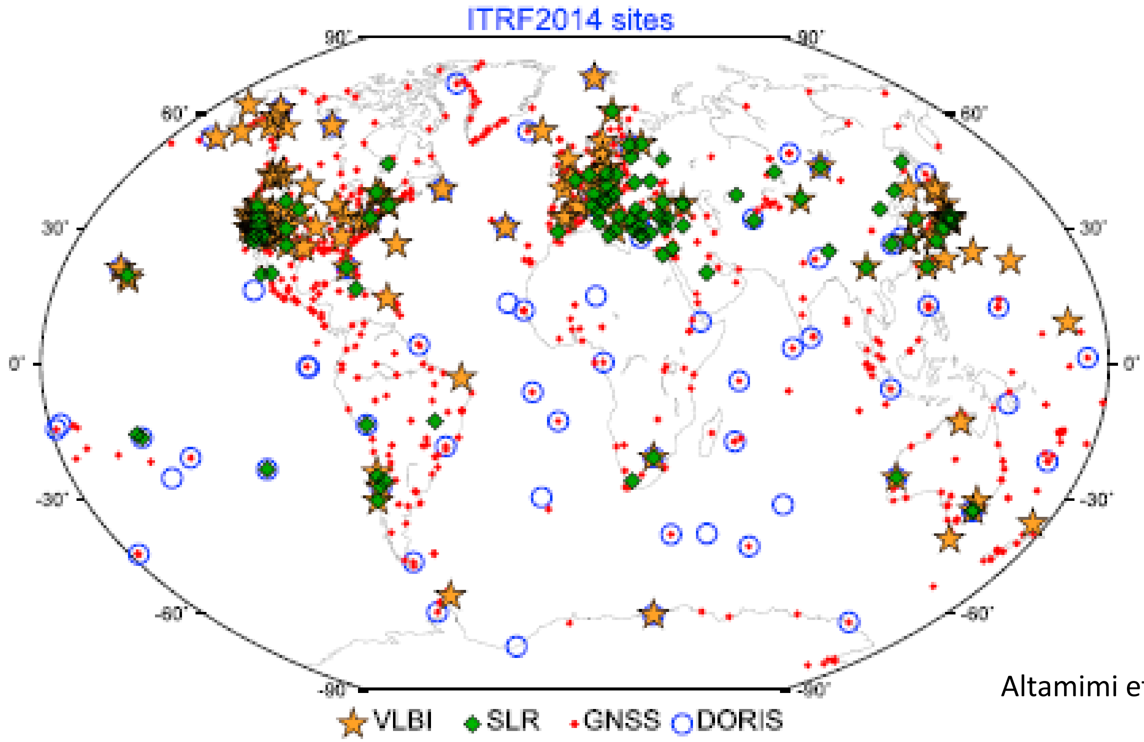
- The ITRF
- Combining VGOS and legacy S/X VLBI networks
- The tie of VGOS and S/X antennas at KPGO
- Systematic errors
- Geodetic results and comparison with optical surveys

Constructing the ITRF (1)

- International Terrestrial Reference Frame

  Description: ~1000 locations on the surface of the Earth with accurate (~10 mm) 3-D coordinates

  Separate networks: SLR/VLBI/GNSS/ DORIS



Altamimi et al 2016

Combining the techniques

- Measure local ties at sites with multiple techniques
  - Optical surveys are the only practical way since it isn't yet possible to observe in a common native mode, e.g. SLR-VLBI or GPS-VLBI
  - Surveys can determine relative positions of physical points on an antenna or telescope with mm accuracy
  - Not possible to accurately determine (at the mm level) the offset between the physical reference point and the electromagnetic reference point
    - e.g. GPS: Antenna Ref Point to electrical phase center

Constructing the ITRF (2)

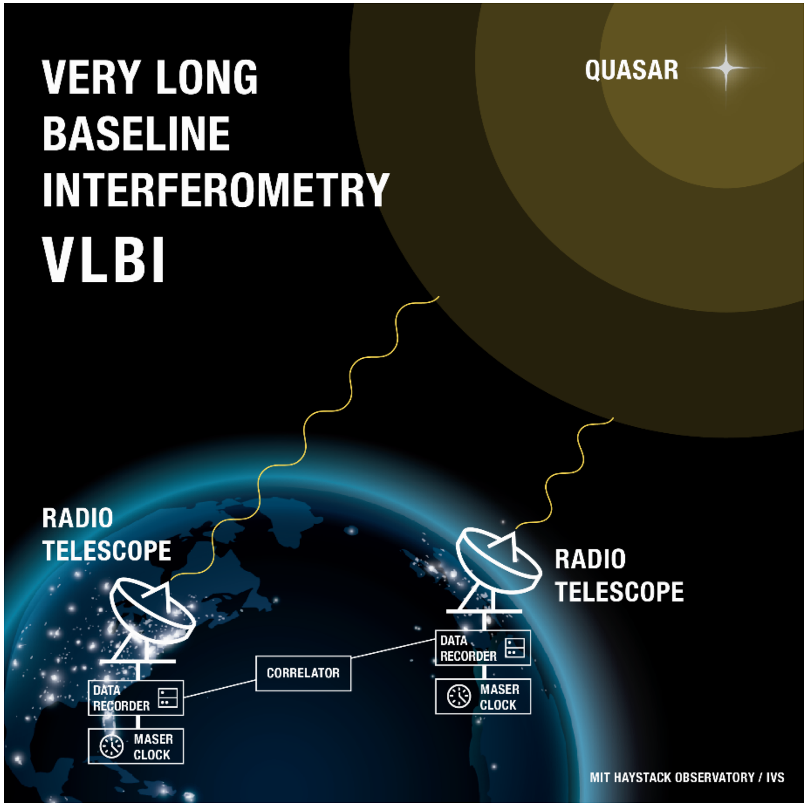
- Goal of next generation geodetic systems
  - 1 mm position and 0.1 mm/yr velocity
  - Only possible if different networks tied together to <1 mm
  - The tie accuracy limits the accuracy of the ITRF
- Systematic errors that limit the accuracy (mostly UP)
  - Inconsistent corrections for atmospheric effects
  - Inconsistent correction to reference values (e.g. temperature and pressure)
  - Thermal deformation of antenna structures and towers
  - Gravitational deformation (primarily VLBI)

Geodetic VLBI (1)

VLBI – Very Long Baseline Interferometry

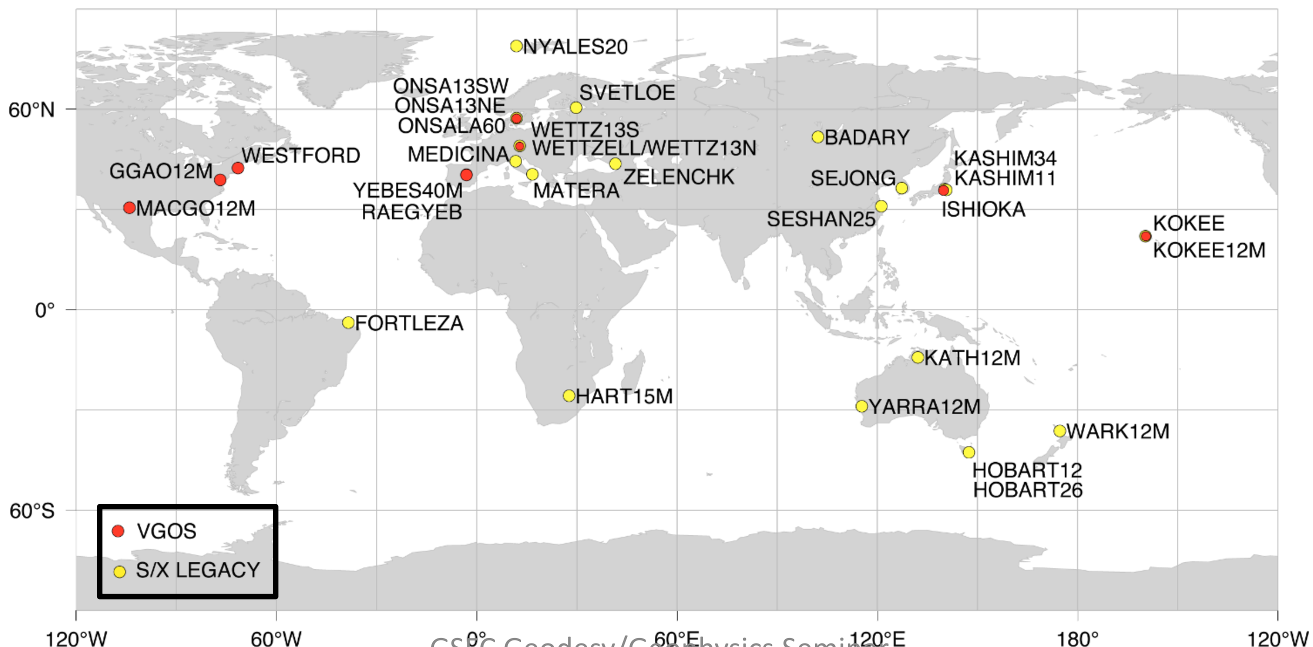
Observe extragalactic sources with a network of large (12m to 30m) paraboloidal antennas at centimeter radio wavelengths.

- Important to note that VLBI measures the vector between the radio reference points of the antennas (Intersection of Axes).
- This Intersection of Axes can be determined via surveying.

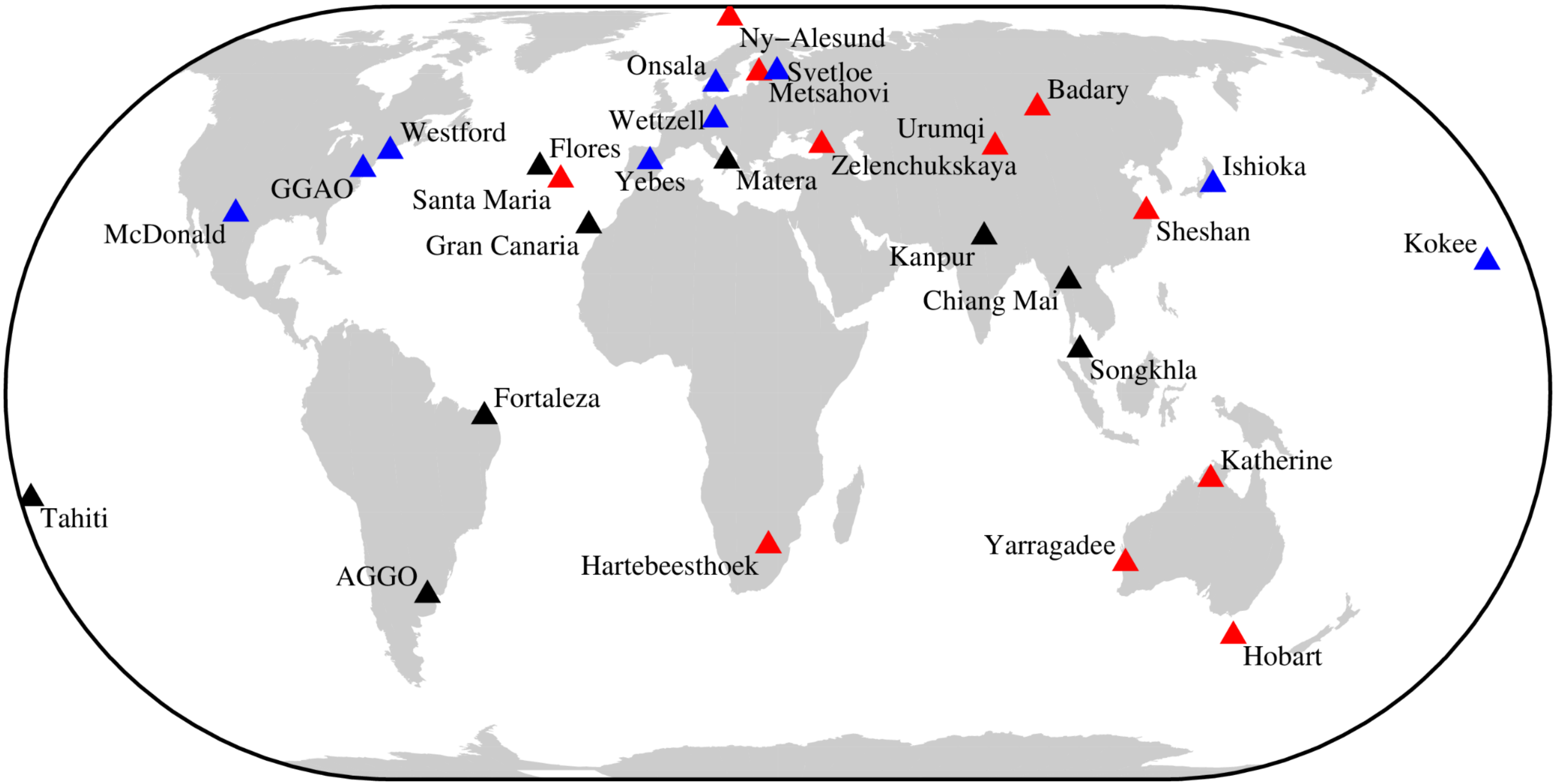


Geodetic VLBI (2)

- Two VLBI networks in operation
  - Legacy S/X (since approximately 1980)
    - Larger, generally slower antennas with analog electronics
  - The newer VLBI Global Observing System (VGOS) (since 2015)
    - Generally smaller, faster antennas with modern digital signal processing



Anticipated VGOS network



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

Courtesy D. Behrend

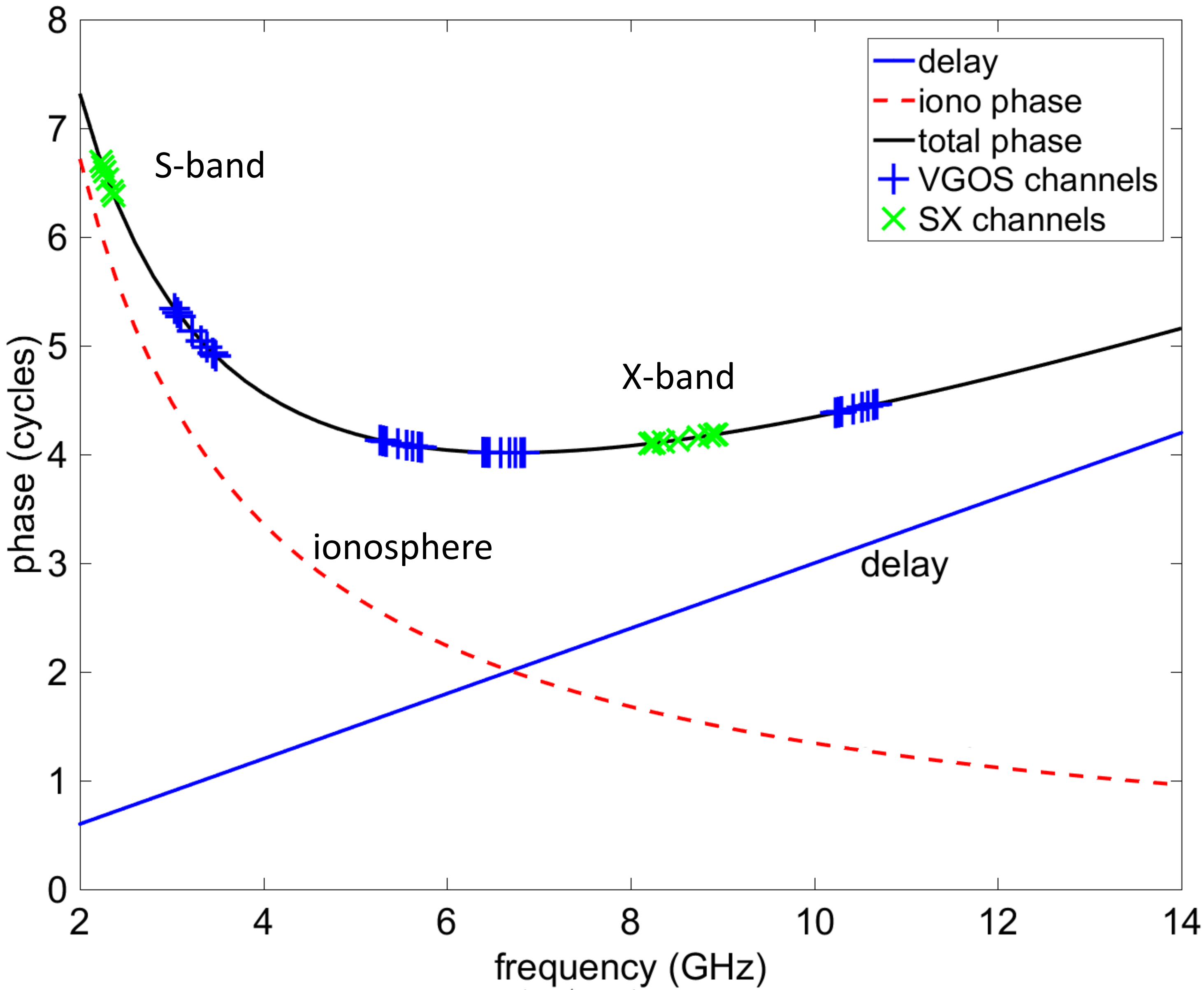
Main legacy S/X – VGOS differences

- Typical values

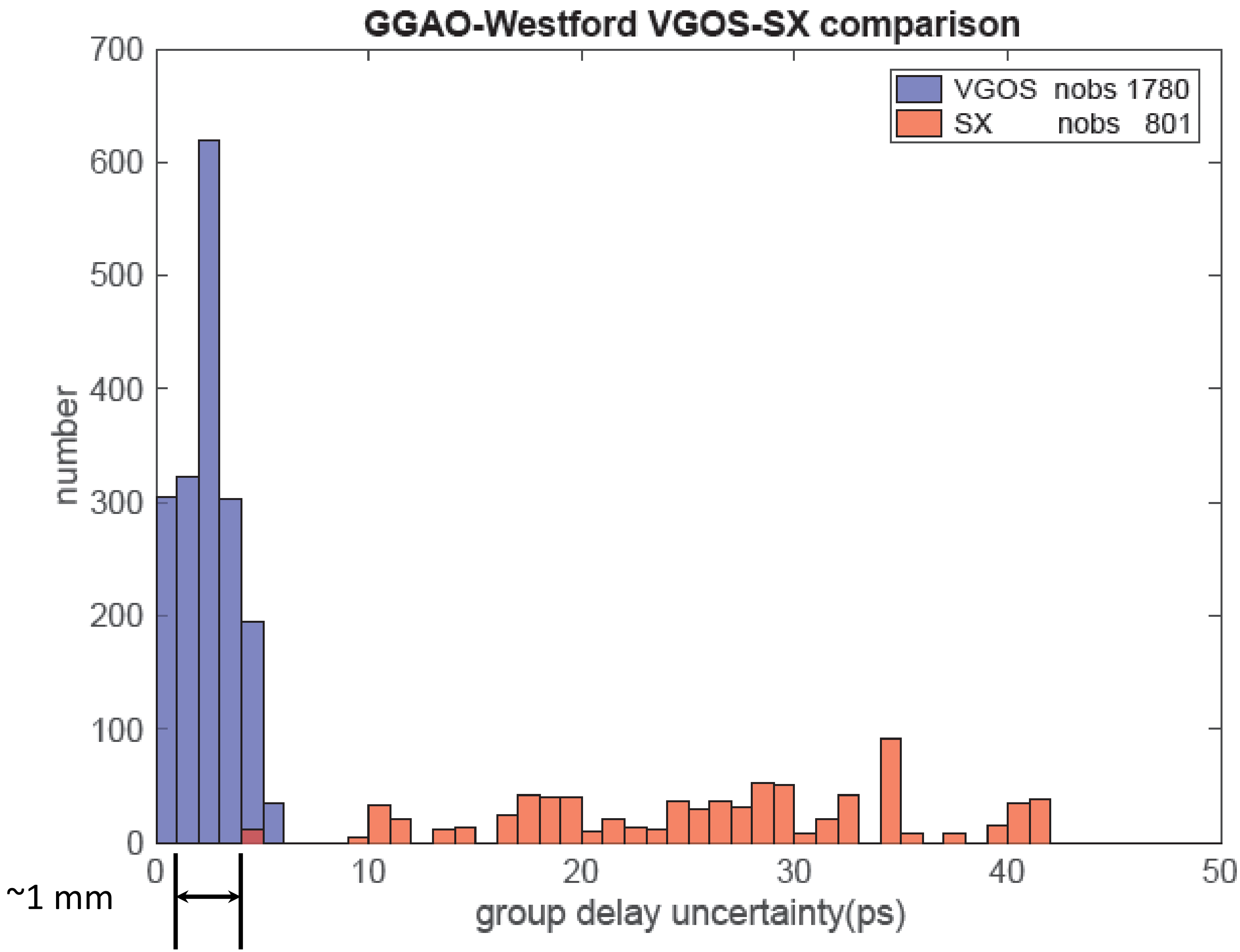
	S/X	VGOS
Frequencies	2 bands	4 bands
Data record rate	0.5 Gbps	≥ 8 Gbps
Polarizations	1	2
Antenna slew rate	a few °/sec	5 to 12 °/sec

- VGOS antenna positions are much more accurate than legacy S/X
- The two networks are not compatible without degrading VGOS
  - Reduce the number of frequency bands to match S/X
  - Reduce recorded bandwidth and data rate to match S/X
  - Reduce the number of separate scans in a day because of the slower legacy antennas

VGOS and S/X frequencies



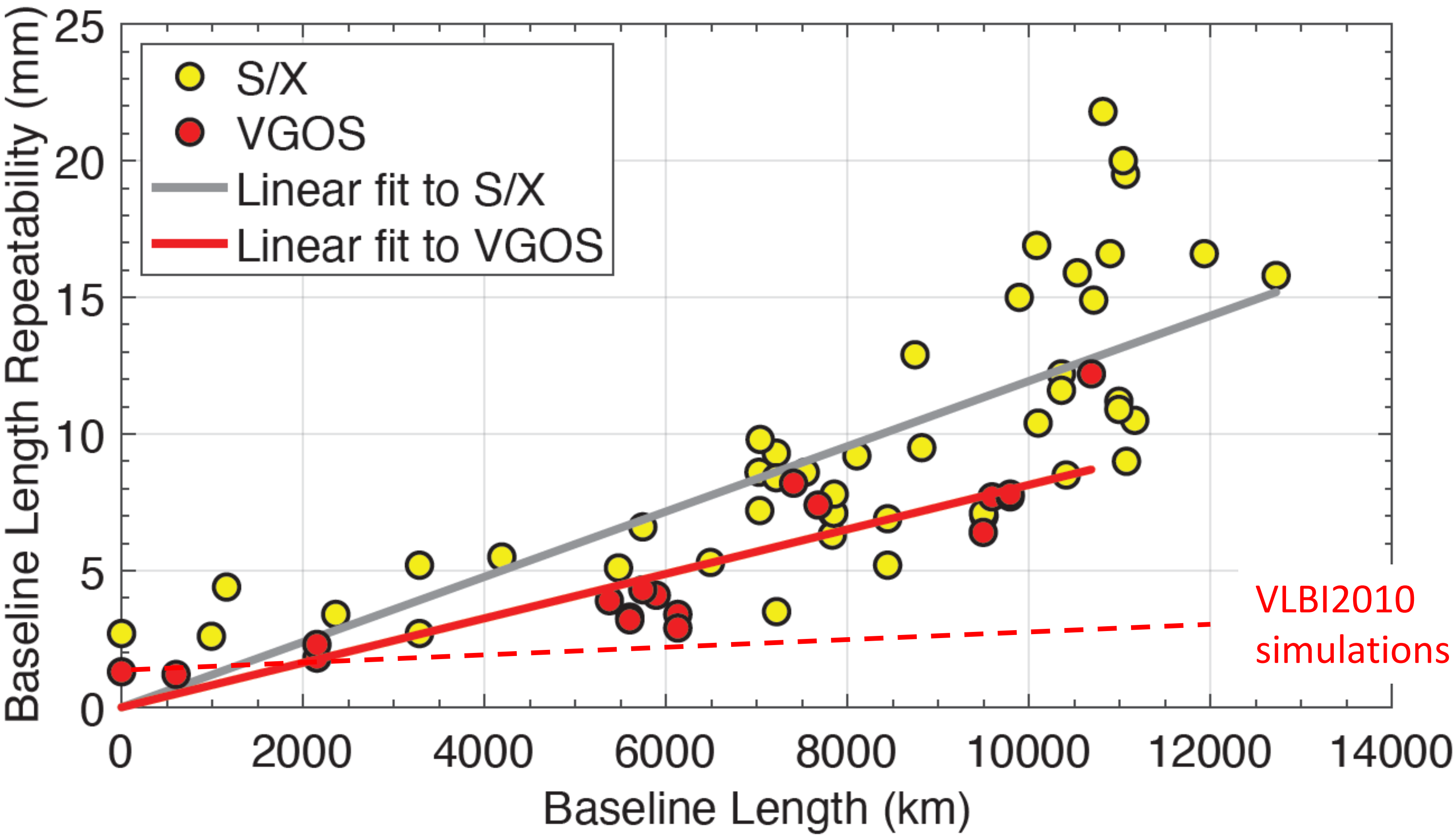
VGOS and S/X group delay uncertainties



Baseline length repeatability

26 sessions in 2019-2020

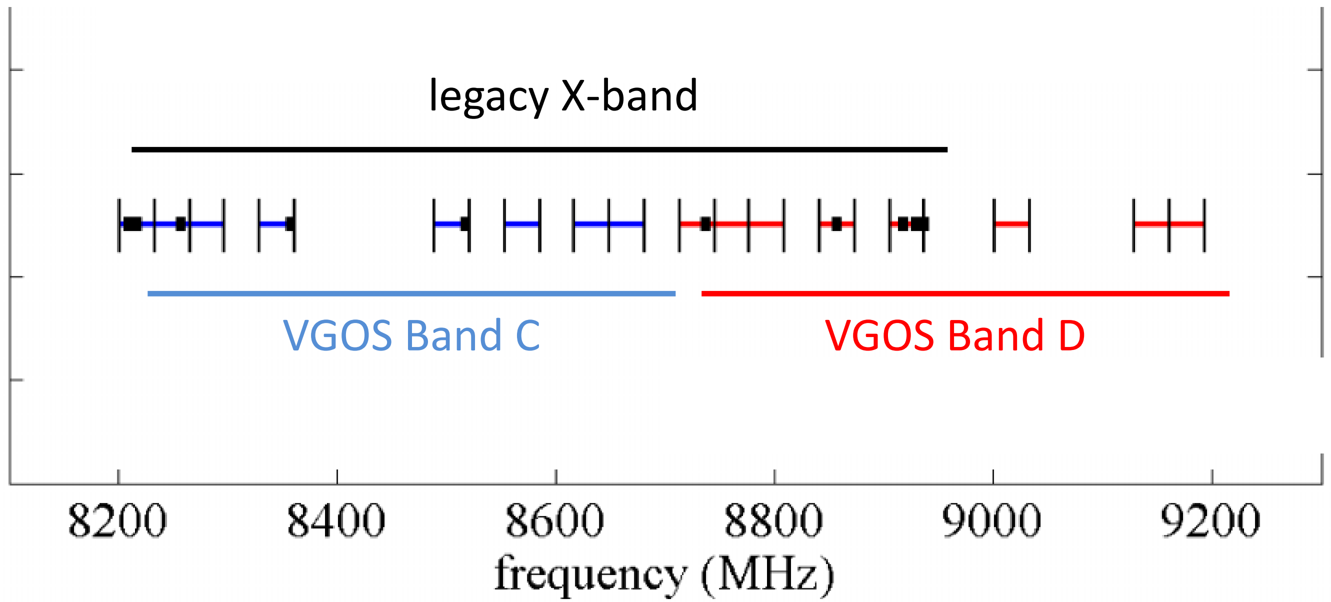
VGOS: 5 to 8 antennas   S/X R1 sessions: 10 to 15 antennas



Combining VGOS and S/X (1)

- Mixed-mode: Use VGOS antenna as an S/X antenna
  - Change VGOS bands to cover S-band and X-band
  - VGOS antennas perform like small S/X antennas
  - Sensitivity limited by S/X channel widths and record rate
  - Scans/hour limited by S/X antenna slew rates
  - Sky coverage limited by common sky with other antennas
  - Get only S/X position accuracy (3-10 mm per session)
  - Gain ~10% by including VGOS-VGOS correlation
    (not full VGOS precision because of limited slew rates)
  - Significant limitation: not all VGOS antennas can receive S-band

Mixed-mode X-band frequencies

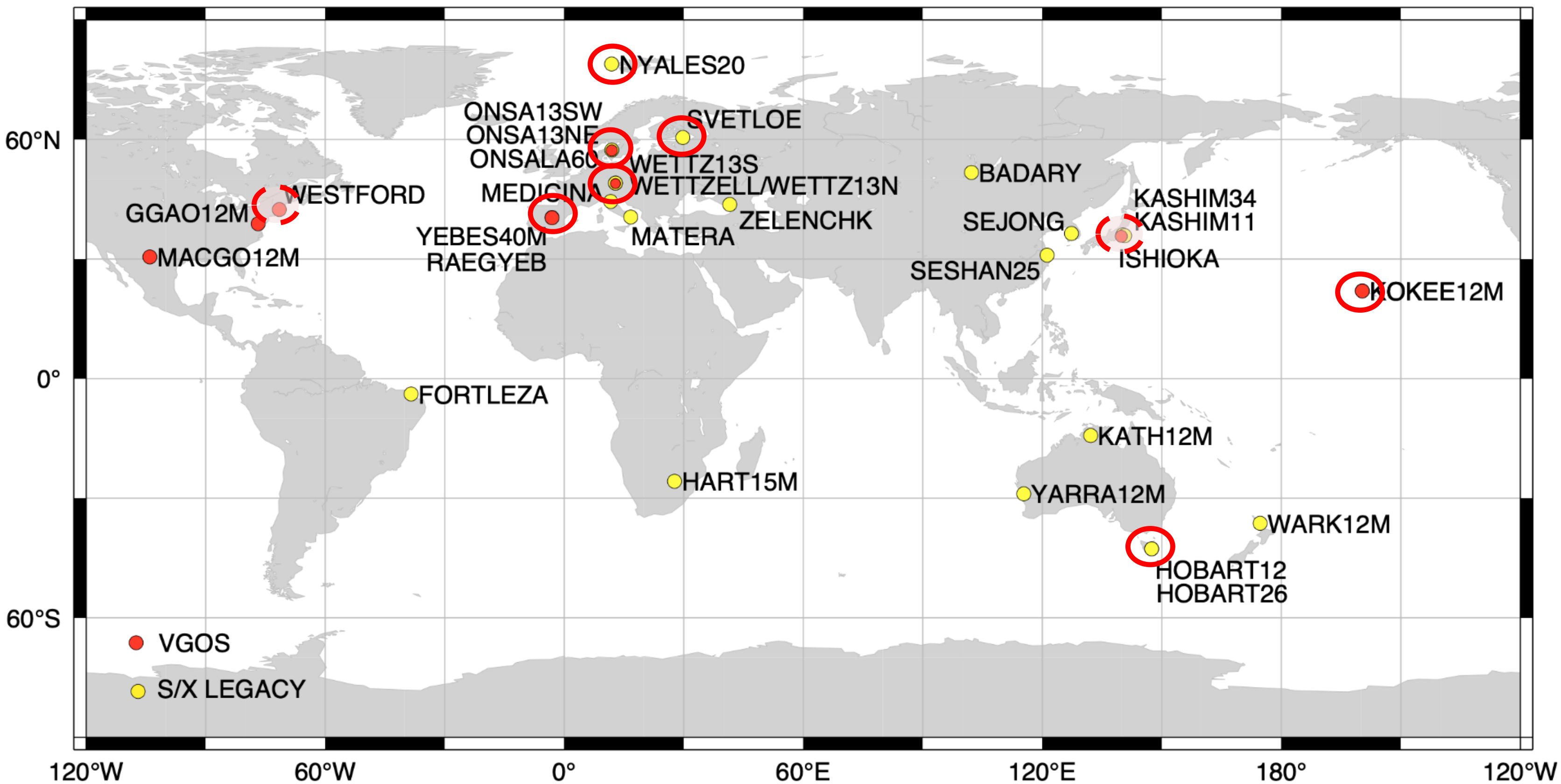


Combining VGOS and S/X (2)

- Local Tie: Use only co-located VGOS and S/X antennas
  - Use phase-delay observations (vs. group delays) to obtain much better delay precision
  - Utilize X-band only
  - Can observe the full sky, aside from local blockage
  - Radio sources are stronger on the short baseline
- Result is relative position uncertainty better than 1 mm

VLBI geodetic networks

Map of operational geodetic VLBI antennas: VGOS and legacy



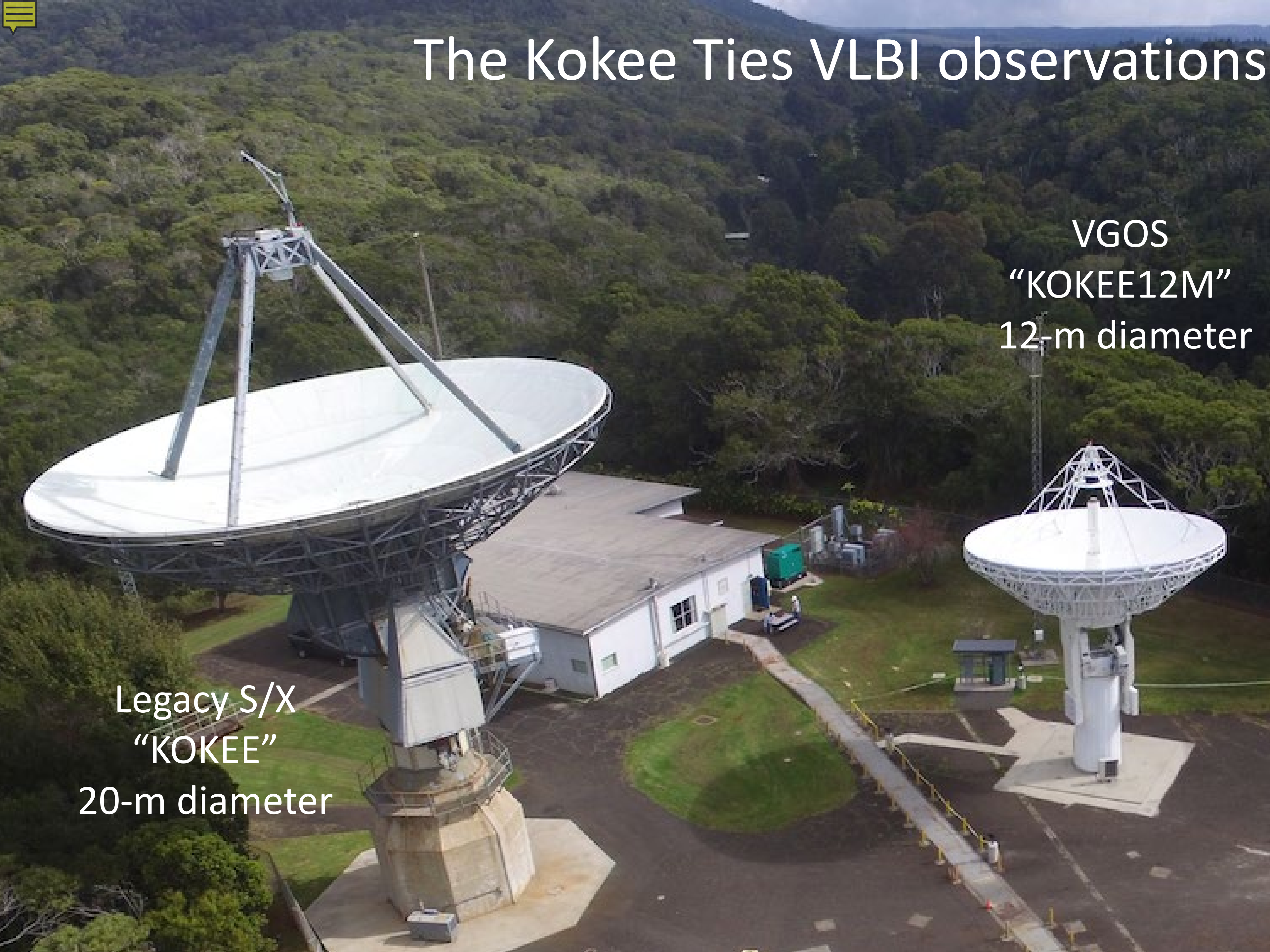
Possible local ties

Dual use: S/X and VGOS

Tying VGOS to S/X (2)

- So how is the VGOS-to-ITRF tie best done?
- Each Mixed-mode session yields a covariance among the VGOS and S/X antennas with uncertainties of 3-10 mm between the positions of any pair of S/X and VGOS antennas, so many sessions are needed to reduce the uncertainty to 1 mm
- Each Tie session yields a covariance with uncertainty of ~1 mm between a pair of S/X and VGOS antennas
  - If one Tie session of ~1 mm precision is made for all eight possible sites, then by including the two common S/X-VGOS antennas when many sessions are combined, the two networks are tied with an uncertainty of ~1 mm

The Kokee Ties VLBI observations



The Kokee Ties observations (1)

- Four Tie sessions were scheduled in 2016
  - These were among the first sessions using KOKEE12M
    - Durations approximately 1, 6, 4, and 22 hours
  - R1/R4 frequencies used so no setup change at KOKEE
  - Horizon mask was derived to minimize blockage of sky by KOKEE as seen from KOKEE12M (~1/4 of sky) (our thanks to Ed Himwich)
  - Only KOKEE and KOKEE12M scheduled in order to get full sky
  - Achieved 17 scans/hour (less than half of VGOS-only)
  - Only X-band was analyzed since ionosphere correction not significant on the 31 m baseline

The Kokee Ties observations (2)

- Fifth session scheduled as mixed-mode in 2018
  - KOKEE12M, Westford, and GGAO12M added to six legacy antennas for already planned R&D session
  - 24-hr session for astrometry of weak sources
    - Opportunity to test setup and processing for mixed-mode
    - Lower SNR than the four KT sessions
    - Only 41 usable observations on KOKEE-KOKEE12M baseline
    - Resulted in much larger geodetic uncertainties, even compared to bi-weekly S/X sessions
    - However, not indicative of mixed-mode capability

Calibrations

- Phase calibration
  - Applied at KOKEE12M
  - Turned off for KOKEE to avoid cross-correlation of phasecal signals
    - But leaves possible 2 mm error in local UP coordinate
- Cable calibration
  - Corrects for orientation-dependent cable errors
  - Applied for both antennas

Correlation

- Correlated using DiFX software correlator at Haystack
  - S and X channels were extracted from VGOS broadband recordings using *zoom* mode
  - Circular polarization at KOKEE was correlated to both linear polarizations of KOKEE12M
- Post-correlation processing
  - Phase and delay offsets between the X and Y linear polarizations for KOKEE12M were derived
  - The two circular-linear correlations were combined coherently using the Y-X offsets

Geodetic analysis

- The X-band group delays and phase delays each analyzed for the position of KOKEE12M relative to KOKEE
  - Separate solution made for each of the five sessions
  - Positions of the radio sources were fixed
  - KOKEE position was fixed
  - Clock and atmosphere delay differences were estimated
- Phase delay solutions
  - Phase ambiguities were resolved manually
  - Additional delay noise of ~4 ps was required to give reduced chi-squared of ~1.0
  - Resulting WRMS of post-fit delay residuals was ~4 ps

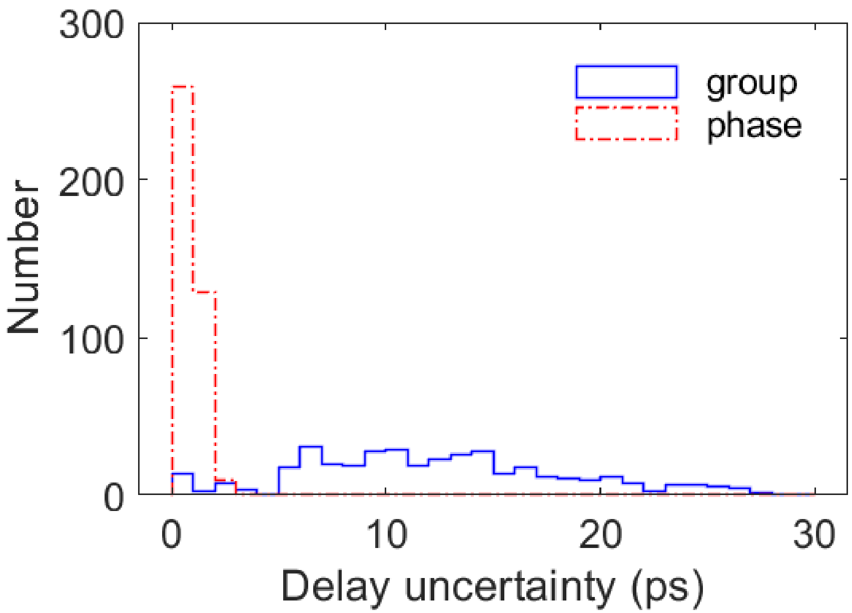
Noise and errors
(next few slides)

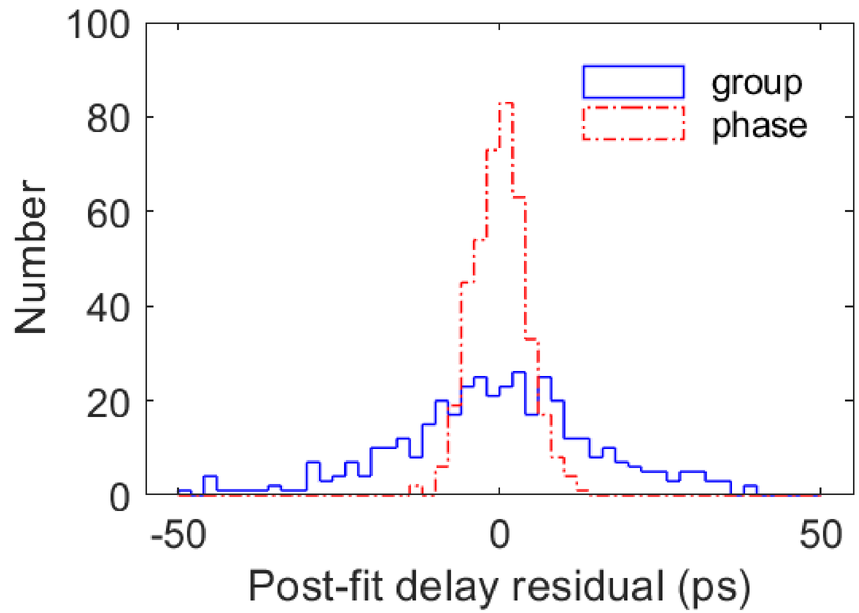
- Random errors (per observation)
  - System noise
- Systematic errors (per session)
  - Thermal deformation
  - Gravitational deformation
  - Elevation dependence of electrical path for KOKEE 20 m

X-band phase and group delay noise

16MAR30VG 22-hrs KOKEE-KOKEE12M

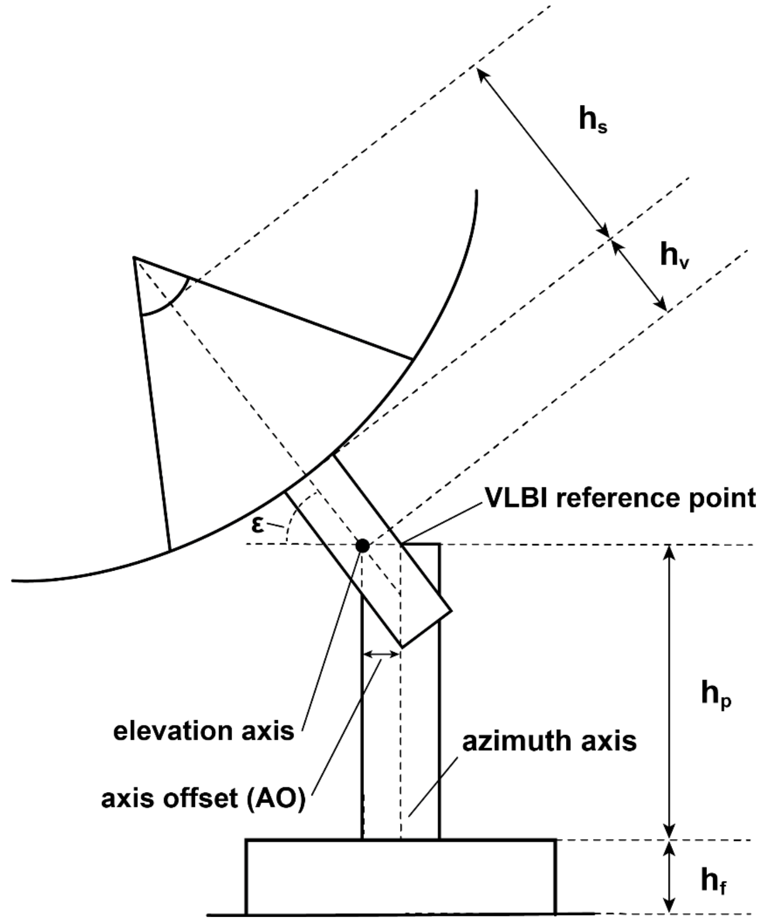
Data limited to legacy X-band frequencies and
total data rate (0.512 Gbps)





Thermal deformation (1)

- Different correction for VLBI and optical survey
  - Optical: only from the ground to VLBI reference point
  - VLBI: delay change through the antenna structure has opposite sign to pedestal change



Model: based on Nothnagel (2009)

Thermal deformation (2)

- Height change is corrected to reference temperature

	KOKEE12M - KOKEE
VLBI	0.2 mm
Optical	-0.1 mm
VLBI – Optical	0.3 mm

- Globally, extreme values of thermal deformation (cold winter night to hot summer day) can be ~5 mm

➔ To achieve 1 mm position accuracy for ITRF:

- The pedestal and reference temperatures are needed with accuracy ~1° C for 0.1 mm correction uncertainty.
- Common reference temperature must be used for all techniques at a site (GNSS/SLR/VLBI/DORIS/Survey)

Gravitational deformation

- No measurement of gravitational deformation
- KOKEE12M: the effect on height expected to be much less than 1 mm
  - Based on finite element modeling and measurements of Onsala VGOS antenna (Lösler et al (2019)
- Effect on KOKEE height could be up to 10 mm
  - By comparison with Onsala 20m measurements (Bergstrand et al 2019)
  - Scaled from 32 m antennas (Sarti et al 2011)

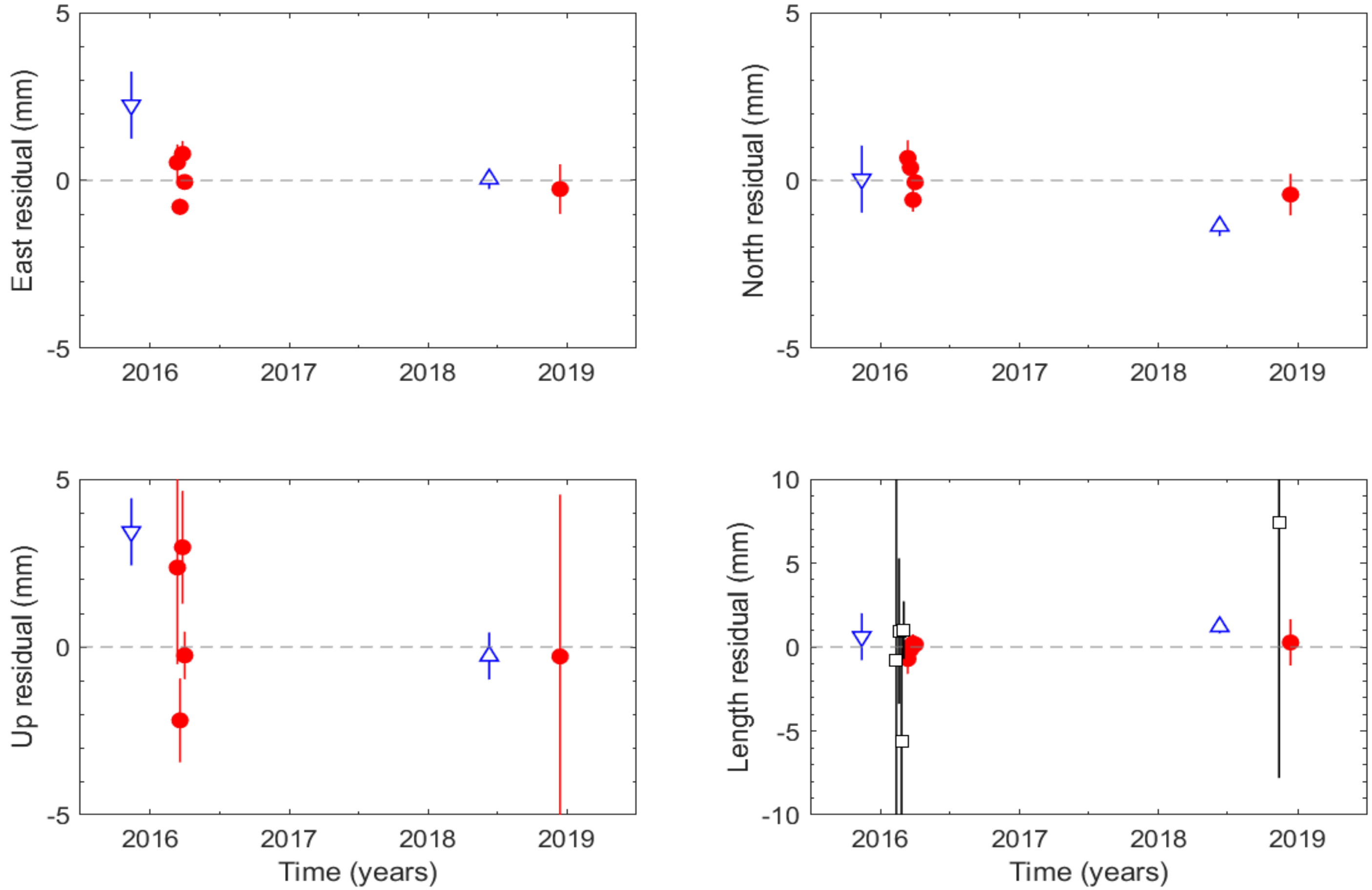
Comparison of phase delay results with optical surveys

	E	N	U	L
• VLBI weighted mean uncertainties (mm)				
	0.3	0.2	0.8	0.3
• NGS survey uncertainties (std dev in mm)				
2015	1.0	1.0	1.0	1.4
2018	0.3	0.3	0.7	0.4
• Baseline components and length differences (mm)				
NGS - VLBI	0.2	-1.3	0.8	1.2
One std dev	0.4	0.4	0.8	0.4
Uncertainties incl deformation	(1.0)	(1.0)	(~10)	(0.4)

Topocentric coordinates

VLBI phase delay – red circle NOAA – blue triangle

VLBI group delay – black square (only length shown)



Summary and recommendations

- Vector tie between co-located VLBI antennas KOKEE and KOKEE12M measured with precision of <1 mm using standard weekly R1 setup. Deformation-corrected result as SINEX file
- The tie agrees with optical surveys by NGS to ~1 mm
- The uncertainties for systematic (but correctable) errors are ~1 mm in horizontal, ≤10 mm in local vertical
- To achieve 1 mm position accuracy, thermal deformation corrections should be made by all techniques, for each session, to a common standard reference temperature (this is also important for pressure)
- Uncorrected gravitational deformation may be the limiting error source for the VLBI contribution to the TRF

Thank you

And thanks to:

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Sergei Bolotin	Axel Nothnagel
Steven Breidenbach	Ben Erickson
KPGO staff	NASA/SGP

Phase and group delay differences

- Onsala VGOS antennas relative to 20 m S/X antenna
  - Varenius et al, J of Geodesy (2021)
  - Difference in UP between group and phase of ~3 mm.
  - Kokee Ties: not enough precision in group delay to be able to distinguish such a difference.

Tying VGOS to S/X (1)

- Observing as separate networks means VGOS and S/X antennas must be tied to each other, as well as to the other techniques
- Including VGOS in an S/X session using mixed-mode achieves only S/X position precision, i.e., 3-10 mm, in the S/X frame
- VGOS network antenna positions are expected to reach a precision of 2 mm or better
- Local VGOS-legacy antenna ties at co-located sites can achieve sub-mm position precision
- Several antennas (e.g. Westford, Ishioka) observe in both S/X and VGOS sessions, so no tie vector needed