VLBI/VGOS Basics

Pedro Elosegui, MIT Haystack Observatory

With big thanks to very many of you "out there"

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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

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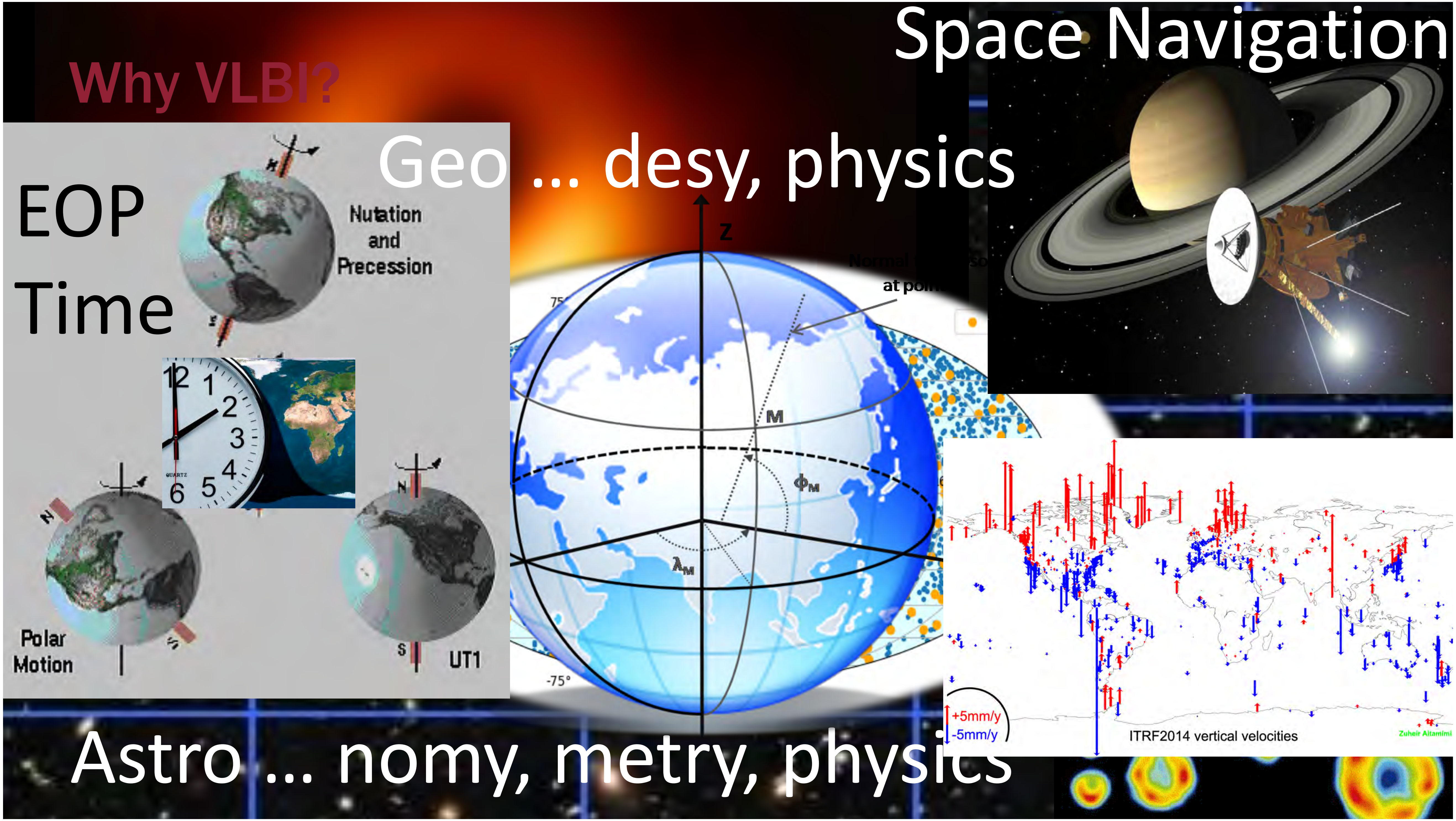
Why VLBI?
Space Navigation
Geo … desy, physics
EOP
Time
Nutation and Precession
Polar Motion
UT1
Z
M
ΦM
λM
-75°
+5mm/y
-5mm/y
ITRF2014 vertical velocities
Astro … nomy, metry, physics

Why VLBI?

CLIMATE CHANGE IS THE DEFINING CHALLENGE OF OUR TIME

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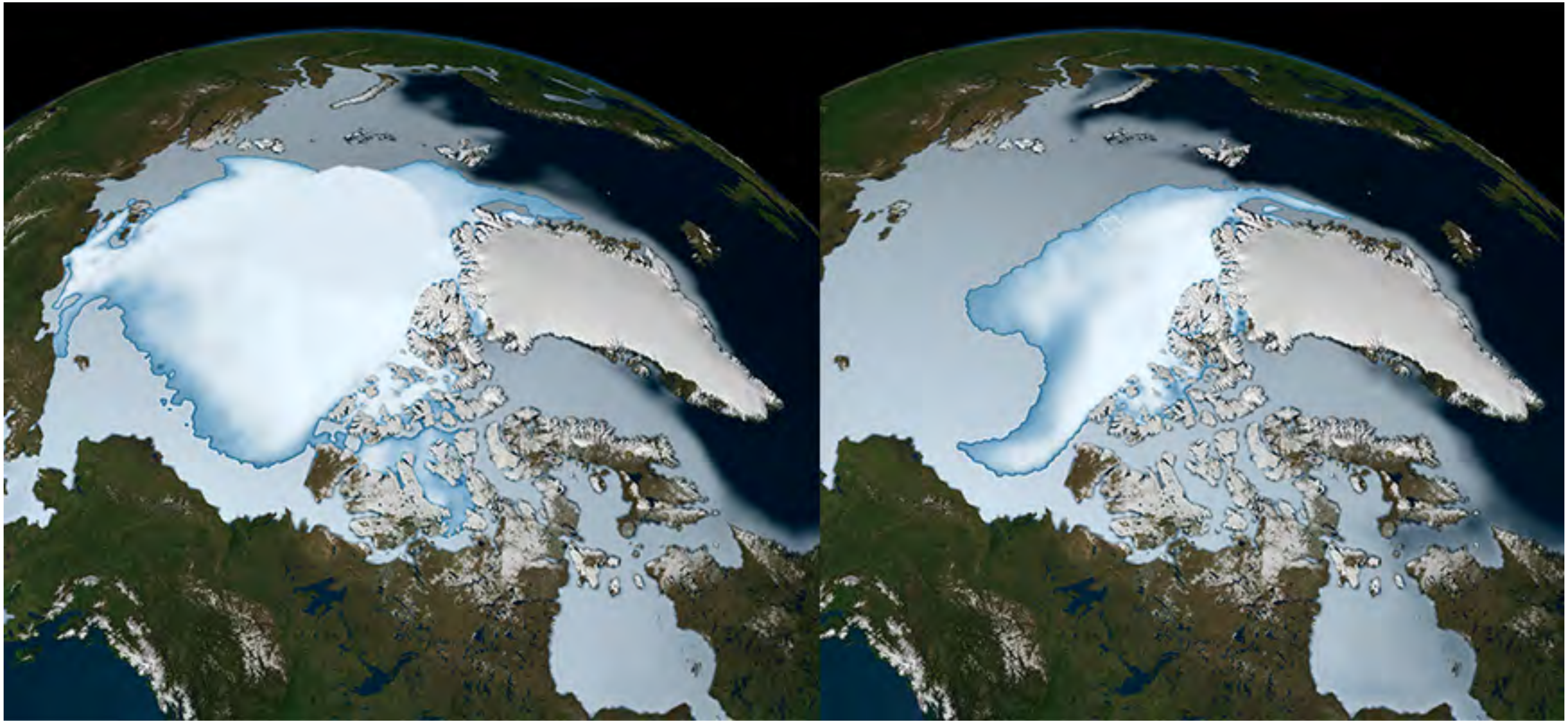
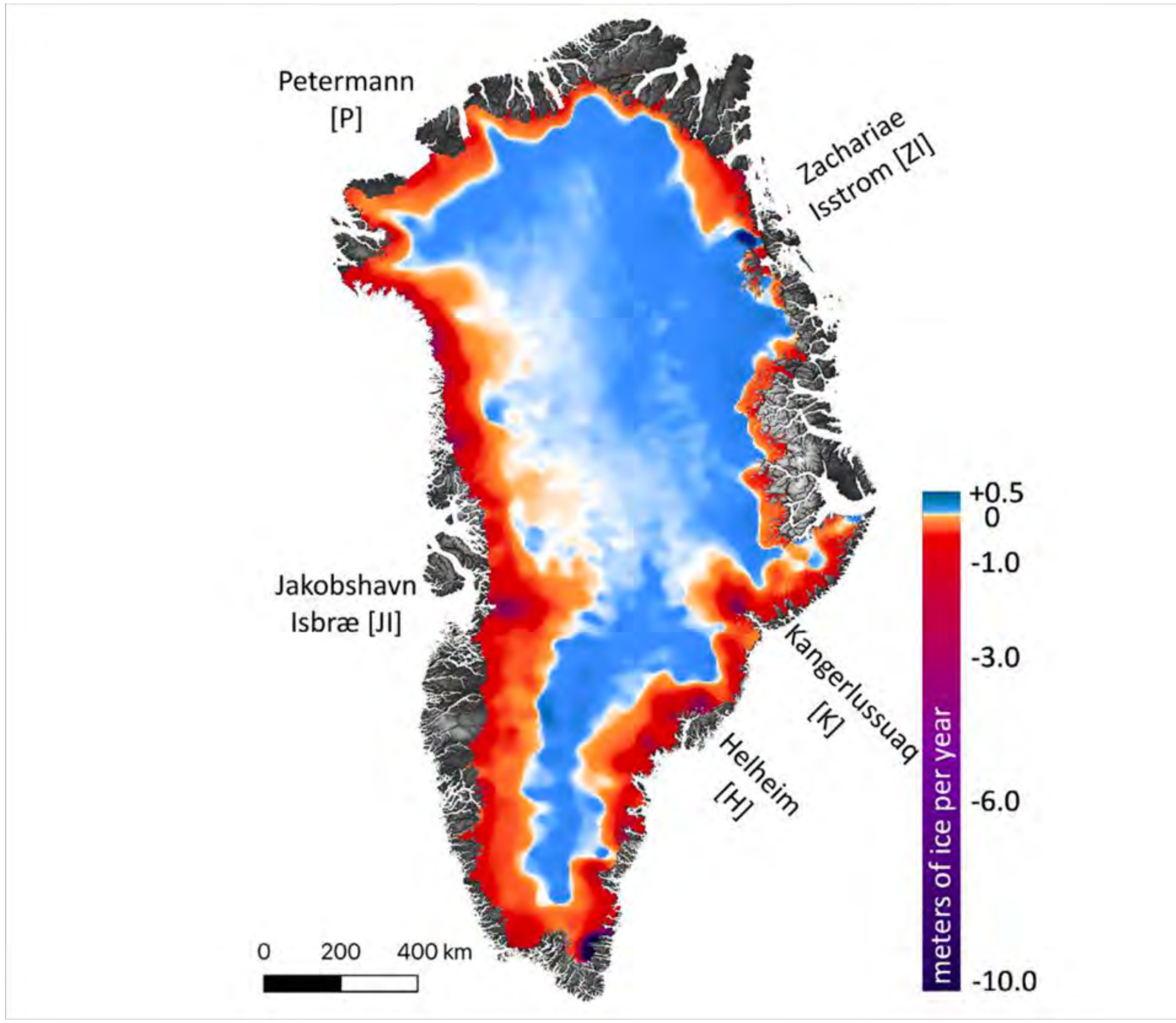
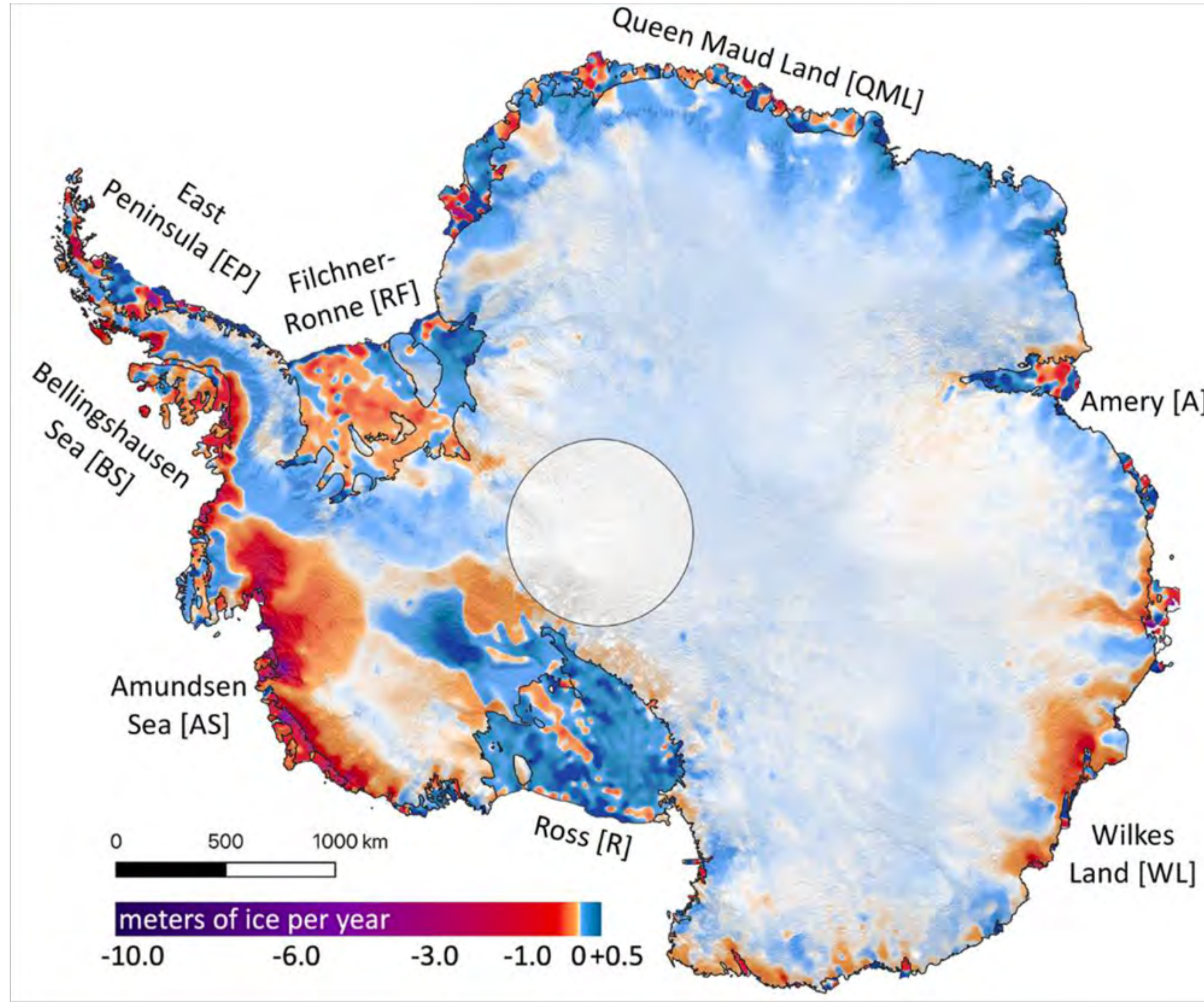
Rapid polar changes: Arctic sea ice loss



[NSIDC/NASA]

Rapid polar changes: Ice sheet mass loss

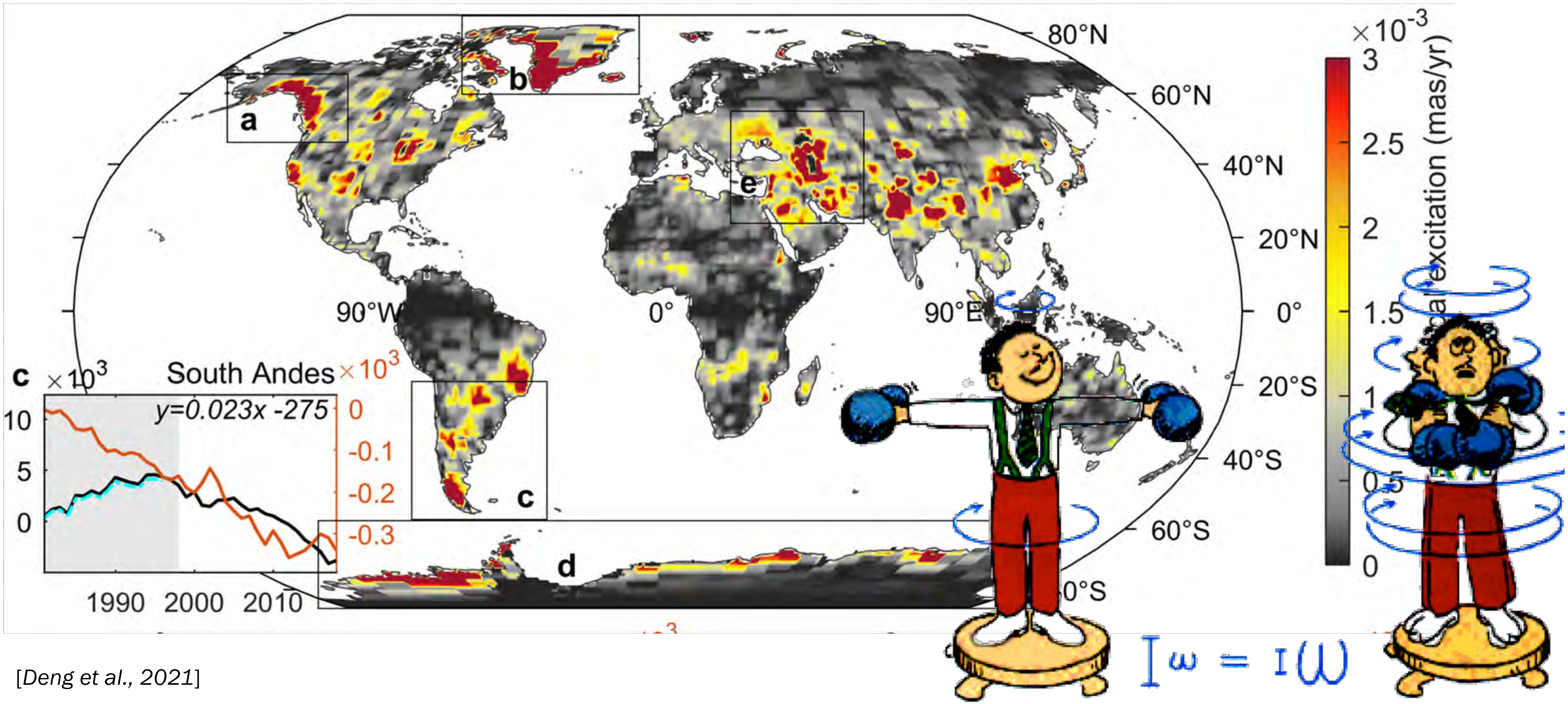




[*Smith et al., 2020*]

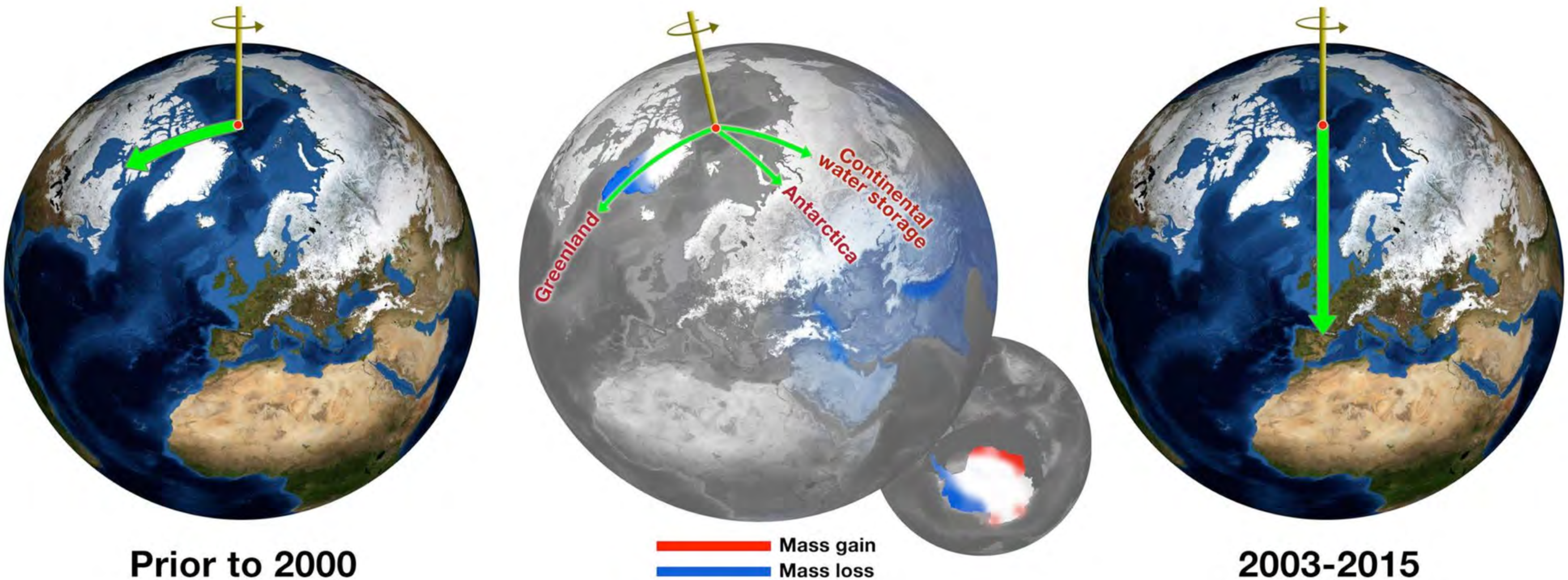

Balog

Rapid terrestrial water storage changes since 2000



[*Deng et al., 2021*]

Rapid polar motion changes since 2000

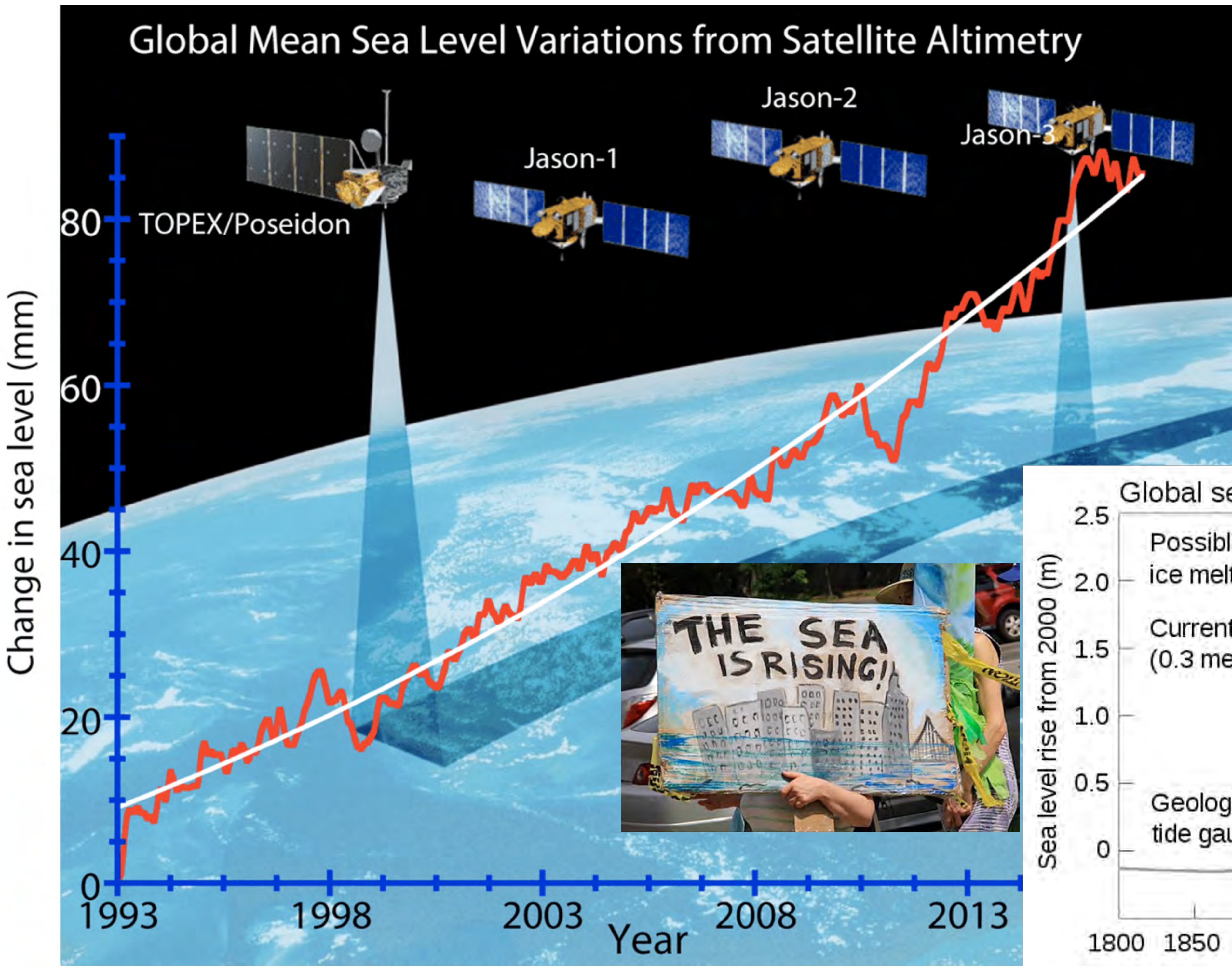


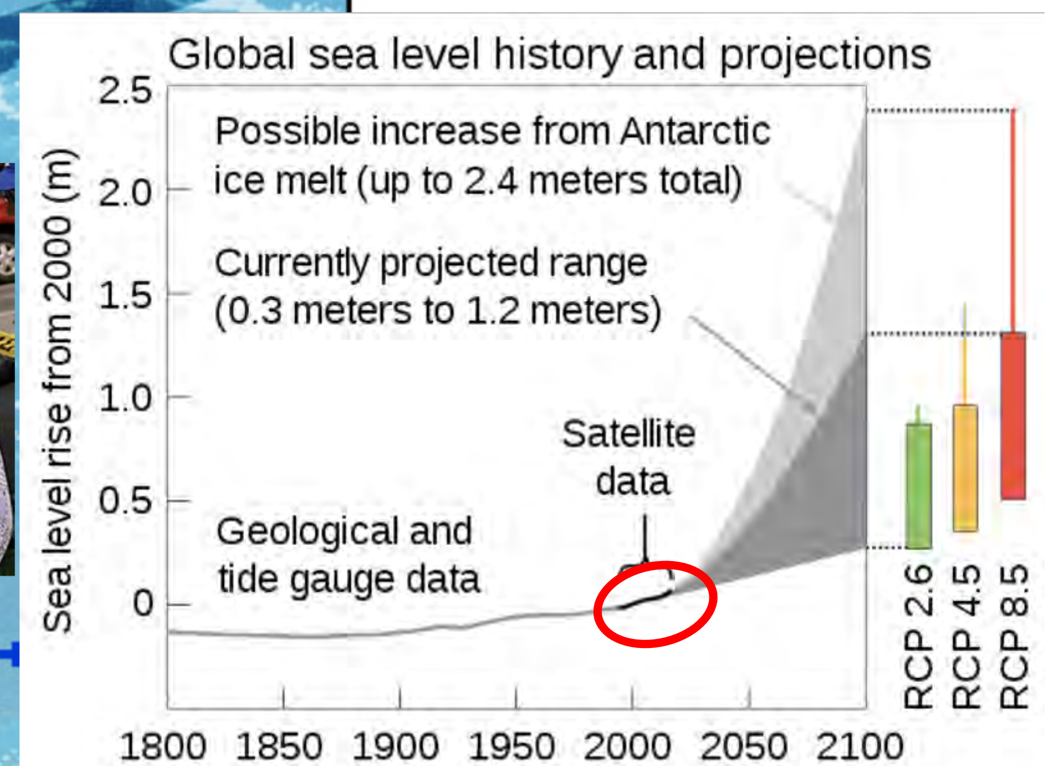
Prior to 2000

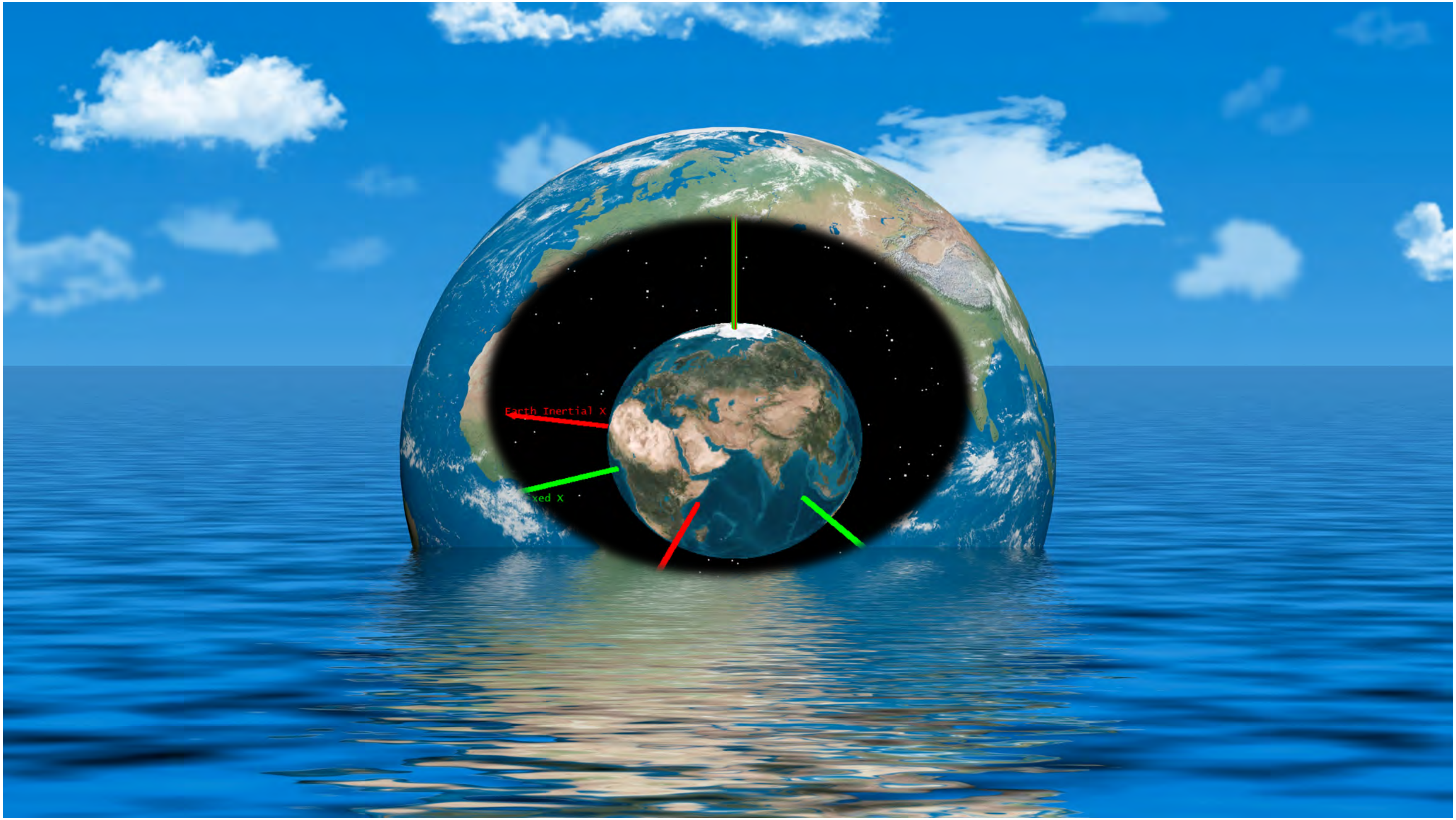
2003-2015

[*Adhikari et al., 2016*]

Rapid global sea level rise






Earth Inertial X

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

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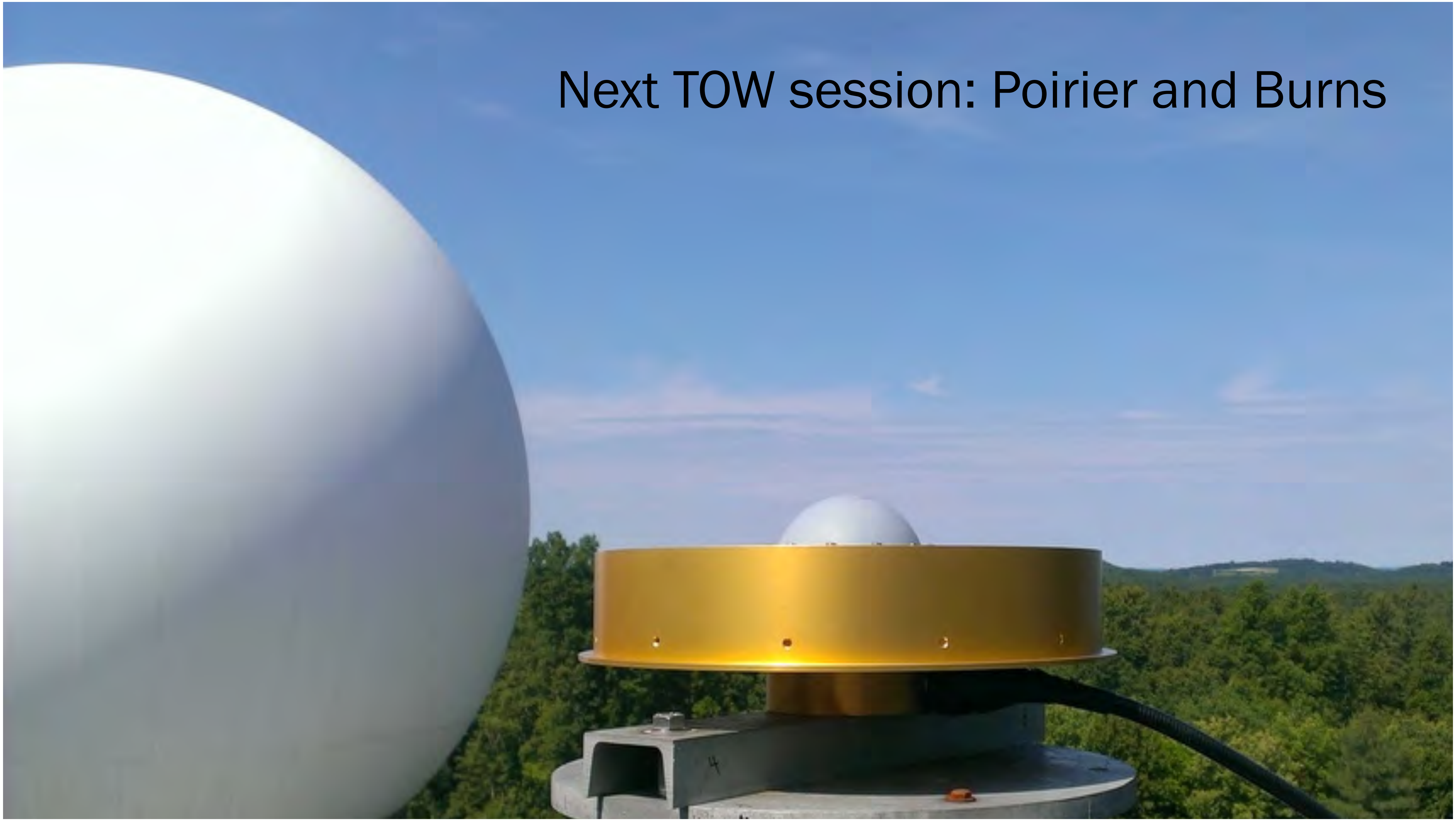
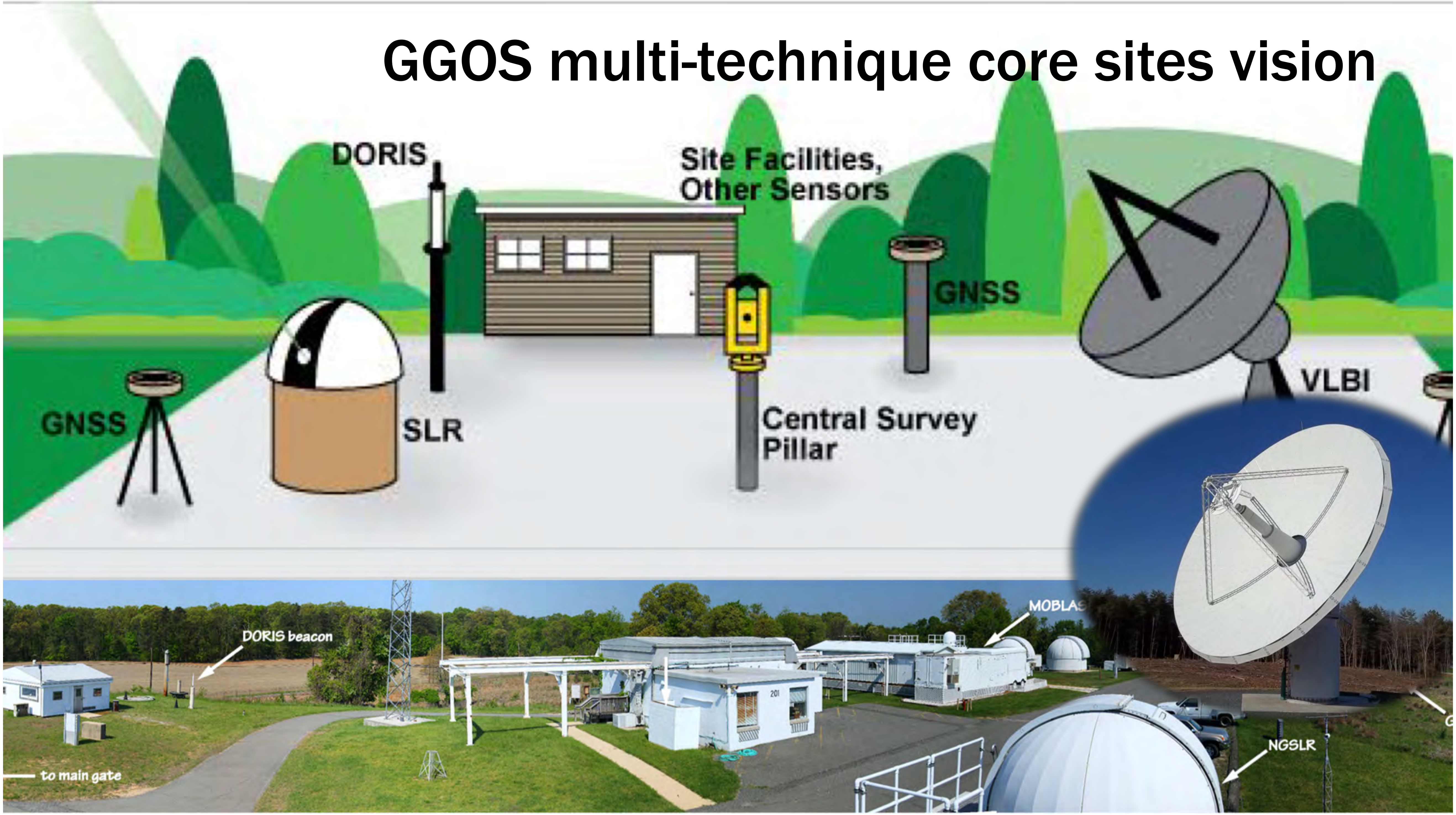
WESTFORD RADIO
GPS

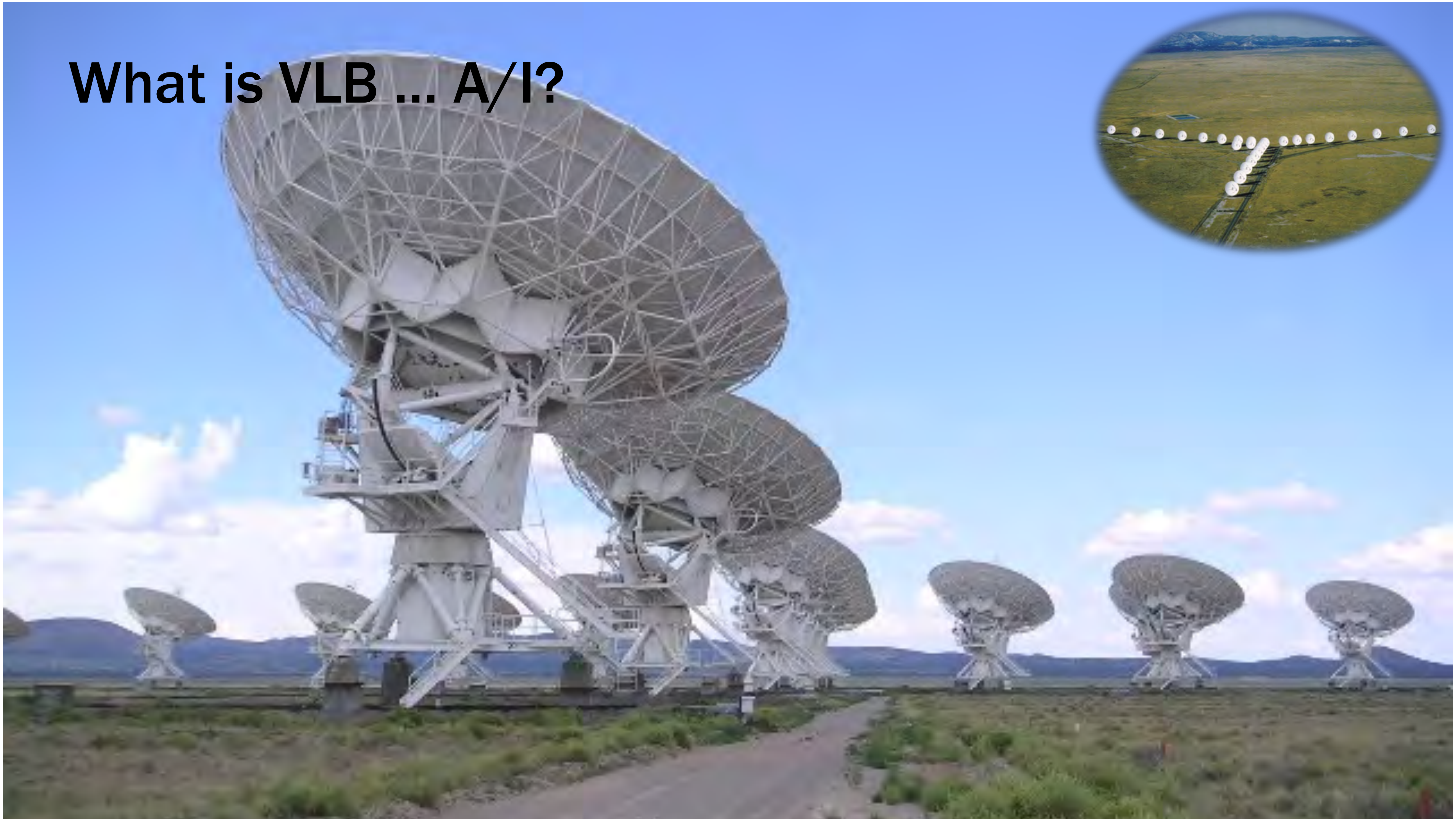
Next TOW session: Poirier and Burns



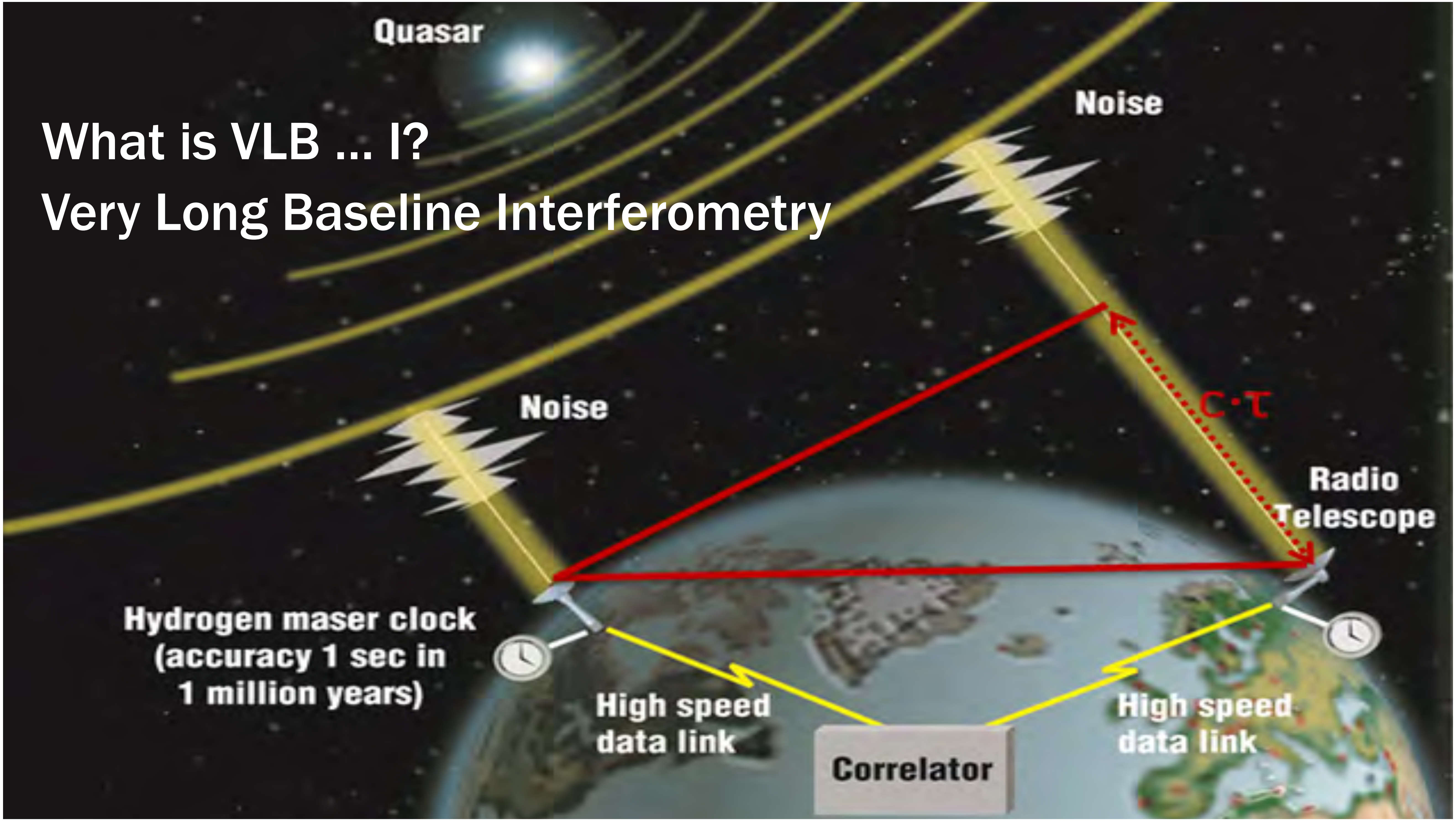
GGOS multi-technique core sites vision



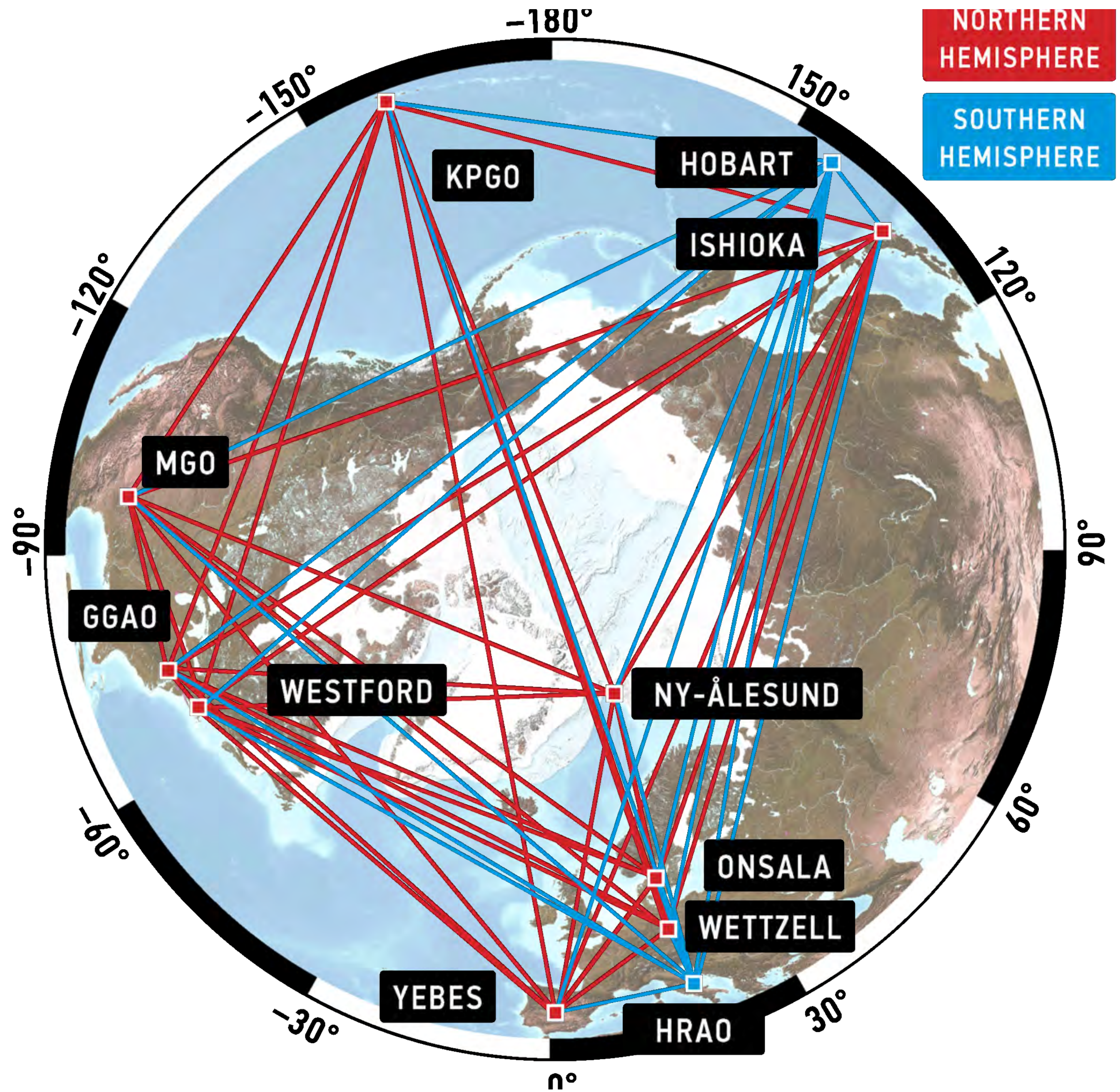
What is VLB … A/I?



What is VLB … I?
Very Long Baseline Interferometry

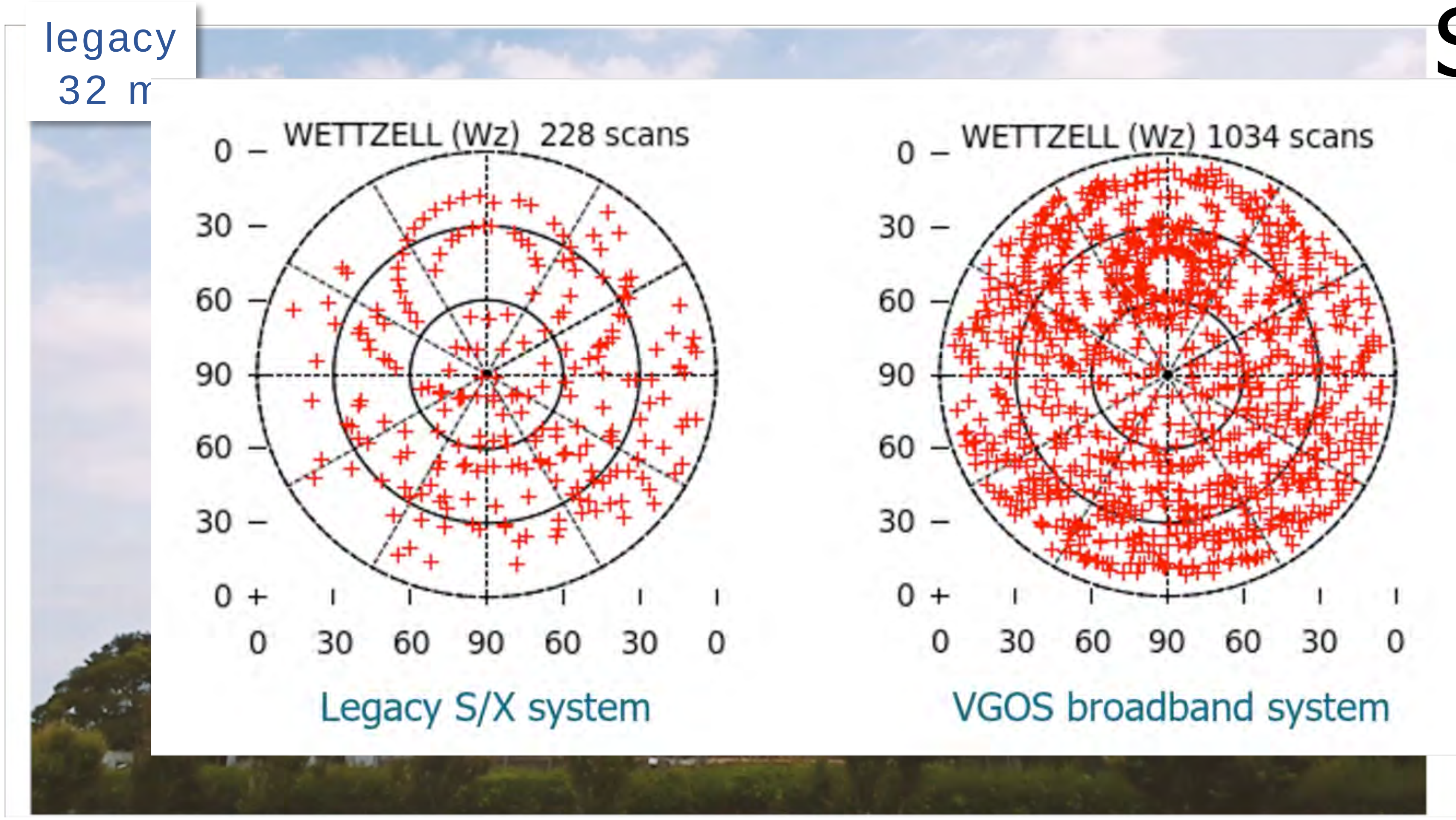


VLBI Global Observing System (VGOS) “today”



See TOW session: Behrend

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

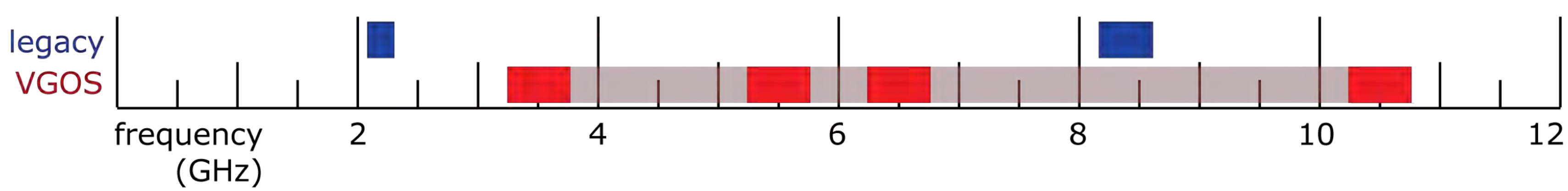


Small, fast, rigid

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

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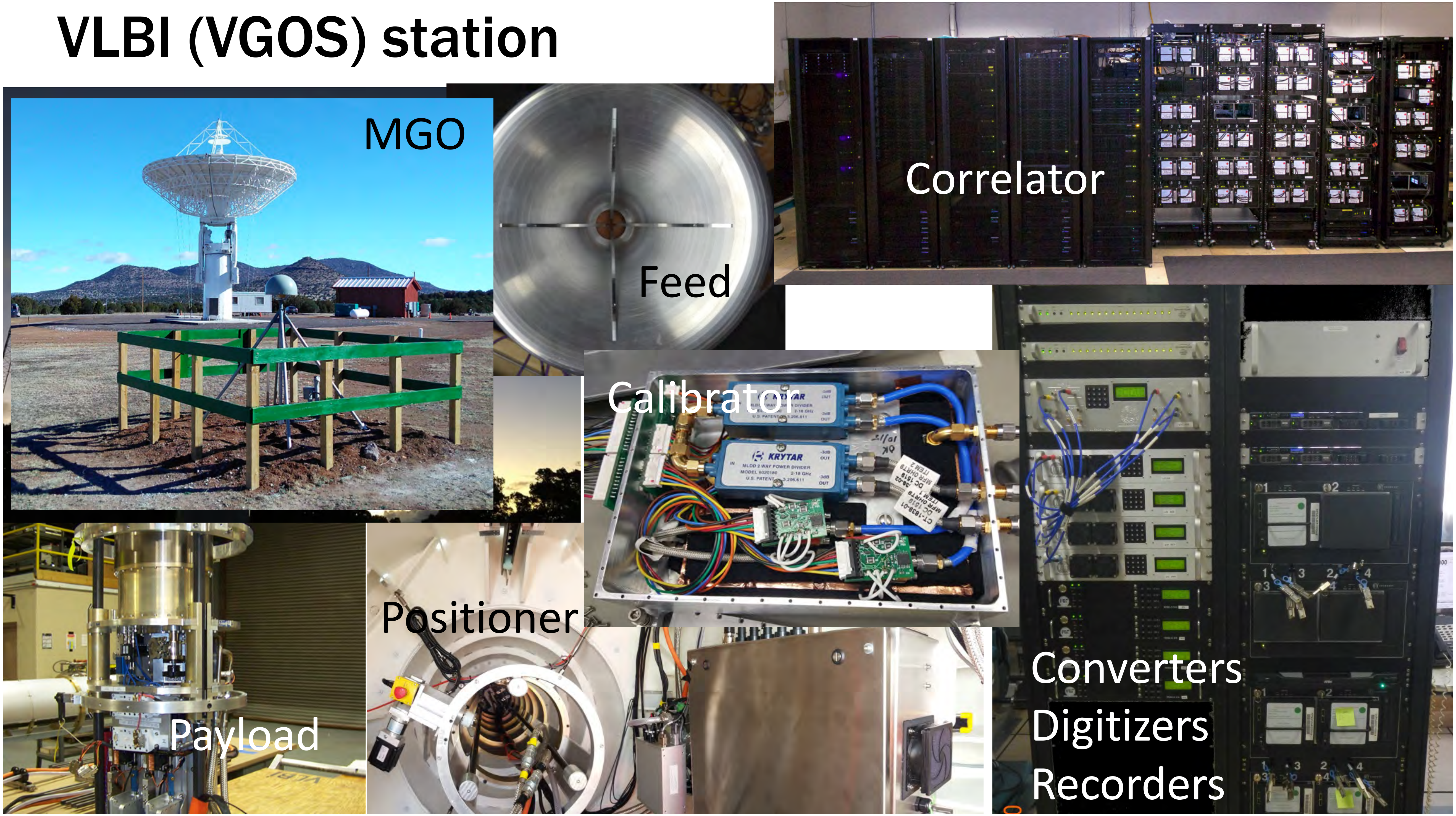
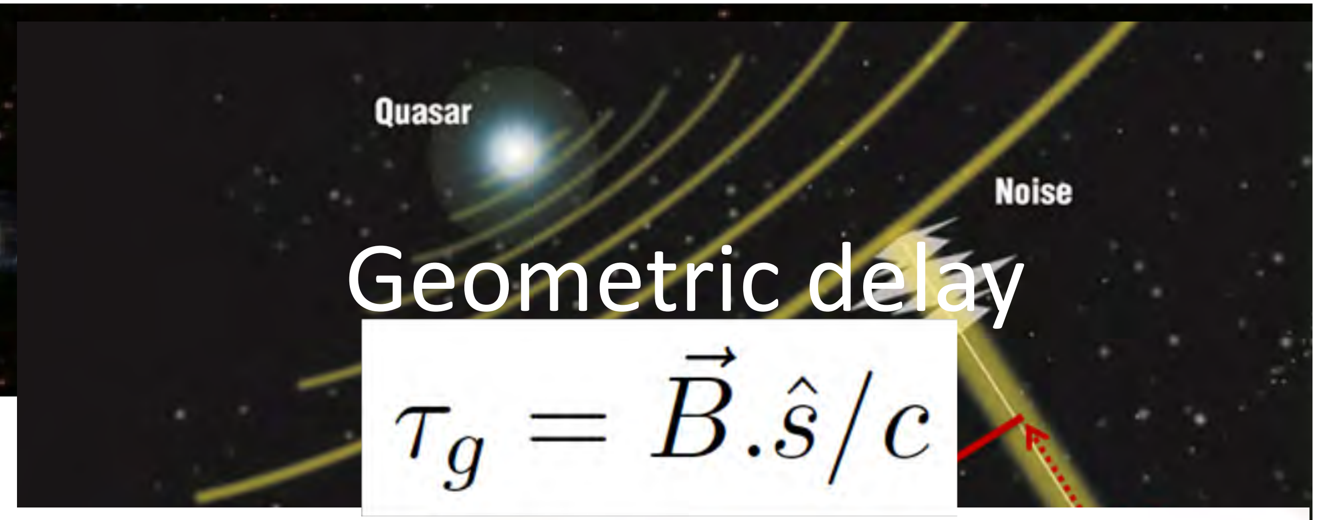
VLBI (VGOS) station



The Geodetic Measurement

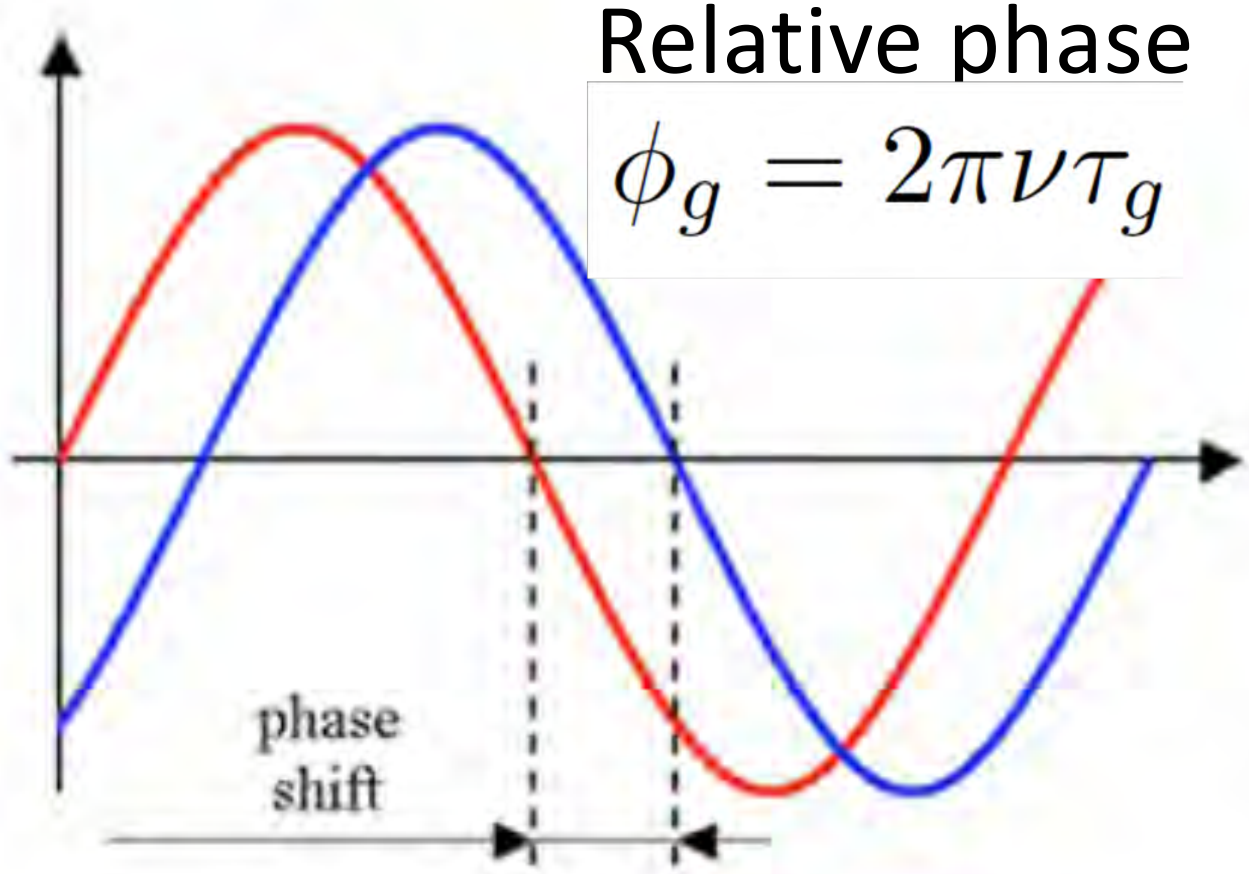


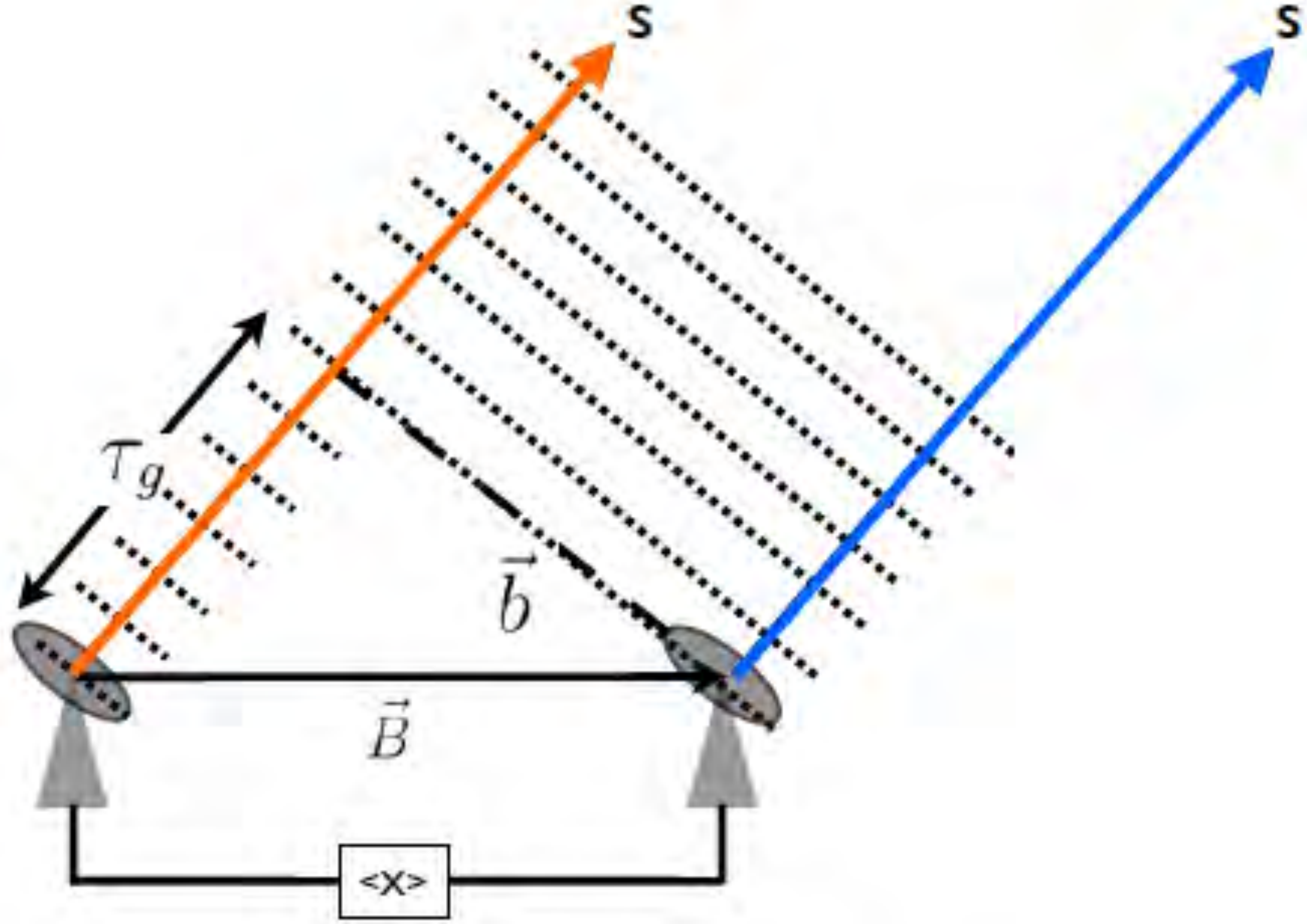
Geometric delay

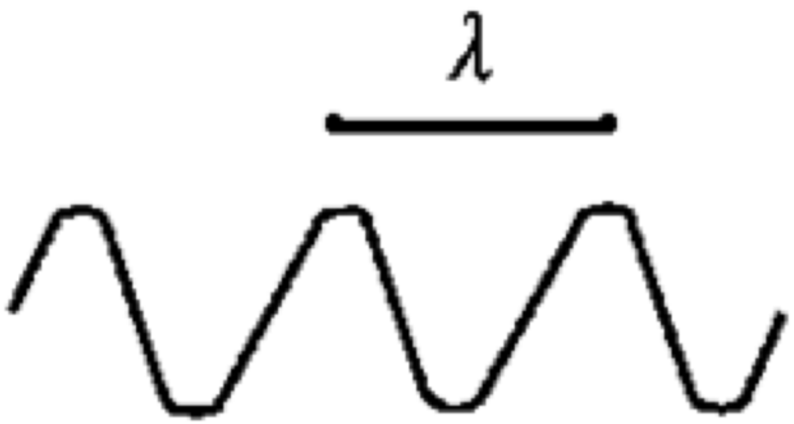
$$\tau_g = \vec{B}.\hat{s}/c$$

Relative phase

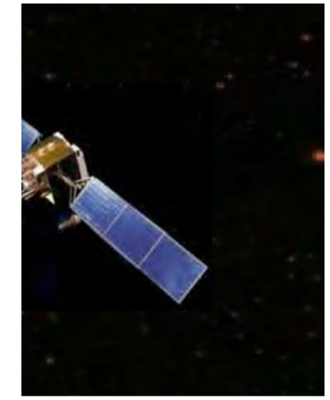
$$\phi_g = 2\pi\nu\tau_g$$

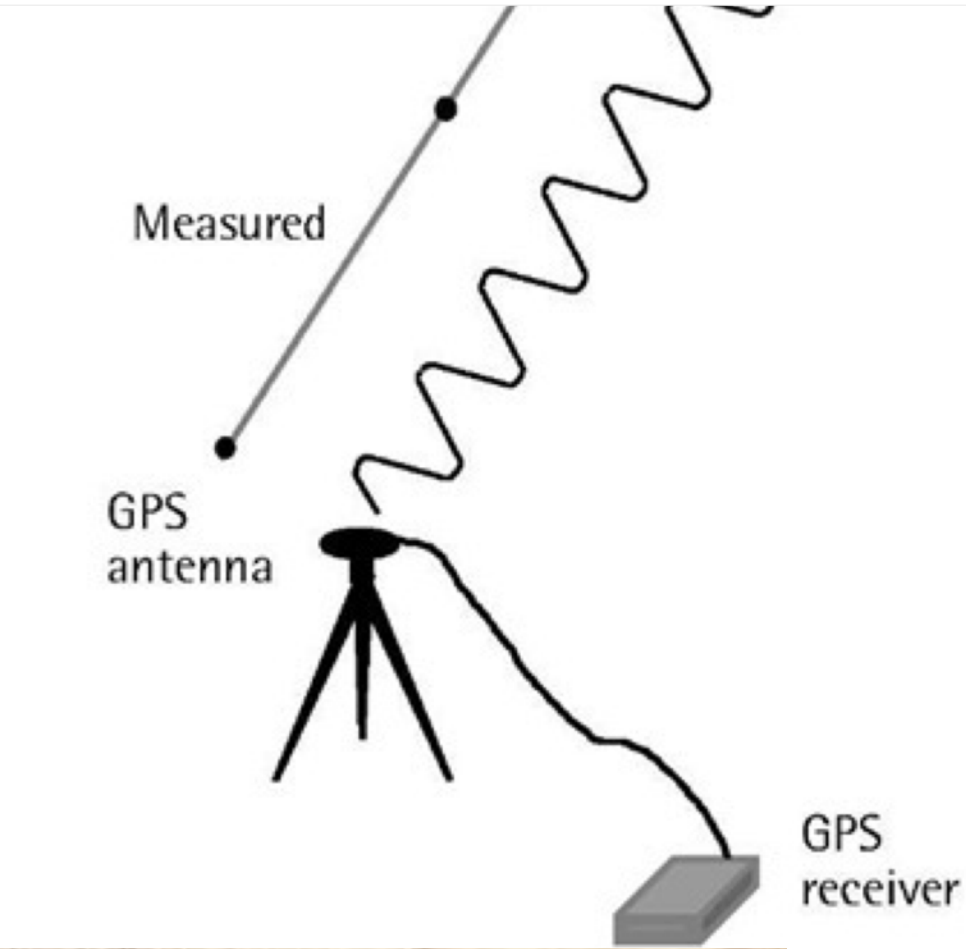


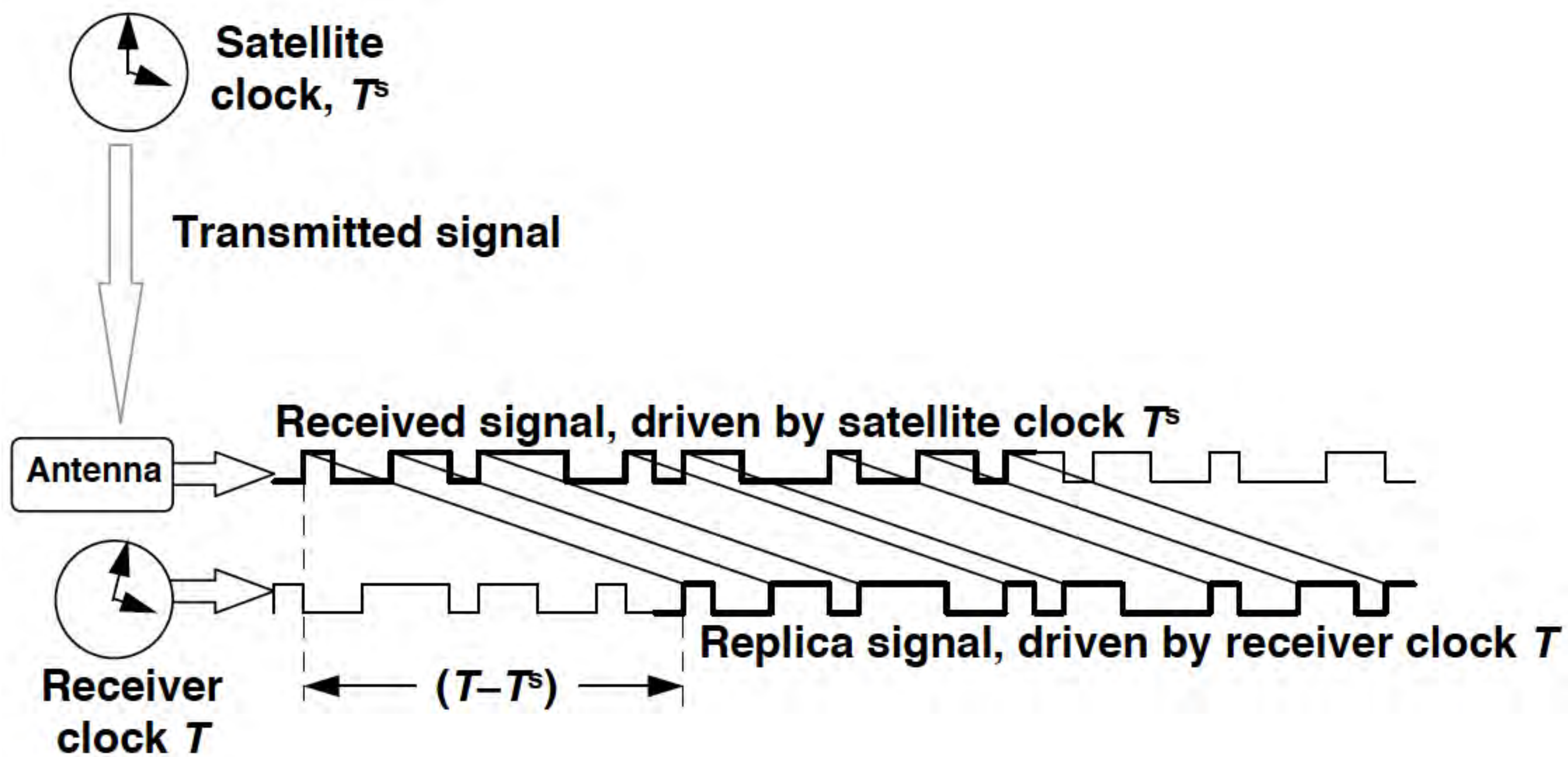



λ


1
0
0000111010011010001111100110...




Measured
GPS antenna
GPS receiver


Satellite clock, T^s
Transmitted signal
Received signal, driven by satellite clock T^s
Antenna
Replica signal, driven by receiver clock T
Receiver clock T
$(T-T^s)$

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)

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

See TOW session: Lindqvist, Varenius

- 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

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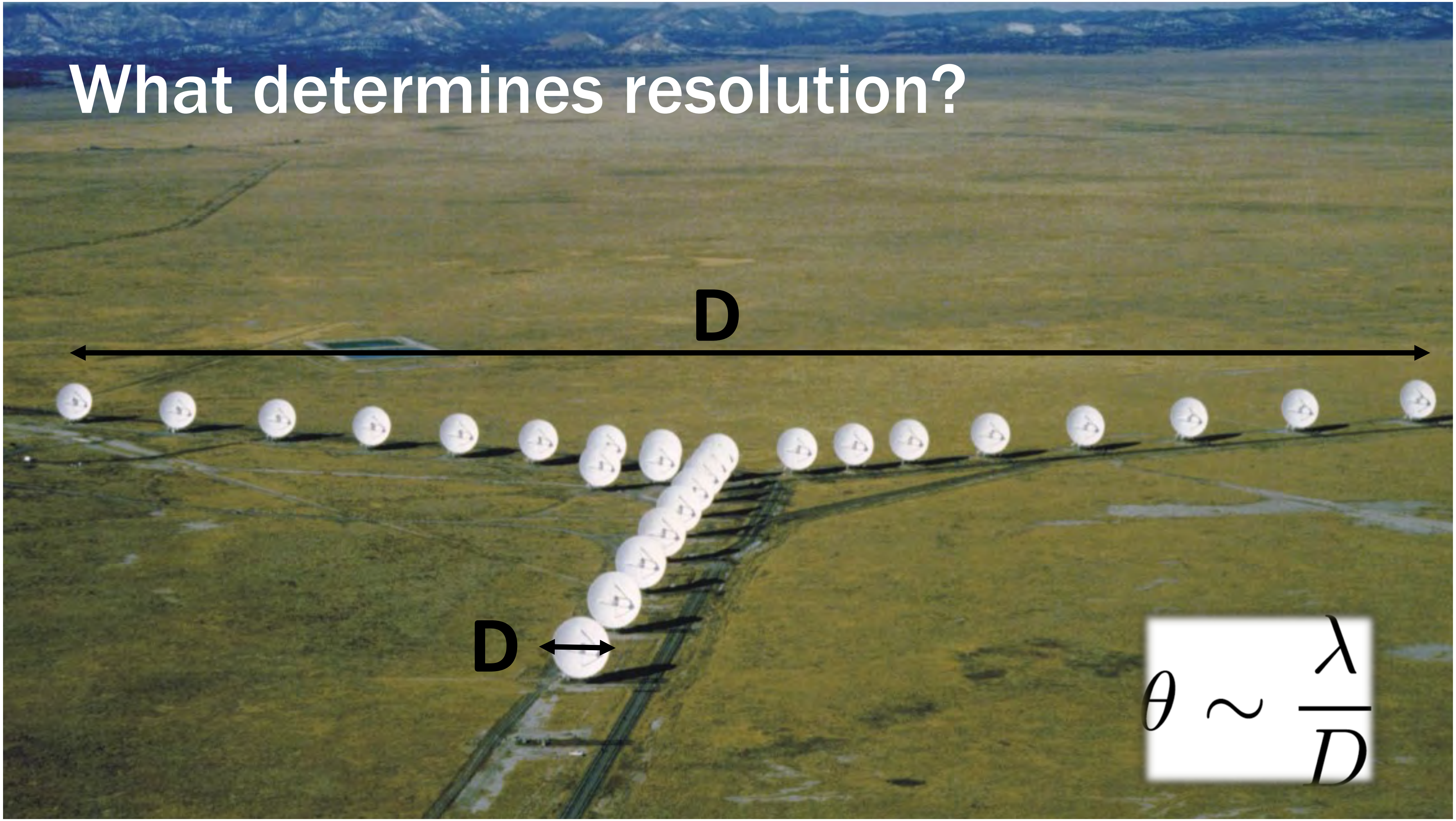
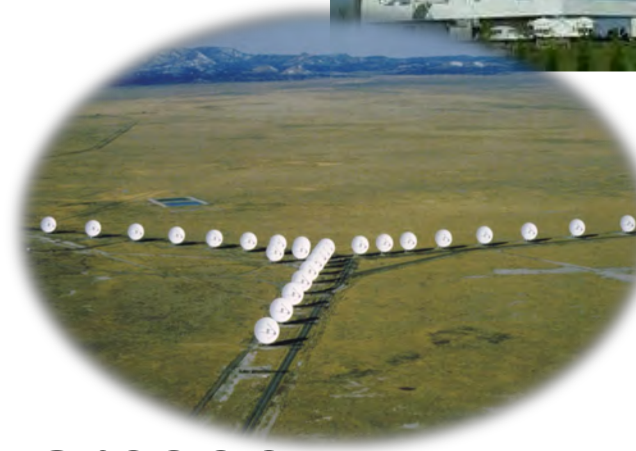

What determines resolution?
D
D
$\theta \sim \frac{\lambda}{D}$

A few resolution examples



100 m telescope at λ=1cm (30 GHz)
→ ~20 arcsec

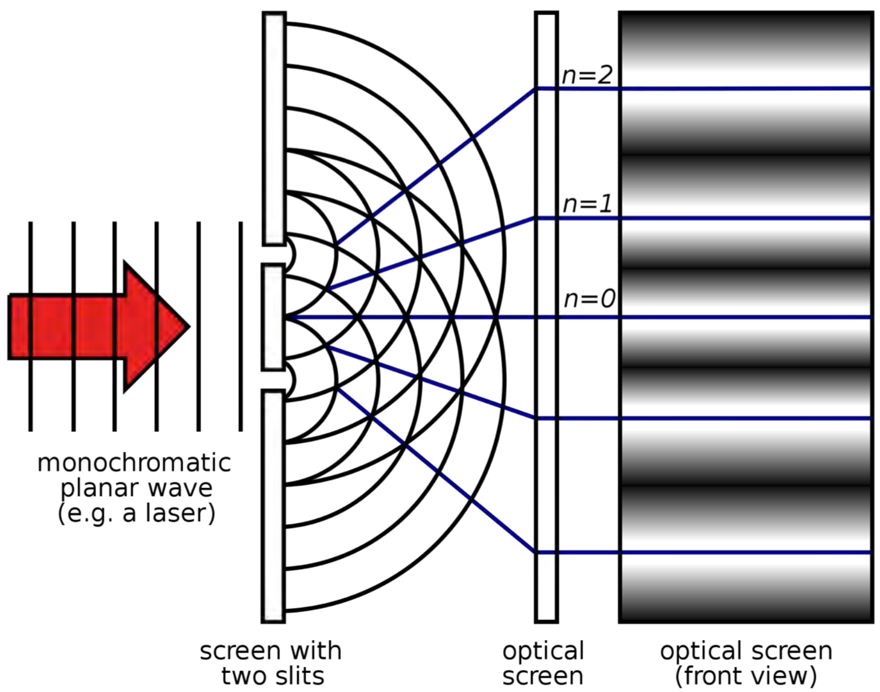
VLA (~35 km) at λ=1cm → ~0.1 arcsec
(~2 km on moon; ~2 m at 5000 km)

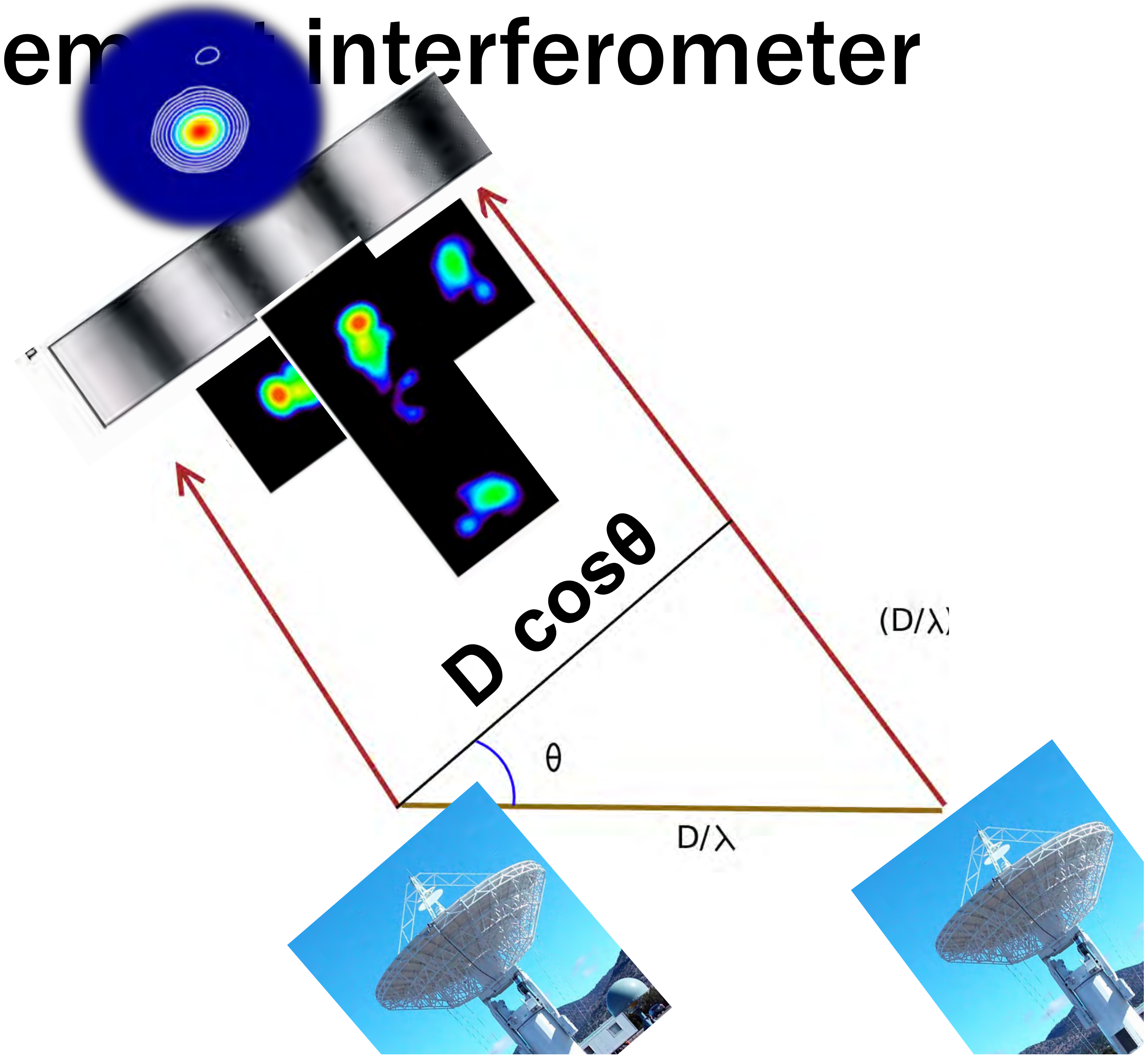
10,000 km telescope at λ=1cm→ ~200 micro-arcsec
(~40 cm on moon; ~5 mm at 5000 km)

10,000 km telescope at λ=1mm → ~20 micro-arcsec
(~4 cm on moon; ~0.1 m at 1000 km)

Principle of two-elem... interferometer

Young double-slit experiment

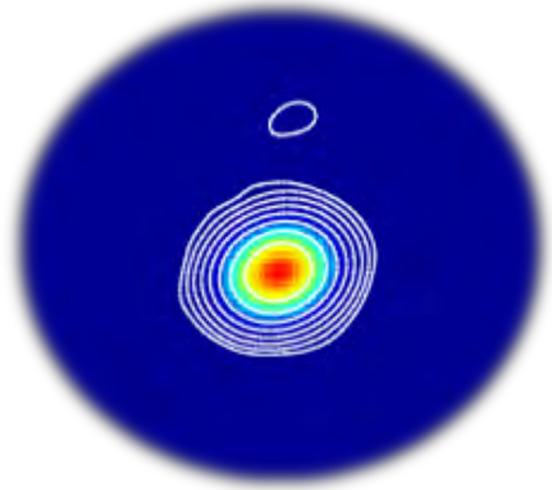


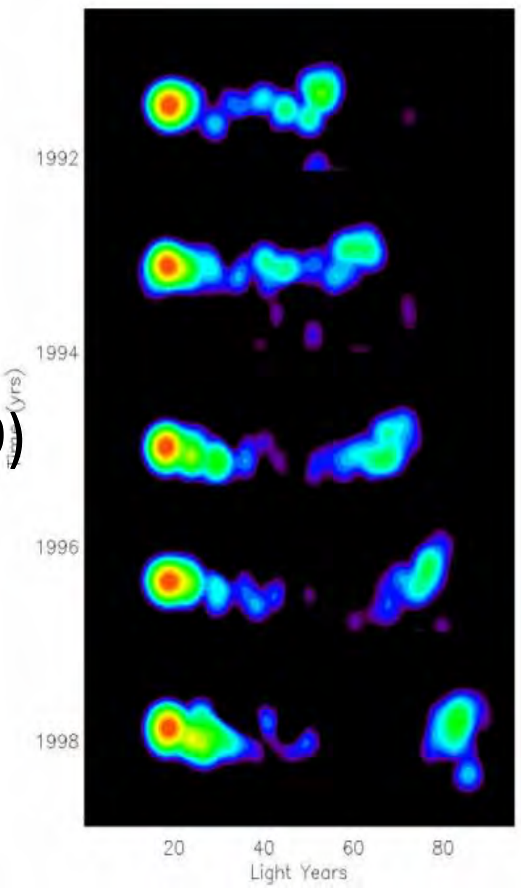


Geodetic VLBI radio sources

- 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

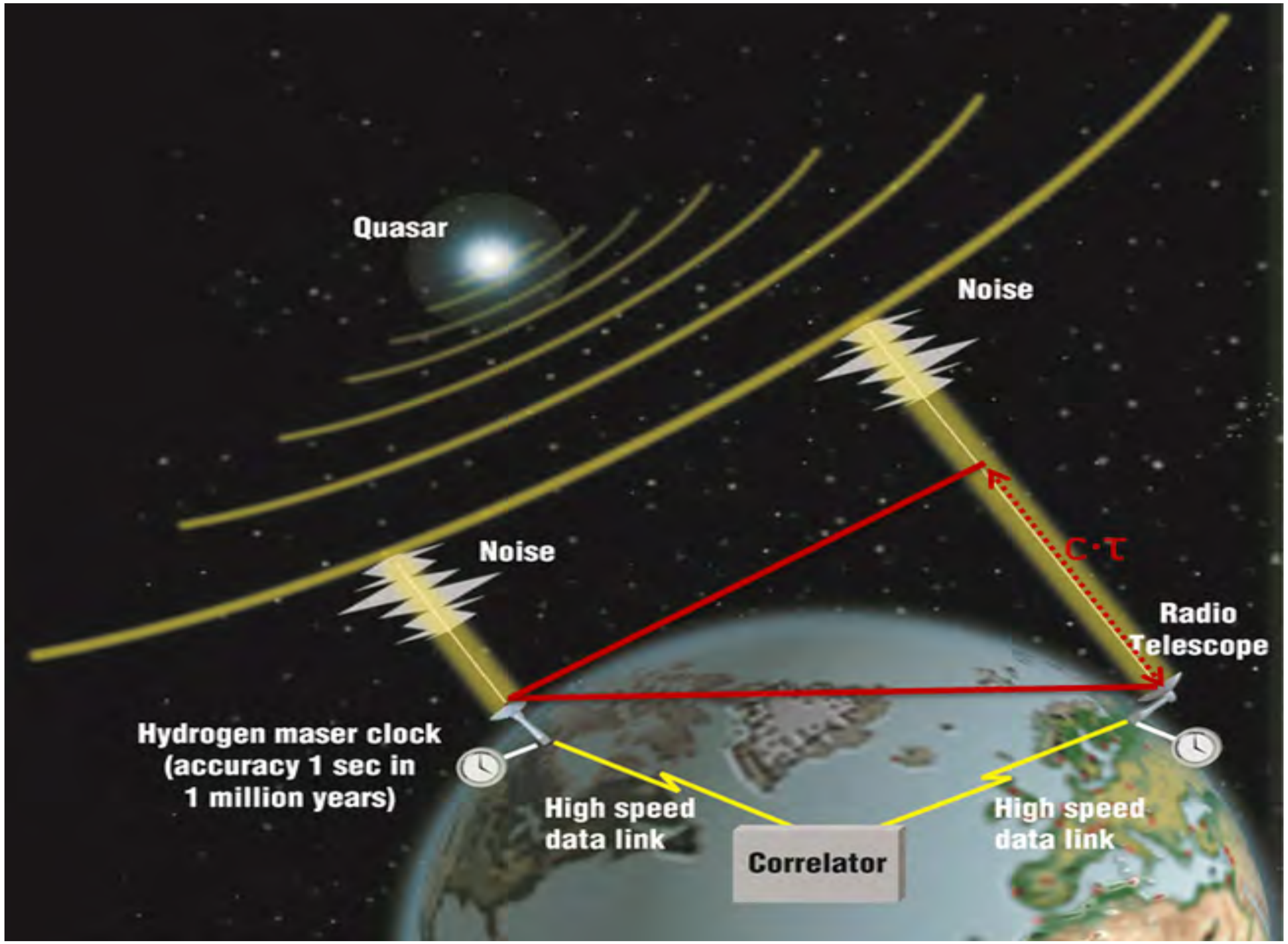
"Nice" (1300+580)





"Ugly" (3C279)

Principle of (geodetic) VLBI/VGOS

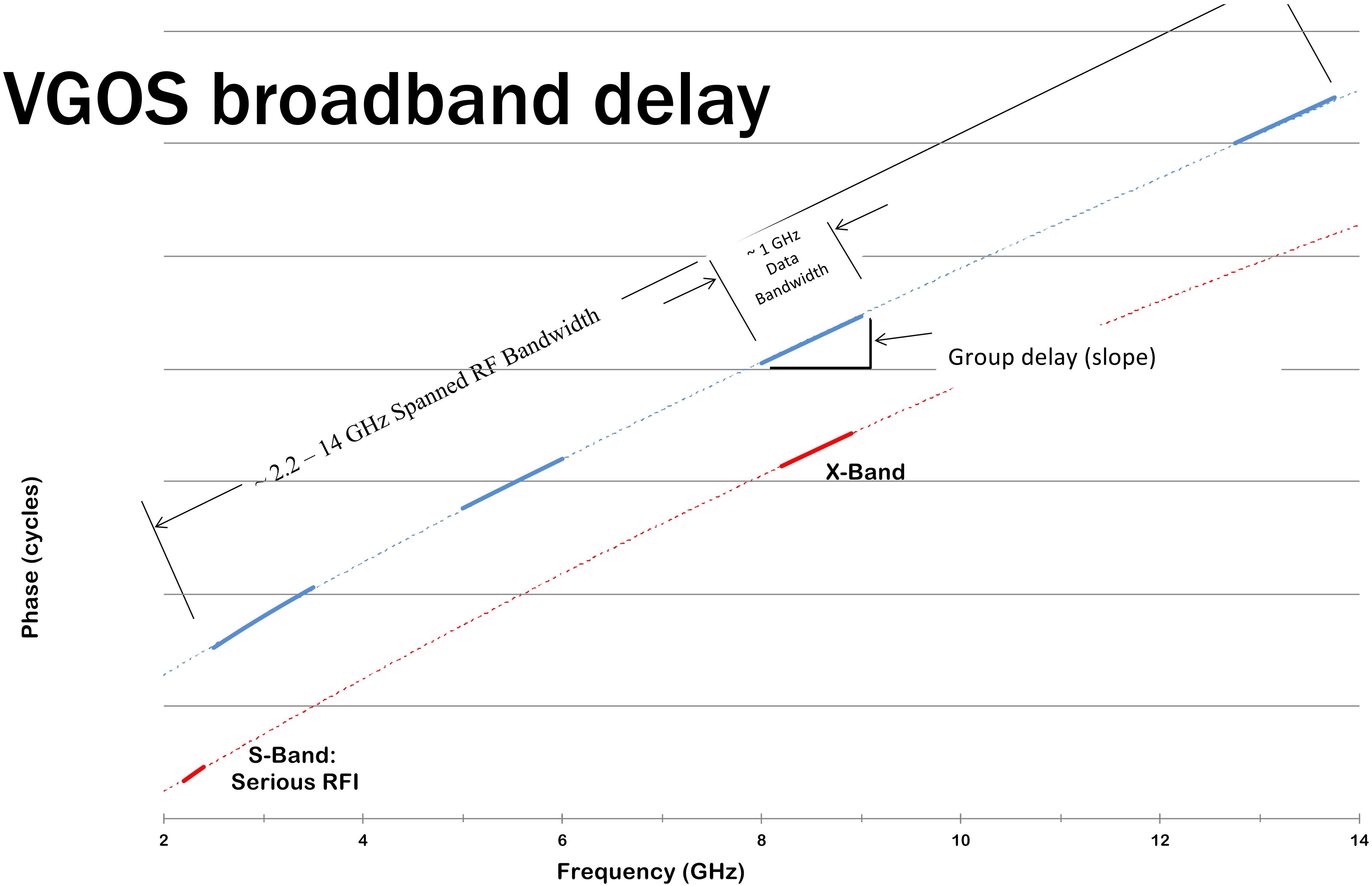


- Measure time-of-arrival difference (delay) accurately
- mm-level positioning requires delay precision of a few picoseconds (3 ps = 1 mm)

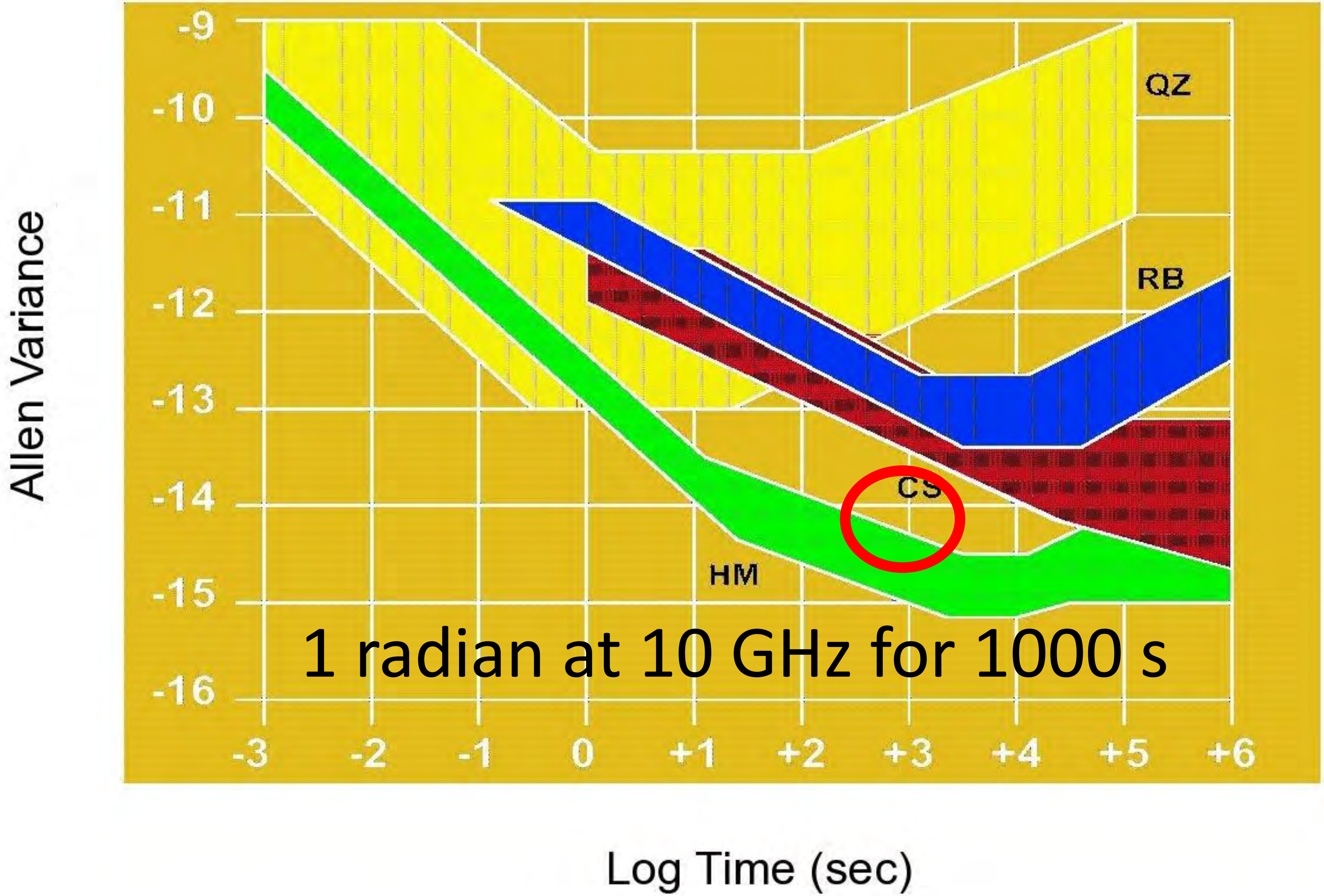
VGOS station requirements

- Observing “noise” from quasars (contaminated by various noise sources)
- Measuring a (group) delay (a time measurement), whose 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)

VGOS broadband delay




Mk1
1967
720 kbps
1st VLBI
Mk6
16 Gbps
4 Mbps
Mk2C
See TOW session:
Ruszczyk, Verkouter
Mk5
2006
2 Gbps
2010
4 Gbps
Mk3/
1977
224 Mbps
Mk4
1990
512 Mbps



QZ
RB
CS
HM
-9
-10
-11
-12
-13
-14
-15
-16
-3
-2
-1
0
+1
+2
+3
+4
+5
+6
Allen Variance
Log Time (sec)
1 radian at 10 GHz for 1000 s

Legacy S/X vs. VGOS comparison

	Legacy S/X	VGOS
Antenna Size	5–100 m dish	~ 12 m dish
Slew Speed	~20–200 deg/min	≥ 720 deg/min
Sensitivity	200–15,000 SEFD	≤ 2,500 SEFD
Frequency Range	S/X band	~2–14 GHz
Recording Rate	128, 256 Mbps	8–16 Gbps
Data Transfer	Usually ship disks, some e-transfer	Both e-transfer and disks

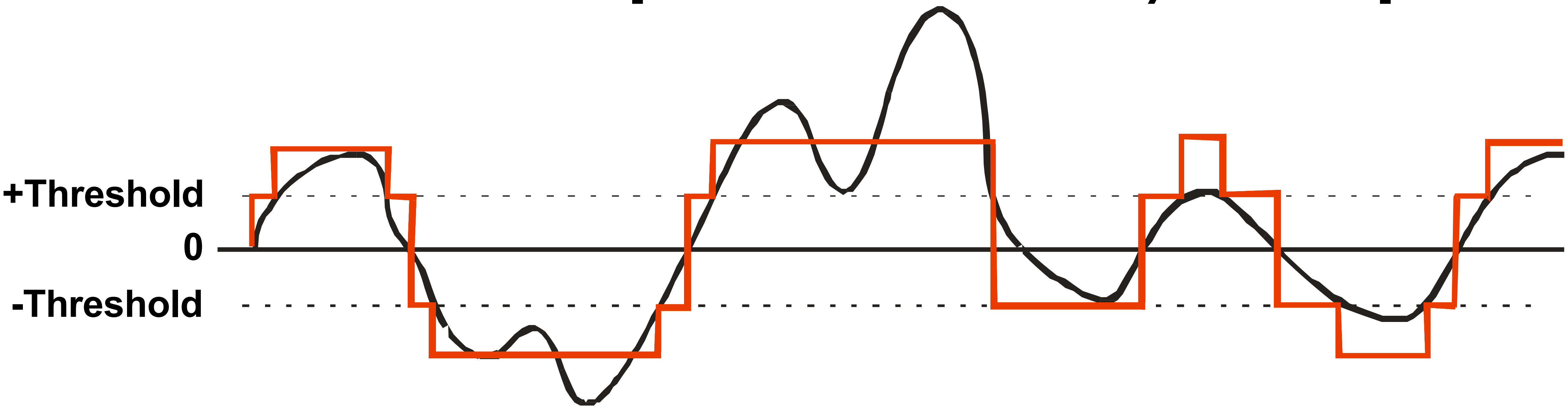
See TOW session: Behrend

What is the recorded VGOS 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 also another important consequence, it is not a big deal to lose a small amount of data

Waveform sampled at 2 bits/sample



- 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)

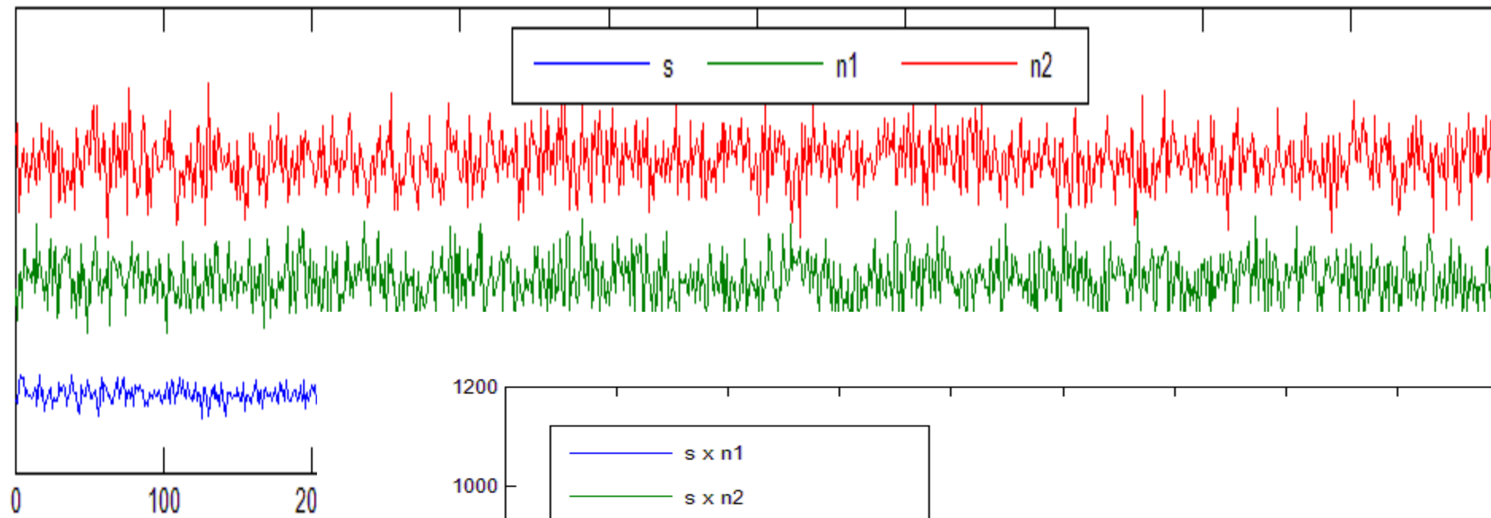
- Relative to infinite bit sampling, VLBI SNR at 1 and 2 bits/sample is only 63% and 87%, respectively, better compensated by increasing recording bandwidth

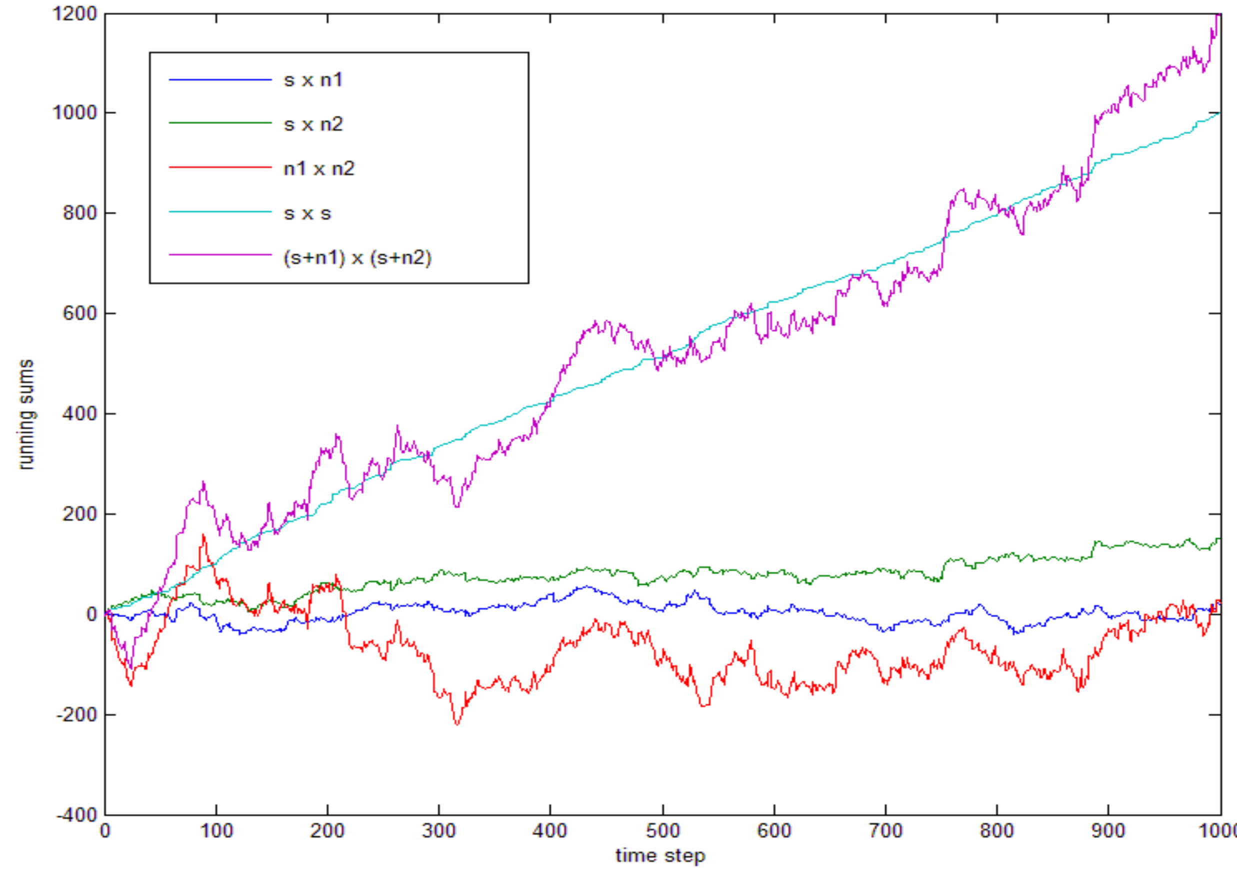
Cross-correlation of weak signals

Receiver 1 noise $n_1(t)$ →

Receiver 2 noise $n_2(t)$ →

Signal $s(t)$ →



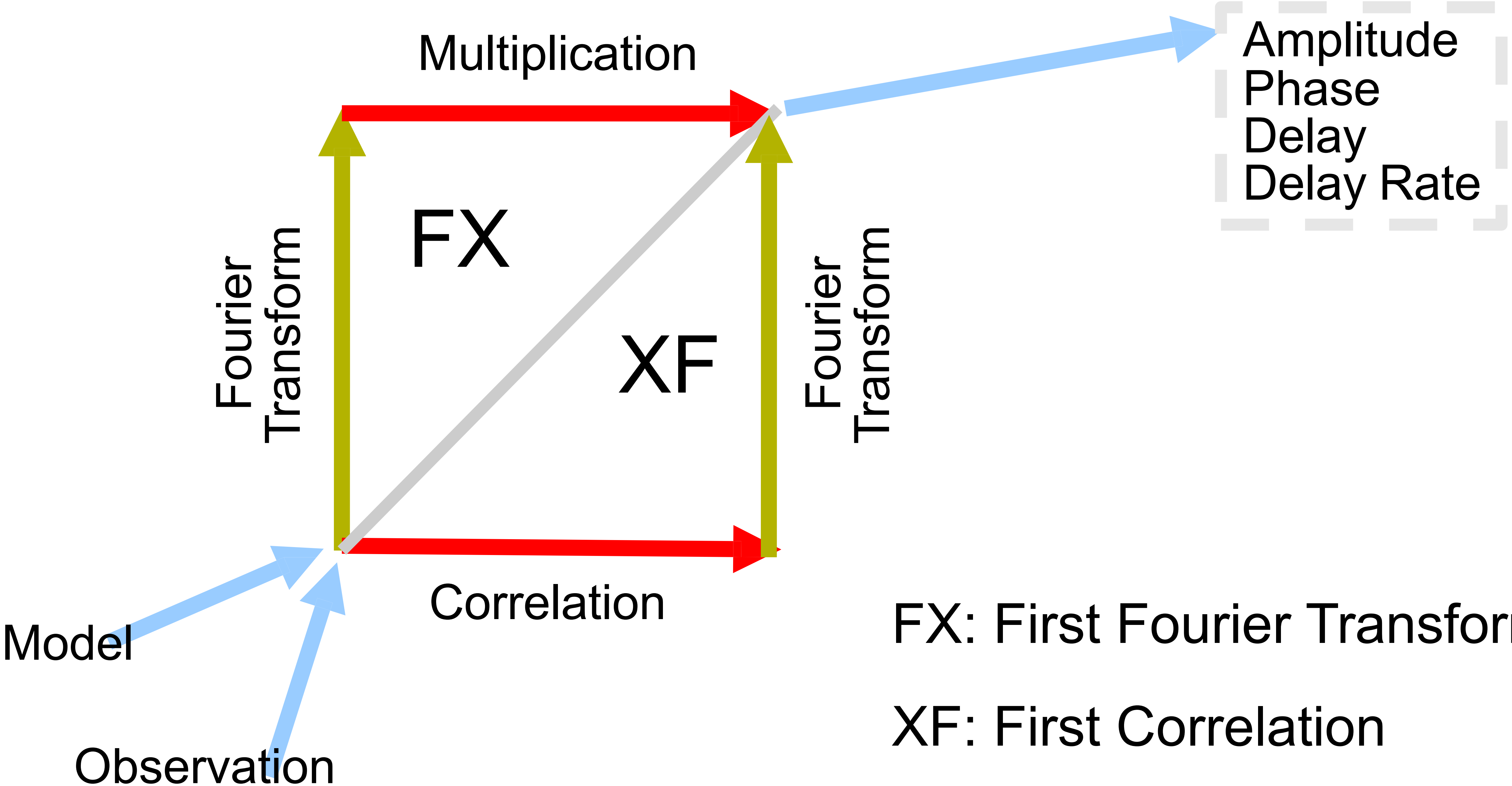


Correlation is product and accumulation, pulling signal from the noise:

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

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

Correlators: two flavors of processors

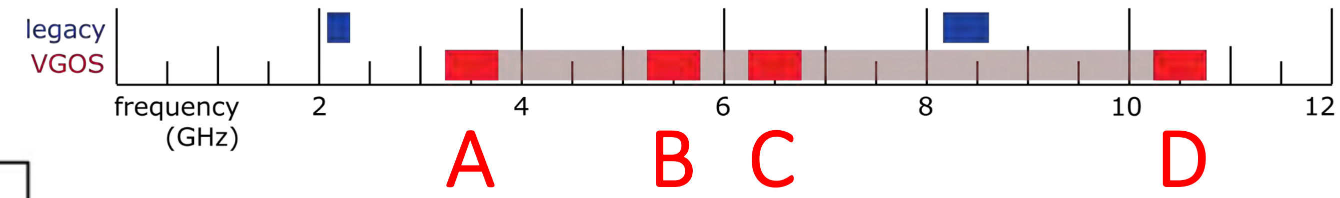


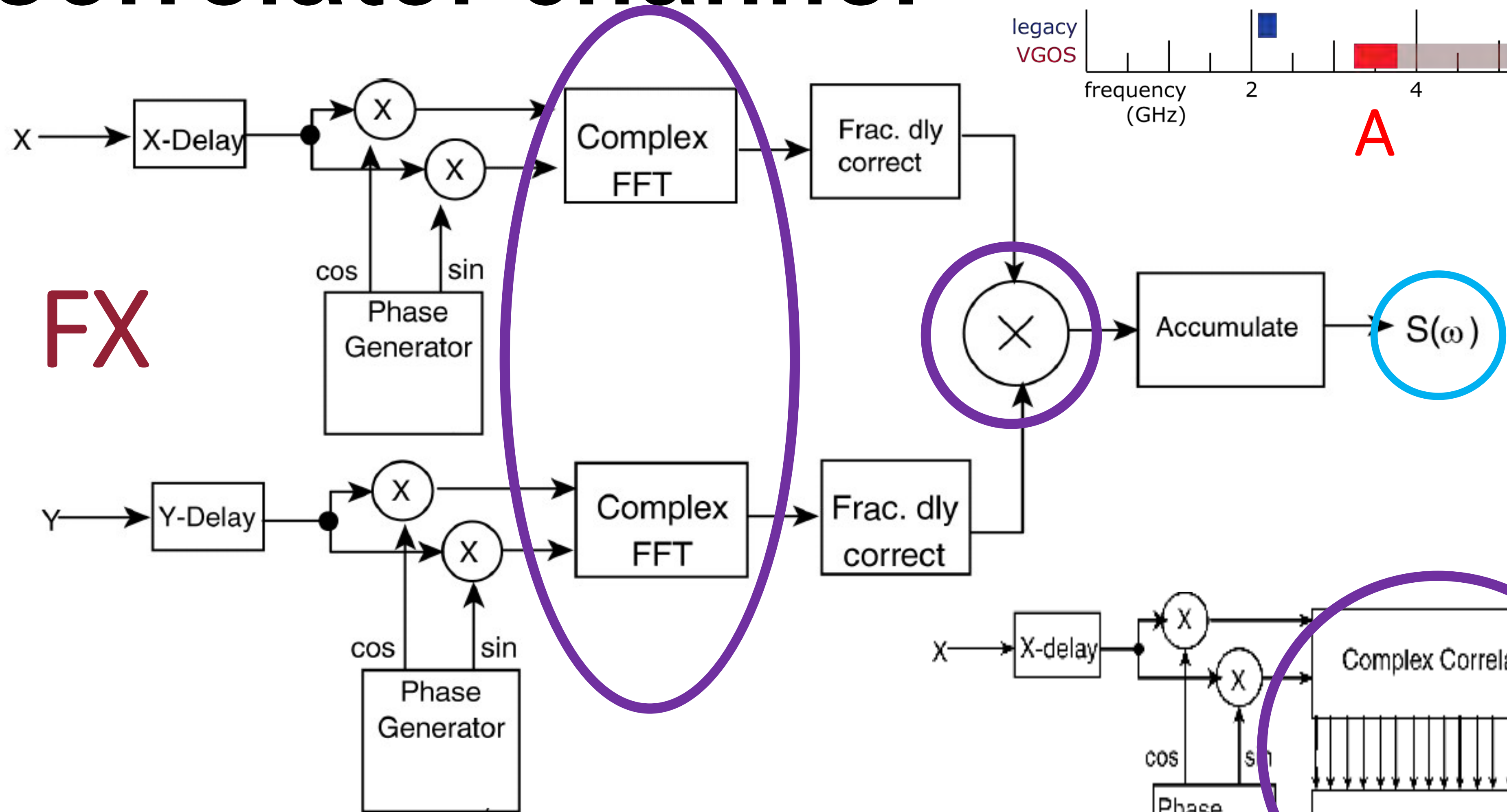
FX: First Fourier Transform

XF: First Correlation

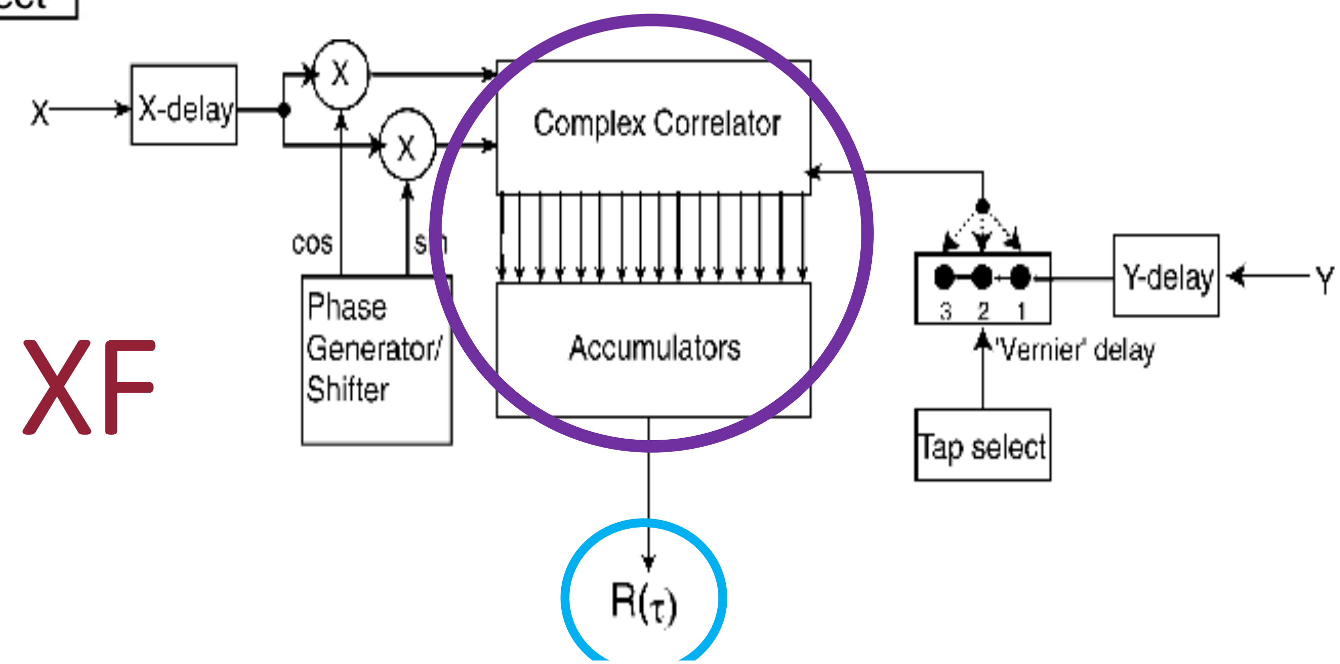
Correlator channel

VGOS: 8 channels/band x 4 bands





[Whitney et al., 2000]



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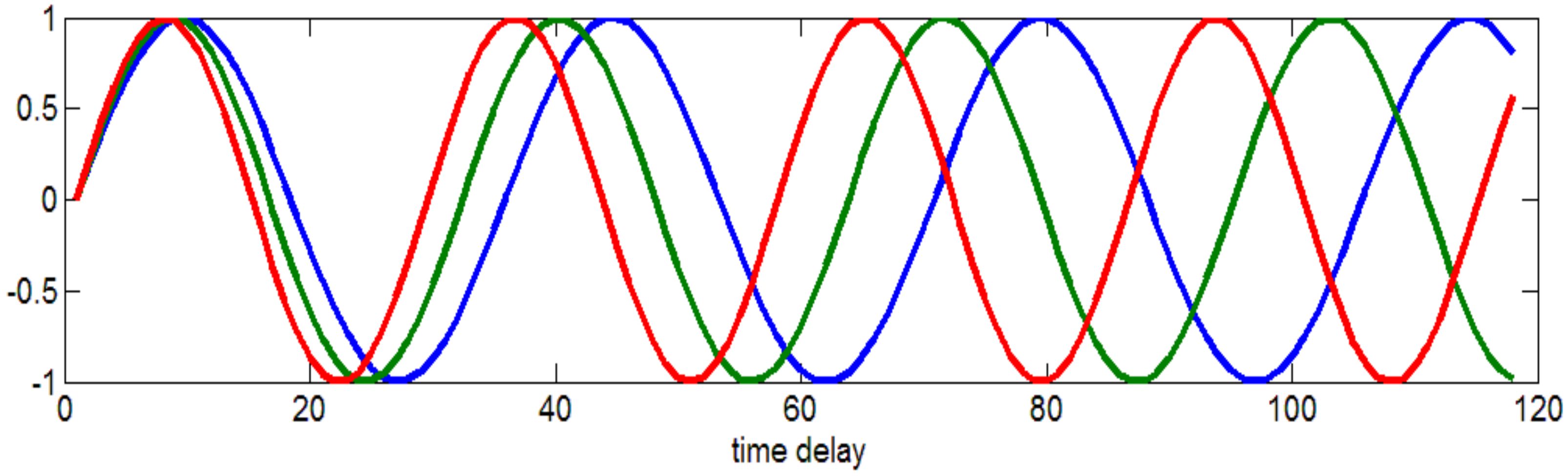
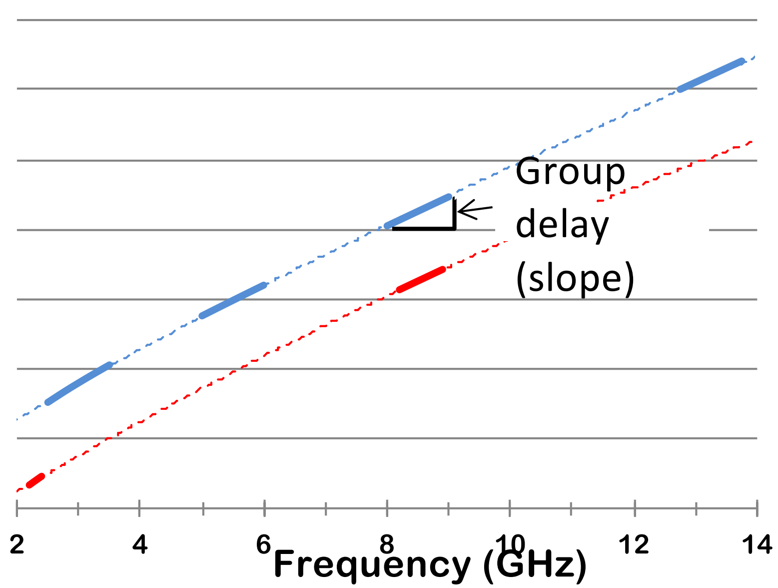
Combine channels via "bandwidth synthesis"

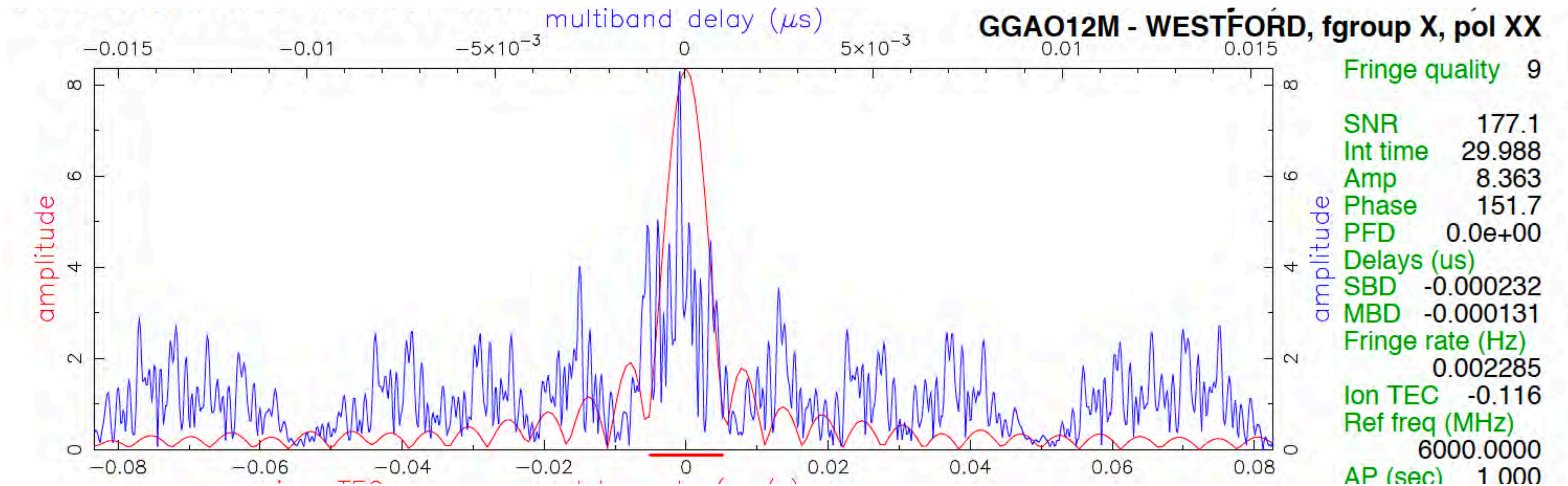
The goal is to measure the group delay, defined as dθ/dω

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

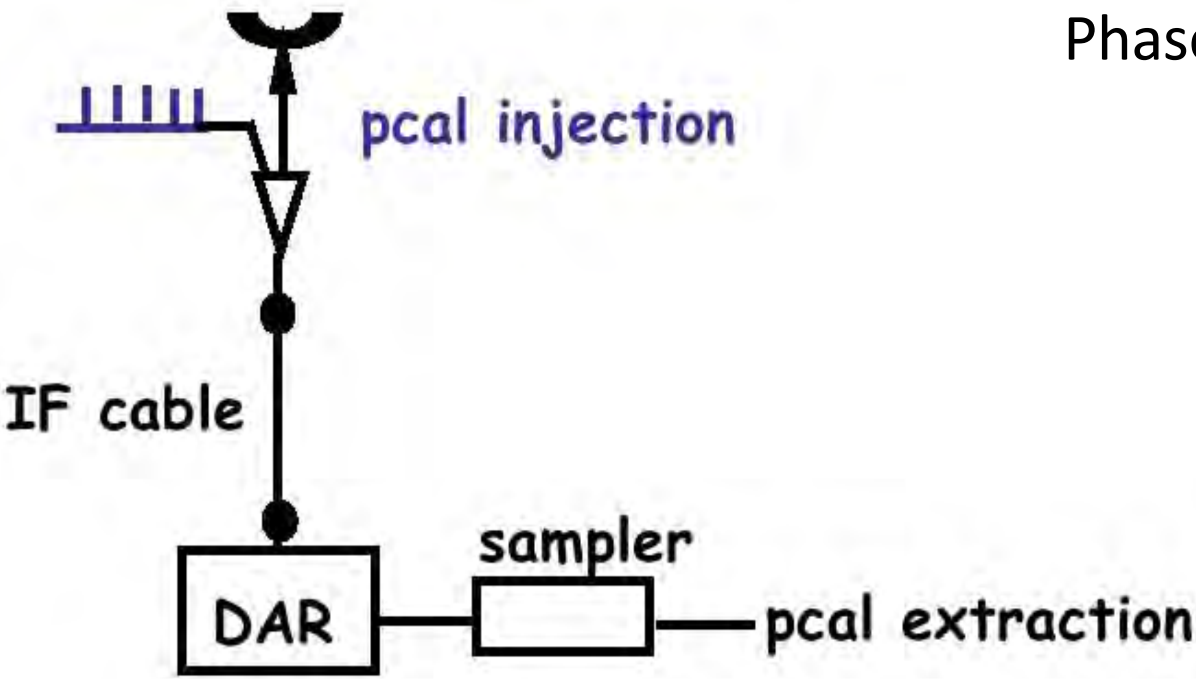
For a given delay, the higher the fringe frequency, the greater time-rate change in phase:

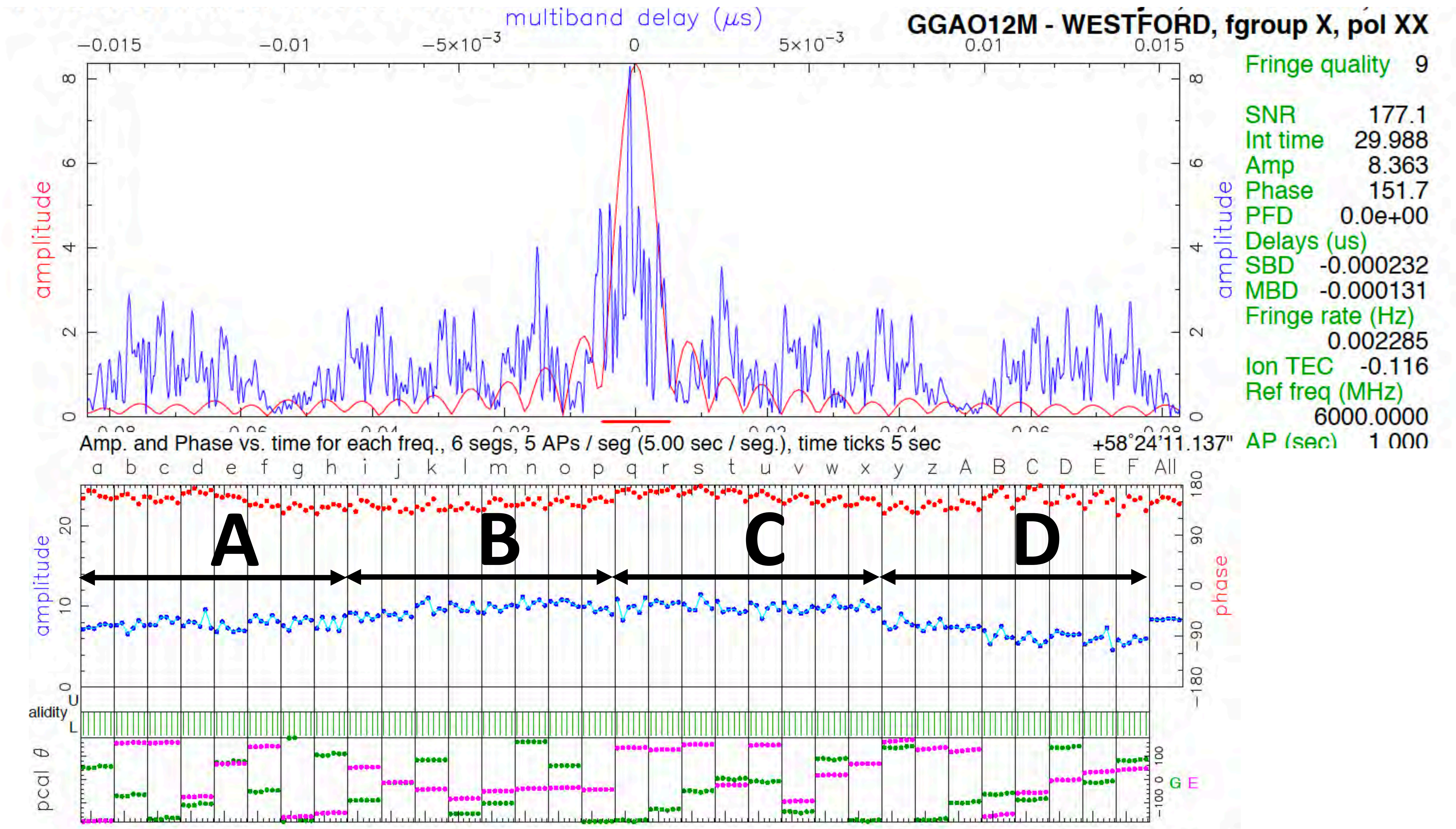




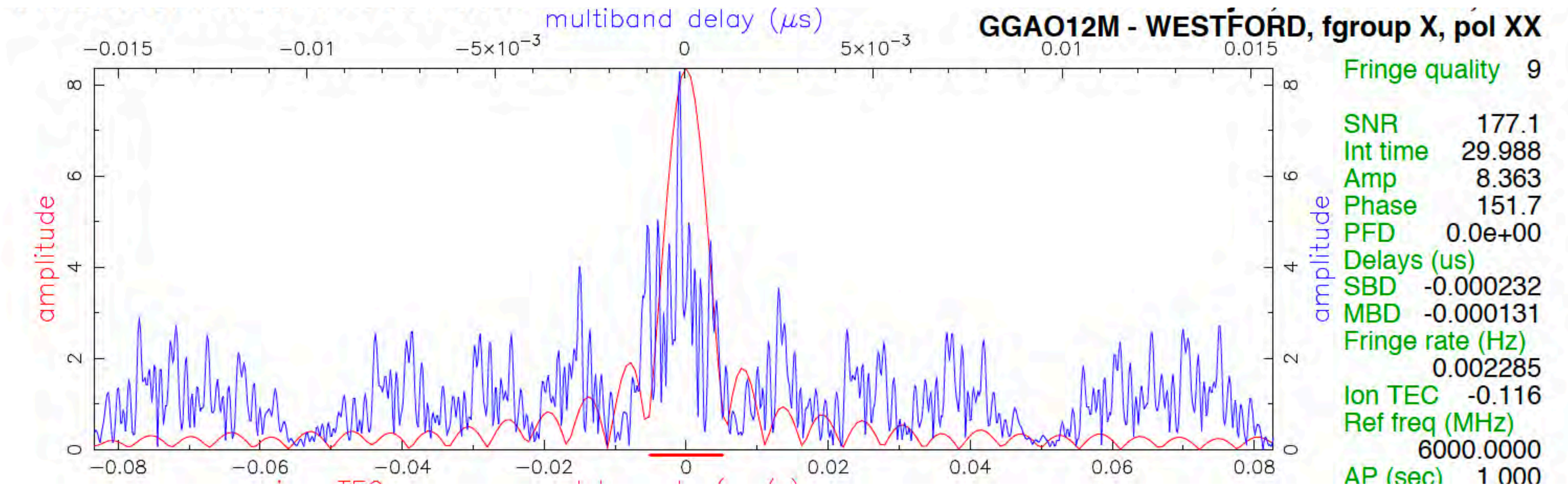


Phase and cable calibration system





GGAO12M - WESTFORD, fgroup X, pol XX
multiband delay (μs)
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
amplitude
phase
pcal θ
G E



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!!!

See TOW session: Haftings, Sargent

High-precision geodetic science

Observation = Model + Error

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

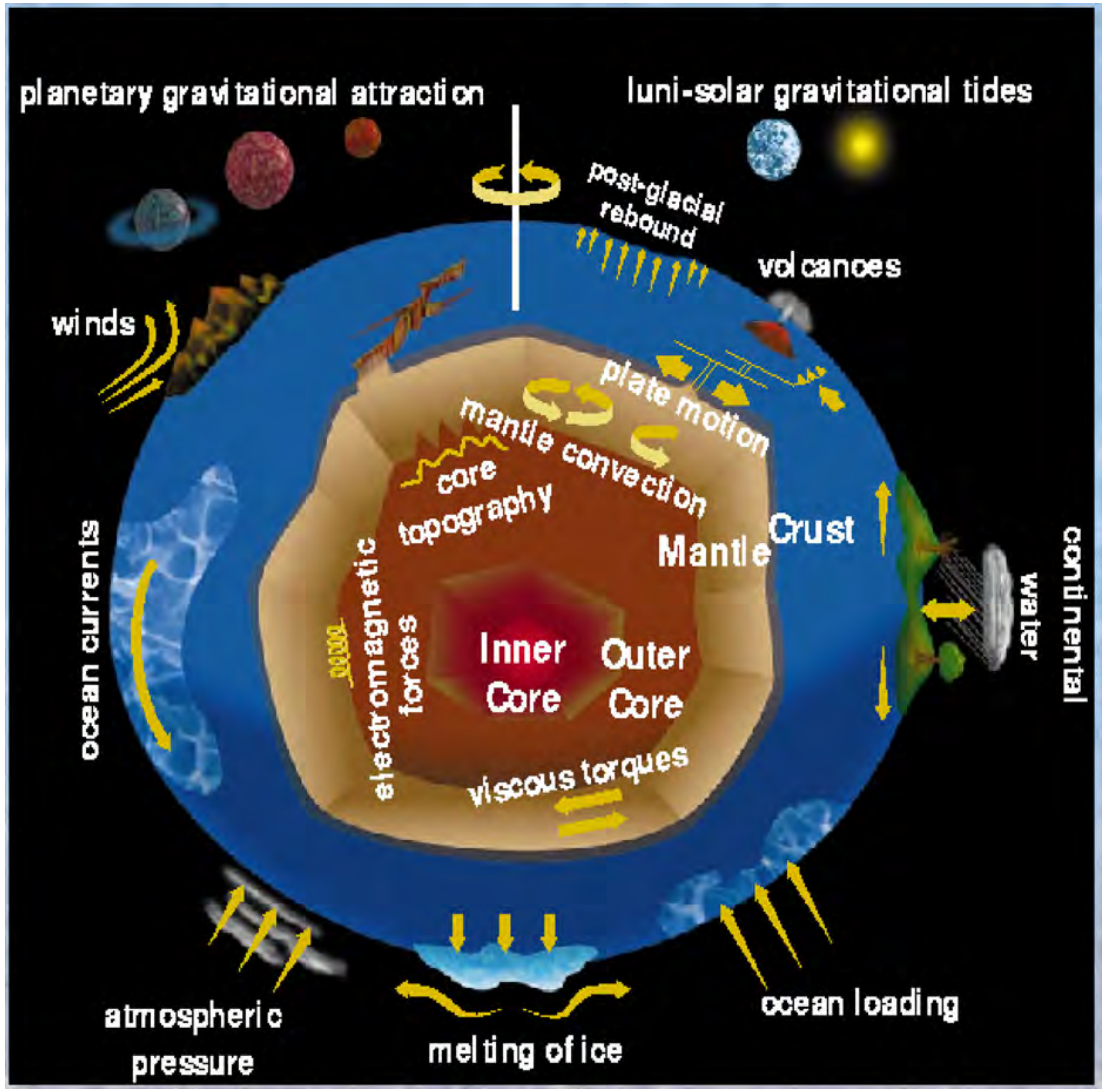
Signal (geometry => position, orientation) rest is all **“noise”**

VLBI

SLR

GNSS

DORIS



Living on a dynamic Earth

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

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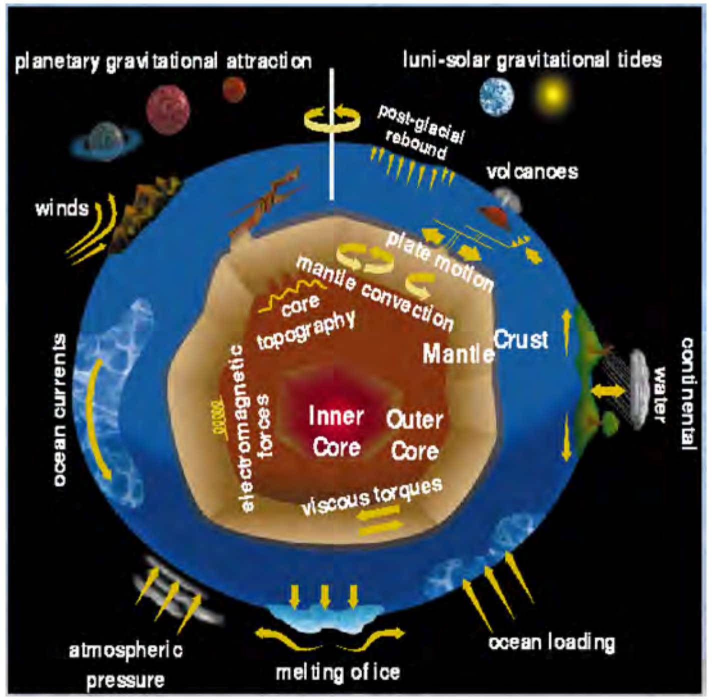
Modeling the dynamic Earth



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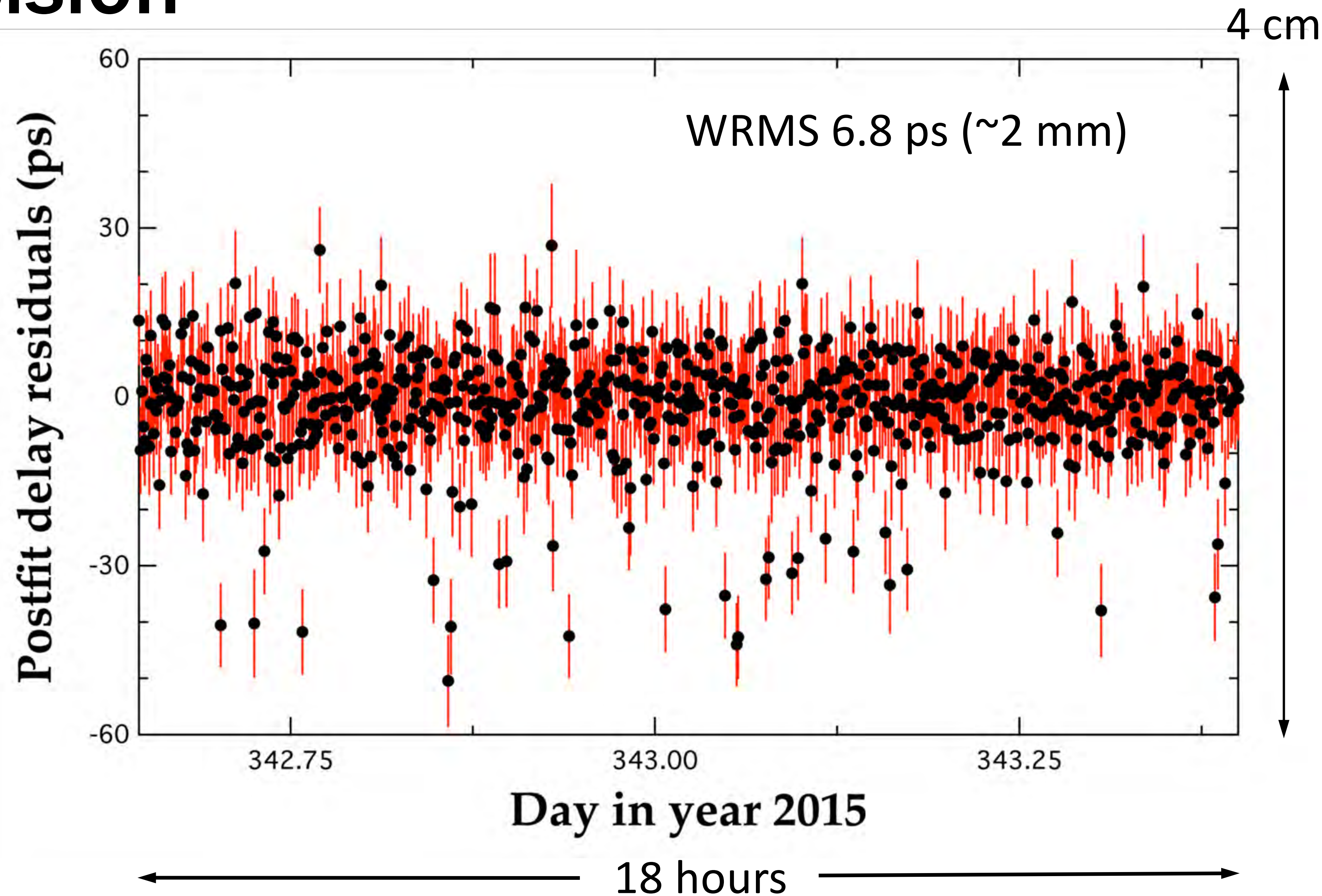
Adapted from *Sover et al., (1998)*

Item	Approx Max.	Time scale
Zero order geometry.	6000 km	1 day
Nutation	$\sim$ 20”	< 18.6 yr
Precession	$\sim$ 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	$\sim$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	$\sim$ 1.2 years
UT1 (Earth rotation)	Several mas	Various
Ionosphere	$\sim$ 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 precision



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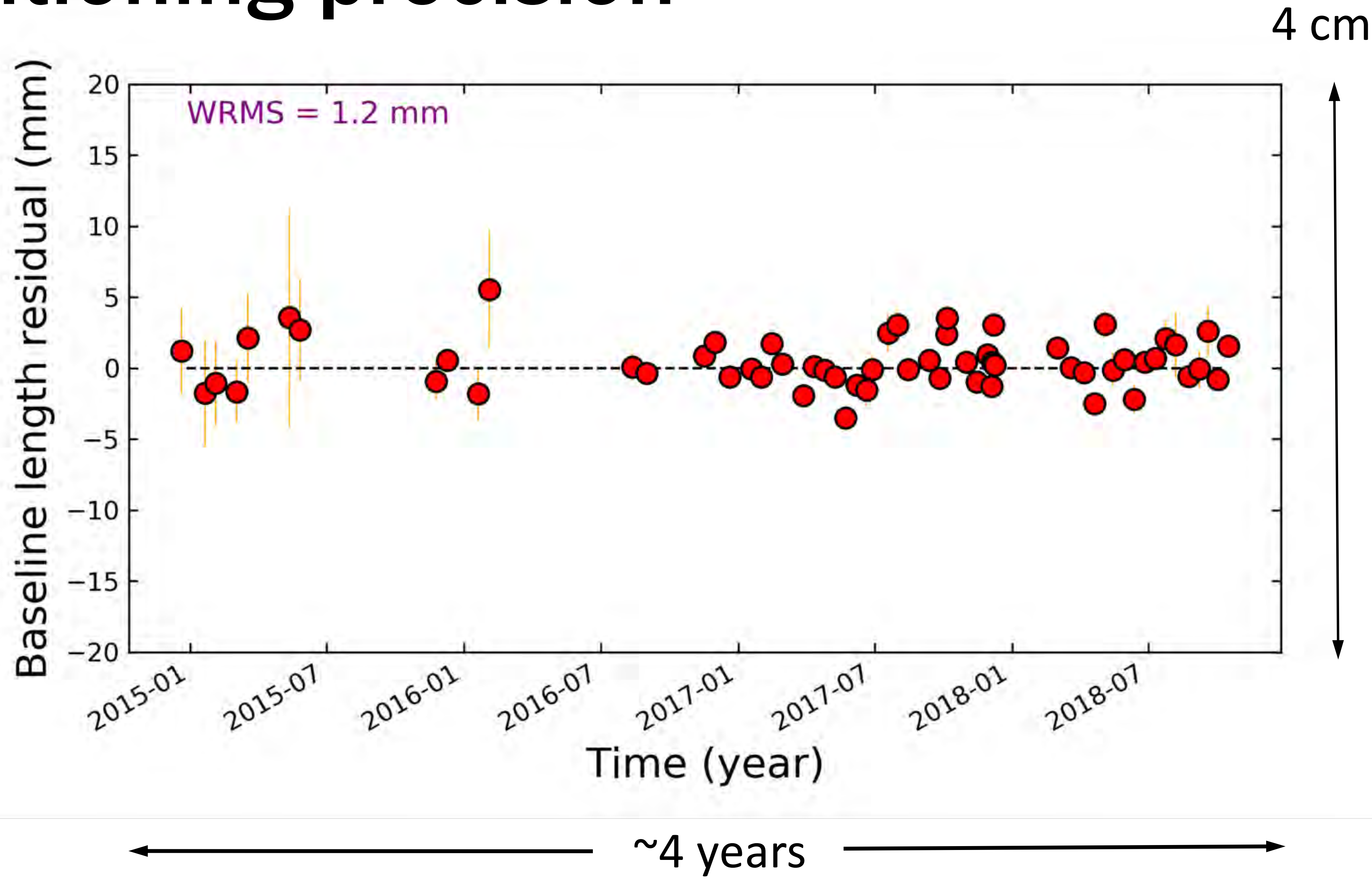
VGOS positioning precision

[Niell et al., 2018]



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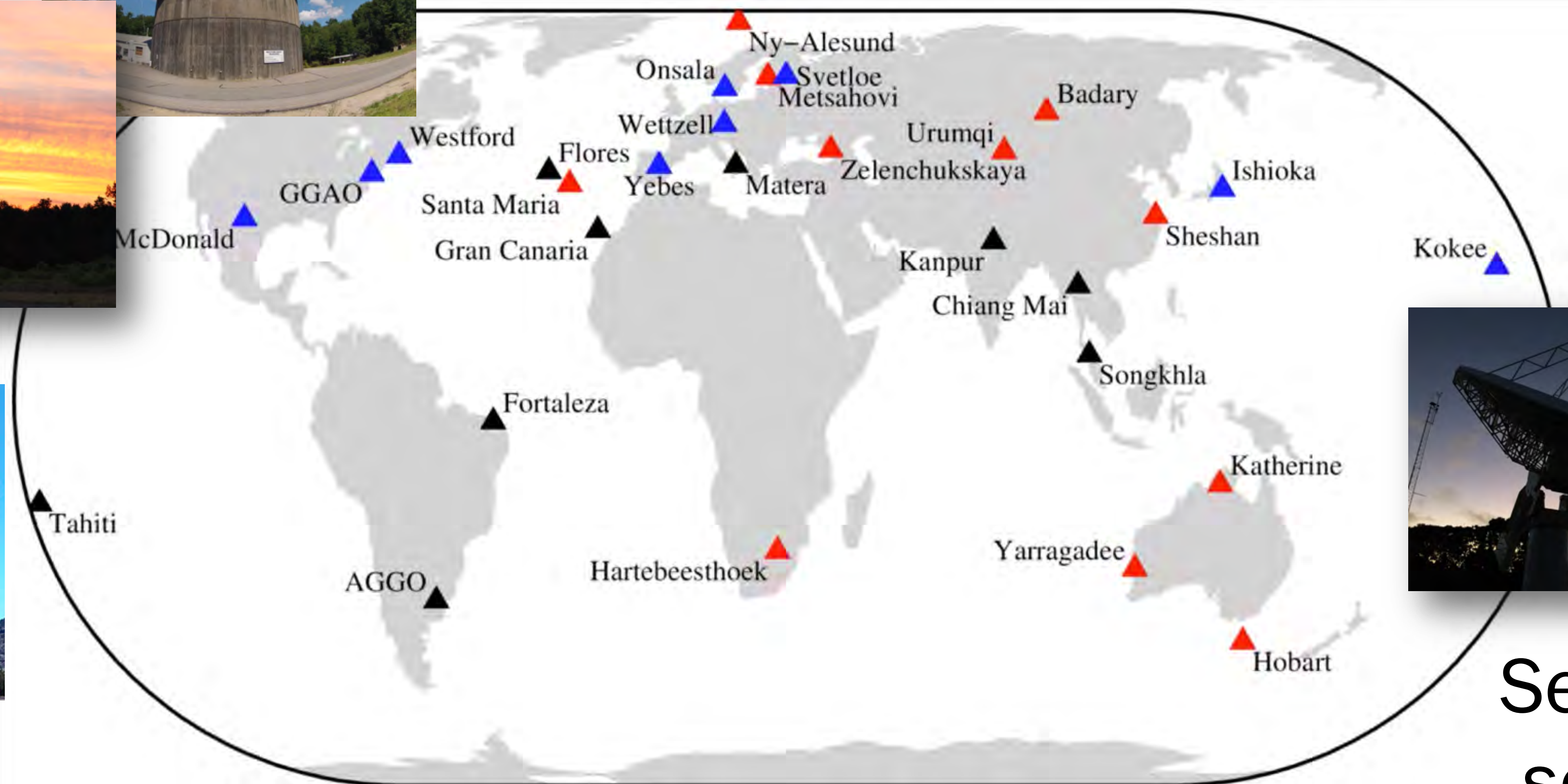
VGOS network rollout



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

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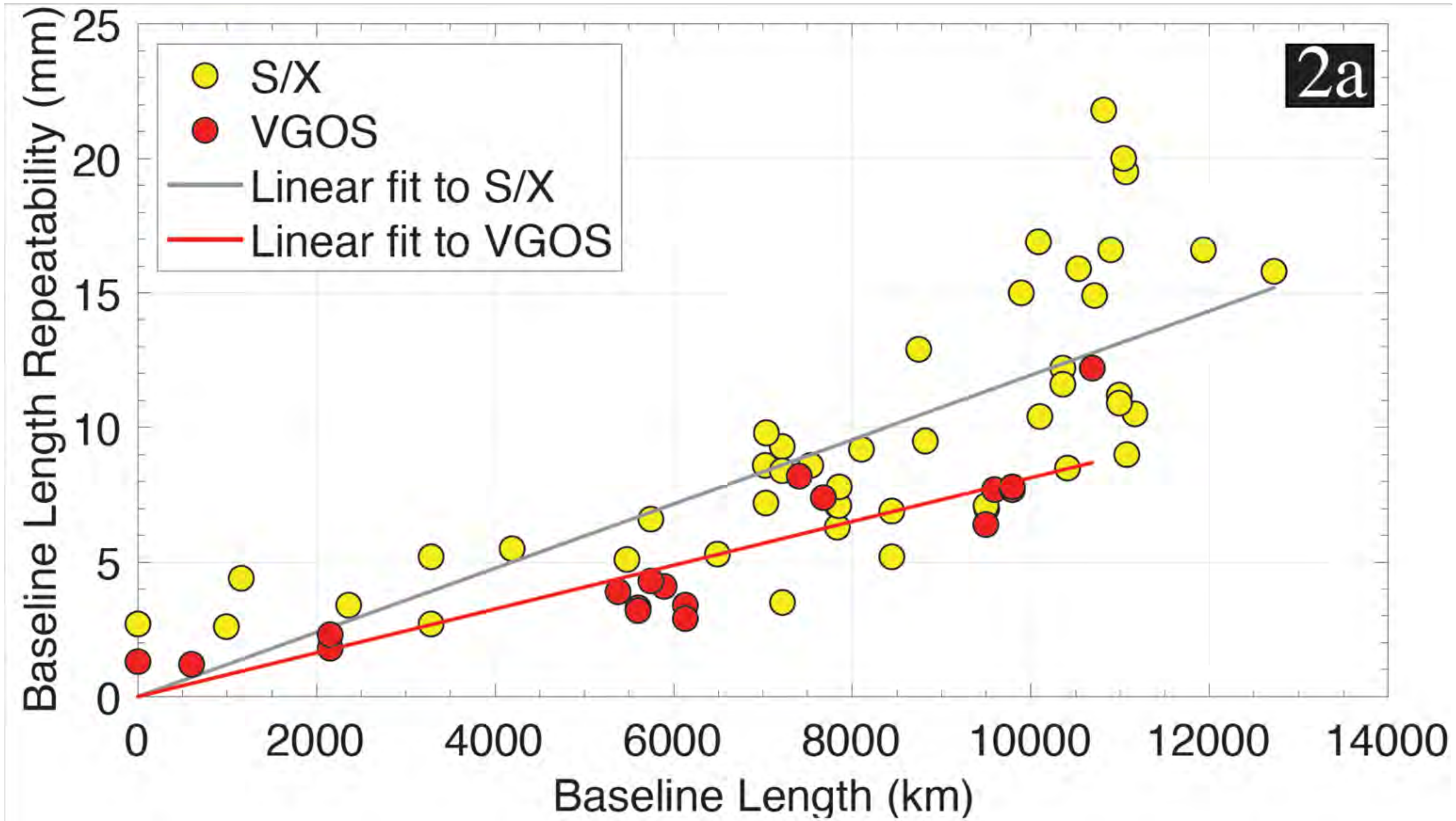
See TOW session: Behrend

VGOS vs. VLBI S/X positioning precision



[Mondal et al., 2021]

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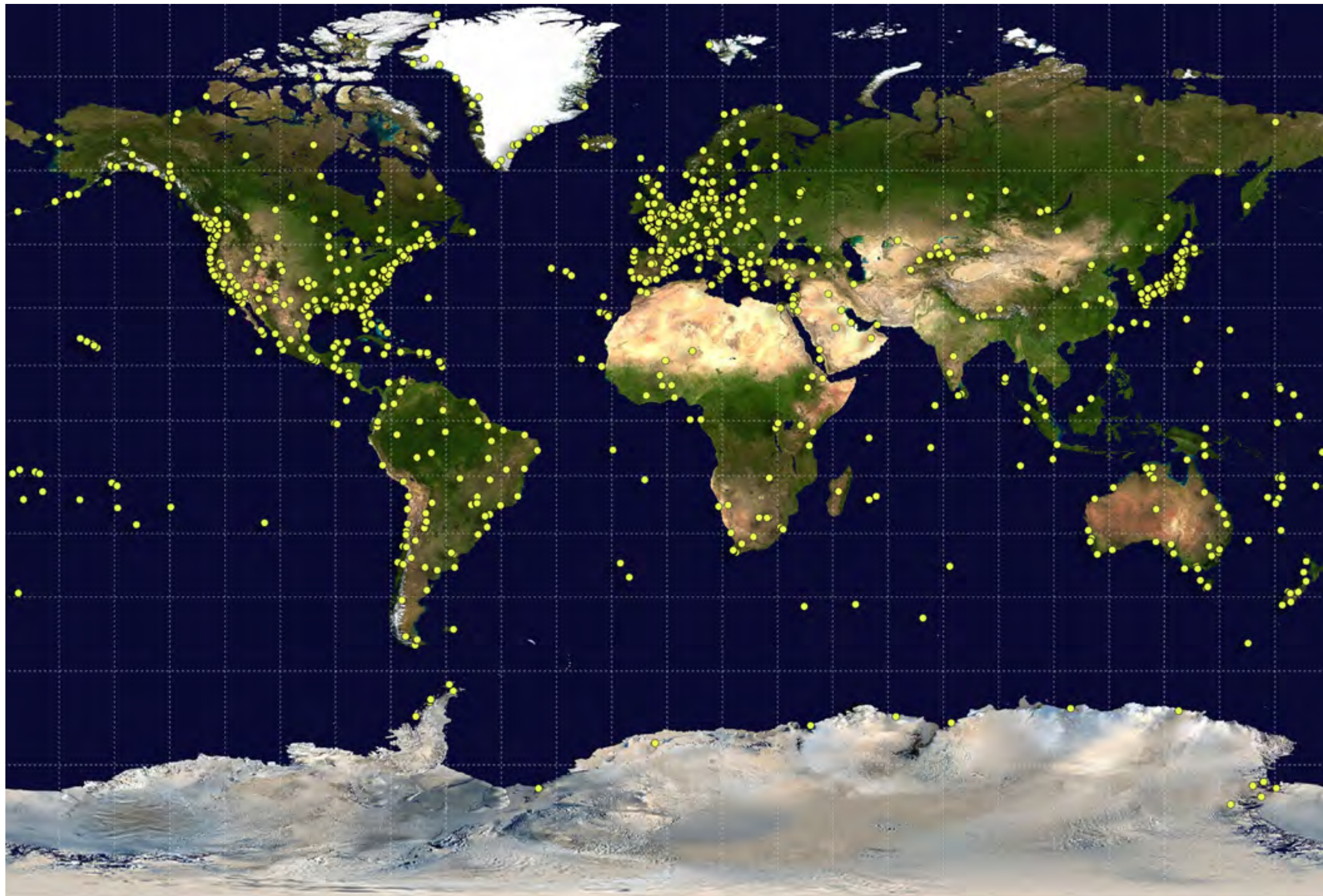
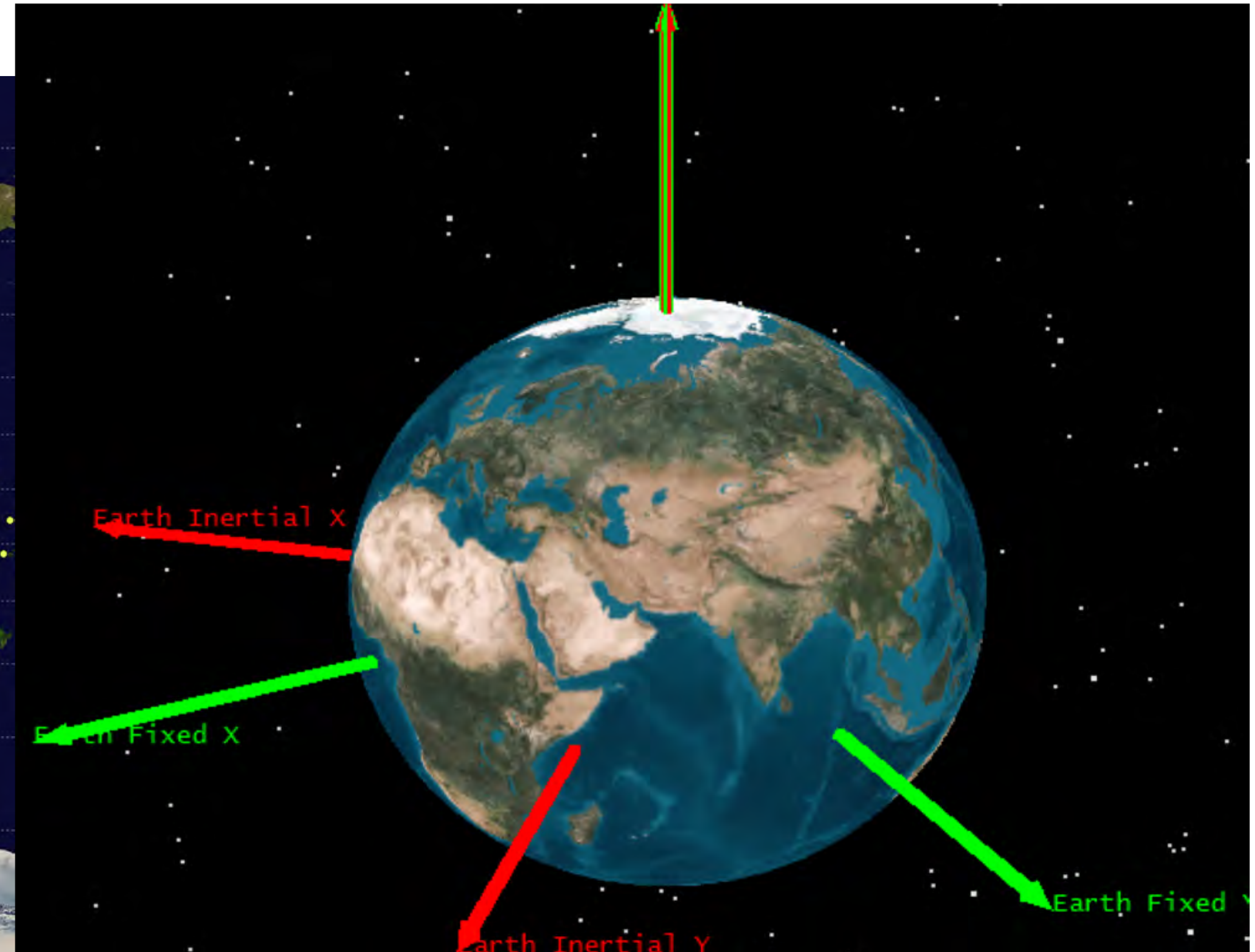
Improved Terrestrial Reference Frame and EOP



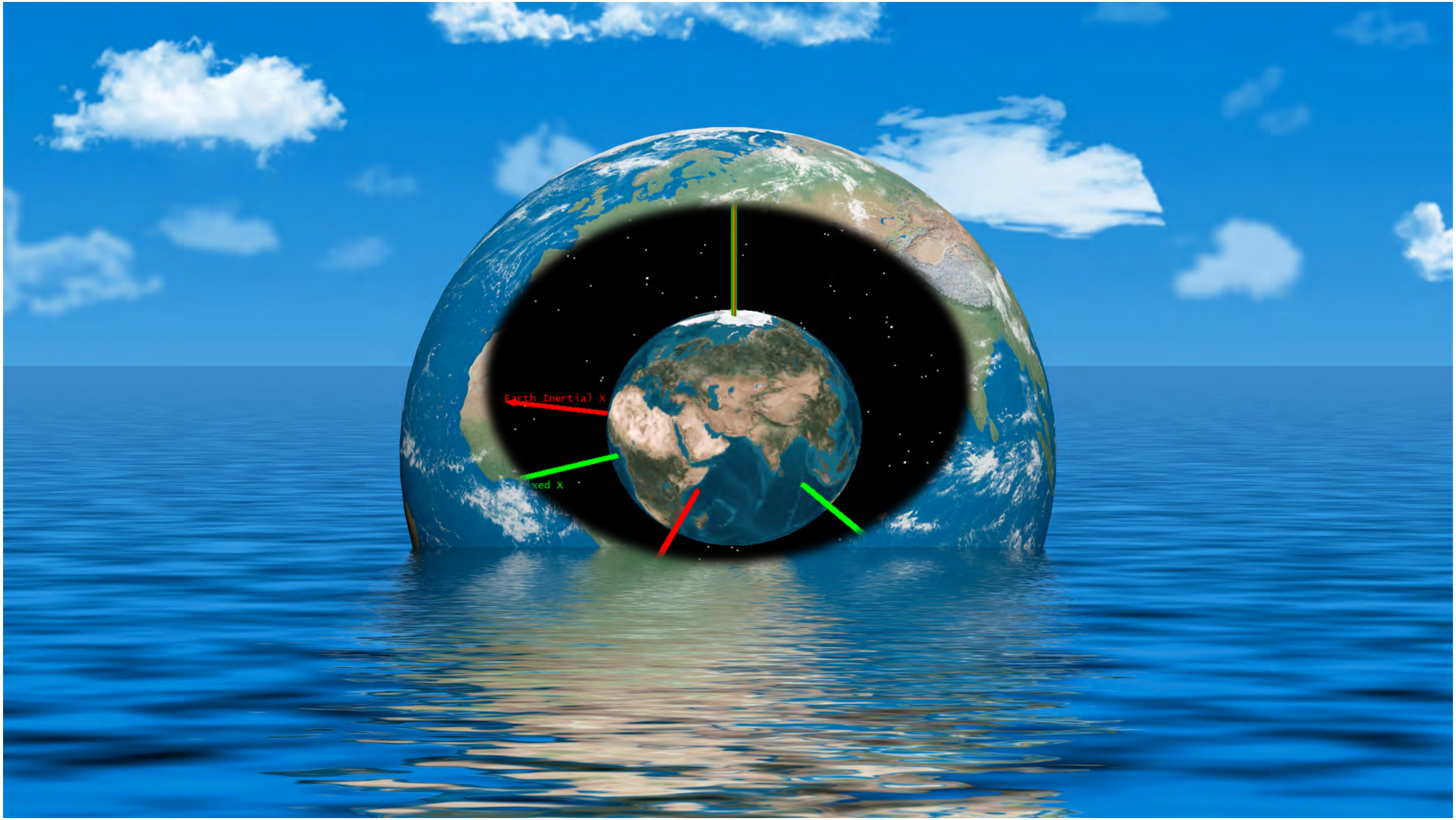


VLBI

SLR

GNSS

DORIS


Earth Inertial X

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

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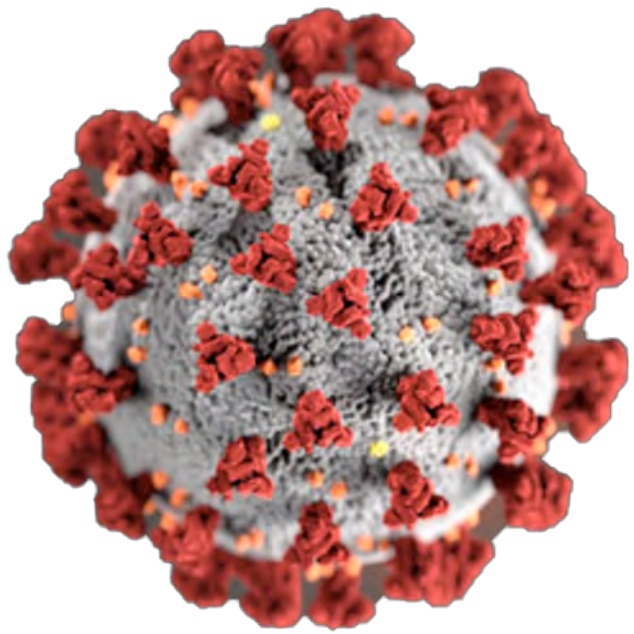
And that's pretty much it for today



Have all a healthy, productive, holly-jolly TOW!

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