VLBI Basics

Pedro Elosegui, MIT Haystack Observatory

With thanks to many of you (here and “out there”)

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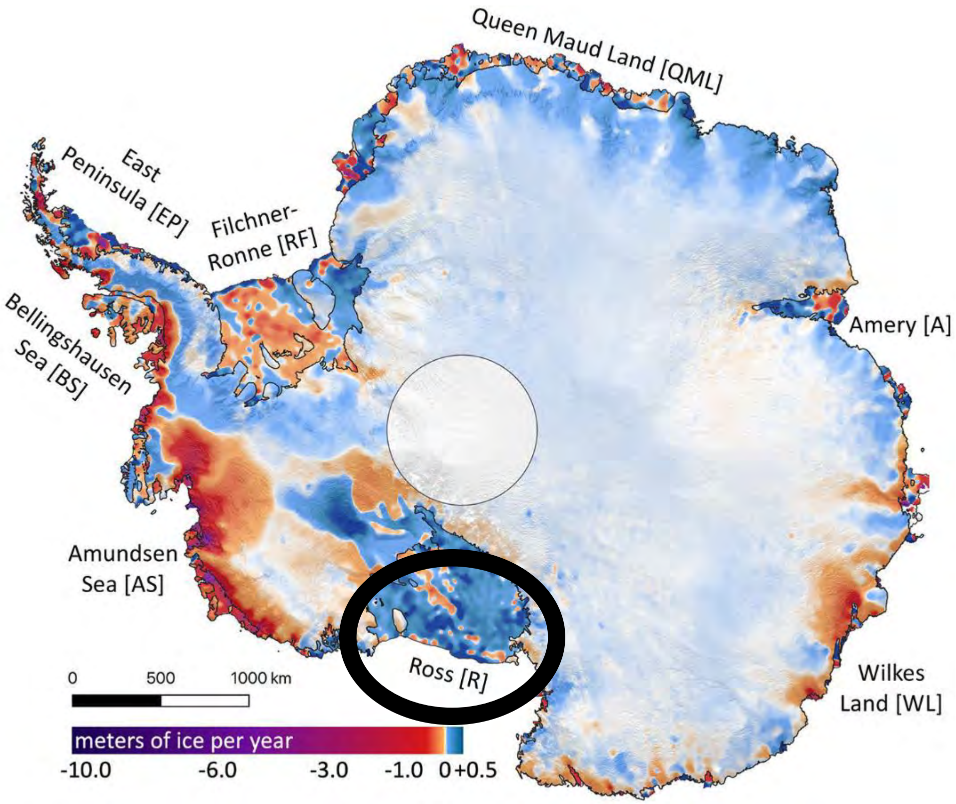
VLBI Astrometry
Satellite
Astronomy
GPS (Polar)
ARAON
VLBI/GPS Geodesy
SI04
SI05
Arctic Ocean
Antarctic
ice-shelf penetrator
Greenland
Westford
Google earth

Antarctic ice penetrator: Ross Ice Shelf



[*Smith et al., 2020*]

Outline for today

- Motivation: WHY do we do VLBI?

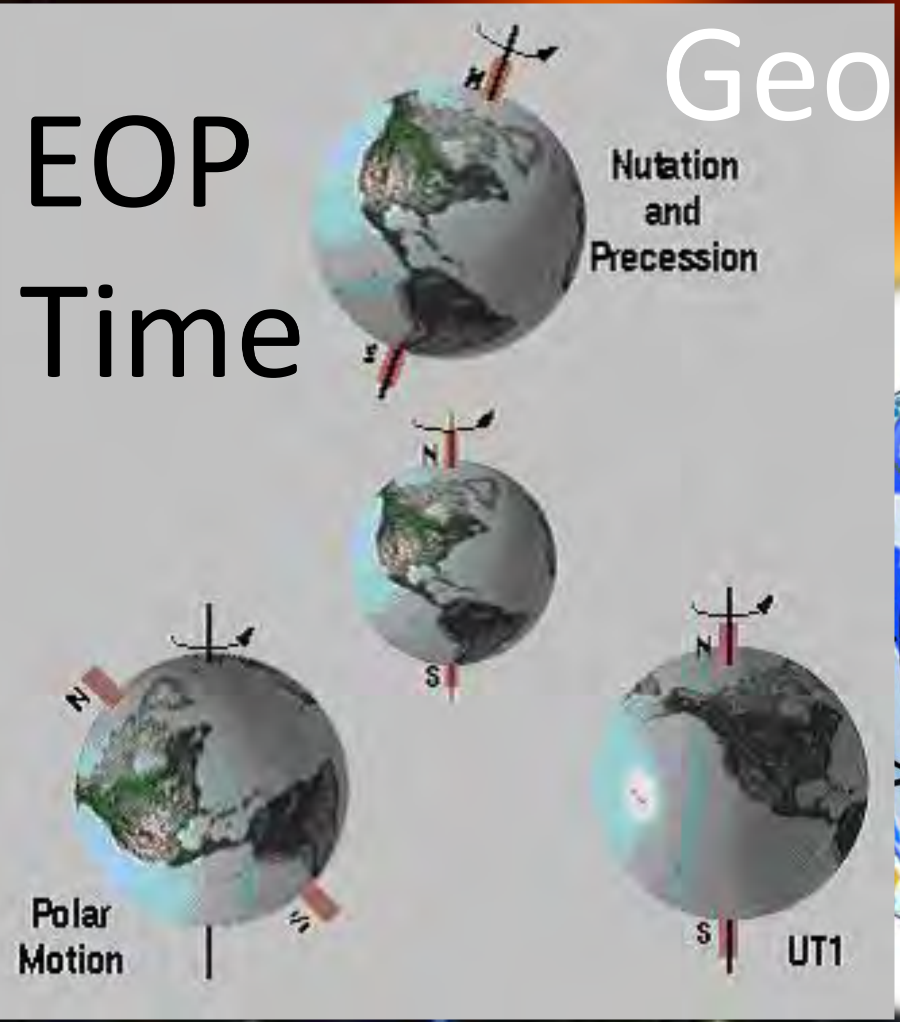
- Hands-on: HOW do we do VLBI?
    - Geodetic radio telescopes
    - VLBI vs. GPS concept
    - Station requirements
    - VLBI digitization
    - VLBI correlation
    - Geodetic post-processing and VGOS precision

Why VLBI?

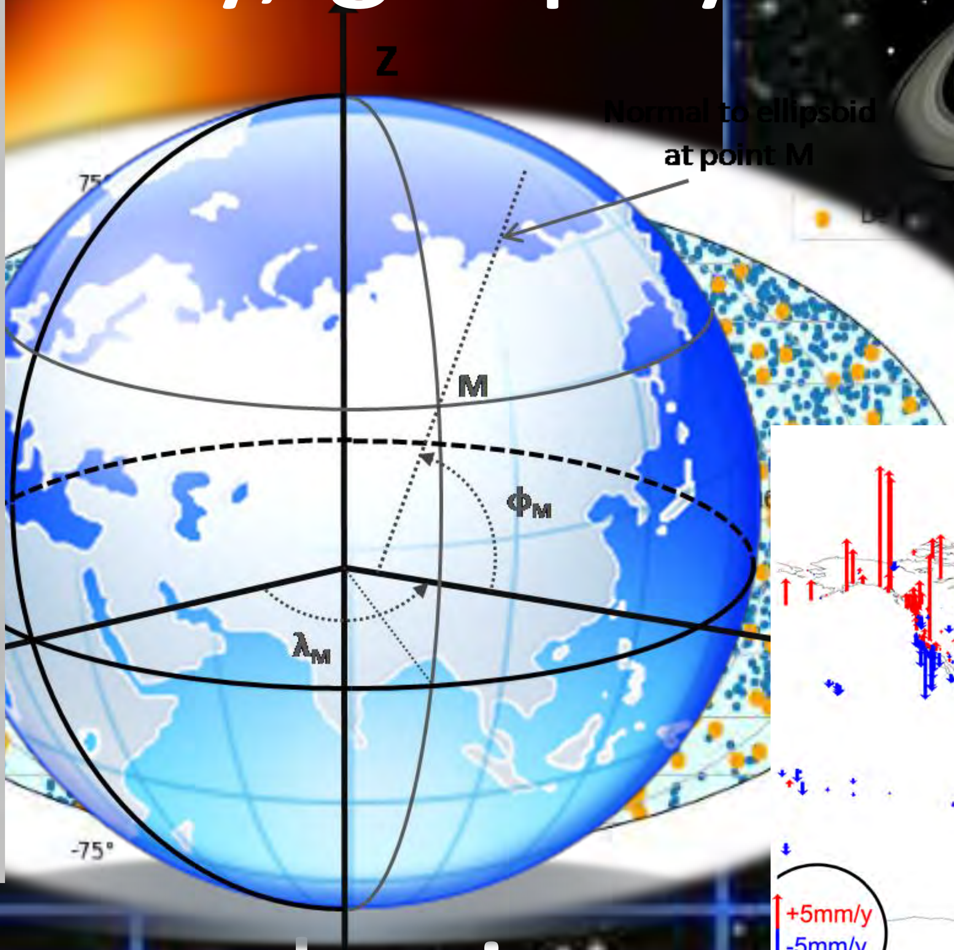
Space Navigation

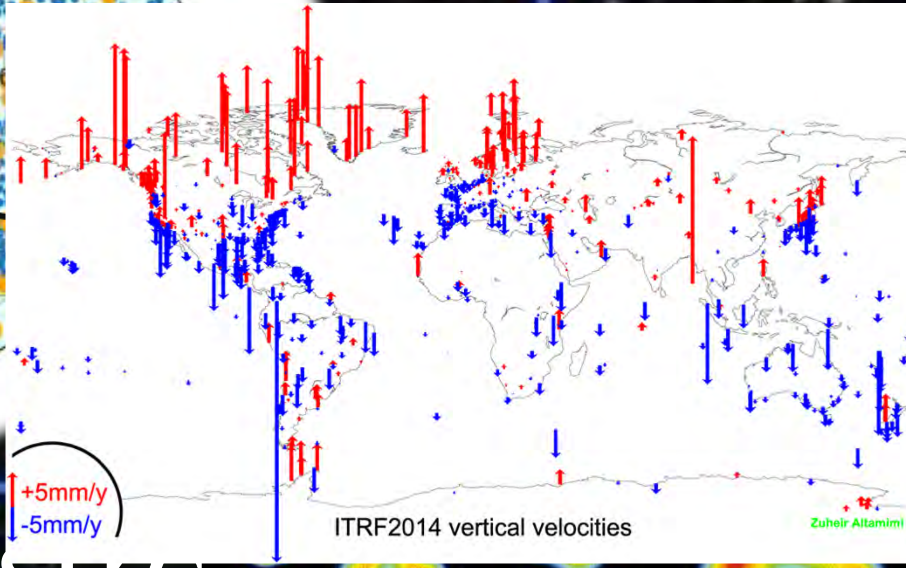
EOP

Time

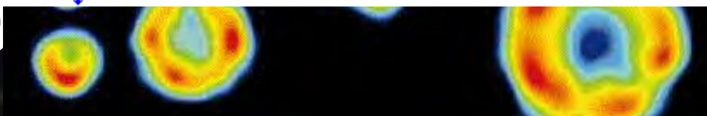


Geodesy, geophysic

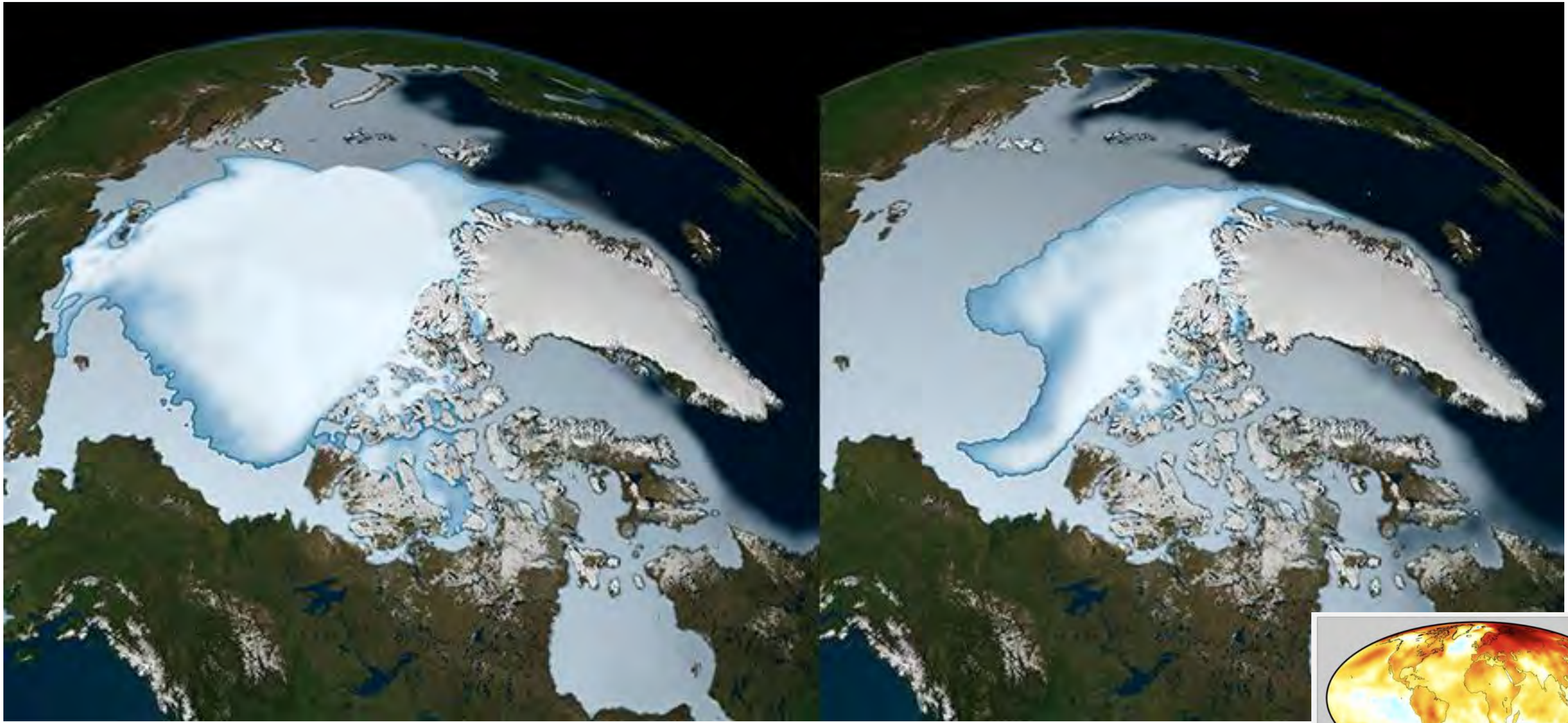




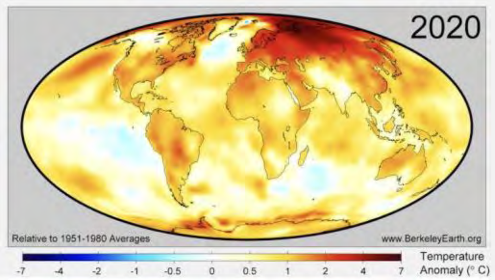
Astronomy, astrophysics, astro



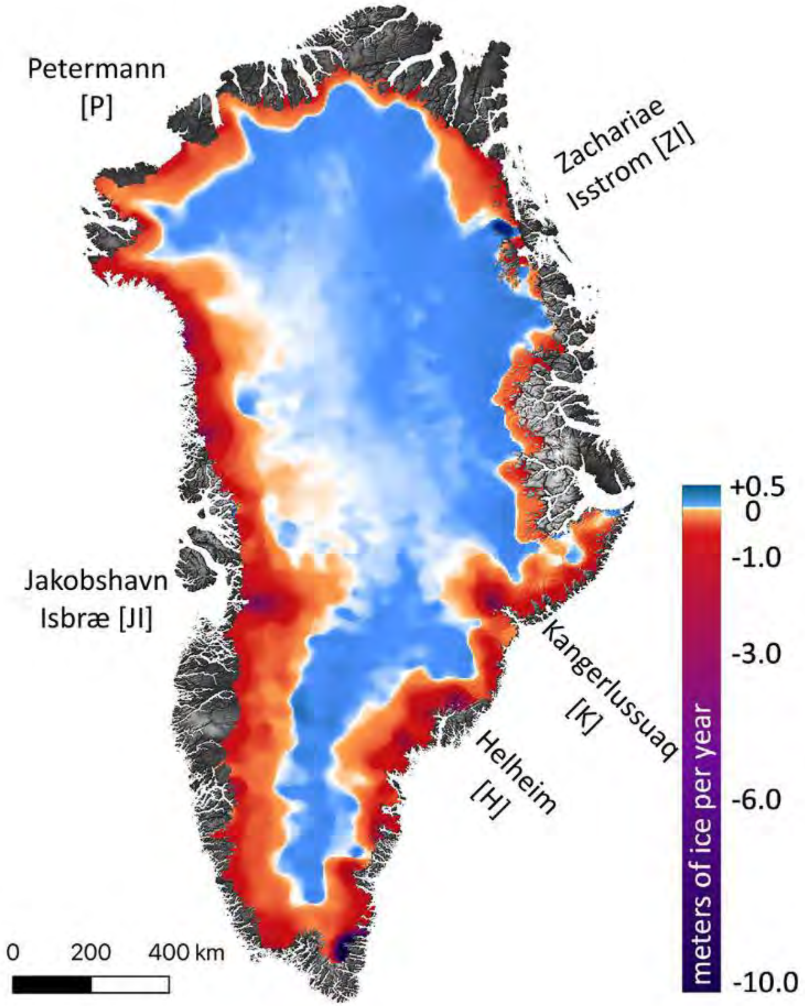
Rapid polar changes: Arctic sea ice loss

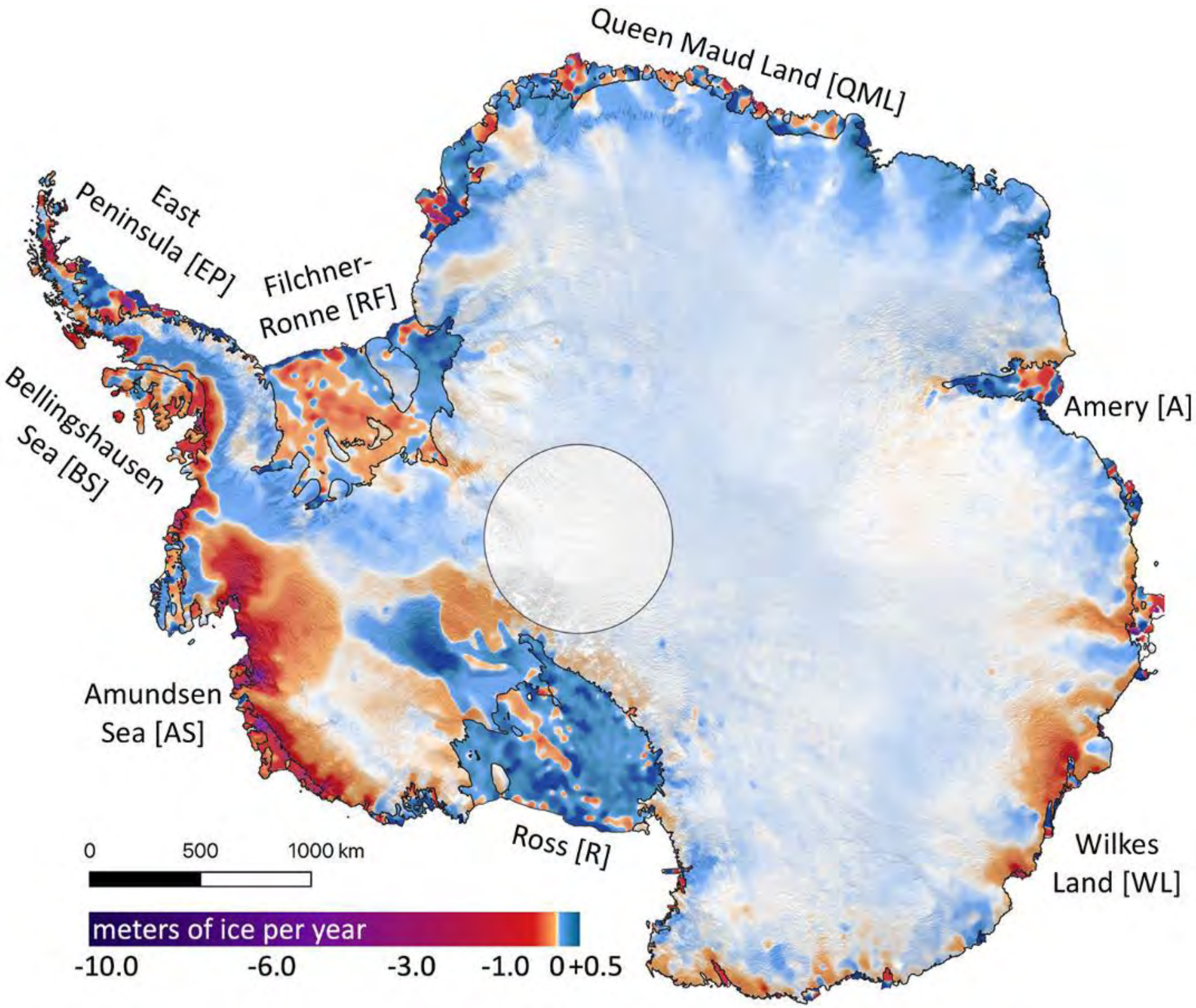


[NSIDC/NASA]

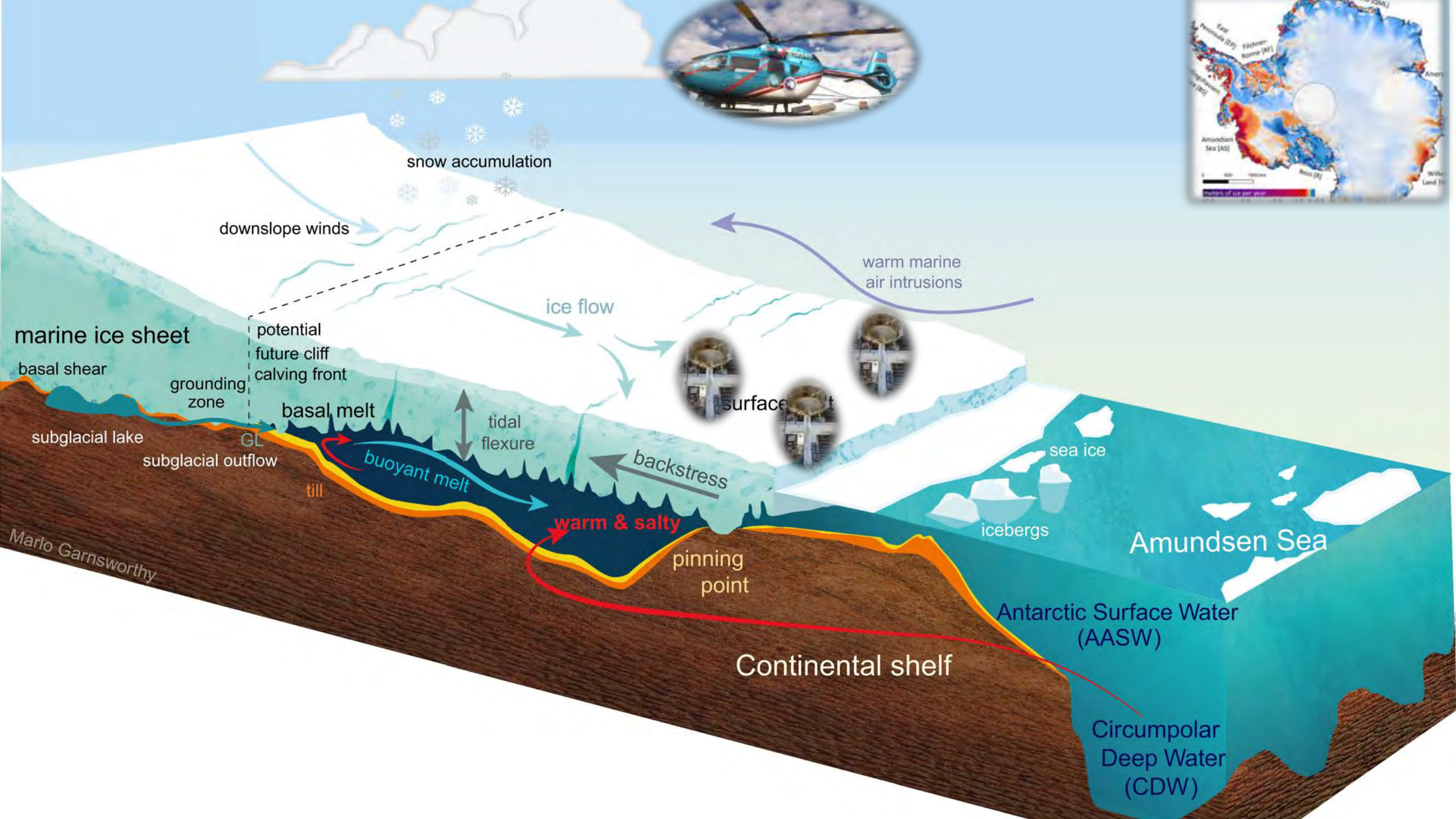


Rapid polar changes: Ice sheet mass loss

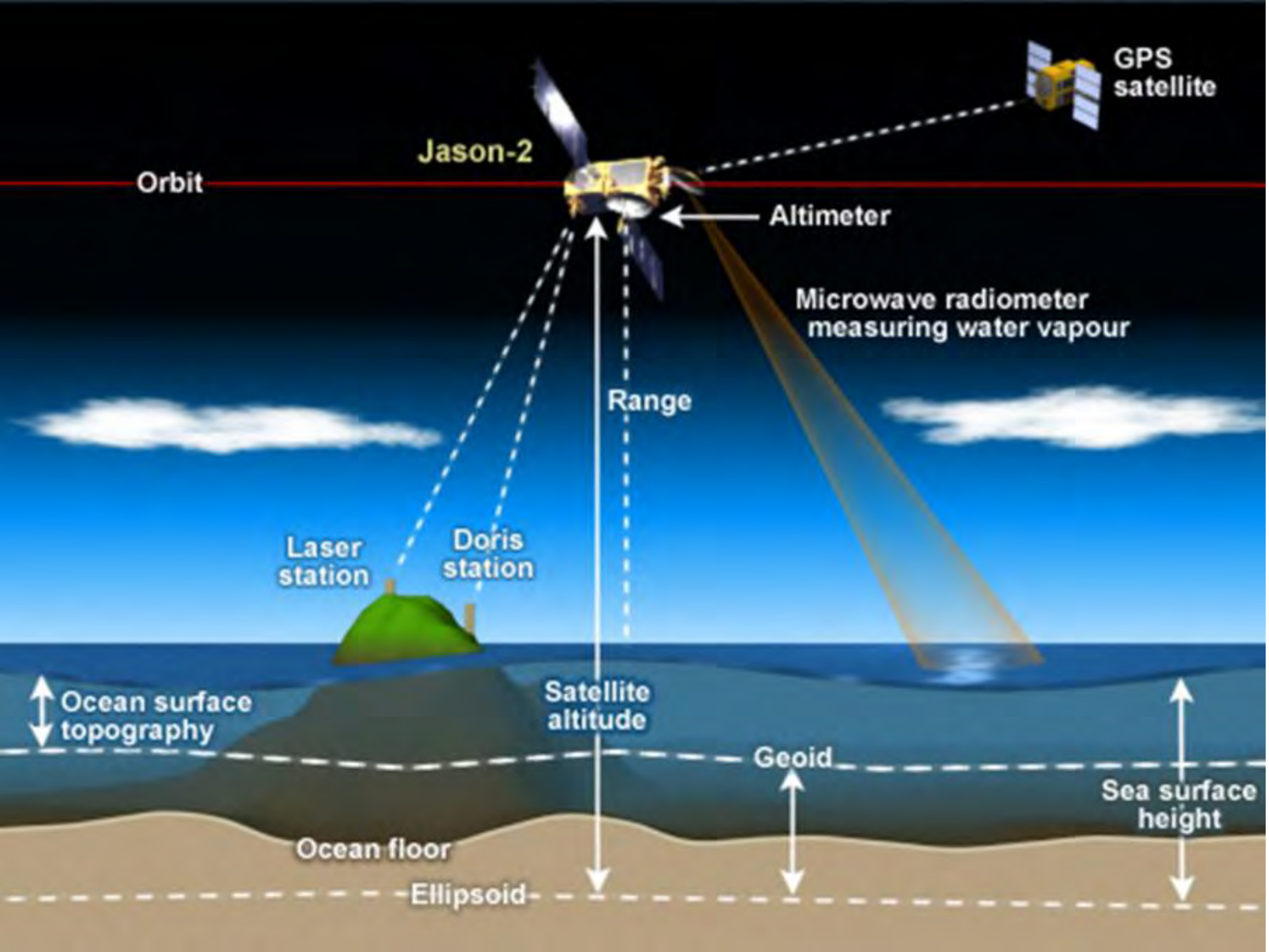




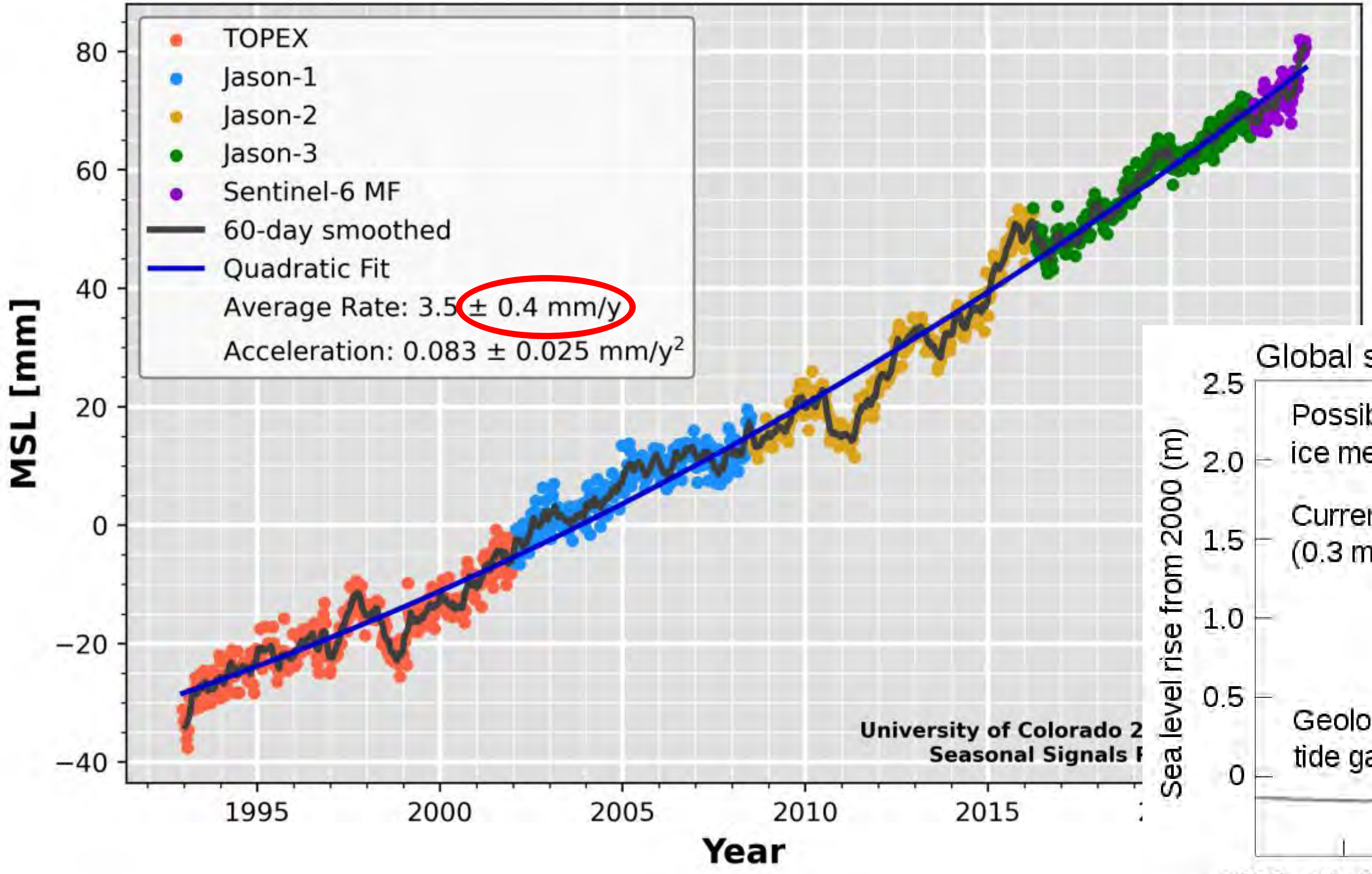
[*Smith et al., 2020*]


snow accumulation
downslope winds
warm marine
air intrusions
ice flow
marine ice sheet
basal shear
grounding
zone
potential
future cliff
calving front
basal melt
tidal
flexure
surface
subglacial lake
GL
subglacial outflow
buoyant melt
backstress
till
sea ice
warm & salty
icebergs
pinning
point
Amundsen Sea
Marlo Garnsworthy
Antarctic Surface Water
(AASW)
Continental shelf
Circumpolar
Deep Water
(CDW)

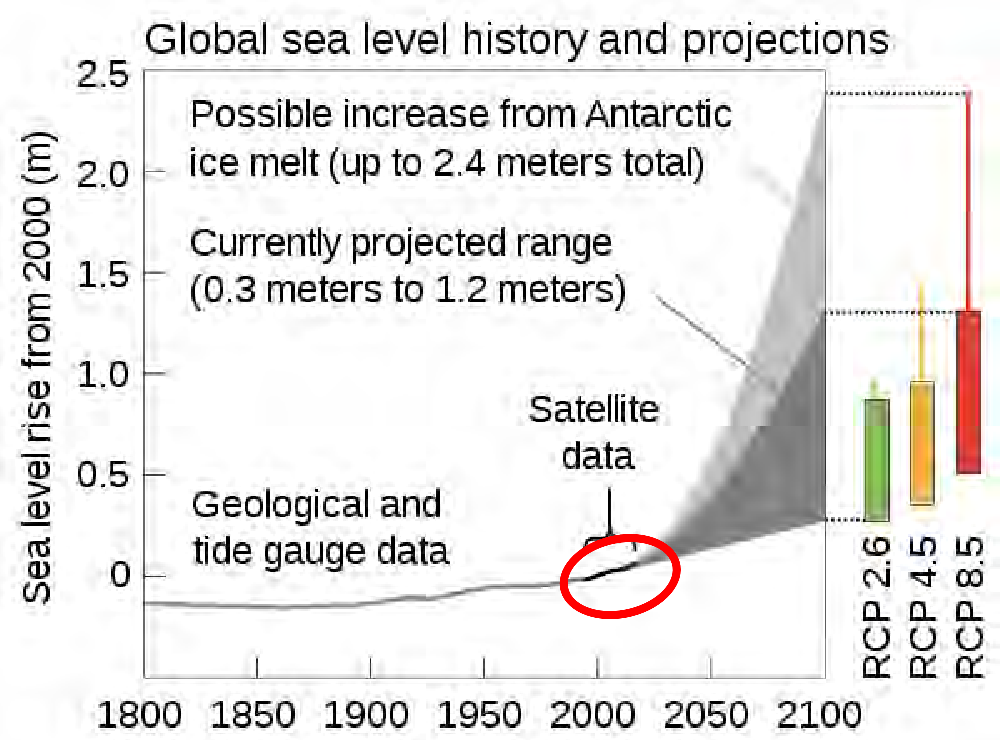
Sea level, satellite altimetry

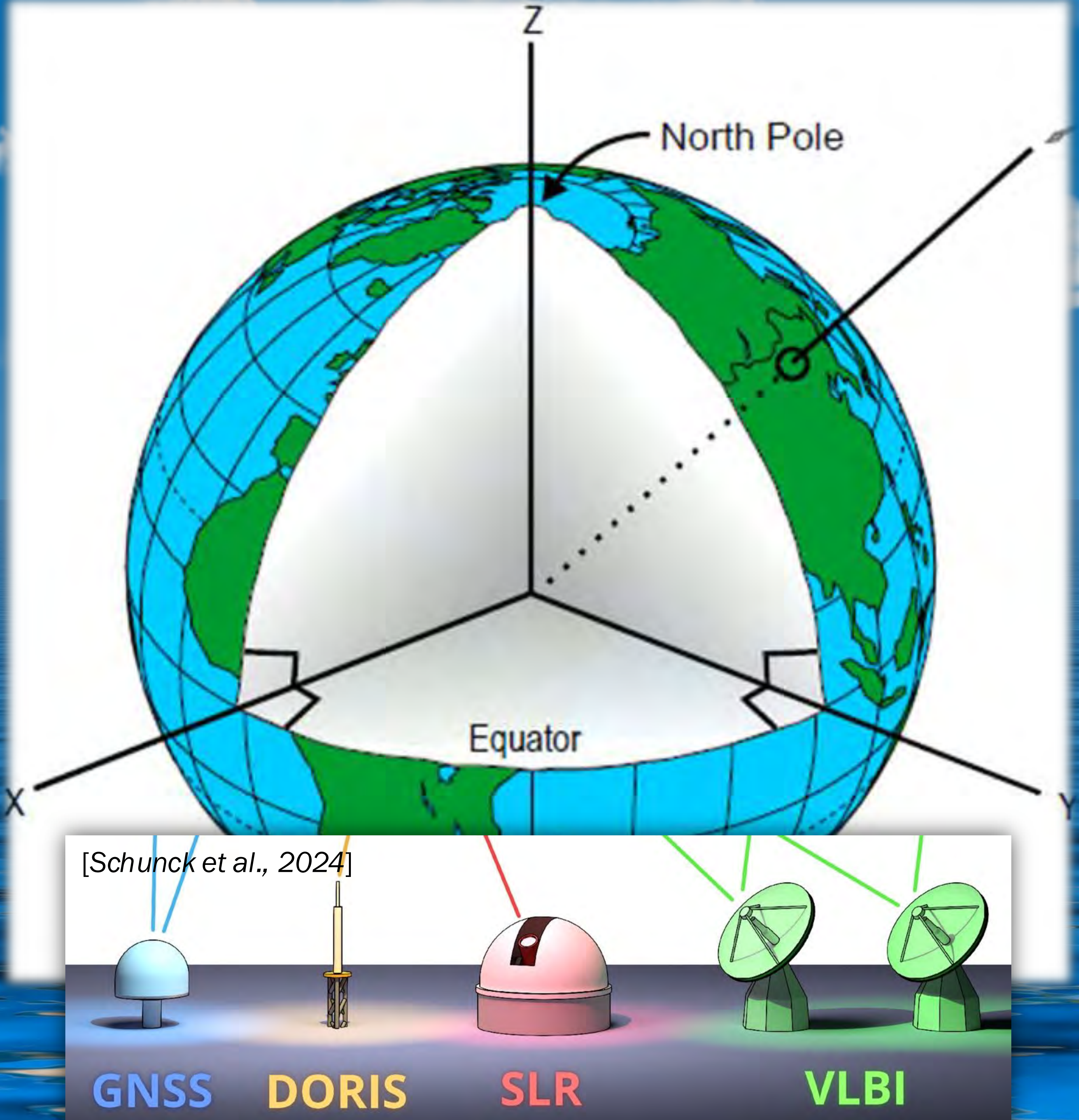


Global mean sea level (MSL) from satellite altimetry



Rapid global sea level rise




Z
North Pole
Equator
X
Y
[Schunck et al., 2024]
GNSS
DORIS
SLR
VLBI

Why VLBI?

CLIMATE CHANGE IS THE DEFINING CHALLENGE OF OUR TIME

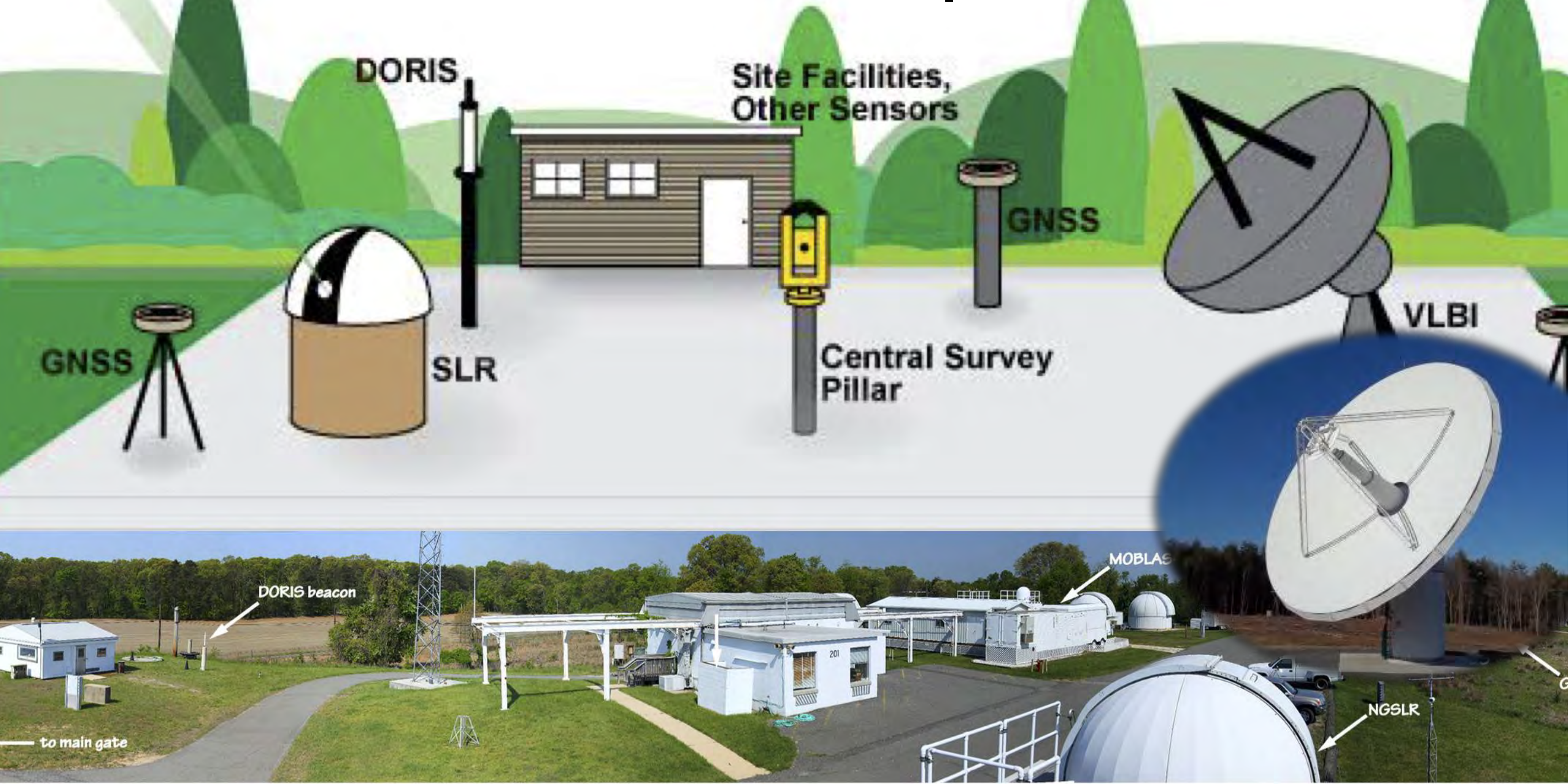
- Climate needs geodesy, geodesy needs VLBI/VGOS, VGOS needs you collecting the very best quality data you can.
- While staying humble, the contribution of each one of you (of us all, really) is terribly important.
- But please do not panic if you miss one scan, one session, something bigger; reflect, learn, connect, come back stronger.

Outline for today

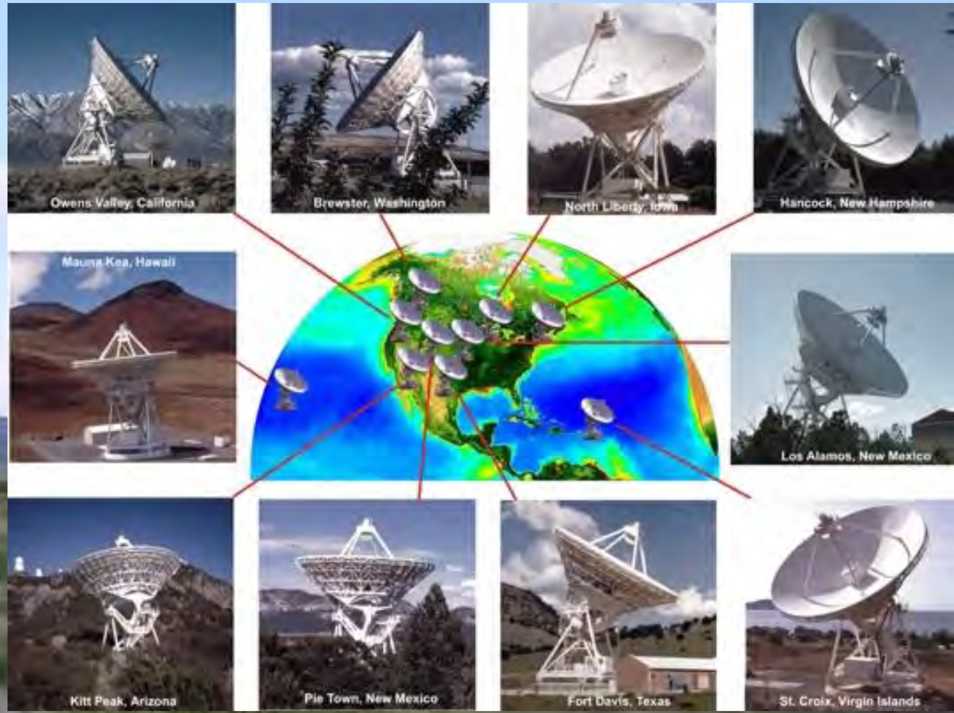
- Motivation: WHY do we do VLBI?
  - Climate change is the defining challenge of our time.
- Hands-on: HOW do we do VLBI?
  - Geodetic radio telescopes
  - VLBI vs. GPS concept
  - Station requirements
  - VLBI digitization
  - Correlation
  - Geodetic post-processing and VGOS precision


WESTFORD RADIO
GPS

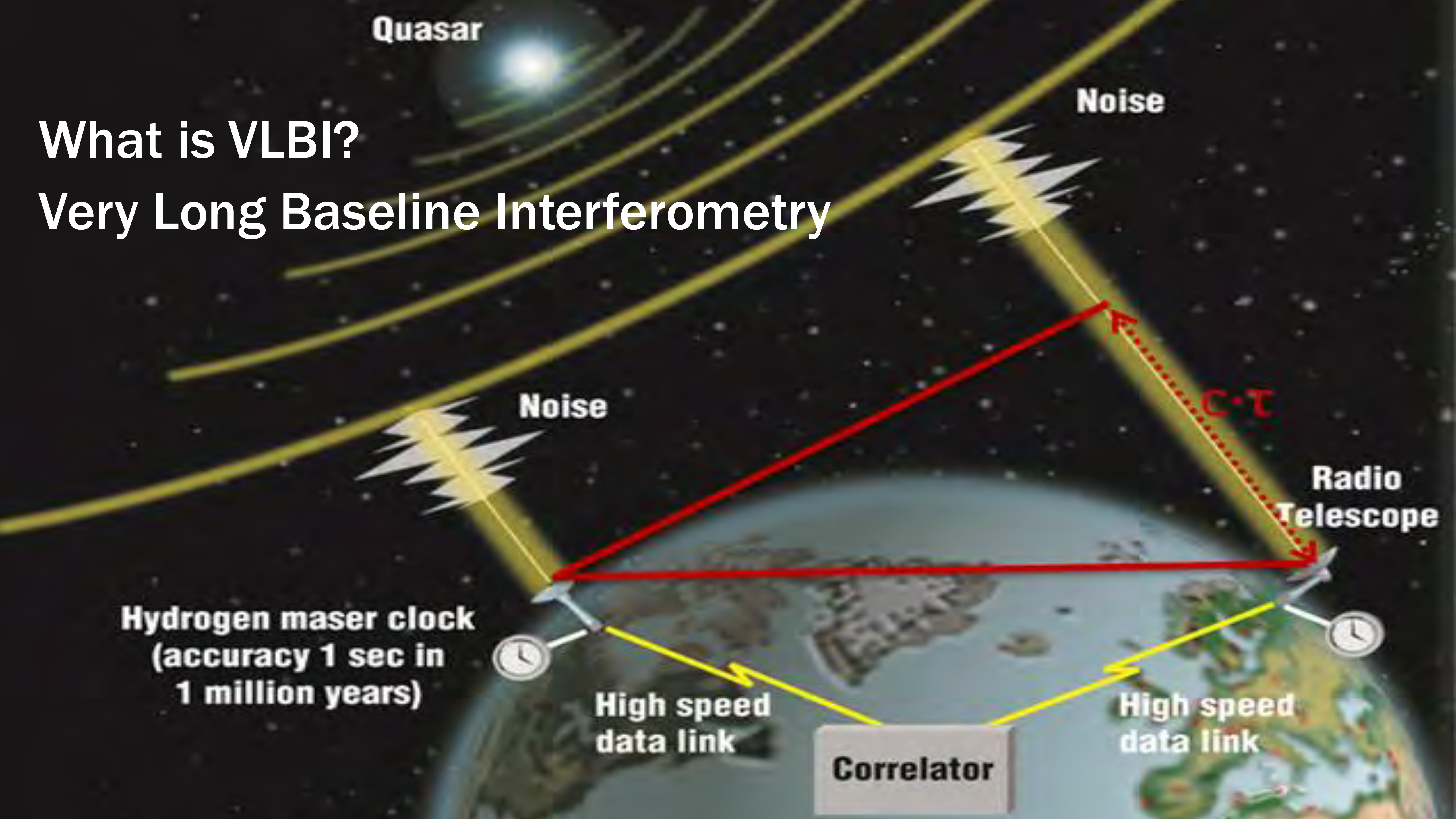
GGOS multi-technique core sites vision



What is VL ...A, ...BA, ..BI, ...?

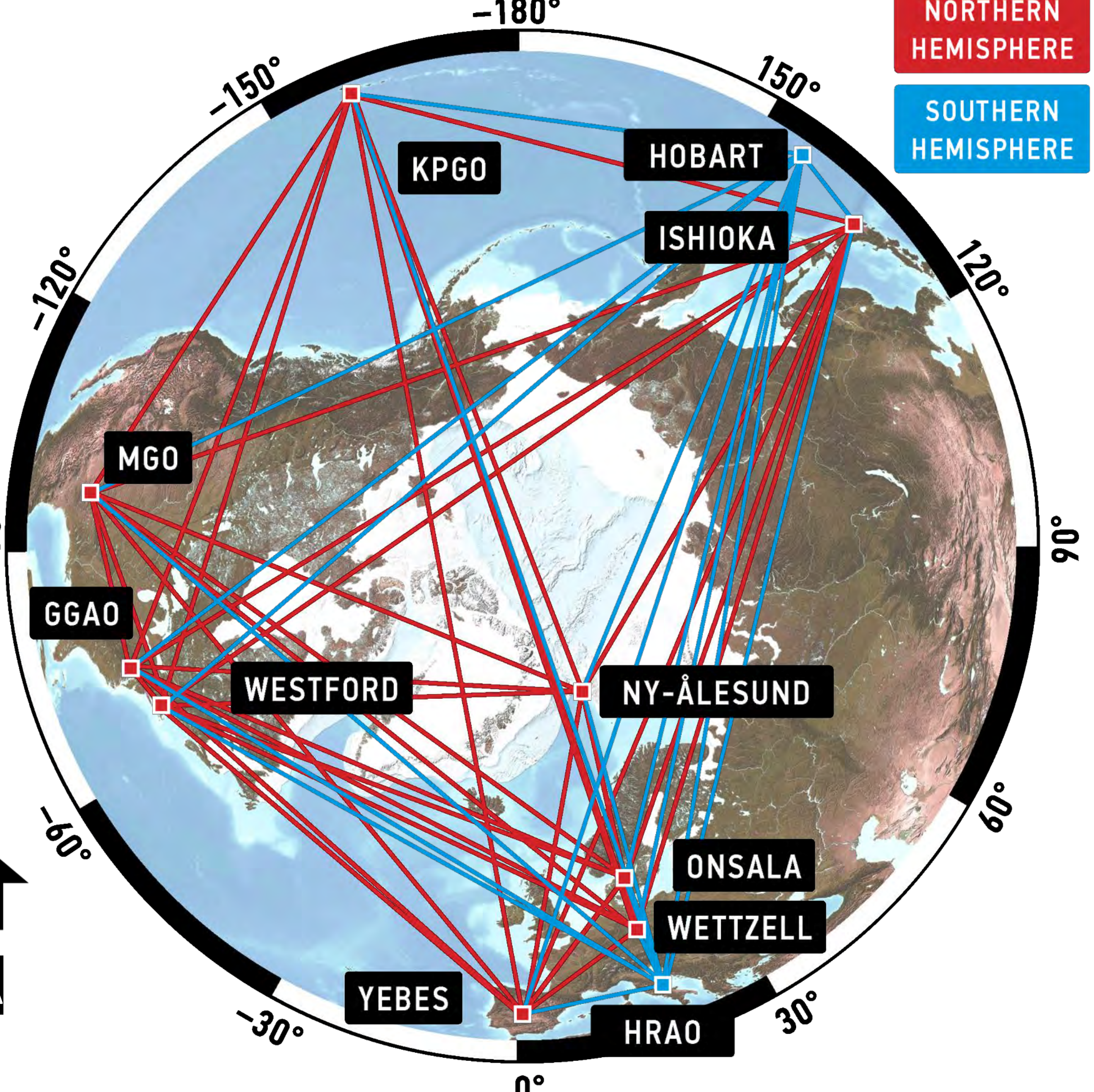


What is VLBI?
Very Long Baseline Interferometry

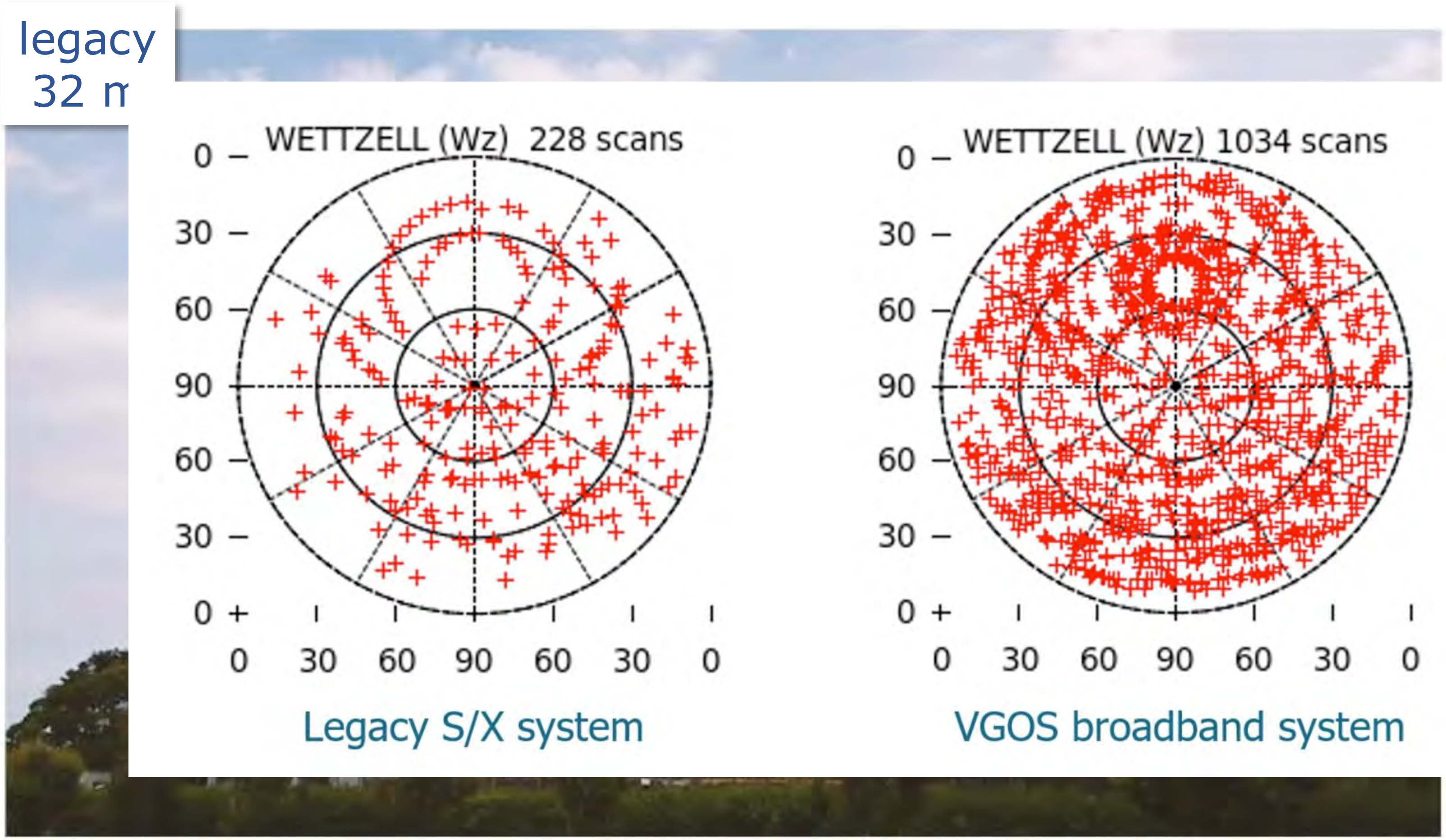


VLBI Global Observing System (VGOS) “today”

FORTALEZA



VGOS virtues (vs. “legacy S/X”) in a nutshell

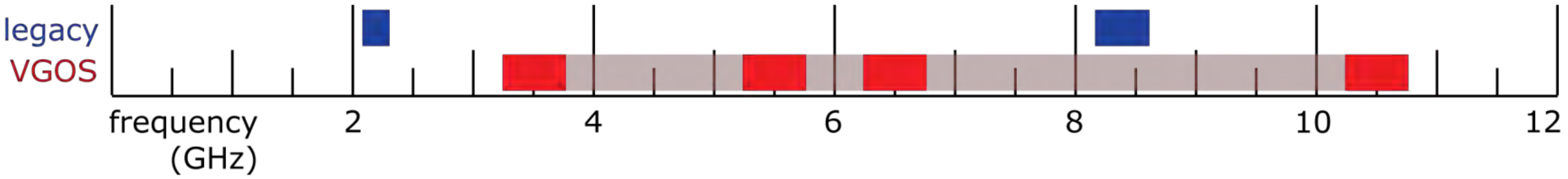


Small, fast, rigid

(improved errors)

Broad bandwidth

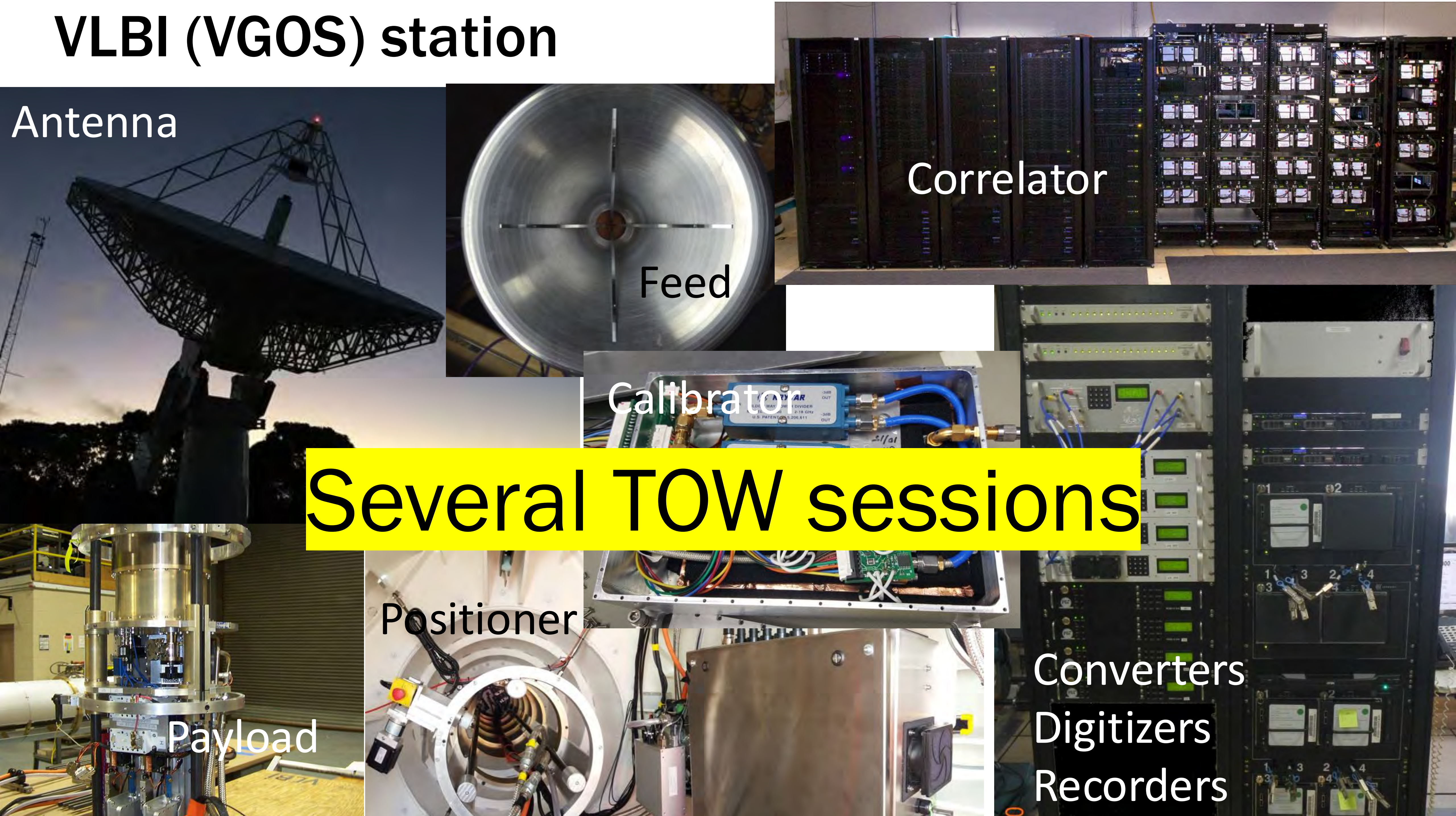
(better sensitivity)



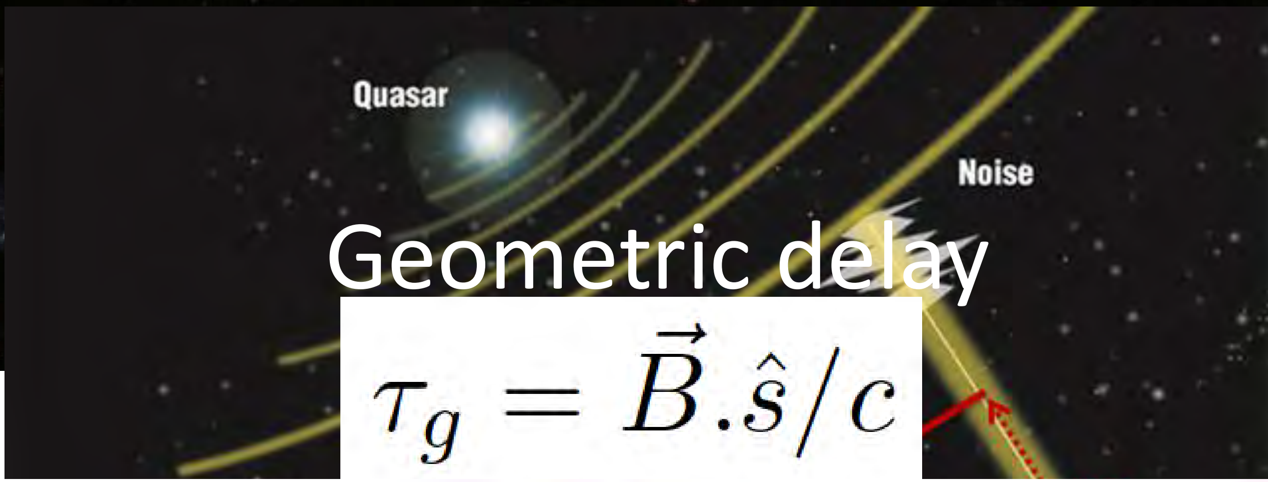
Basic elements of VLBI (geodesy)

- Antennas
- Receivers
- Analog and digital stages
- Recorders and data transport
- Correlation, post-processing
- Imaging, positioning, orientation

VLBI (VGOS) station



The Geodetic Measurement System

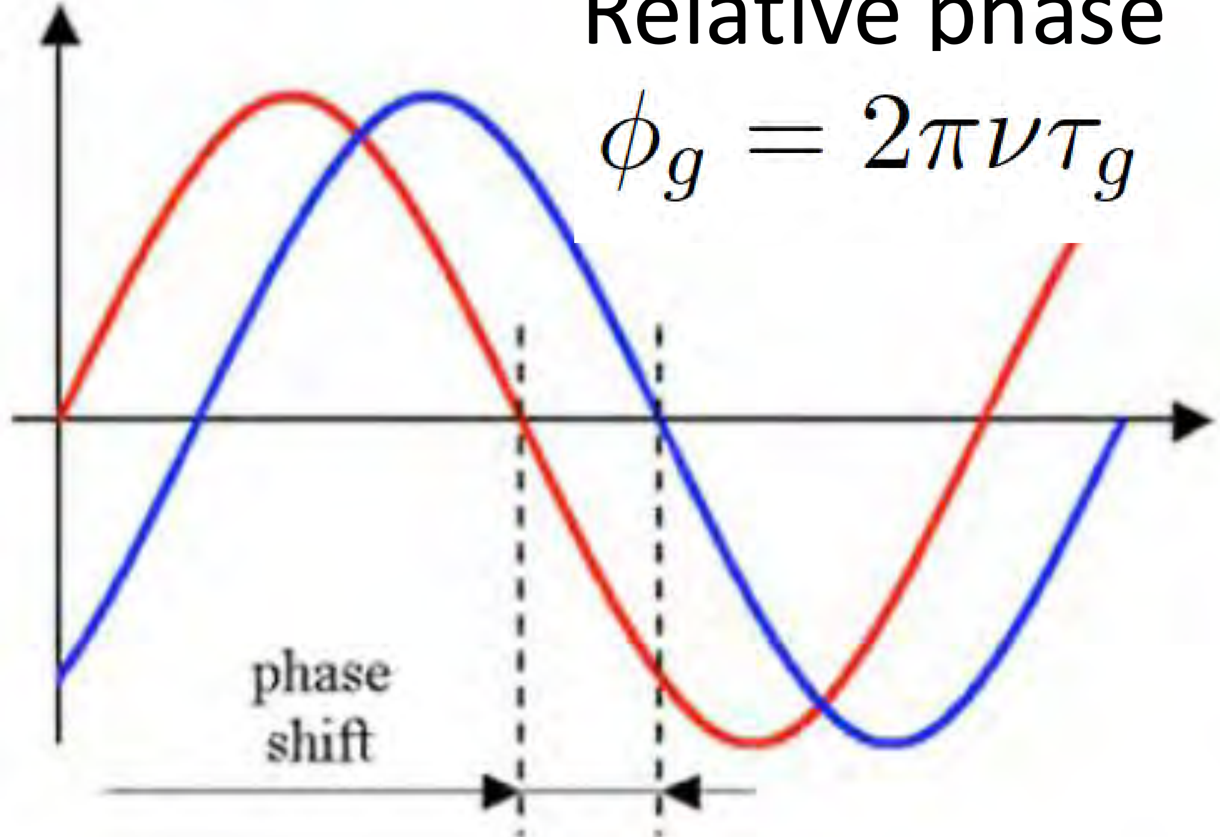


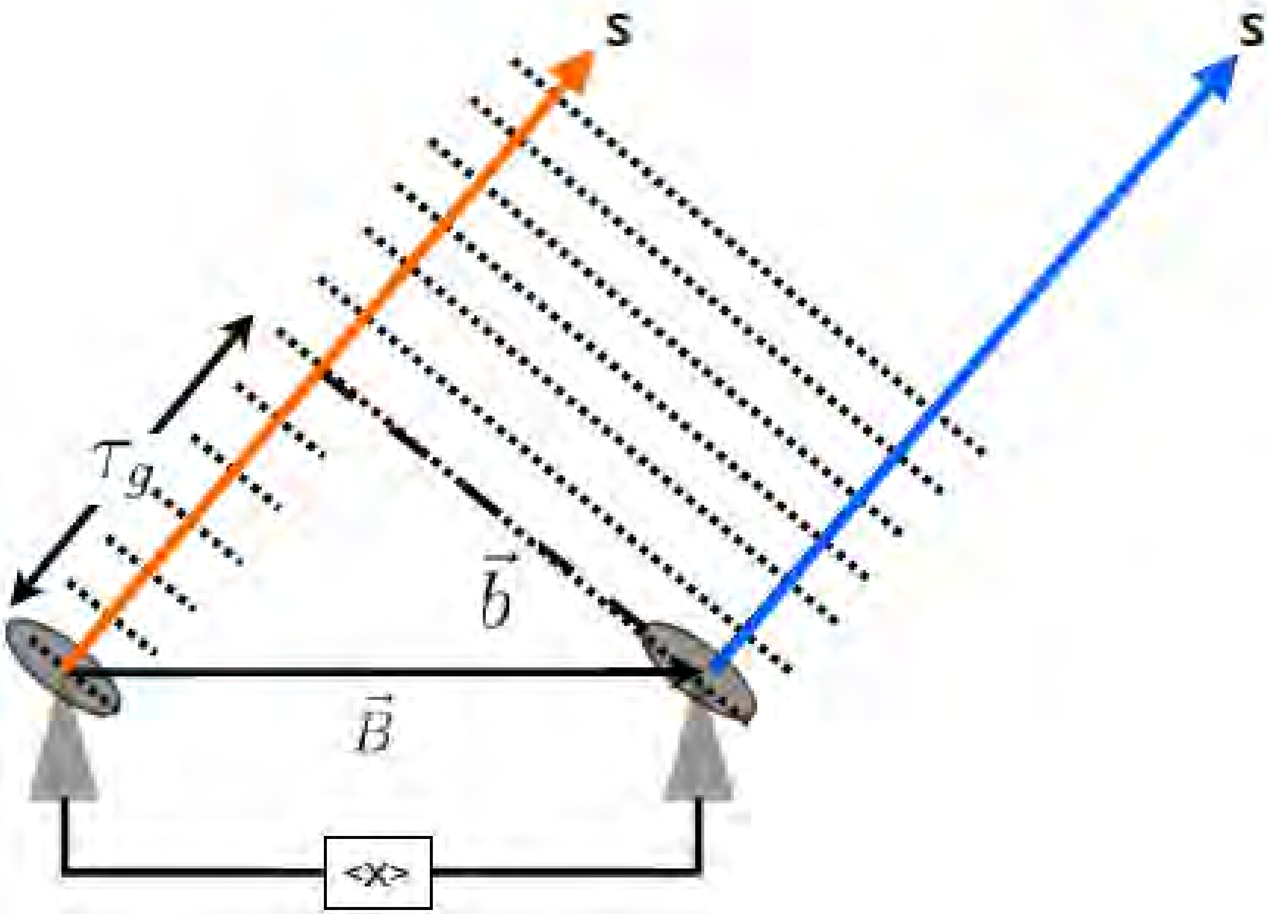
Geometric delay

$$\tau_g = \vec{B}.\hat{s}/c$$

Relative phase

$$\phi_g = 2\pi\nu\tau_g$$





High-precision geodetic science

Observation = Model + Error

$$\tau = \tau_g + \tau_{clk} + \tau_{ion} + \tau_{trop} + \tau_{inst} + \tau_{rel} + \tau_{other} + \epsilon$$

Signal (geometry => position, orientation) rest is all **"noise"**

VLBI

SLR

GNSS

DORIS

Practical VLBI observational goals

High-precision geodesy means observable with small error

$$\sigma_\tau = \frac{1}{2\pi} \cdot \frac{1}{SNR\,\Delta\nu}$$

- Sensitivity = ability to "see" faint objects (interferometer, Jy)

$$\Delta S = \frac{1}{\eta_s} \cdot \sqrt{\frac{SEFD_i \cdot SEFD_j}{2\Delta\nu\,\tau_{acc}}}$$

- Resolution = ability to "see" details in distant objects

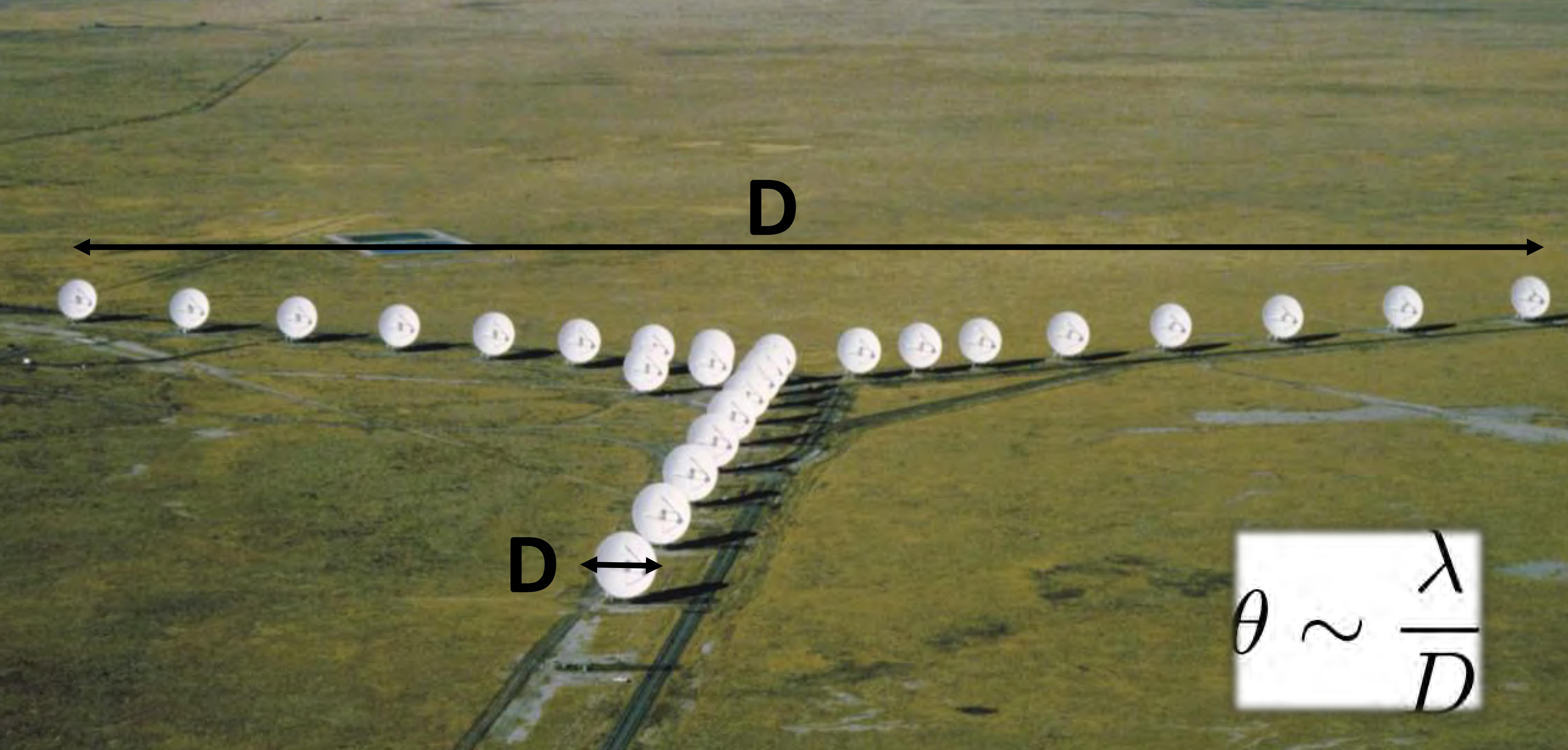
What determines sensitivity?

- Amount of energy collected (Ta, gain, efficiency)
  - Size and quality of the collecting area
    - but cost of bigger antennas tends to increase as D^2.7 (i.e., doubling antenna diameter raises price by ~6!)

  - Bandwidth of the energy spectrum
    - sensitivity improves as square root of observed bandwidth, cost effective

- Quietness of the receiving detectors (Tsys)
  - many receivers are already approaching quantum noise limits, or are dominated by atmospheric noise

What determines resolution?

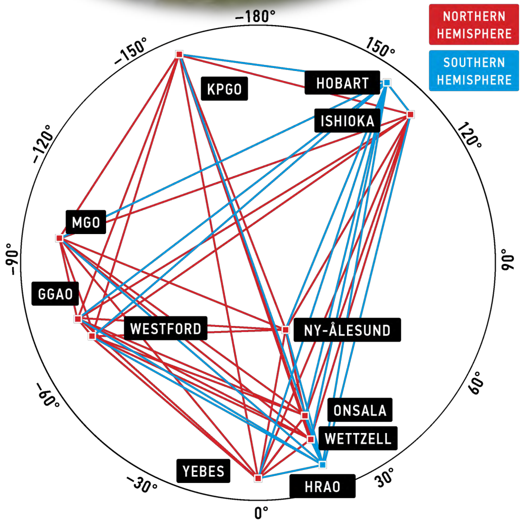


$$\theta \sim \frac{\lambda}{D}$$

A few resolution examples

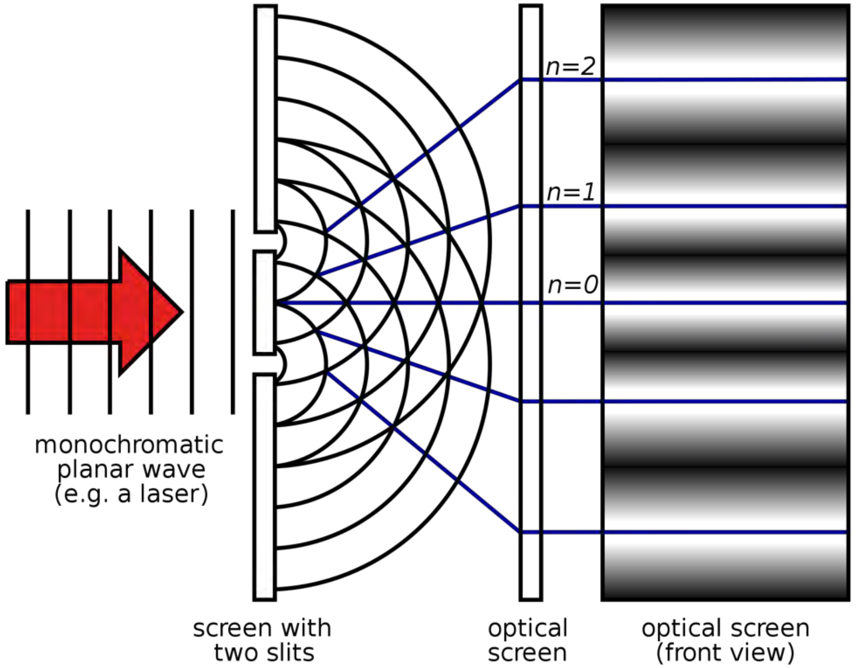
$$\theta \sim \frac{\lambda}{D}$$

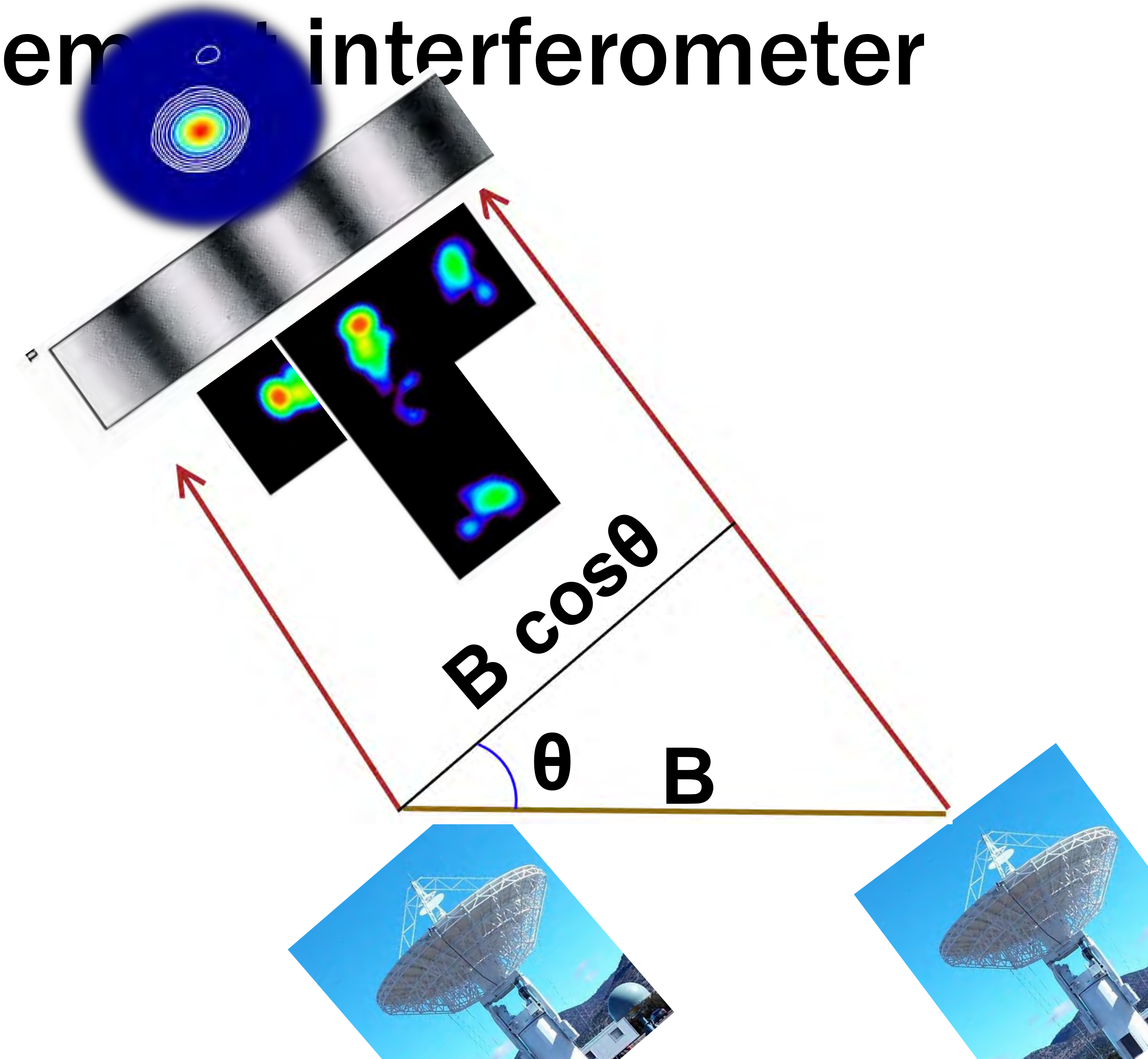
	D	**λ**	**θ**	Moon surface
VGOS antenna	12 m	3 cm (10 GHz)	10 arcmin	1000 km
Effelsberg	100 m	1 cm (30 GHz)	20 arcsec	
VLA	35 km	1 cm	0.1 arcsec	
VGOS	10,000 km	3 cm	0.6 mas	1 m



Principle of two-element interferometer

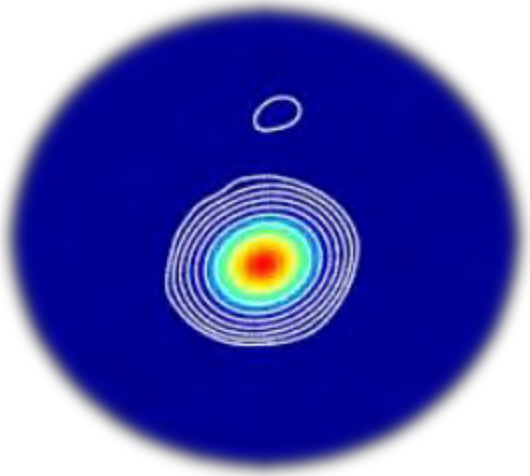
Young double-slit experiment





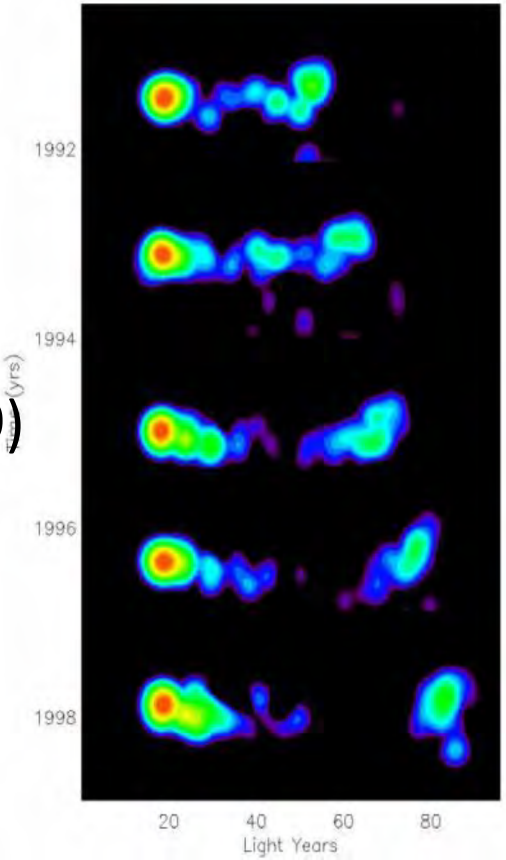
Geodetic VLBI radio sources

“Nice” (1300+580)

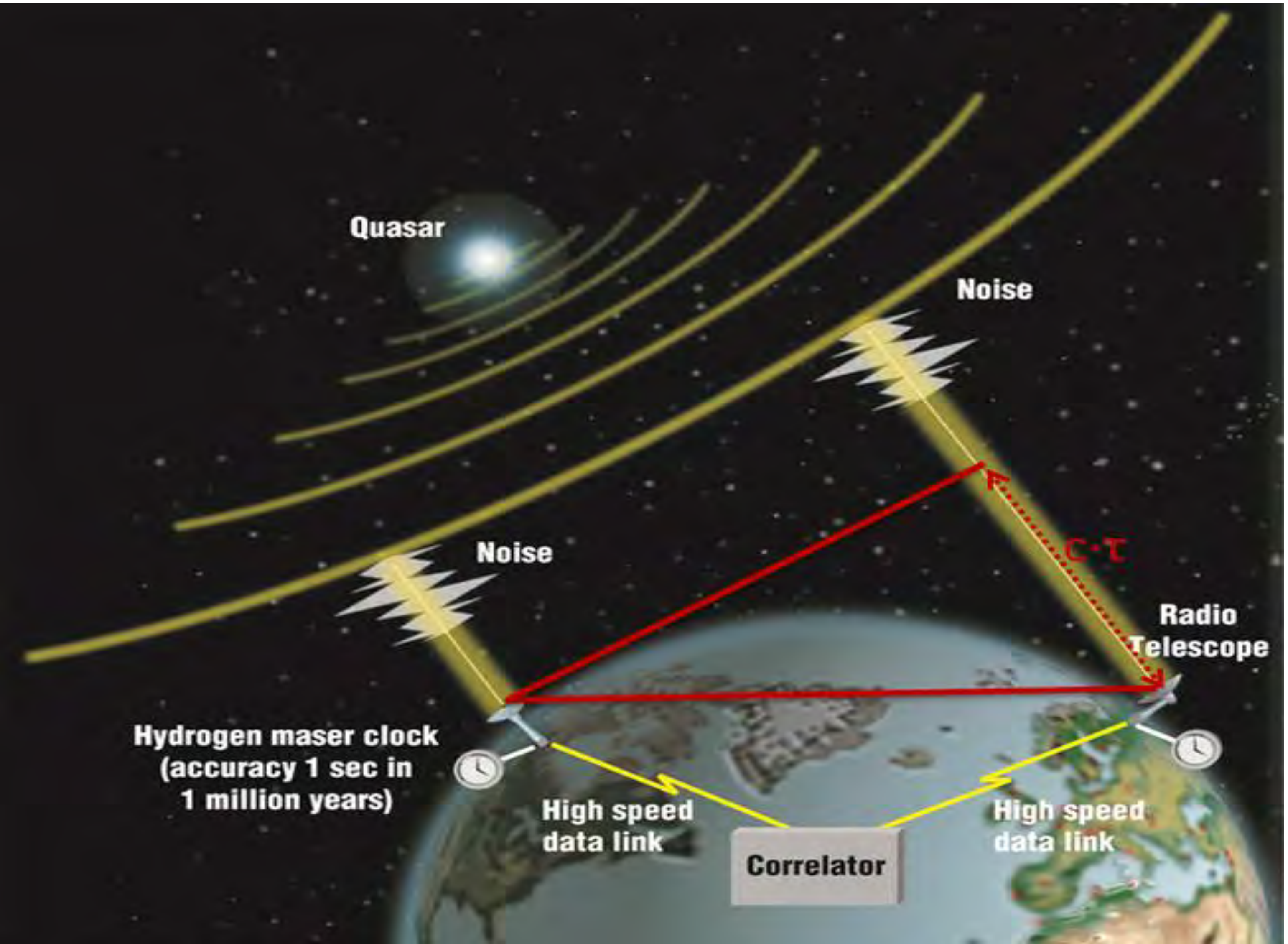


- VLBI geodesy requires sources that are bright, compact, and “stable” both in time and frequency; a challenge
- The total number of available useful sources for current geodetic-VLBI capabilities is small (<~1000)
- VGOS, with its improved sensitivity, should significantly improve the number of available sources

“Ugly” (3C279)



Principle of (geodetic) VLBI/VGOS



- Measure time-of-arrival difference (delay) accurately

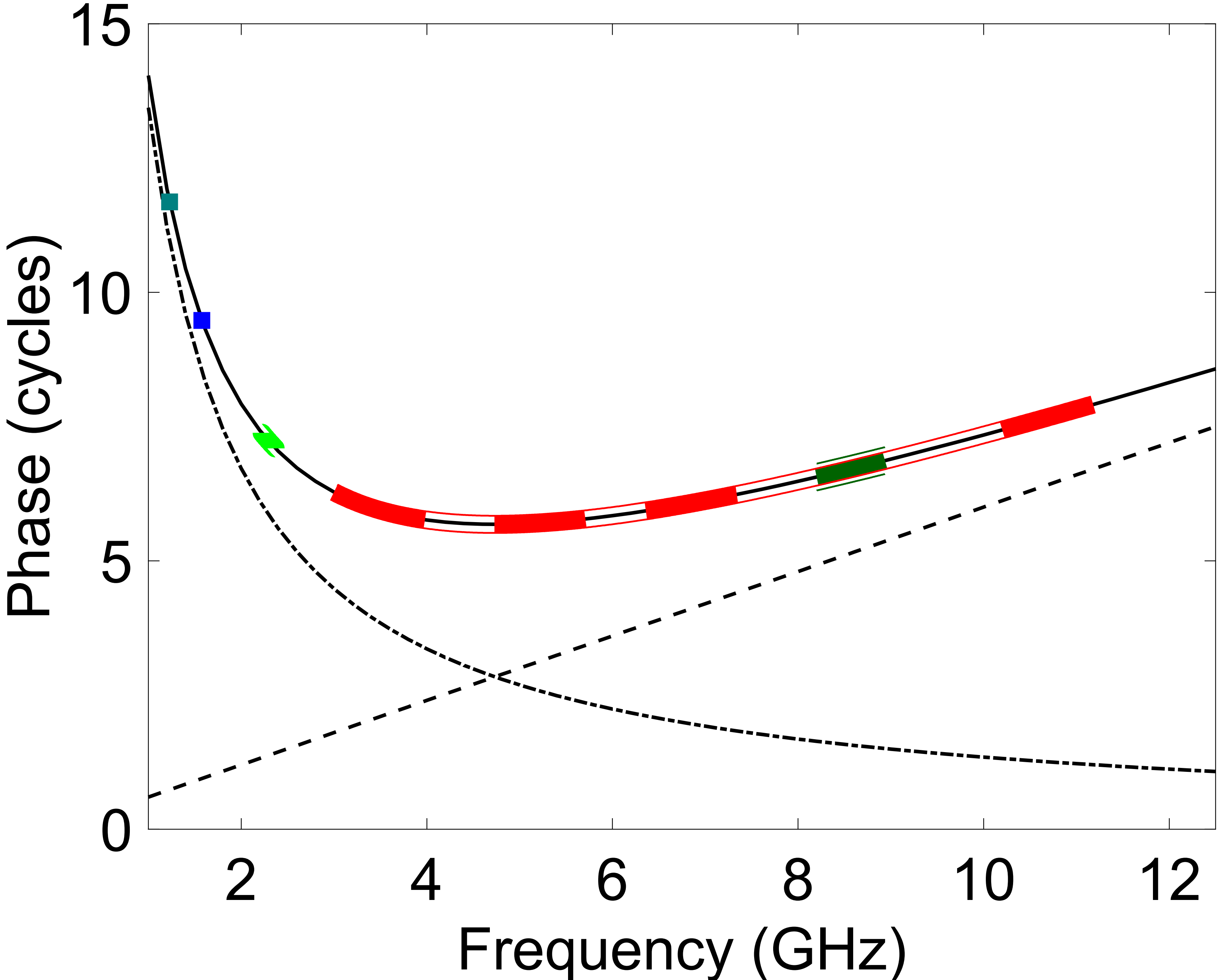
$$\sigma_\tau = \frac{1}{2\pi} \cdot \frac{1}{SNR\,\Delta\nu}$$

- mm-level positioning requires delay precision of a few picoseconds (3 ps = 1 mm)

VGOS station requirements

- Observing “noise” from quasars (contaminated by various noise sources)
- Measuring a (group) delay (a time measurement) whose precision is inverse of spanned bandwidth
  - Requires wideband feeds and receivers (VGOS 2-14 GHz)
  - Multi-band systems to correct for ionosphere delays

VGOS broadband delay



[*Niell et al., 2018*]

VGOS station requirements

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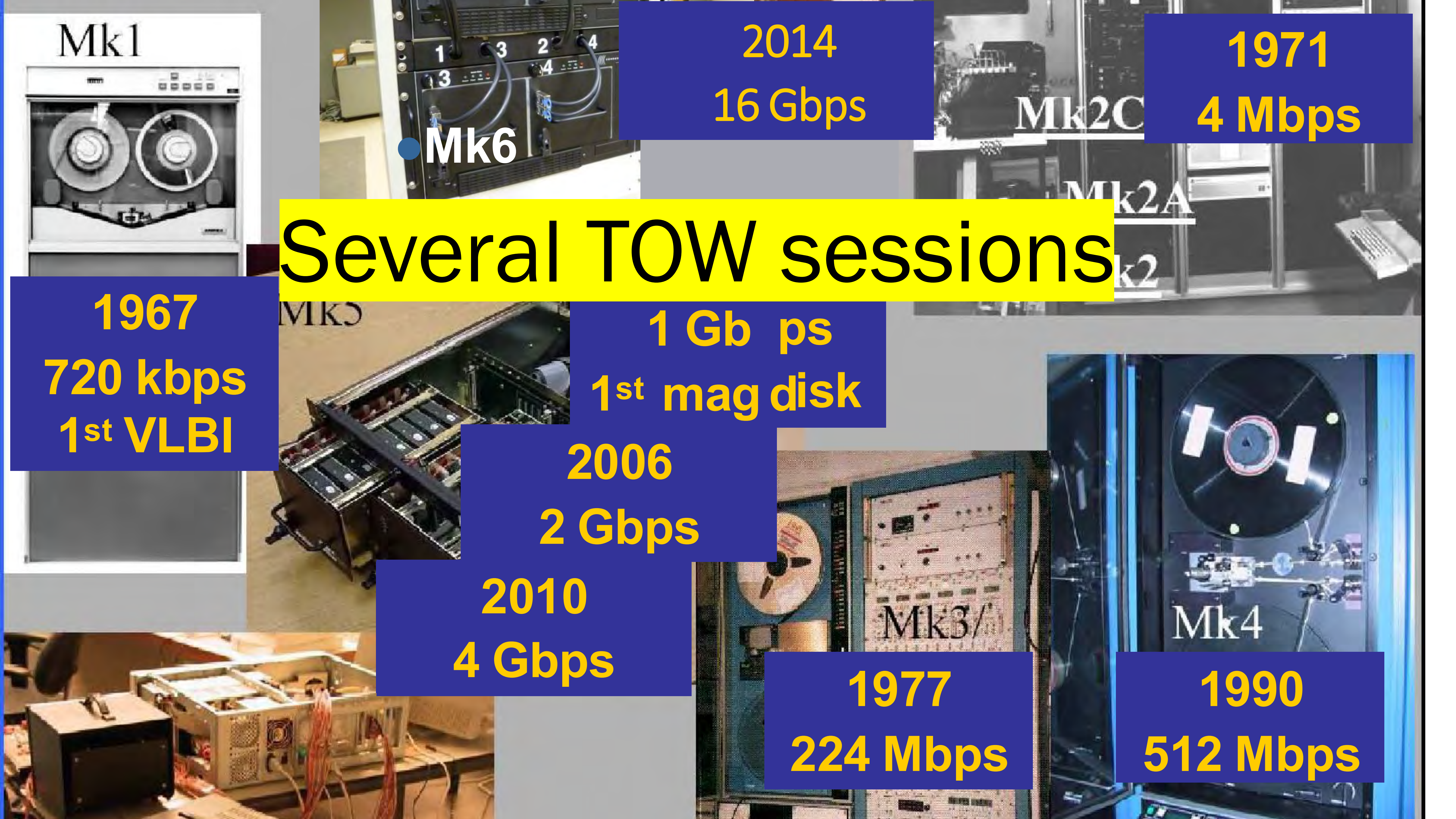
  - Low-noise receivers (low SEFD, antenna efficiency, cryogenics)
  - Antennas that are small, efficient, and fast (atmosphere)
  - High-speed recording for high SNR via large bandwidth (Nyquist)


Several TOW sessions
Mk1
1967
720 kbps
1st VLBI
Mk6
2014
16 Gbps
Mk2C
1971
4 Mbps
Mk2A
Mk5
1 Gb ps
1st mag disk
2006
2 Gbps
2010
4 Gbps
Mk3
1977
224 Mbps
Mk4
1990
512 Mbps

VGOS station requirements

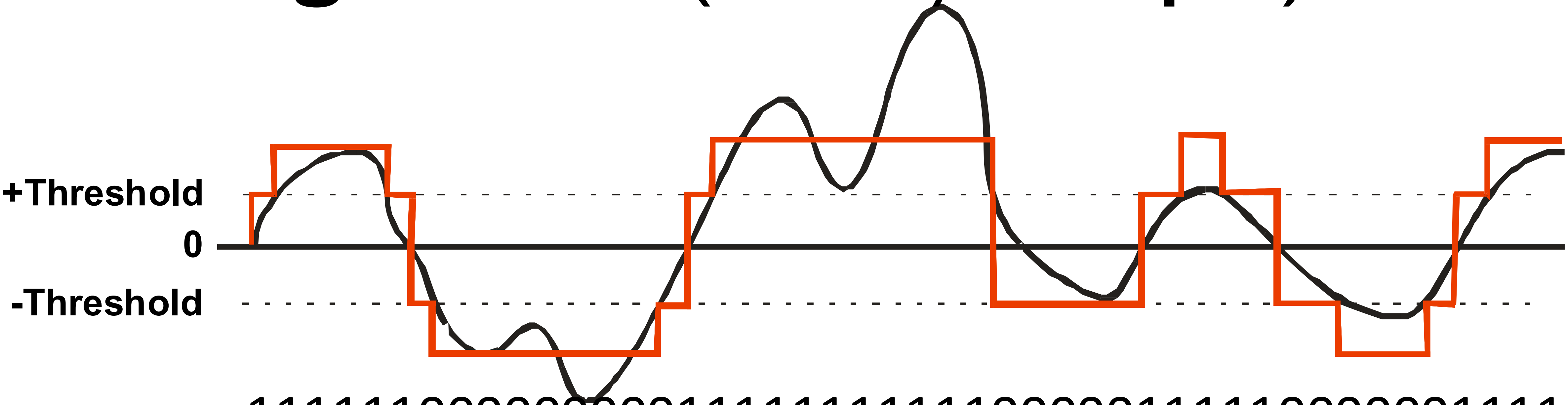
- Observing “noise” from quasars (contaminated by various noise sources)
- Measuring a (group) delay (a time measurement), whose resolution is inversely of spanned bandwidth
  - Requires wideband feeds and receivers (VGOS 2-14 GHz)
  - Multi-band systems to correct for ionosphere delays
  - Low-noise receivers (low SEFD, antenna efficiency, cryogenics)
  - Antennas that are small, efficient, and fast (atmosphere)
  - High-speed recording for high SNR via large bandwidth (Nyquist)
  - Hydrogen maser frequency standards
  - Accurate time synchronization (to ~300 nsec with GPS time)
  - Instrumental calibrations (cable delays and phase calibration)

What is the recorded VLBI data?

Answer: precisely timed samples of noise,
usually nearly pure white, Gaussian noise!

- Interesting fact: normally, the voltage signal is sampled with only 1 or 2 bits/sample
- Big consequence, it is near incompressible
- But another important consequence, it is not a big deal to lose a small amount of data

VLBI digitization (2 bits/sample)



111111000000000011111111111000001111100000001111…

011110100000000101111111111111111011001100010111…

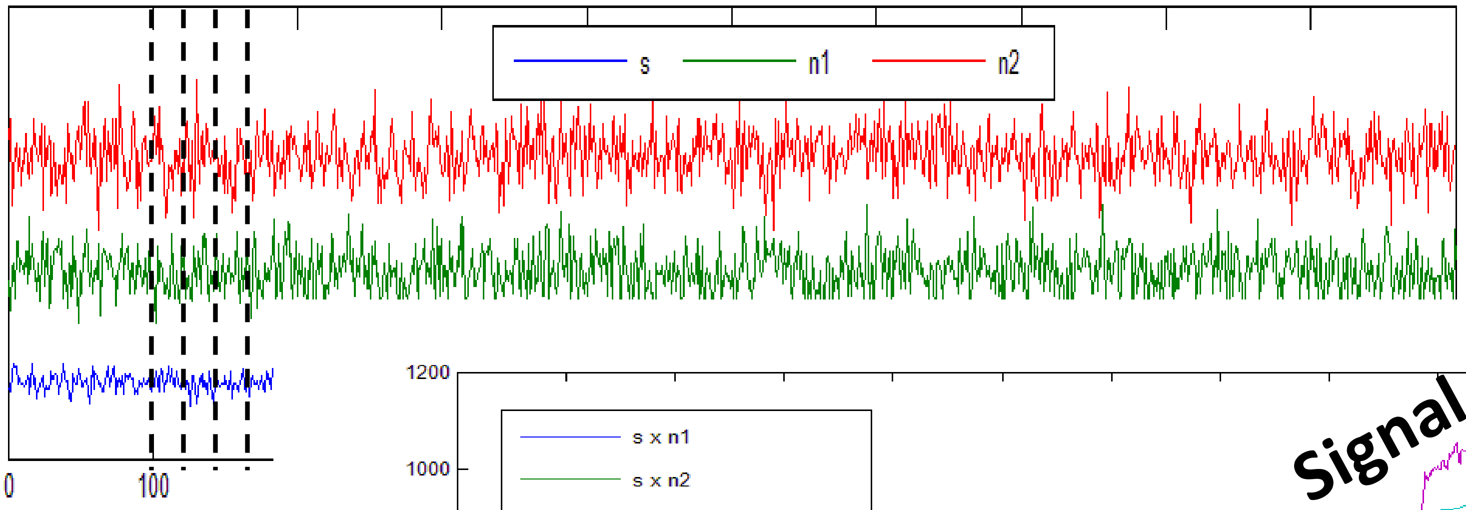
- The spectrum of a Gaussian-statistics bandwidth limited signal may be completely reconstructed by measuring only the sign of the voltage at each Nyquist sampling point (Van Vleck, 1960) [*For 32-MHz VGOS channels, that is 64 Msps = 20 ns*]
- Relative to infinite bit sampling, VLBI SNR at 1 and 2 bits/sample is only 63% and 87%, respectively, better compensated by increasing recording bandwidth

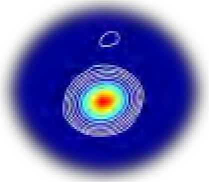
VLBI correlation (of weak signals)

Receiver 1 noise $n_1(t)$ →

Receiver 2 noise $n_2(t)$ →

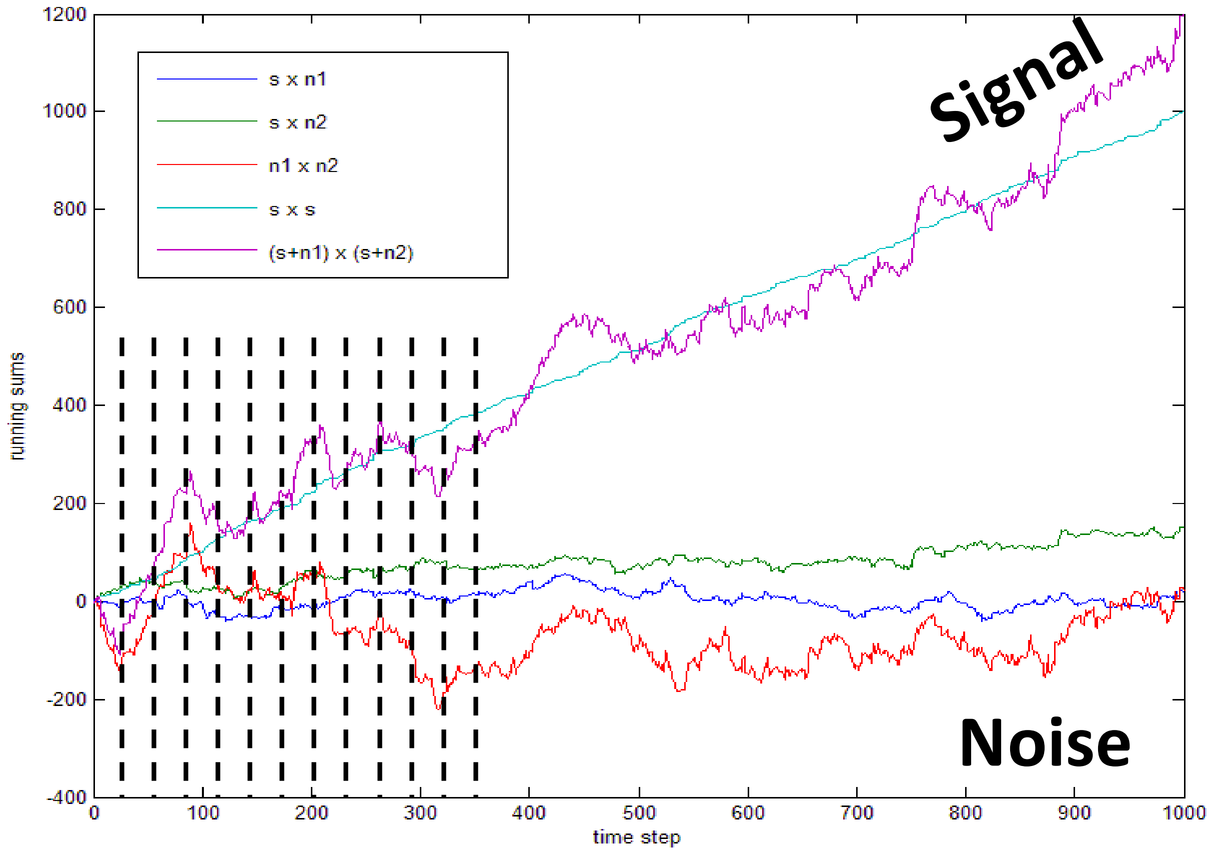
Signal $s(t)$ →





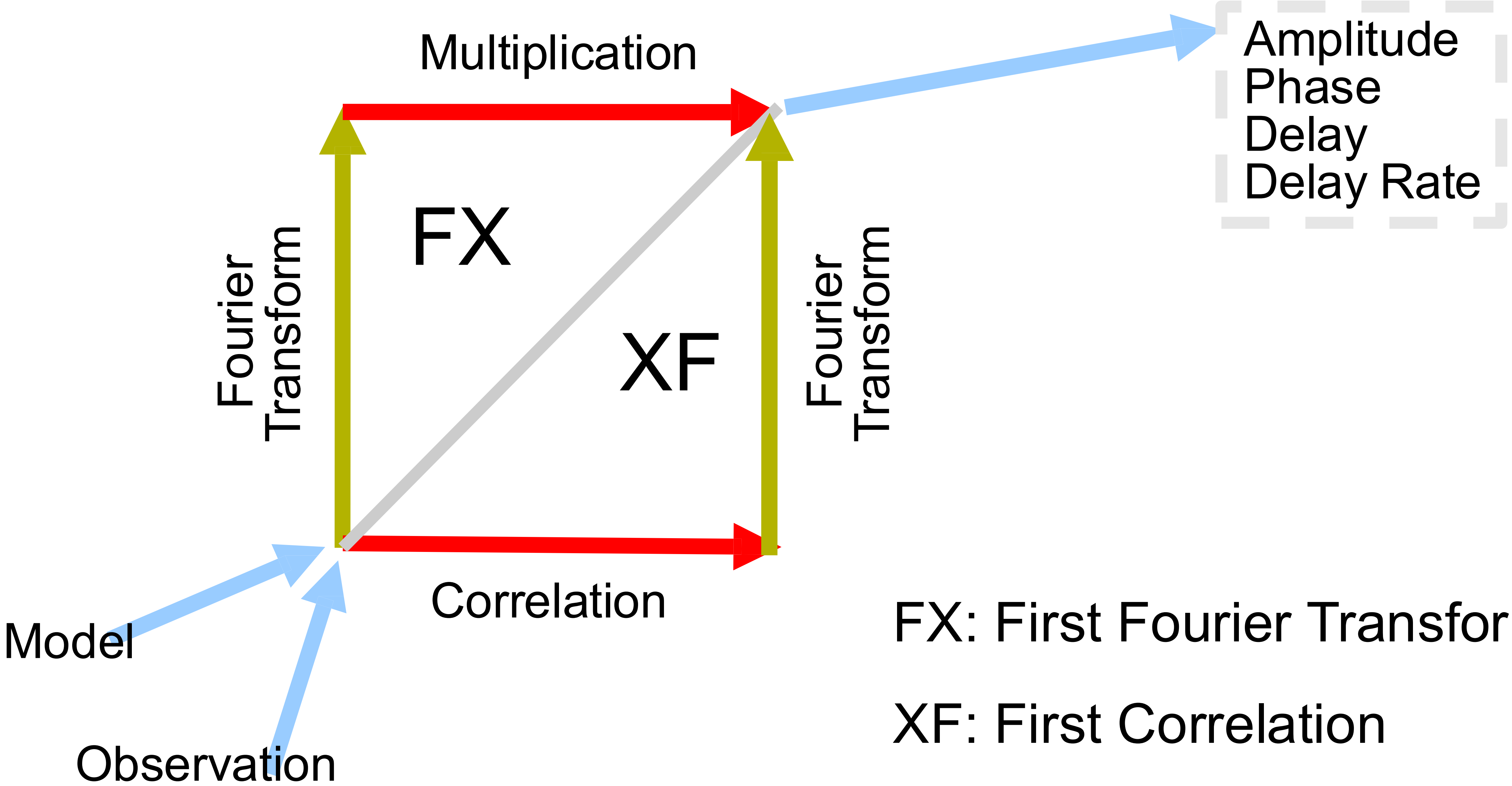
Time-lag correlation = product and addition (pulling signal from the noise):

$$(s + n_1)\,(s + n_2) = s^2 + n_1 s + n_2 s + n_1 n_2$$



(Earth rotation adds complexity because causes time-of-arrival difference and Doppler shift to continually change)

Correlators: two flavors of processors

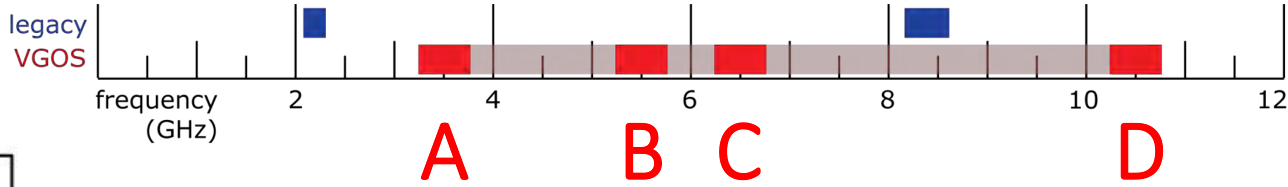


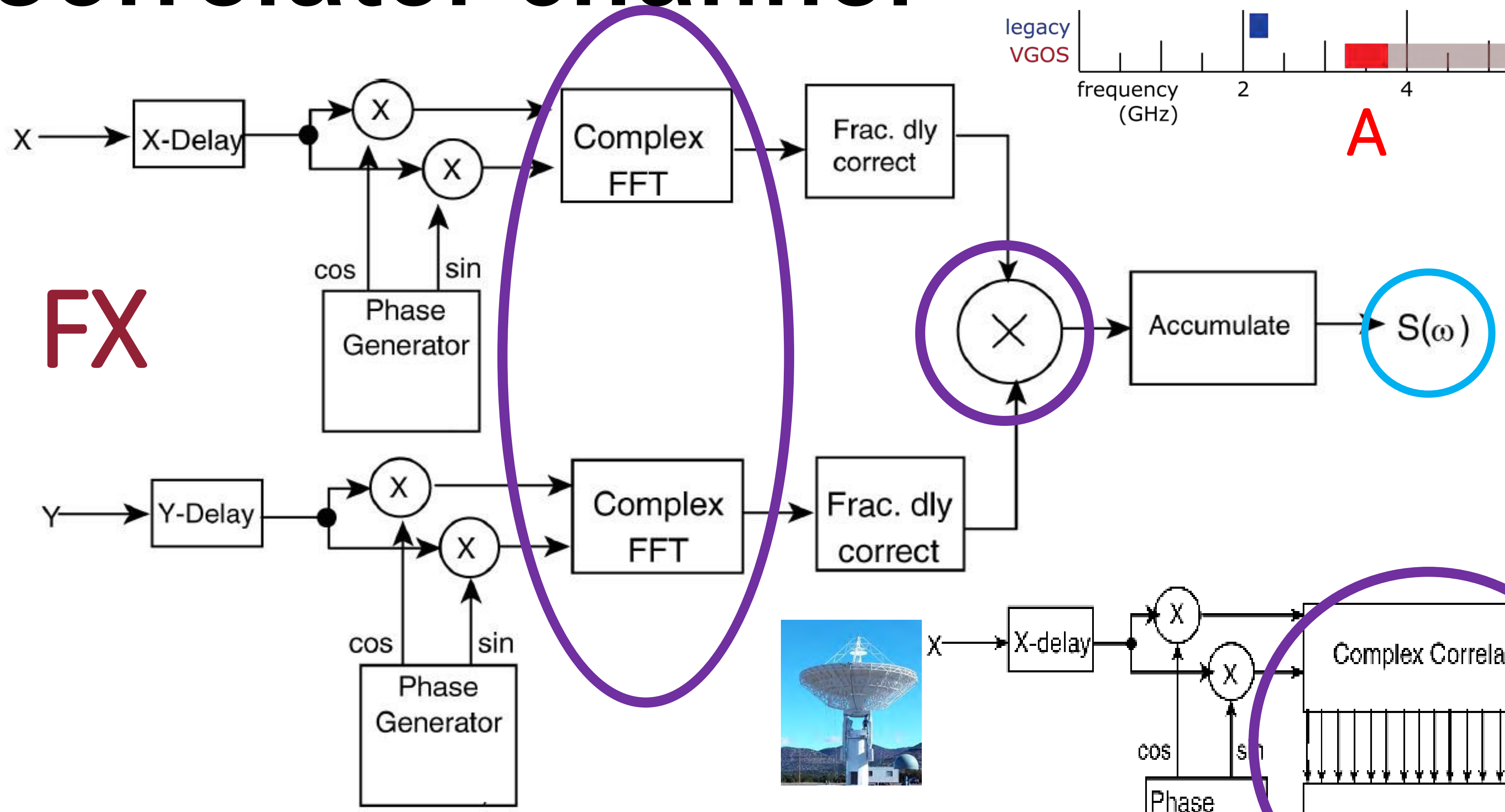
FX: First Fourier Transform

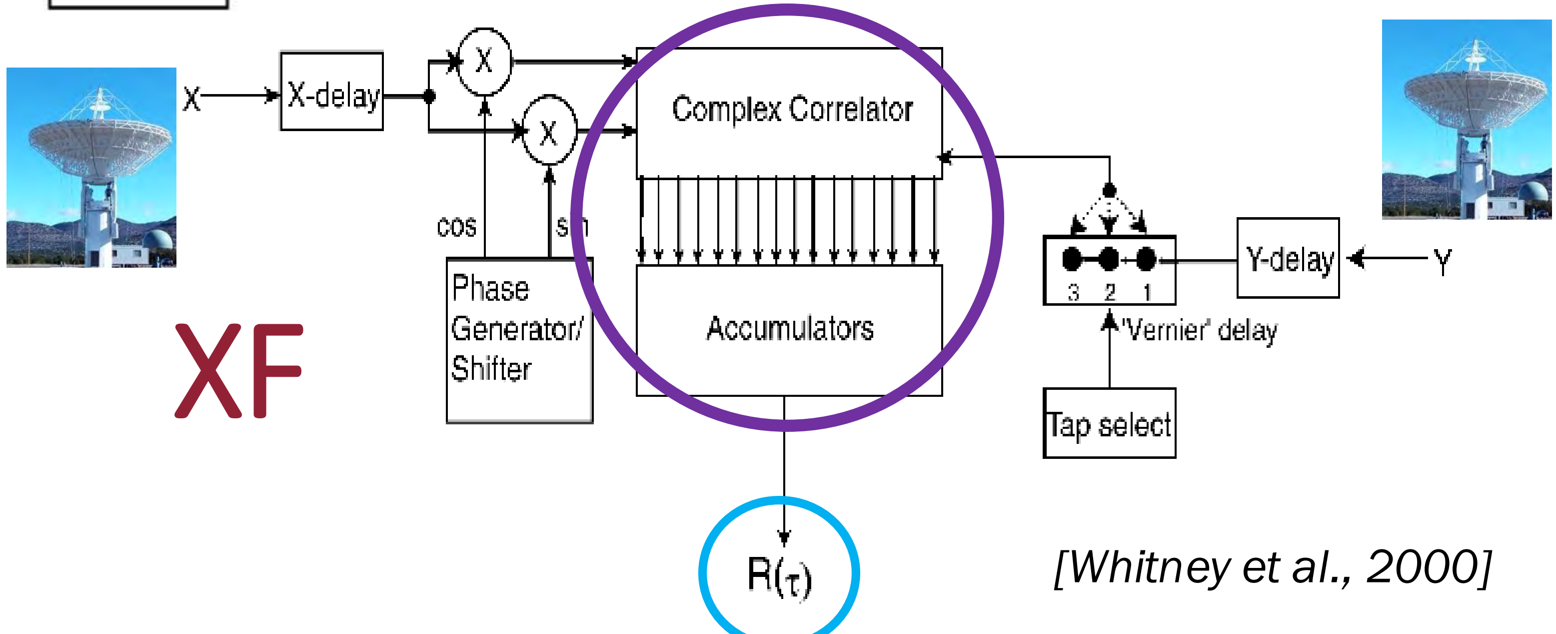
XF: First Correlation

Correlator channel

VGOS: 8 channels/band x 4 bands







[Whitney et al., 2000]

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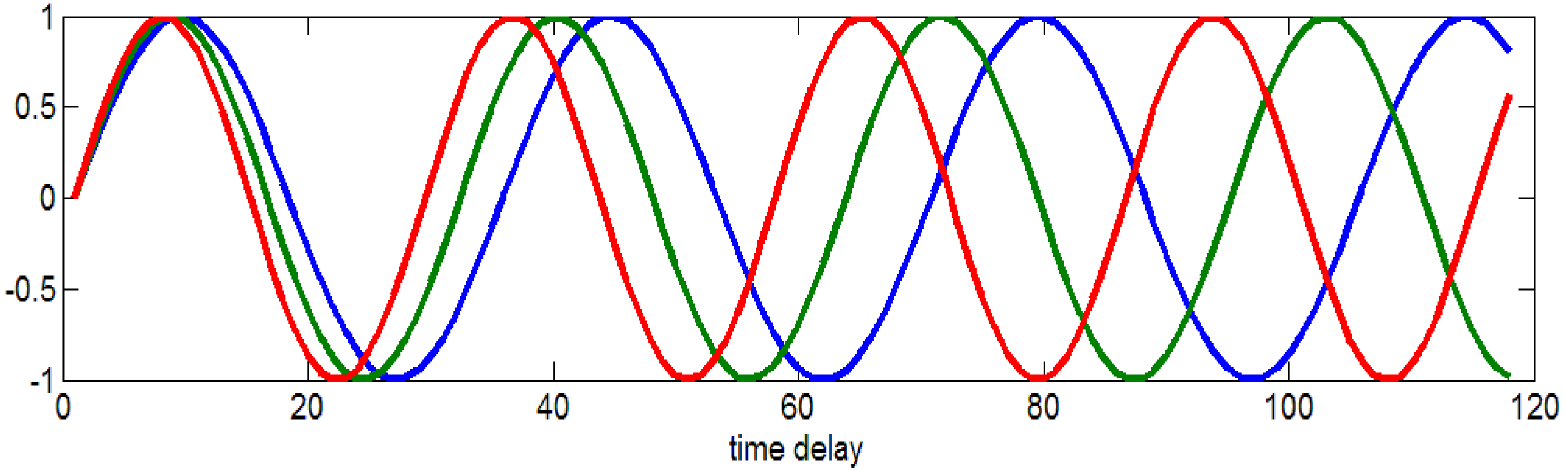
Combine channels via “bandwidth synthesis”

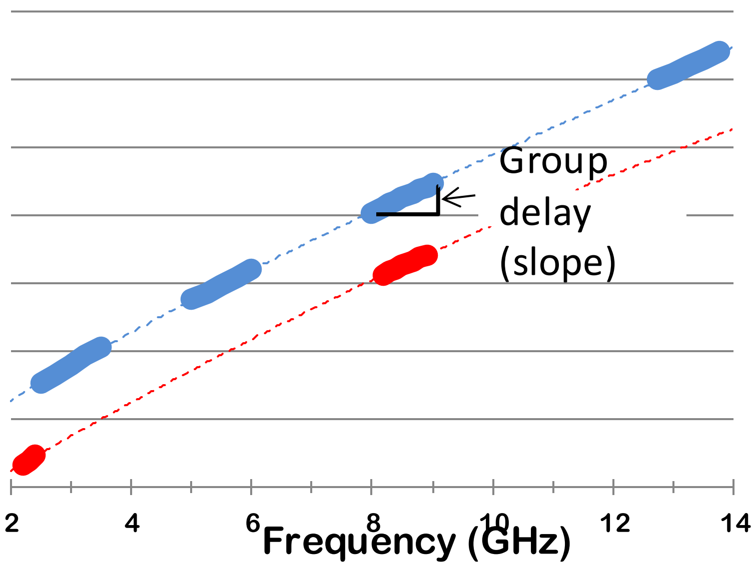
The goal is to measure the group delay, defined as dθ/dω

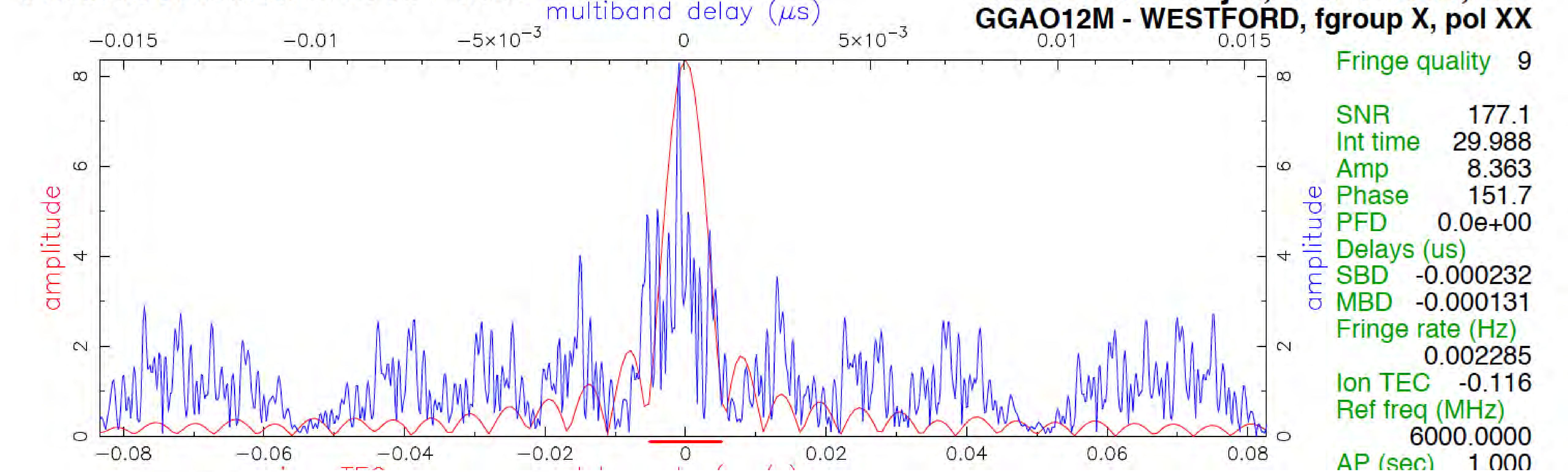
$$\phi_g = 2\pi\nu\tau_g$$

First, we must measure the observed fringe-phase difference for each of the observed frequency channels:

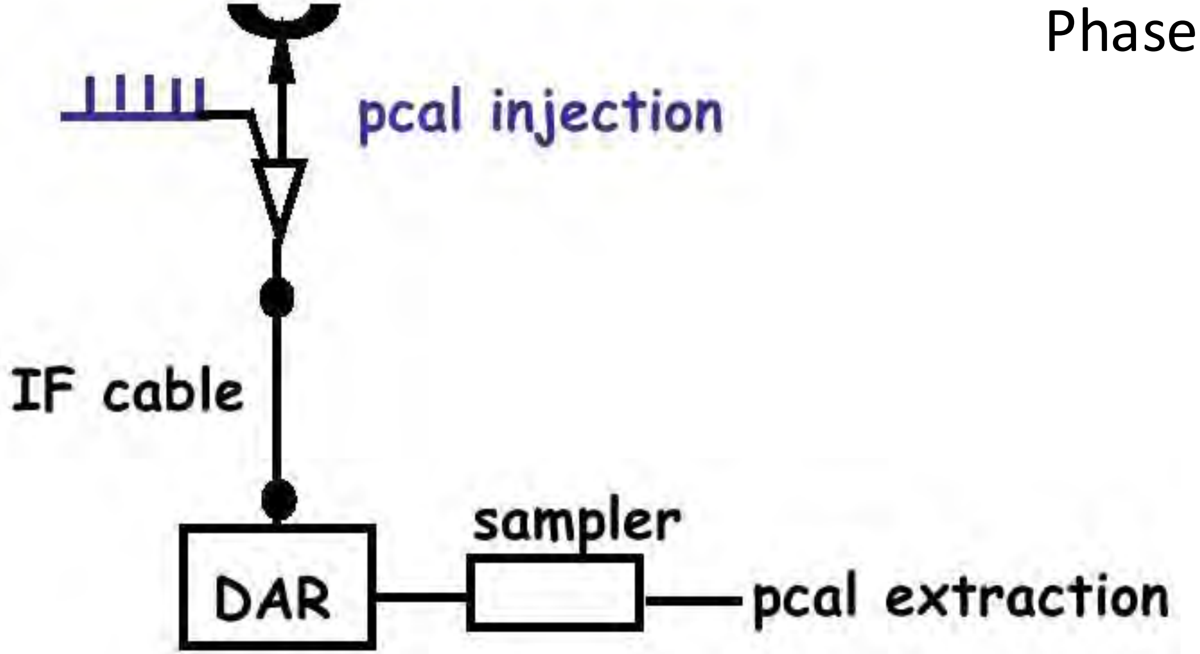
For a given delay, the higher the fringe frequency, the greater time-rate change in phase:

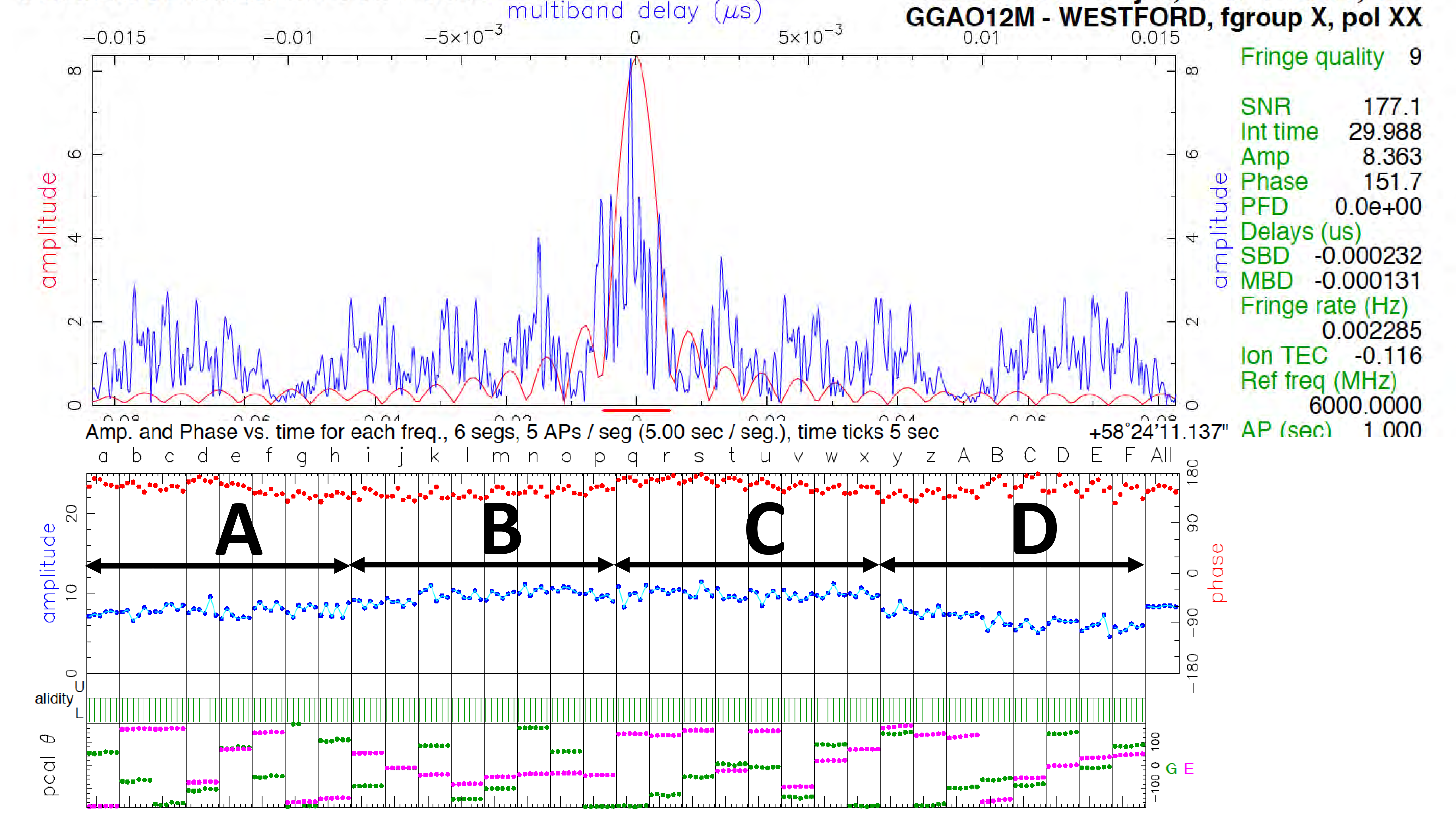






Phase and cable calibration system




GGAO12M - WESTFORD, fgroup X, pol XX
multiband delay (μs)
amplitude
Fringe quality 9
SNR 177.1
Int time 29.988
Amp 8.363
Phase 151.7
PFD 0.0e+00
Delays (us)
SBD -0.000232
MBD -0.000131
Fringe rate (Hz)
0.002285
Ion TEC -0.116
Ref freq (MHz)
6000.0000
AP (sec) 1.000
Amp. and Phase vs. time for each freq., 6 segs, 5 APs / seg (5.00 sec / seg.), time ticks 5 sec
+58˚24'11.137"
a b c d e f g h i j k l m n o p q r s t u v w x y z A B C D E F All
A
B
C
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amplitude
phase
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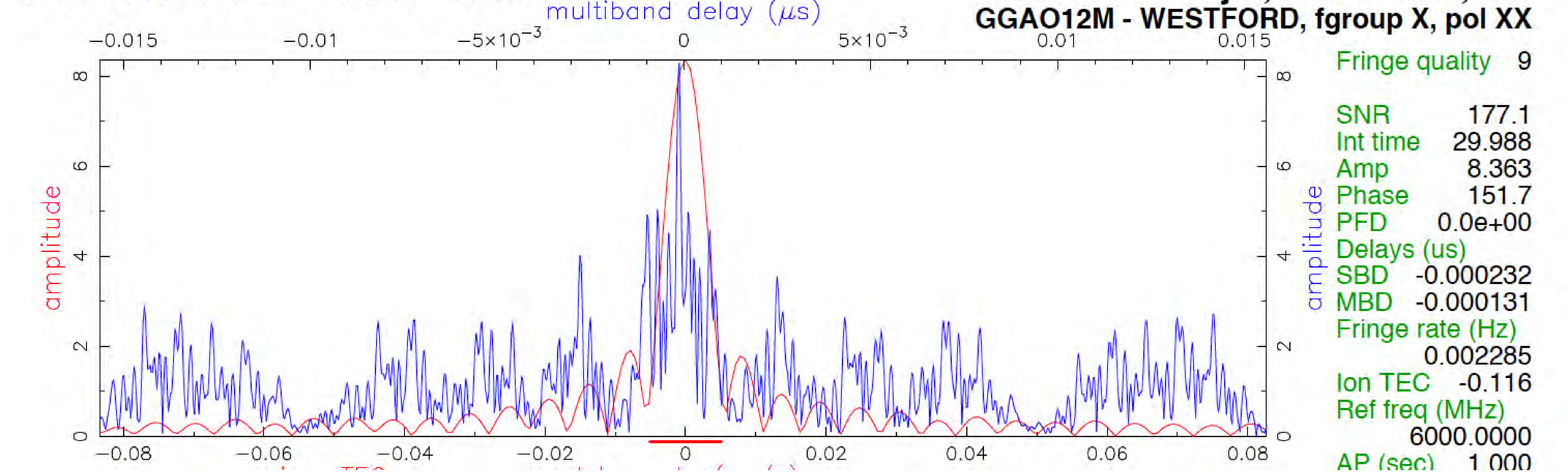

Observables for each baseline-scan:

- Correlation Amplitude
- Correlation Phase (generally 2π ambiguous)
- Total Group Delay
- Total Delay Rate

- All tied to a precise UT epoch

FRINGES !!!

High-precision geodetic science

Observation = Model + Error

$$\tau = \tau_g + \tau_{clk} + \tau_{ion} + \tau_{trop} + \tau_{inst} + \tau_{rel} + \tau_{other} + \epsilon$$

Signal (geometry => position, orientation) rest is all "**noise**"

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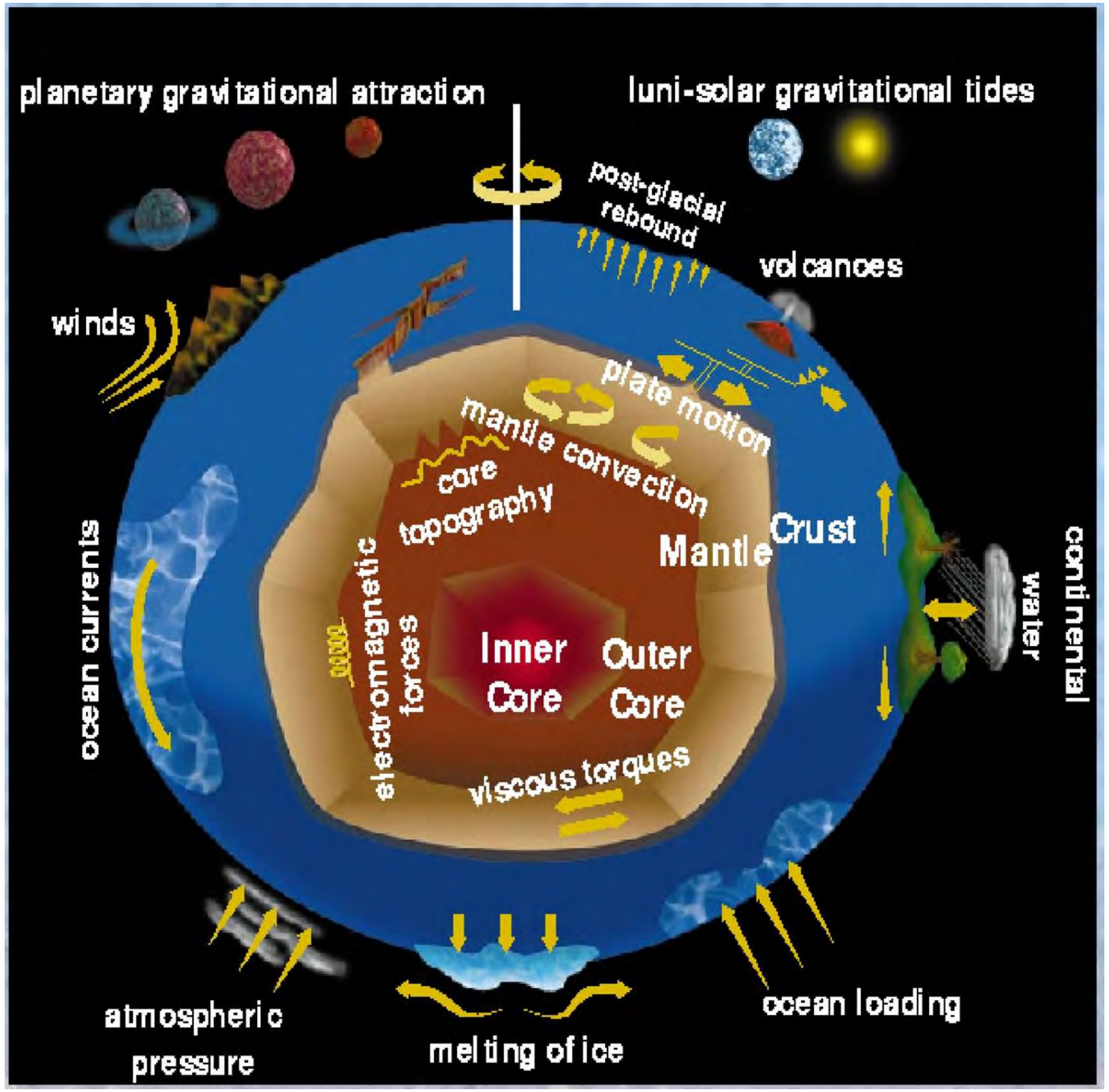
SLR

GNSS

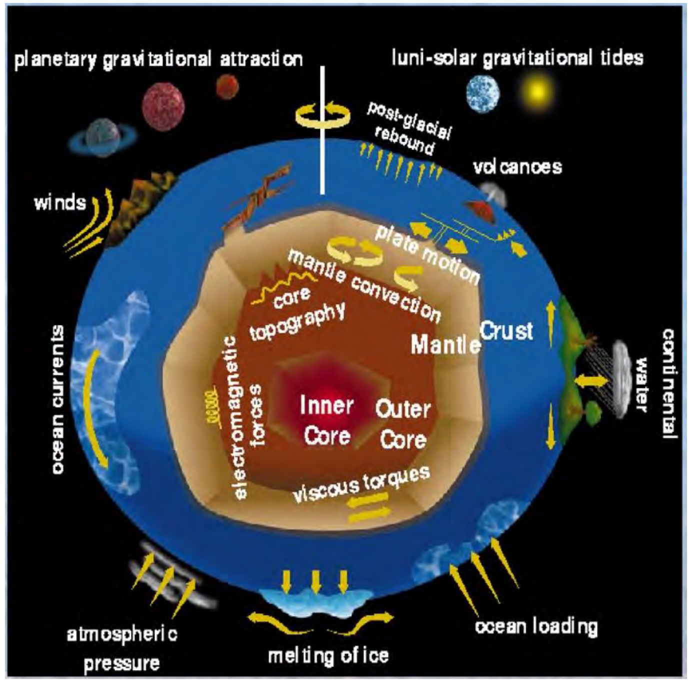
DORIS



Living on a dynamic Earth

The ensemble of observables from a session are only useful if a detailed and highly sophisticated model of the Earth and its messy motions exists

Modeling the dynamic Earth

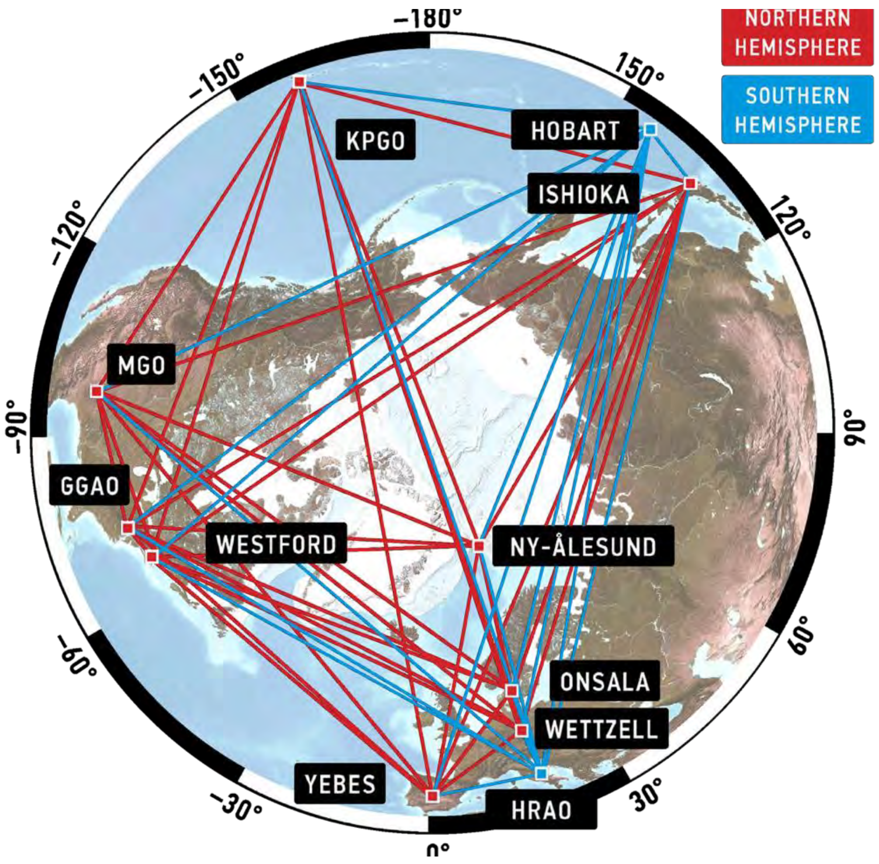


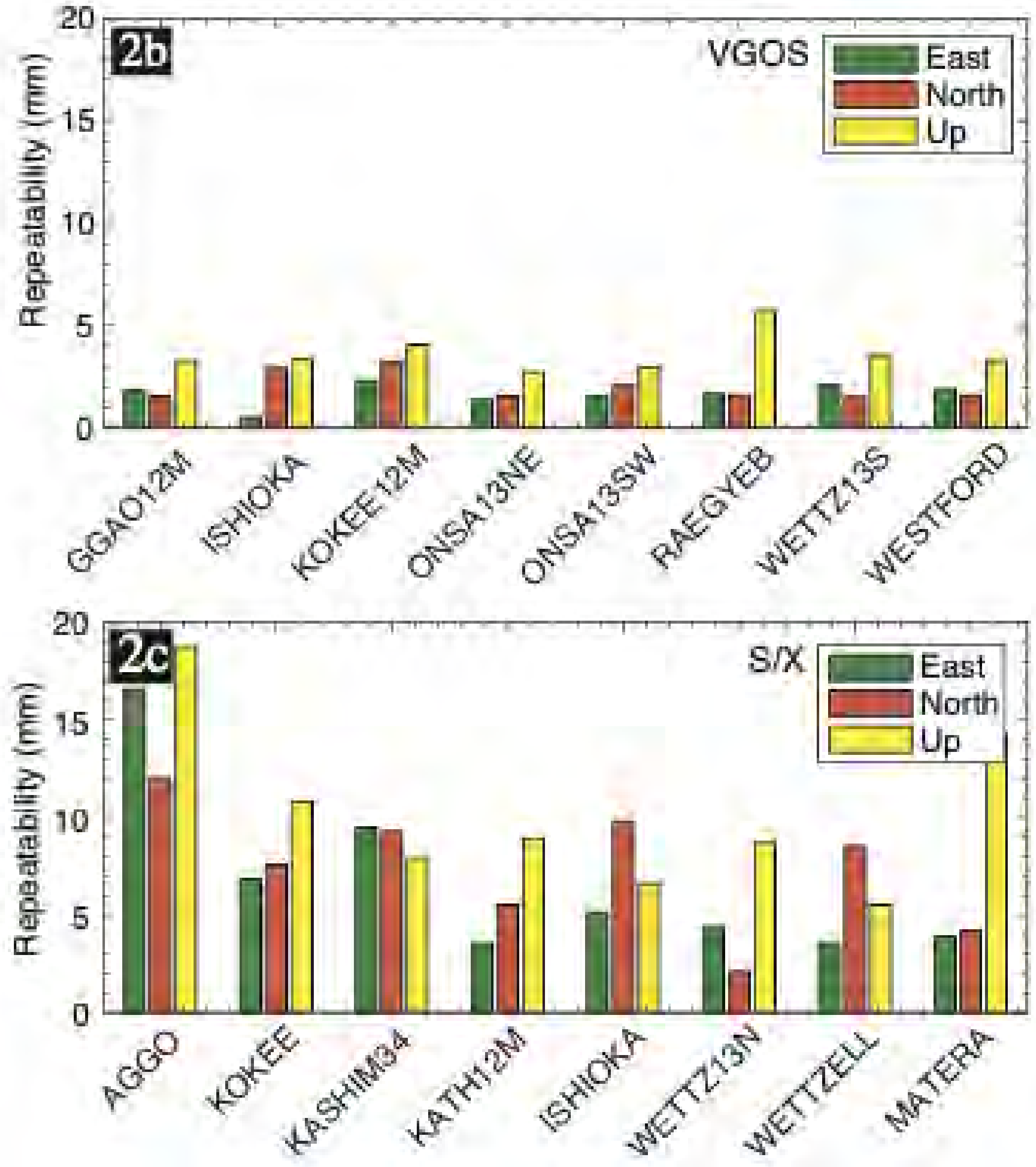
Adapted from *Sover et al., (1998)*

Item	Approx Max.	Time scale
Zero order geometry.	6000 km	1 day
Nutation	~ 20”	< 18.6 yr
Precession	~ 0.5 arcmin/yr	years
Annual aberration.	20"	1 year
Retarded baseline.	20 m	1 day
Gravitational delay.	4 mas @ 90° from sun	1 year
Tectonic motion.	10 cm/yr	years
Solid Earth Tide	50 cm	12 hr
Pole Tide	2 cm	~1 yr
Ocean Loading	2 cm	12 hr
Atmospheric Loading	2 cm	weeks
Post-glacial Rebound	several mm/yr	years
Polar motion	0.5 arcsec	~ 1.2 years
UT1 (Earth rotation)	Several mas	Various
Ionosphere	~ 2 m at 2 GHz	All
Dry Troposphere	2.3 m at zenith	hours to days
Wet Troposphere	0 – 30 cm at zenith	All
Antenna structure	<10 m. 1cm thermal	—
Parallactic angle	0.5 turn	hours
Station clocks	few microsec	hours
Source structure	5 cm	years

VGOS positioning accuracy

[Mondal et al., 2021]





MIT
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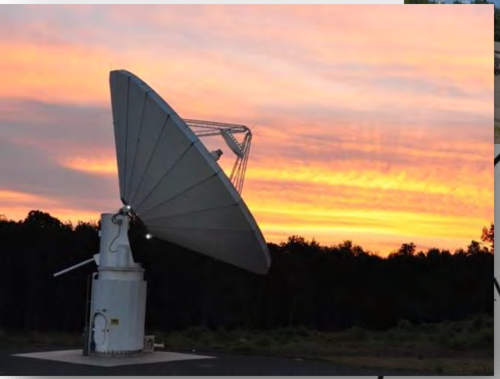
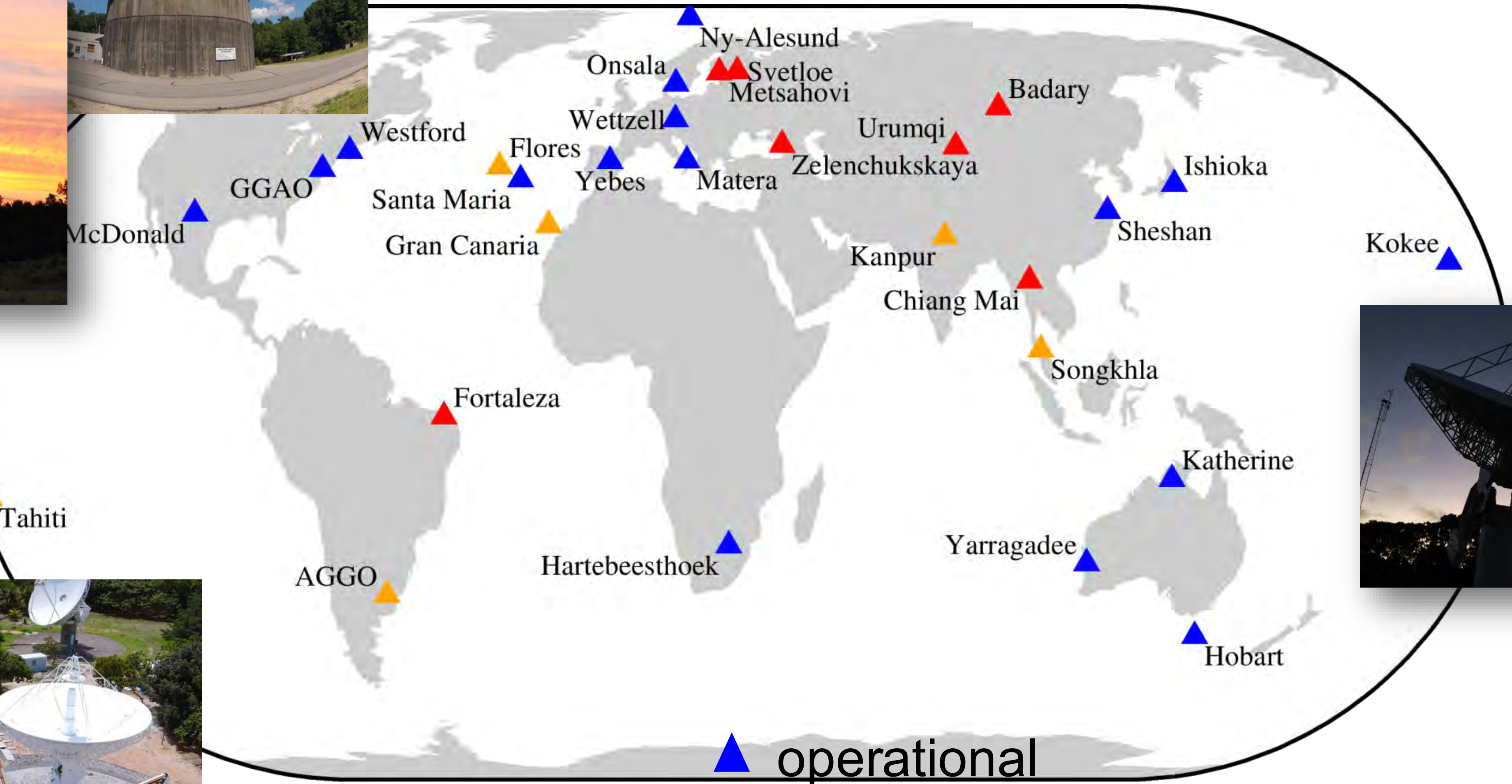
OBSERVATORY

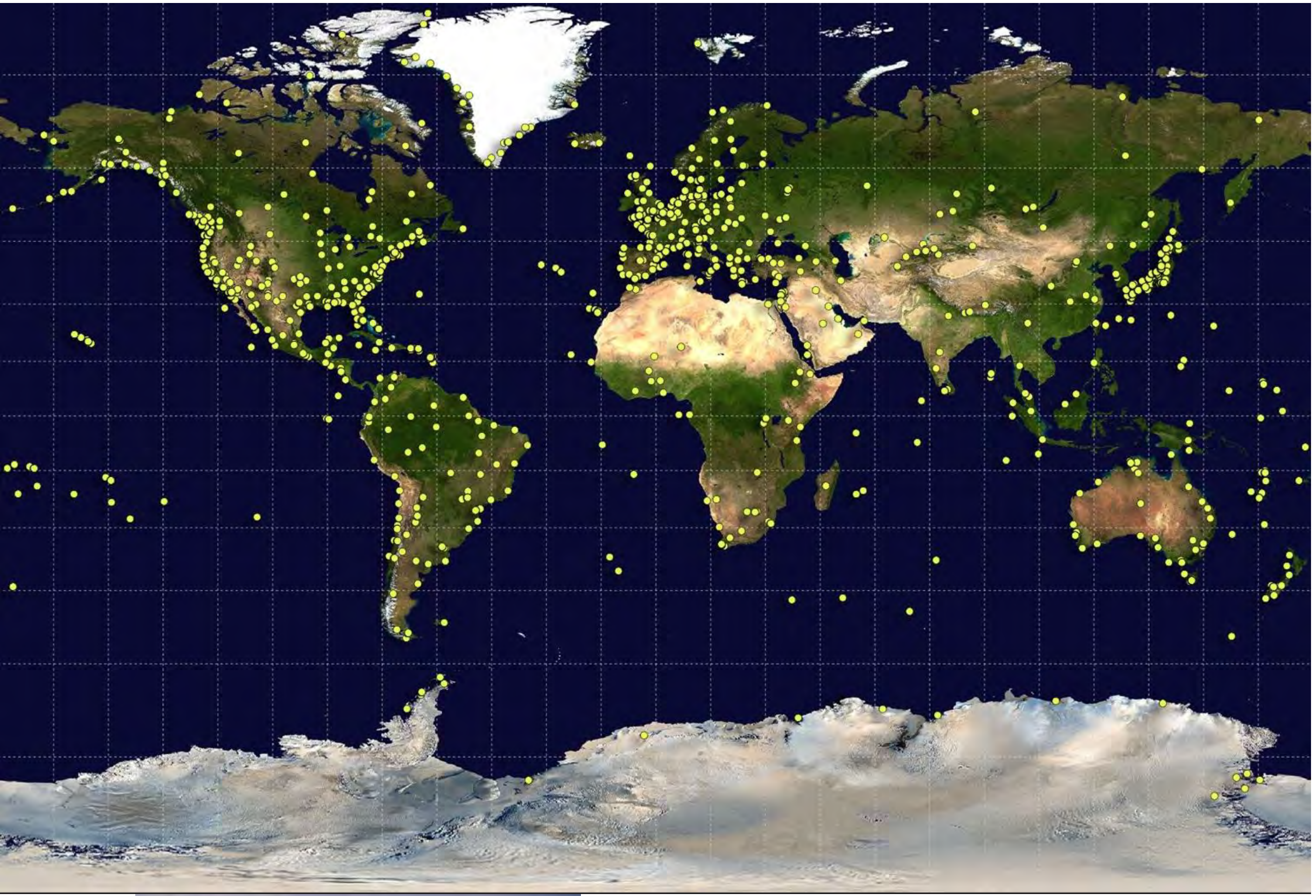
VGOS network rollout

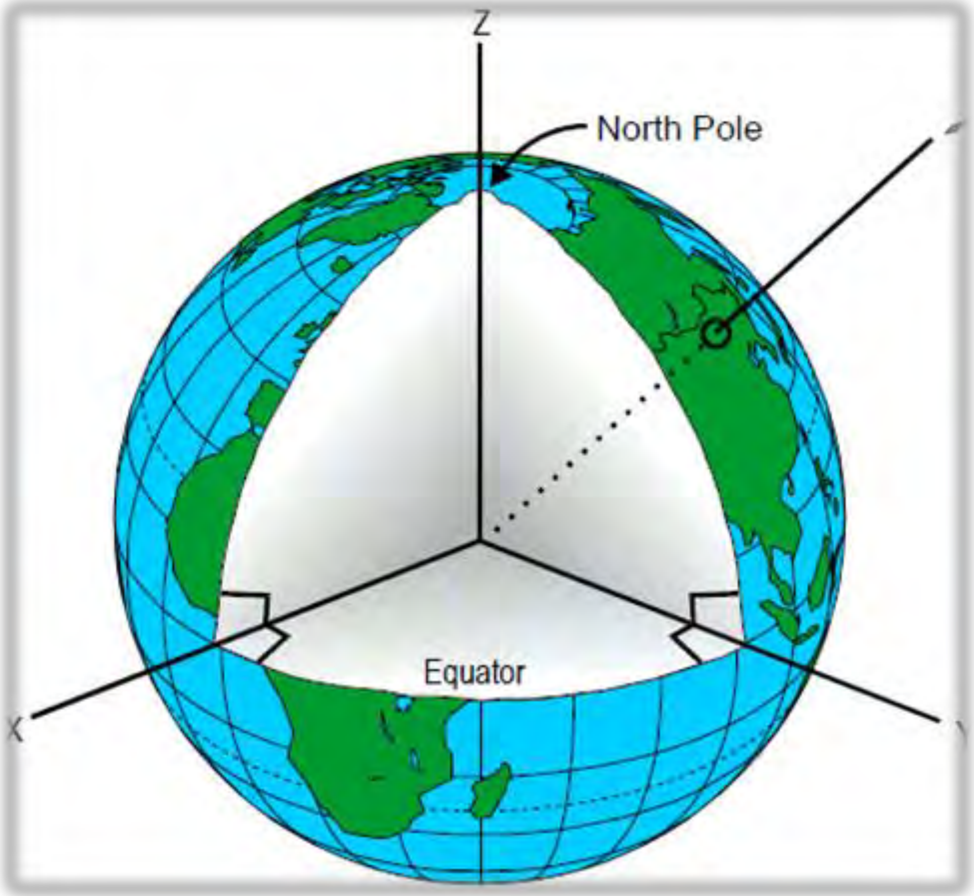




- operational
- antenna built, signal chain work
- in planning stage

Improved Terrestrial Reference Frame and EOP





VLBI

SLR

GNSS

DORIS

In summary

- WHY we do VLBI/VGOS
  - Climate change is the defining challenge of our time
- HOW we do it
  - Geodetic radio telescopes
  - VLBI vs. GPS concept
  - Station requirements
  - VLBI digitization
  - Correlation
  - Geodetic post-processing and VGOS precision

And that's pretty much it for today

IVS Technical Operations Workshop

TOW 2025

MIT Haystack Observatory

May 4-8, 2025

Have a wonderful TOW week!