VLBI Basics

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MIT Haystack Observatory

With big thanks to many of you, here and “out there”

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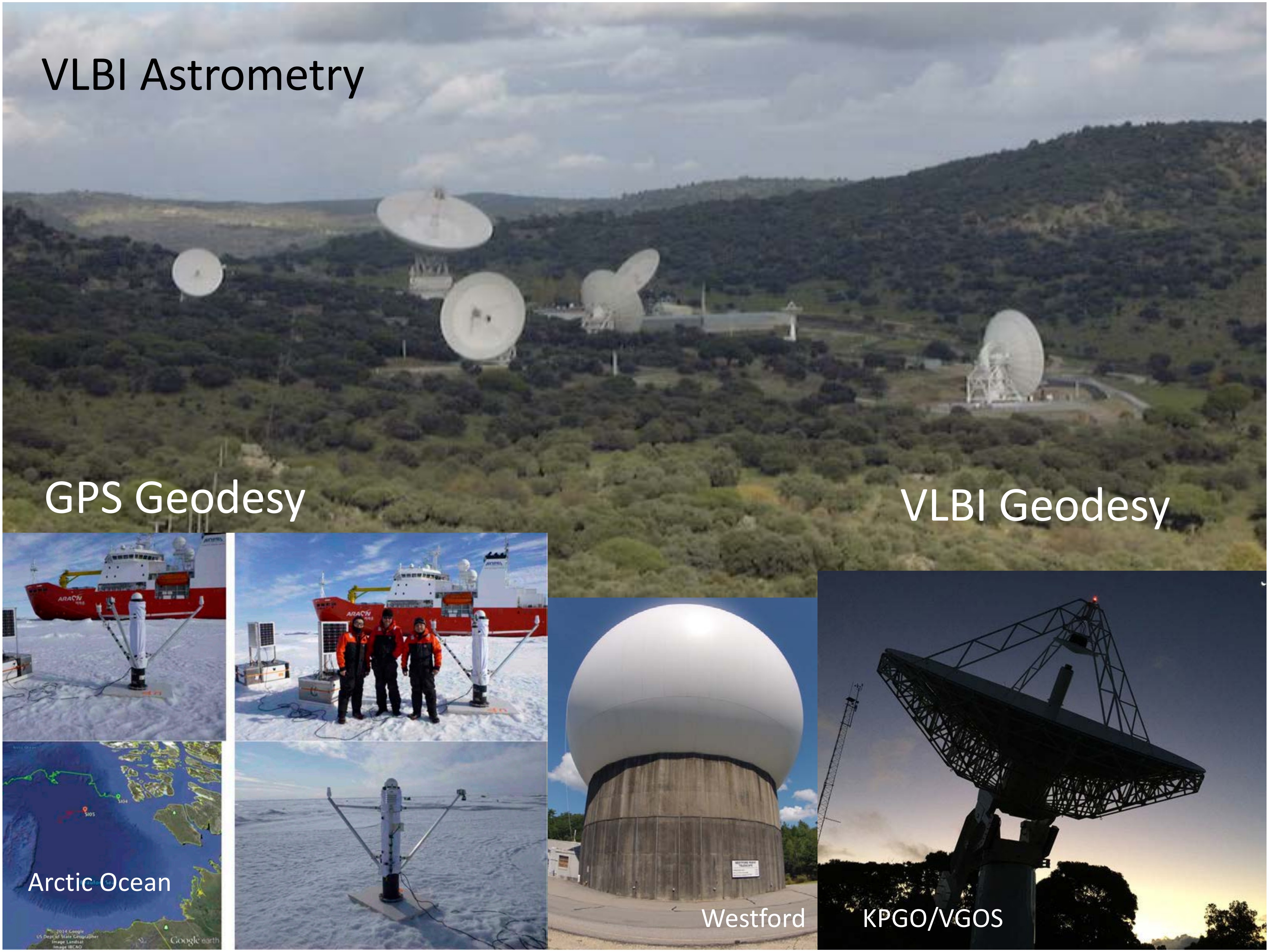
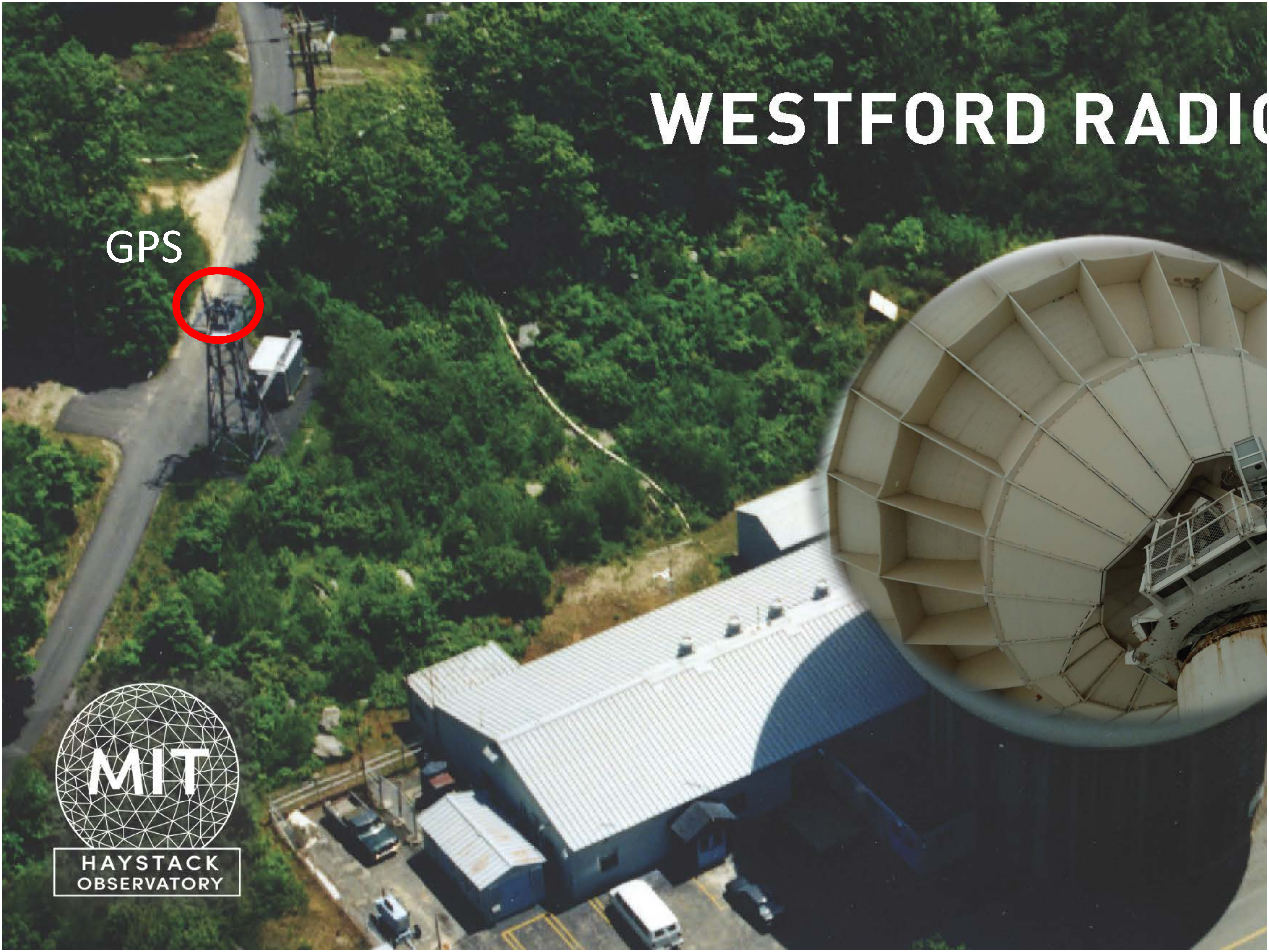
Some of the topics we will cover today

- Geodetic radio telescopes
- VLBI vs. GPS concept
- Station requirements
- VLBI digitization
- Correlation
- Geodetic post-processing, a dynamic planet


VLBI Astrometry
GPS Geodesy
VLBI Geodesy
Arctic Ocean
Westford
KPGO/VGOS


WESTFORD RADIO
GPS
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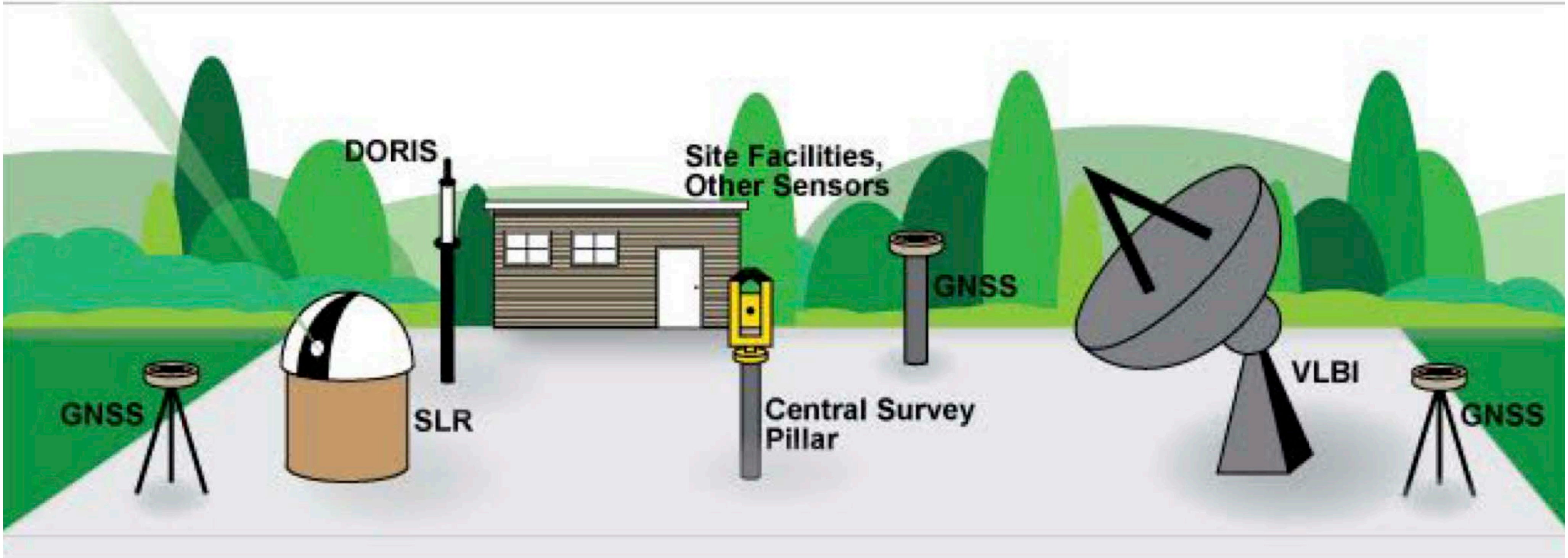
VLBI Global Observing System (VGOS)
Multi-technique core sites



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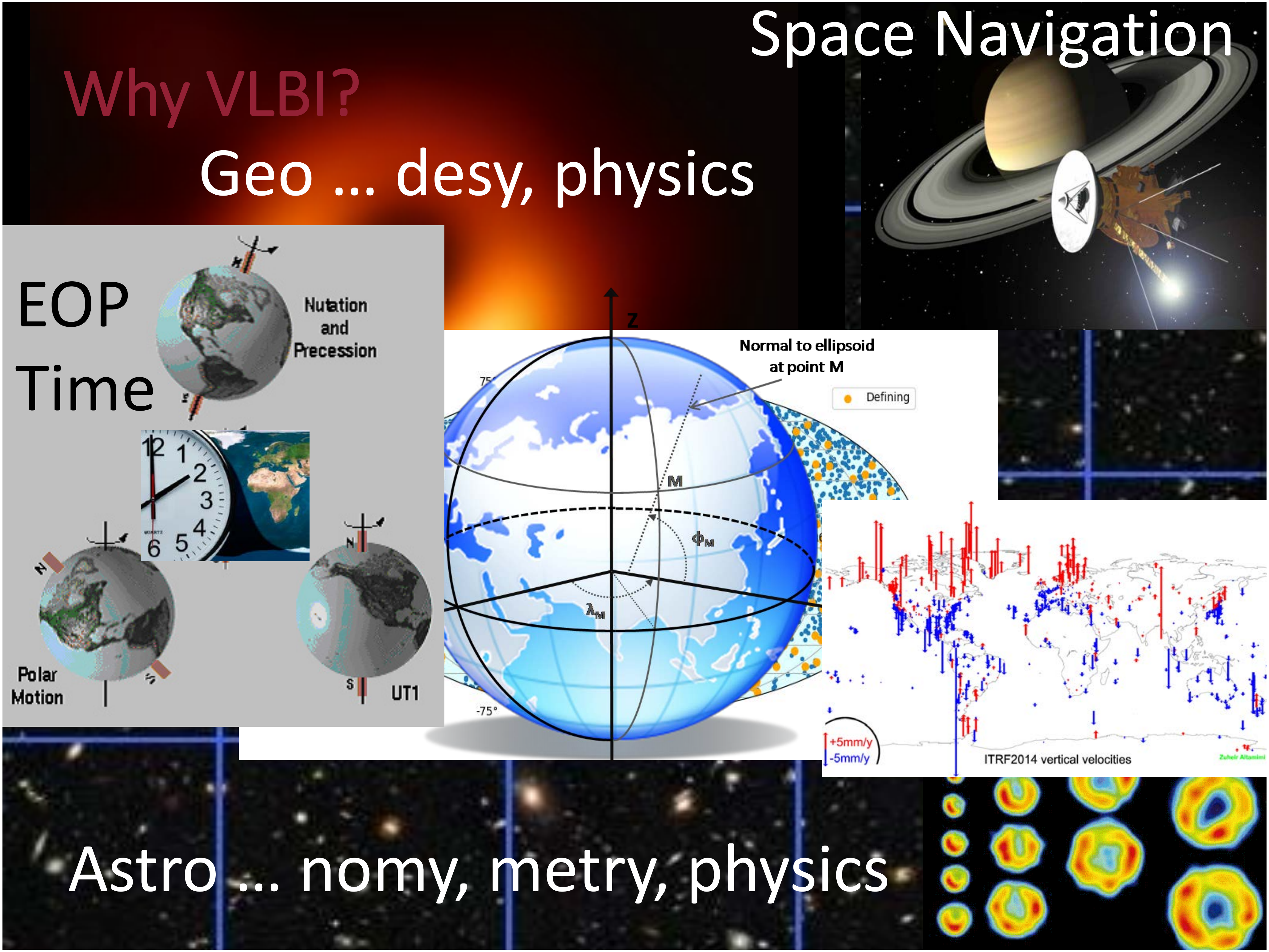
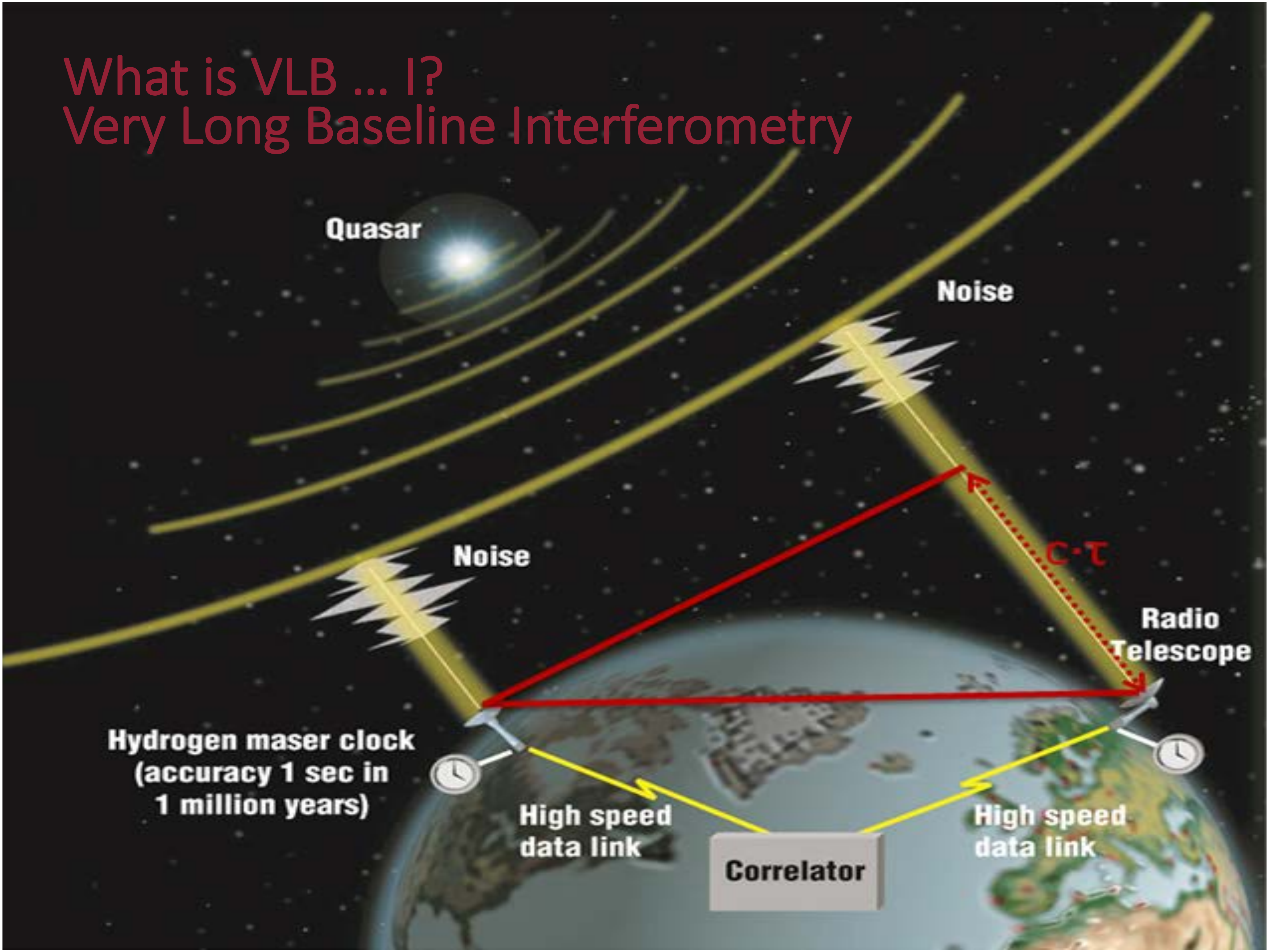


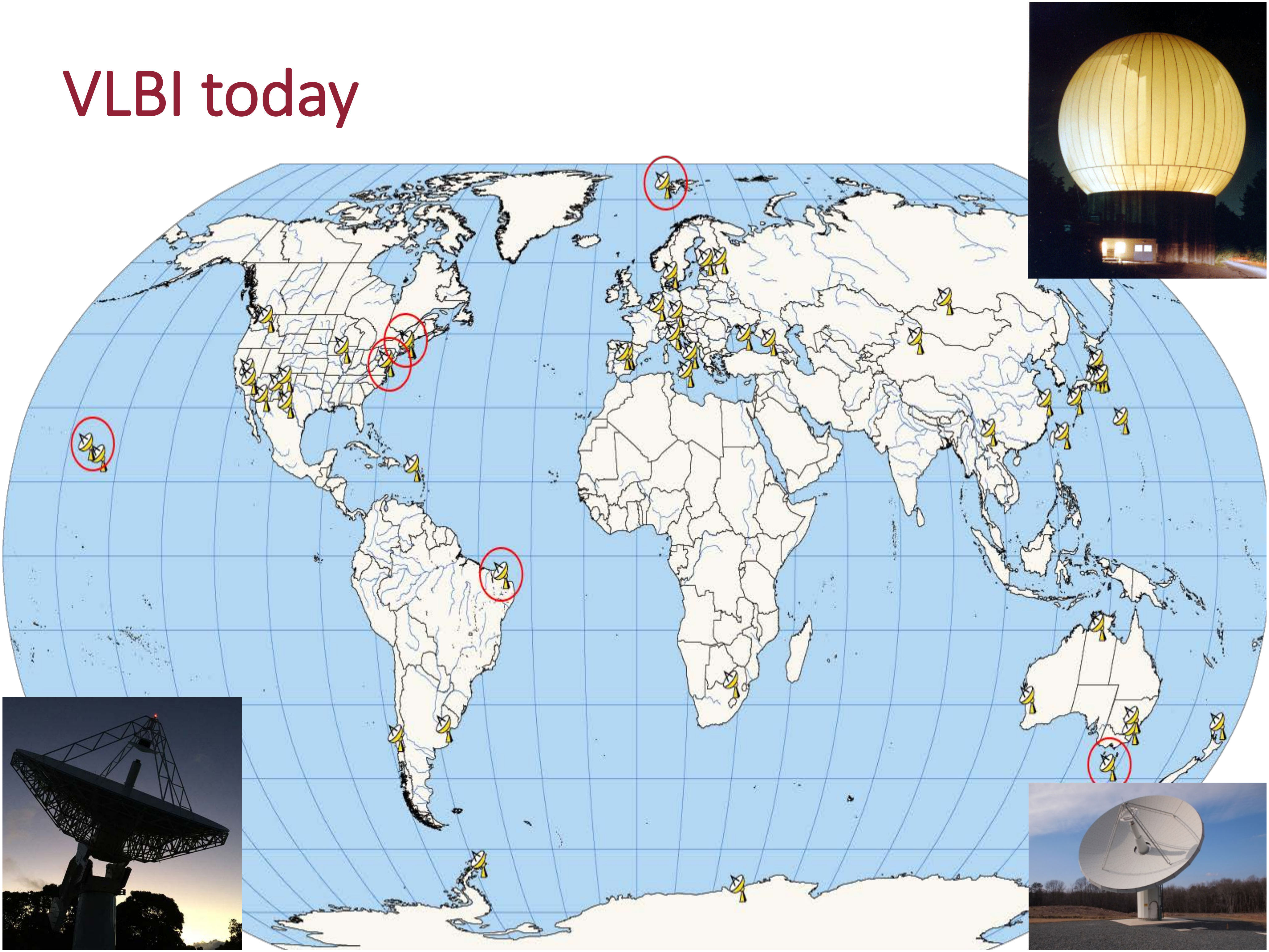
Space Navigation
Why VLBI?
Geo ... desy, physics
EOP
Time
Nutation and Precession
Polar Motion
UT1
Normal to ellipsoid at point M
Defining
M
ITRF2014 vertical velocities
+5mm/y
-5mm/y
Astro ... nomy, metry, physics

What is VLB … A/I?

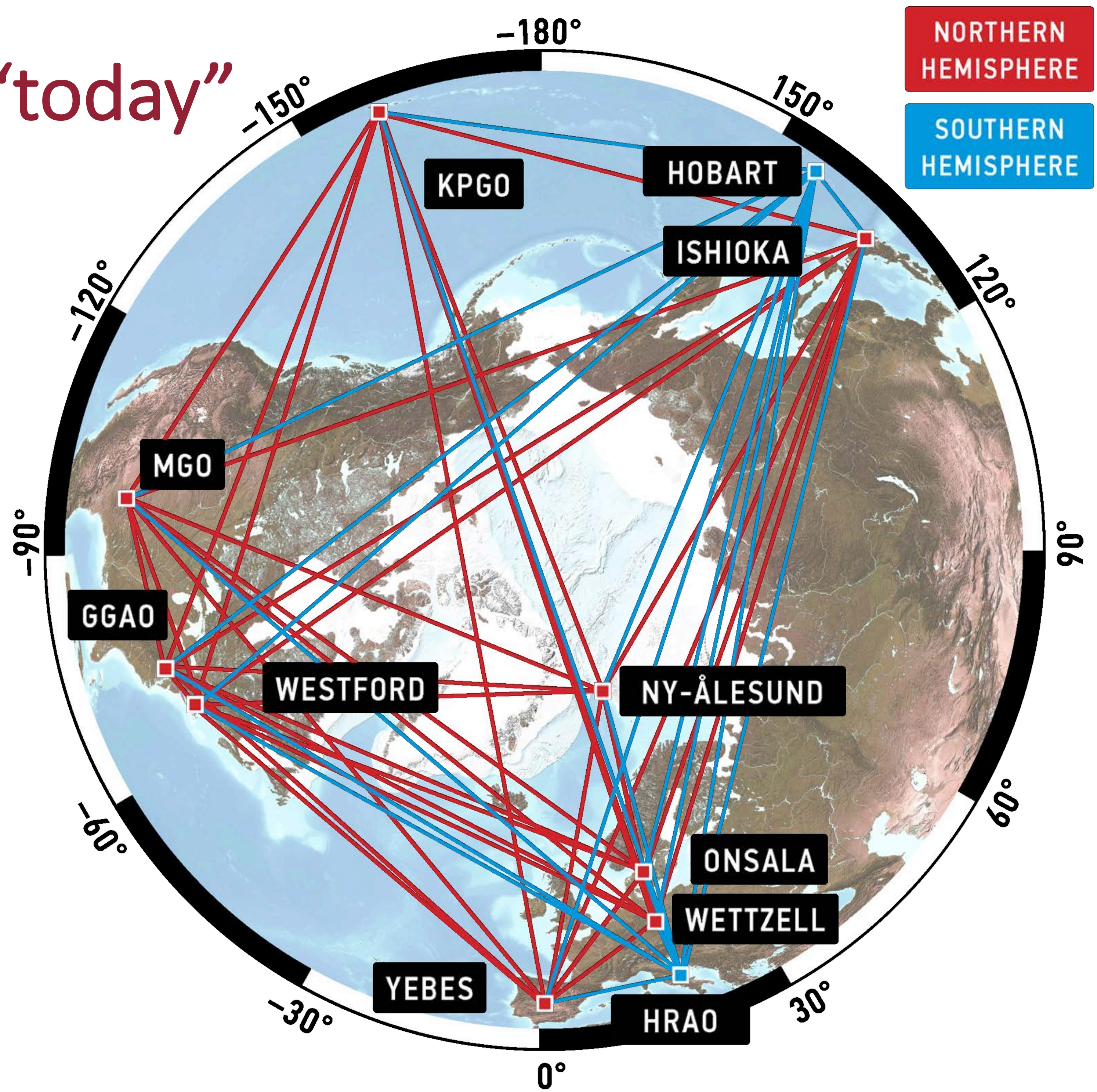
What is VLB … I?
Very Long Baseline Interferometry



VLBI today



VGOS “today”

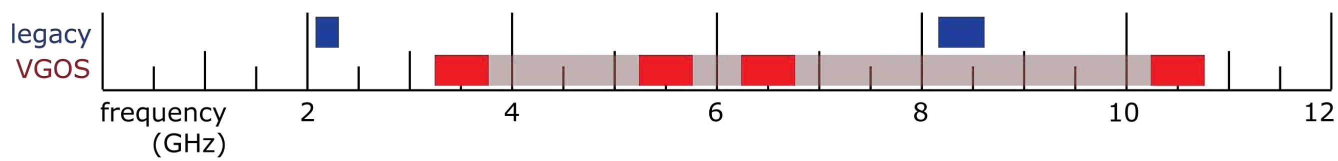


NORTHERN HEMISPHERE
SOUTHERN HEMISPHERE
−180°
−150°
150°
−120°
120°
−90°
90°
−60°
60°
−30°
30°
0°
KPGO
HOBART
ISHIOKA
MGO
GGAO
WESTFORD
NY-ÅLESUND
ONSALA
WETTZELL
YEBES
HRAO

VGOS virtues (vs. "legacy") in a nutshell

Small, fast, rigid
(improved errors)

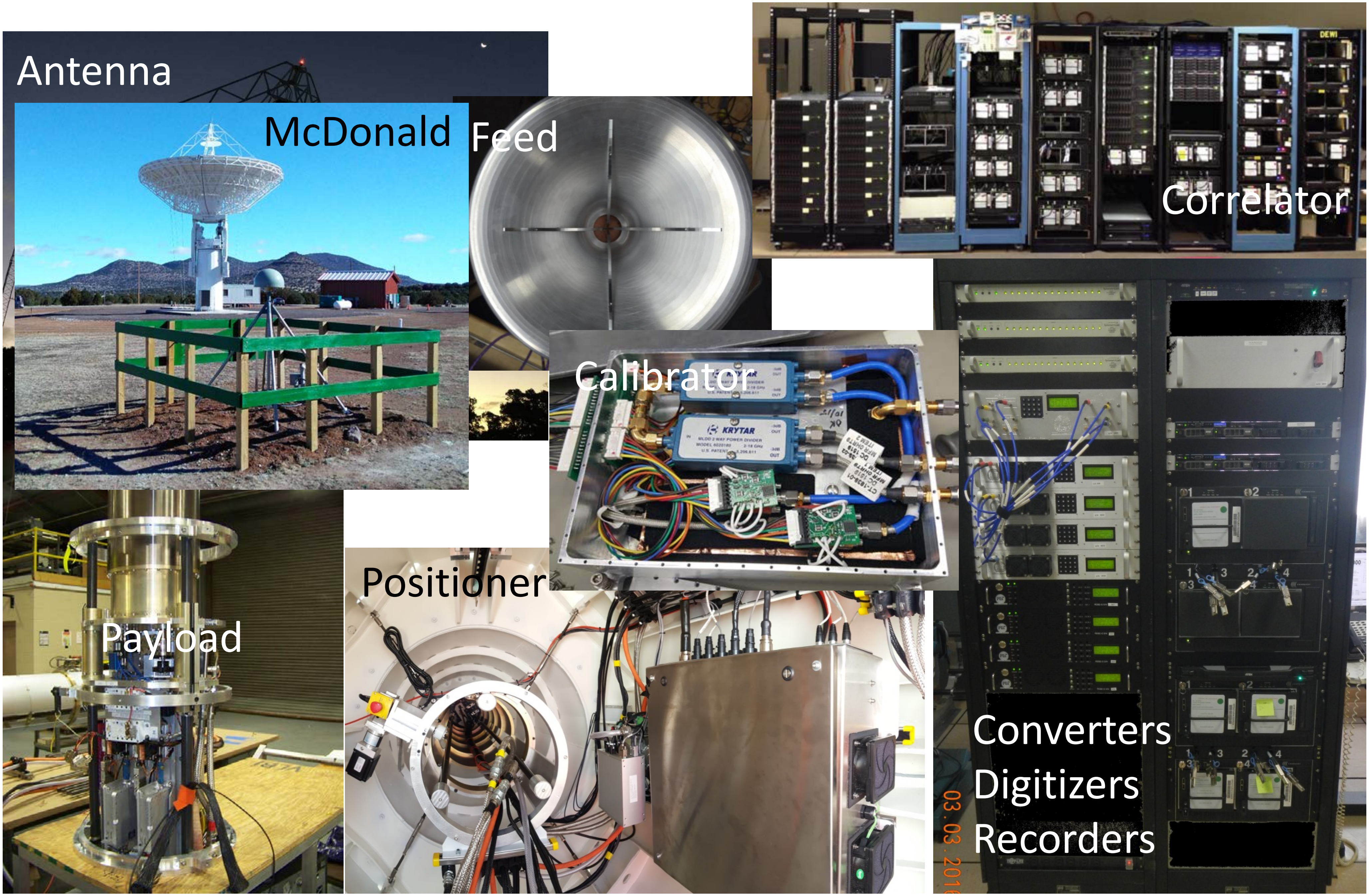
Broad bandwidth
(better sensitivity)



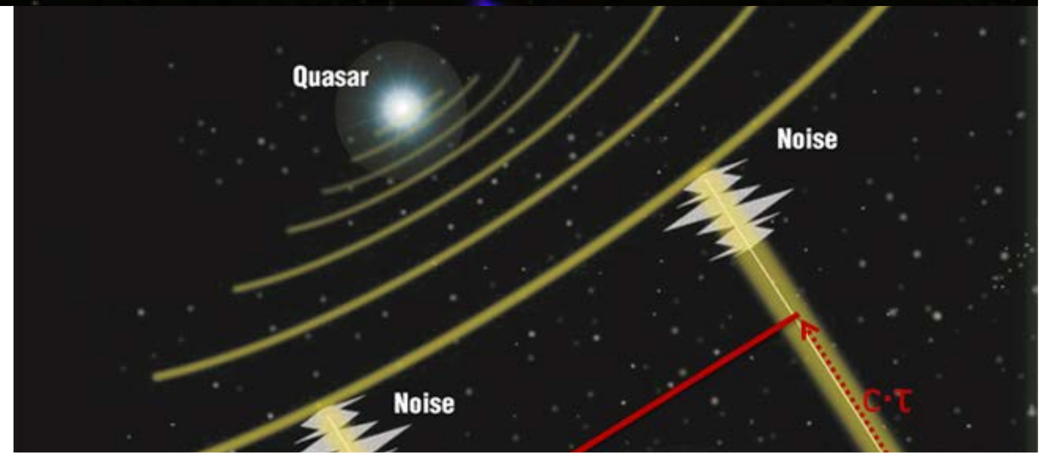
Basic elements of VLBI (geodesy)

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

VLBI (VGOS) station



VLBI

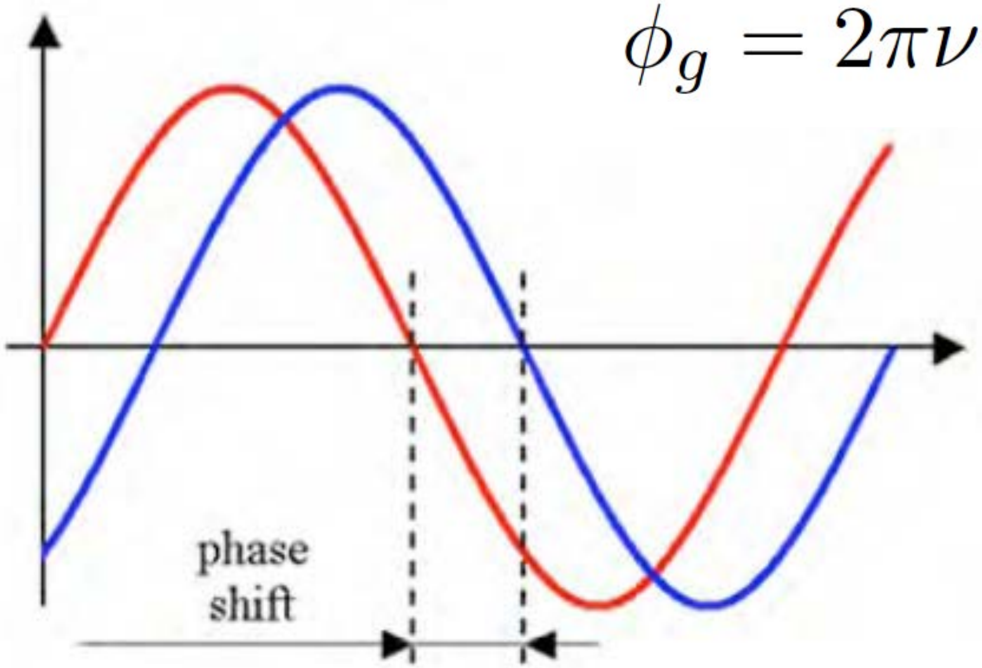


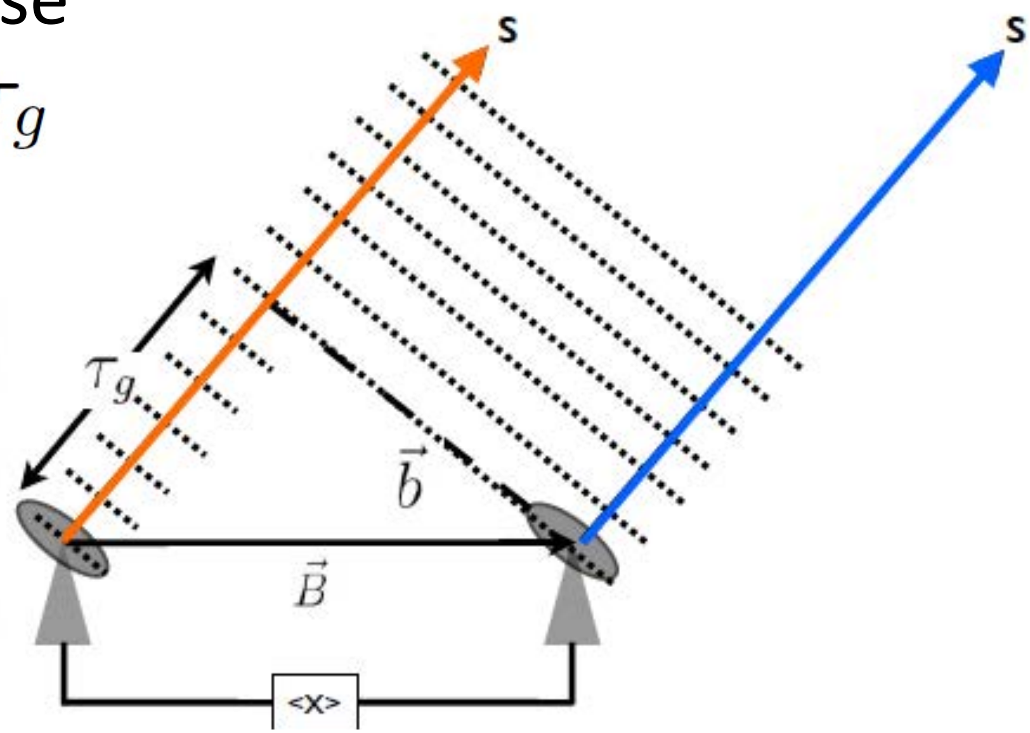
Geometric delay

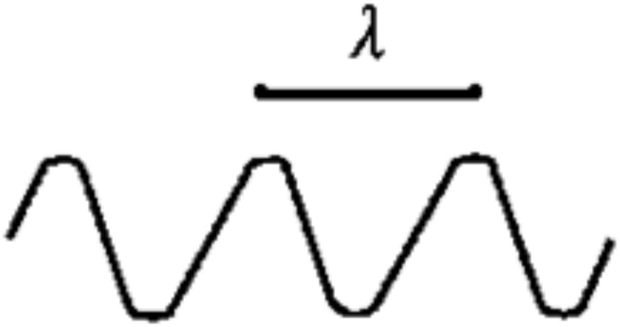
$$\tau_g = \vec{B}.\hat{s}/c$$

Relative phase

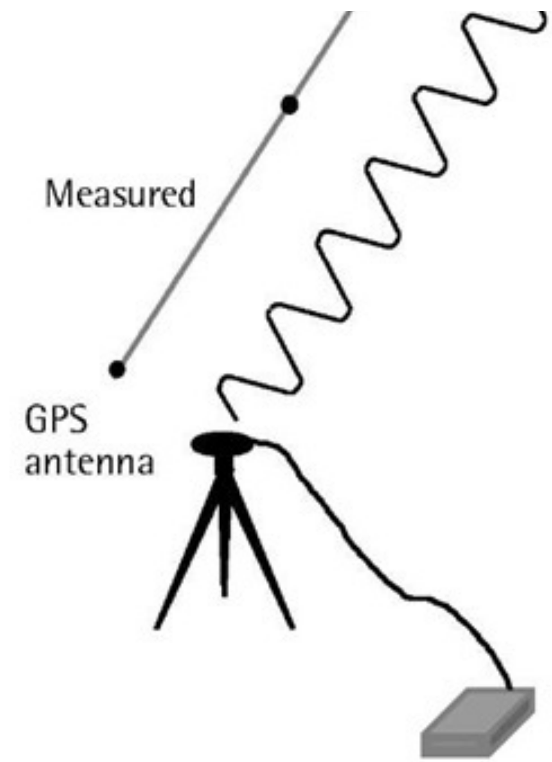
$$\phi_g = 2\pi\nu\tau_g$$

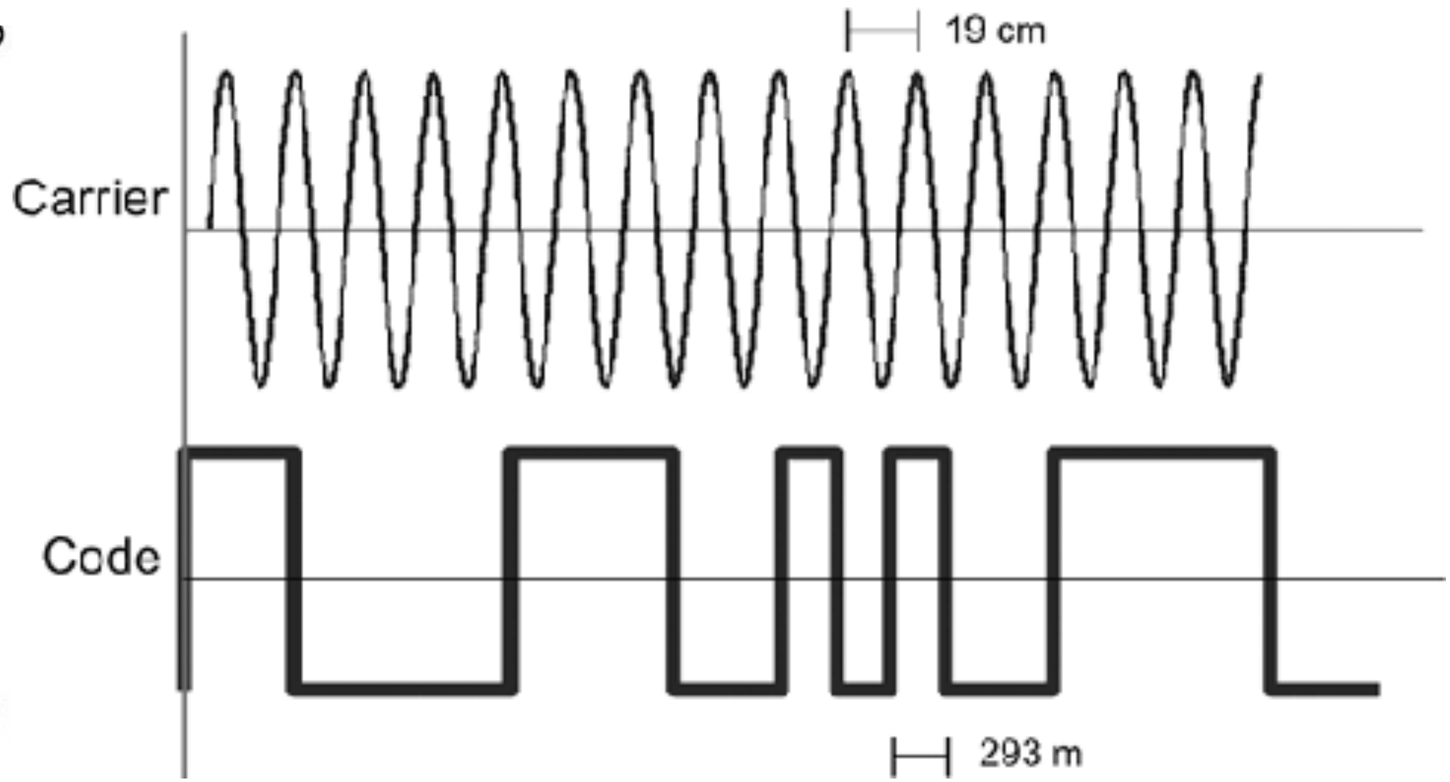





λ

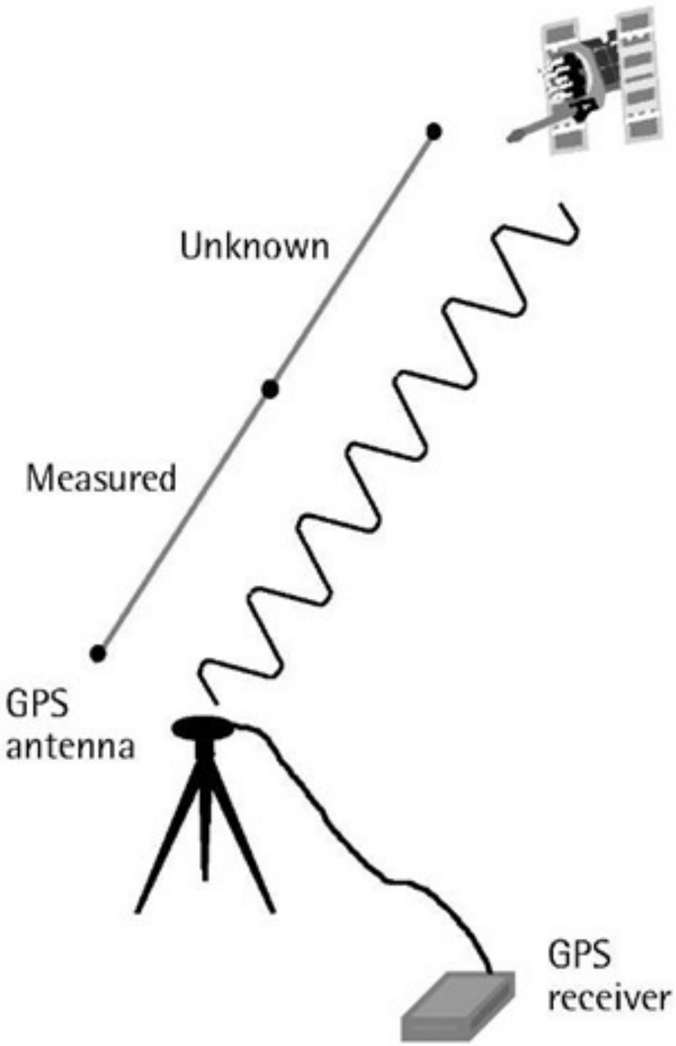

1
0
00001110100110100011100110...

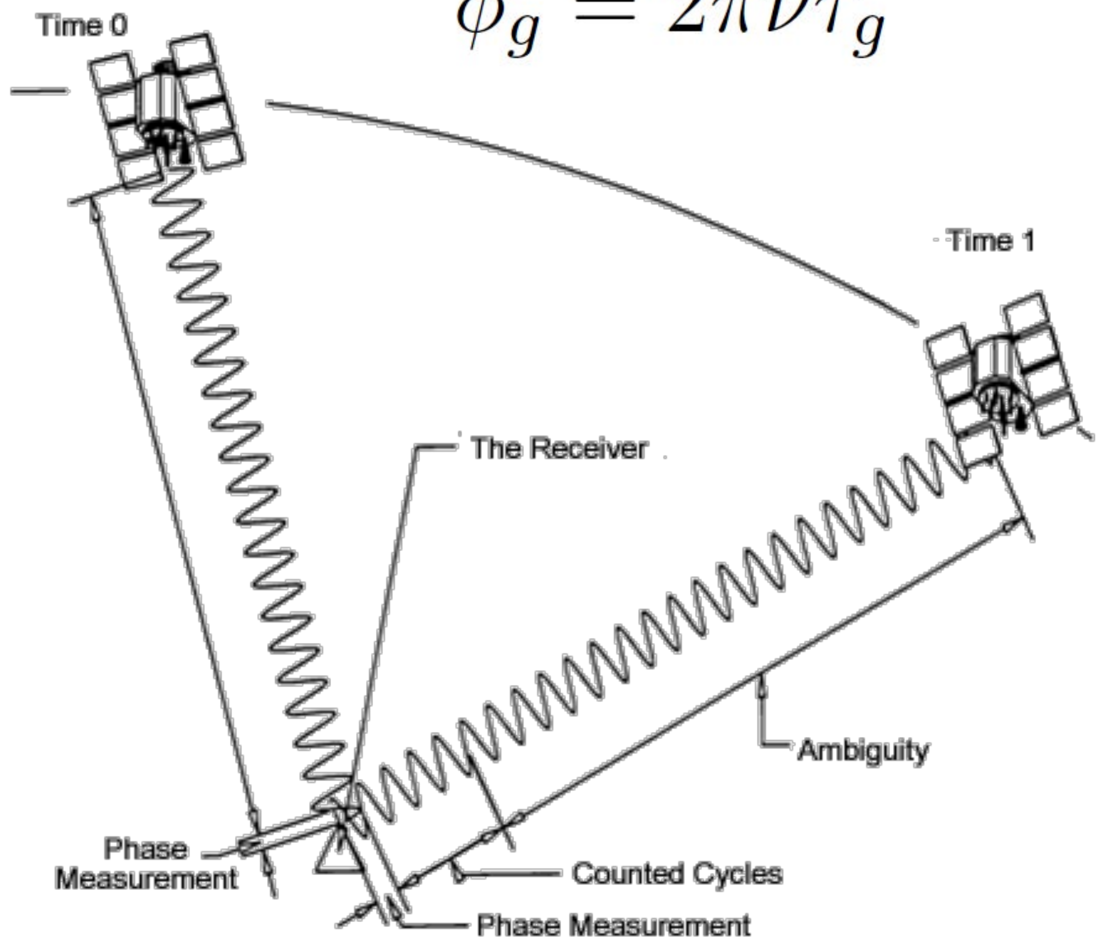

Measured
GPS antenna


19 cm
Carrier
Code
293 m

"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 uncertainty

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

- 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

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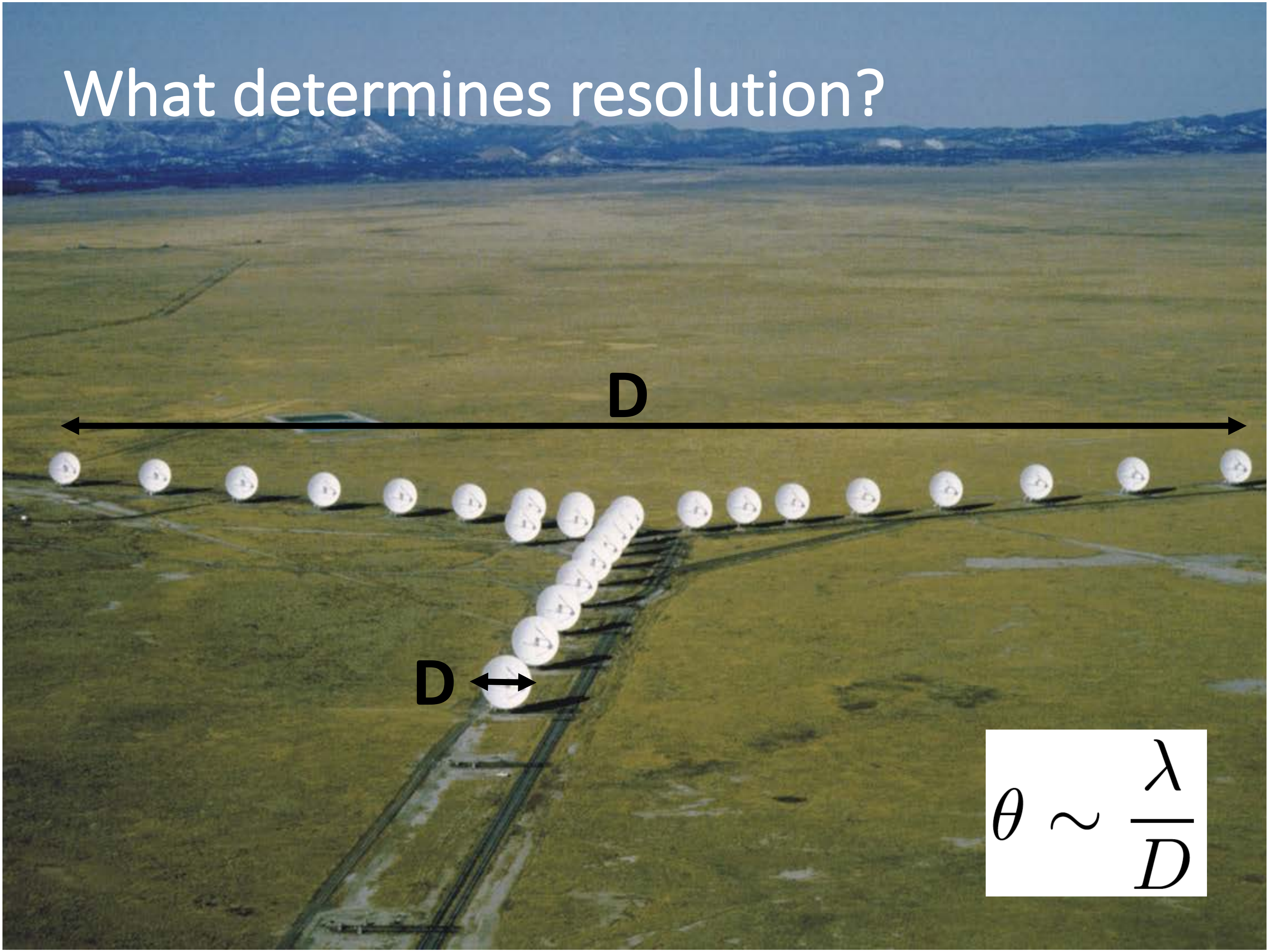
What determines sensitivity?

- 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?
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)

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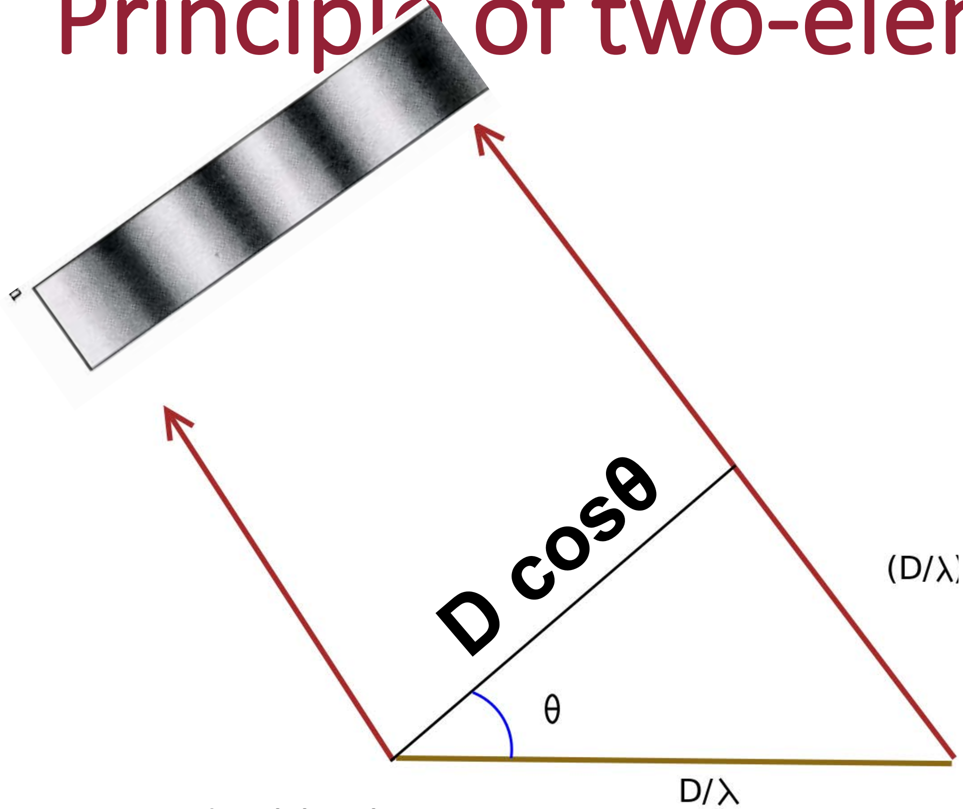
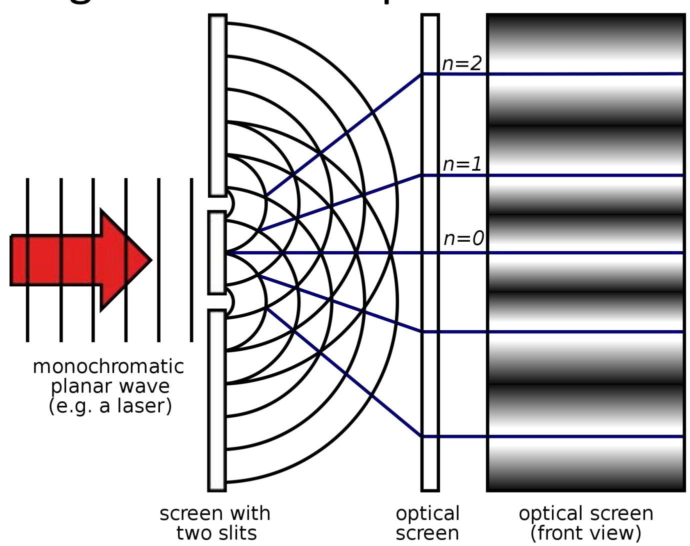
Principle of two-element interferometer

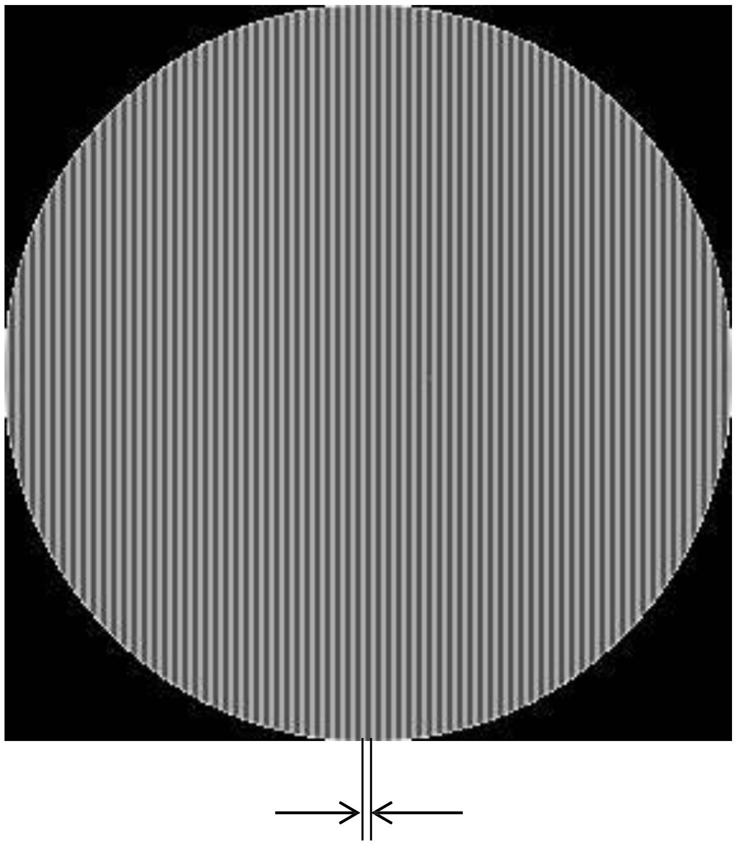


Young double slit experiment

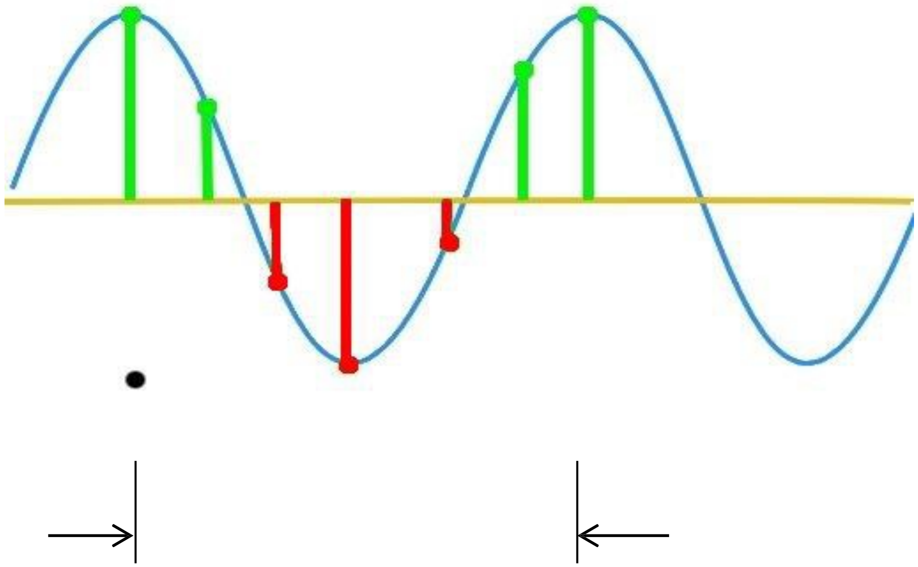


- Projected baseline = D*cos θ
- Fringe-pattern spacing on sky
  - = λ/(projected baseline)
  - = λ/(D*cos θ)
- As source moves, response changes as cos (projection)

Fringe pattern

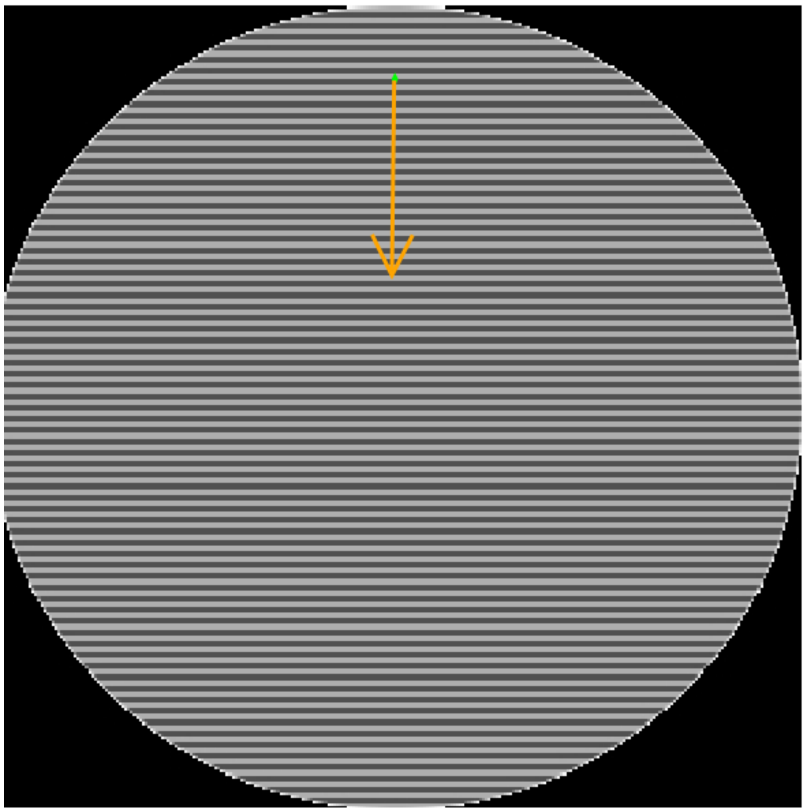


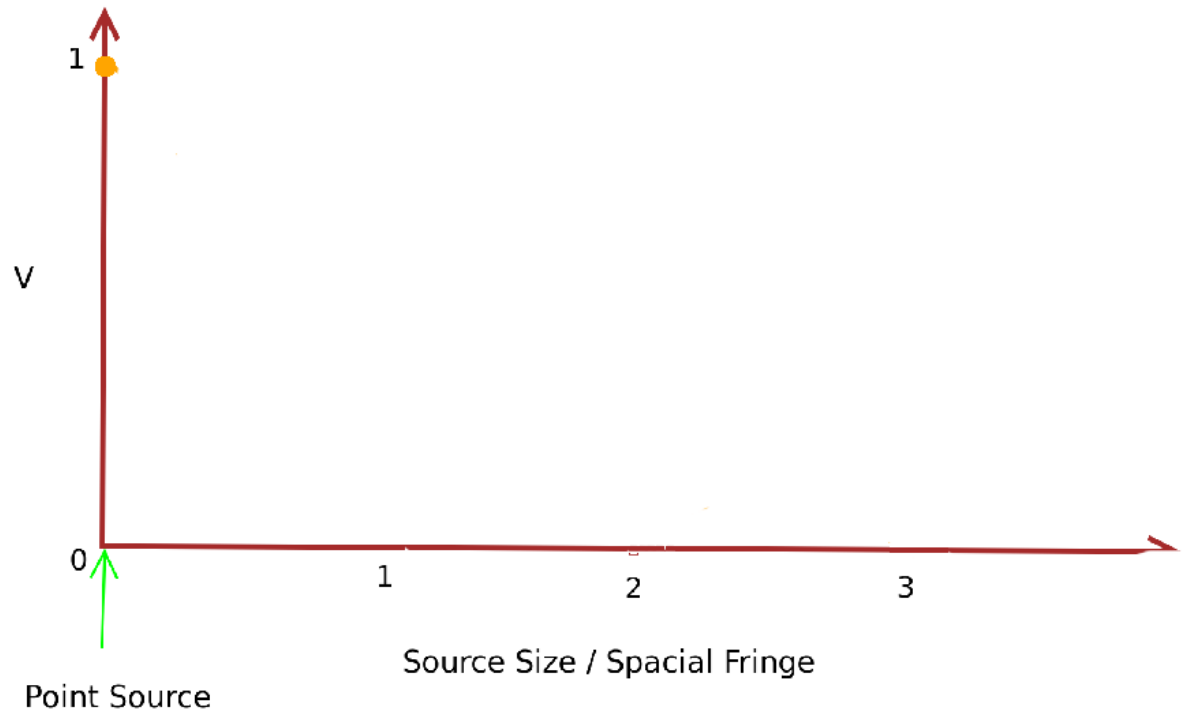
Fringe spacing
λ/(D*cos θ)



Fringe spacing
λ/(D*cos θ)

Interferometric response to point source





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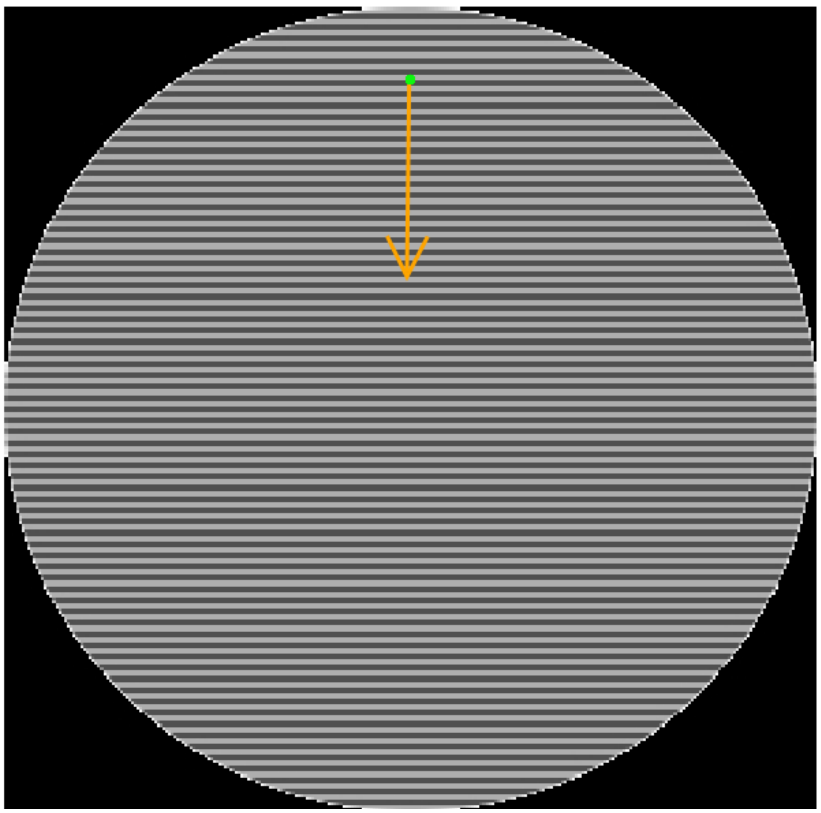
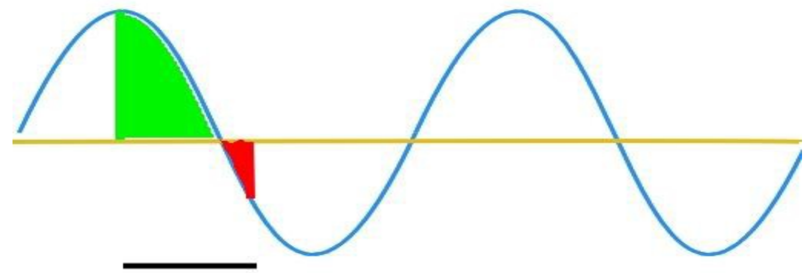
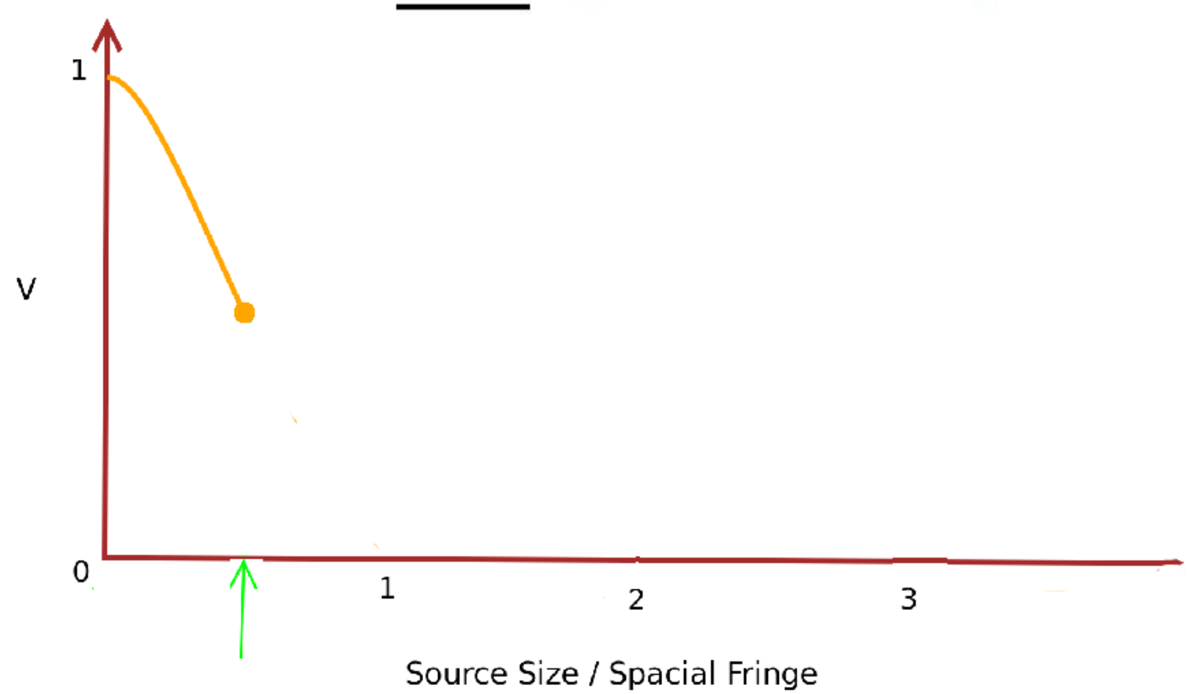
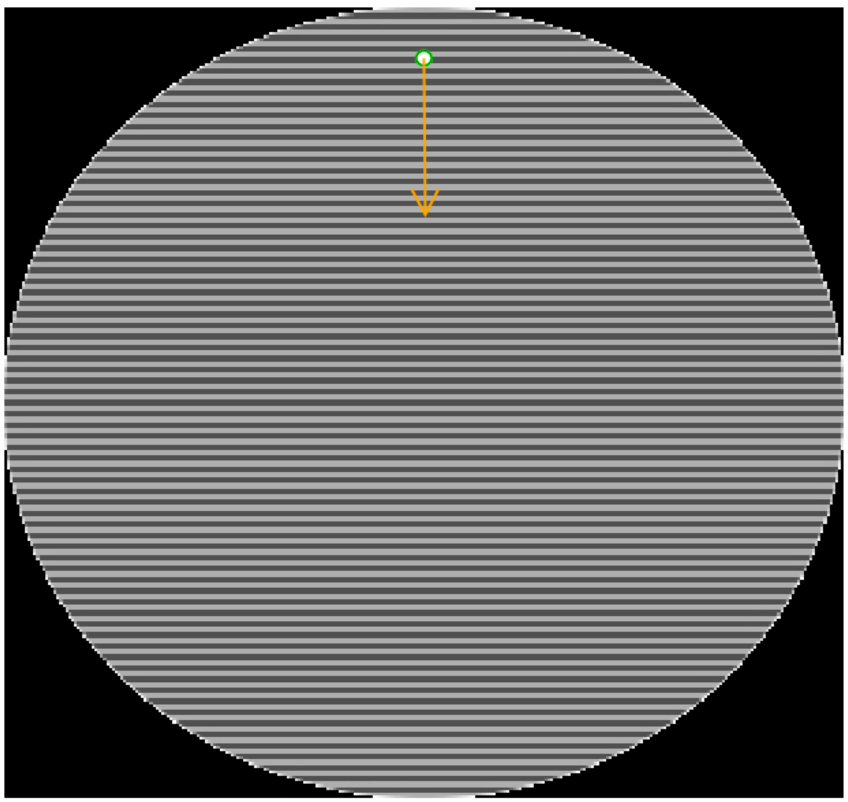
Extended radio source

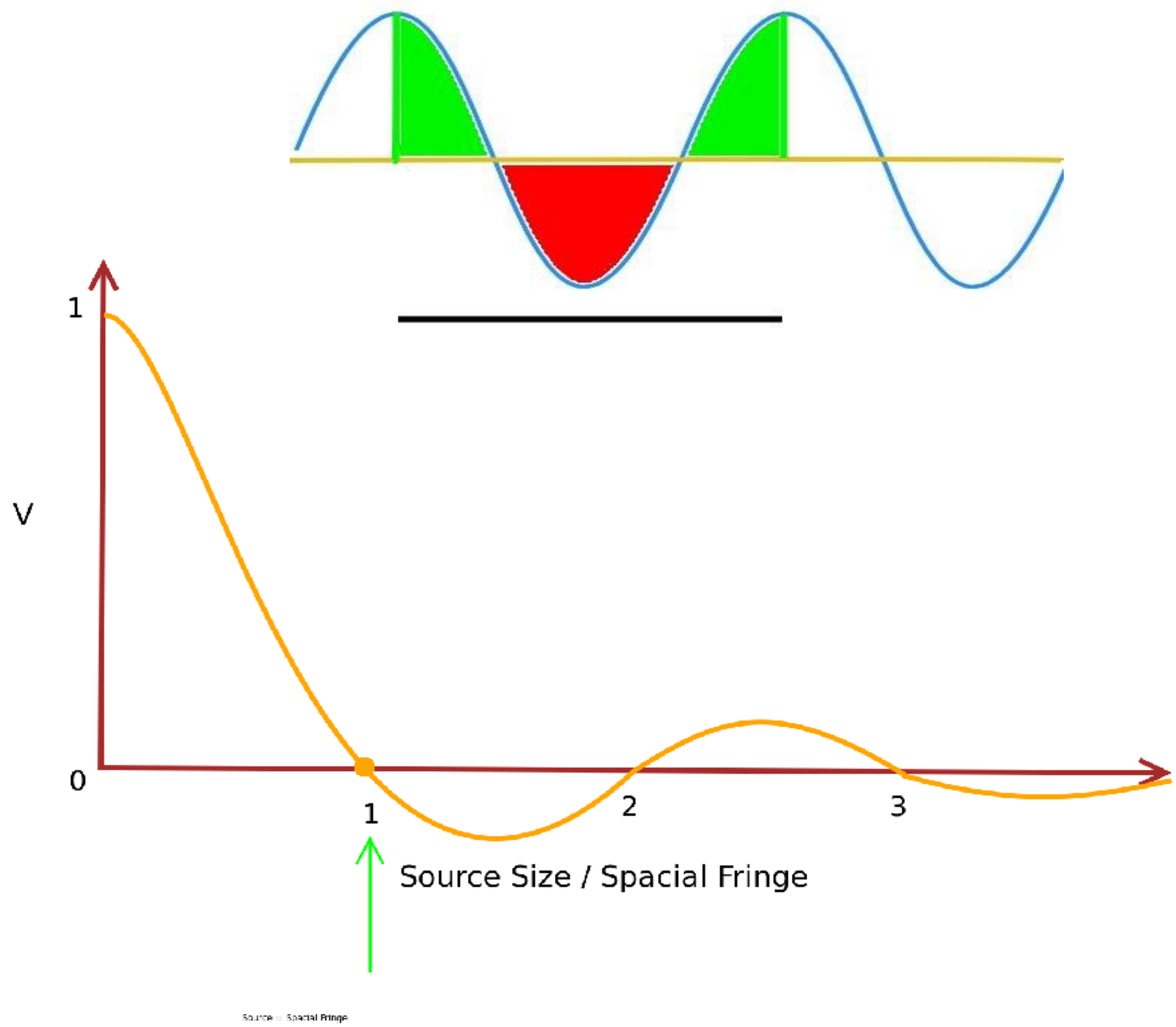






Extended radio source (one fringe width)

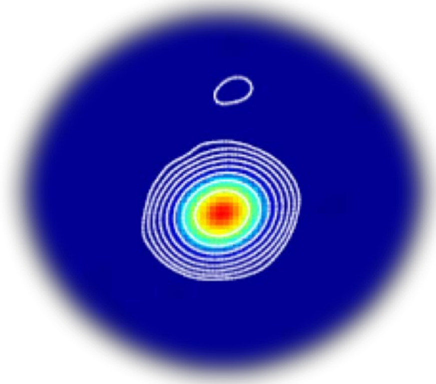




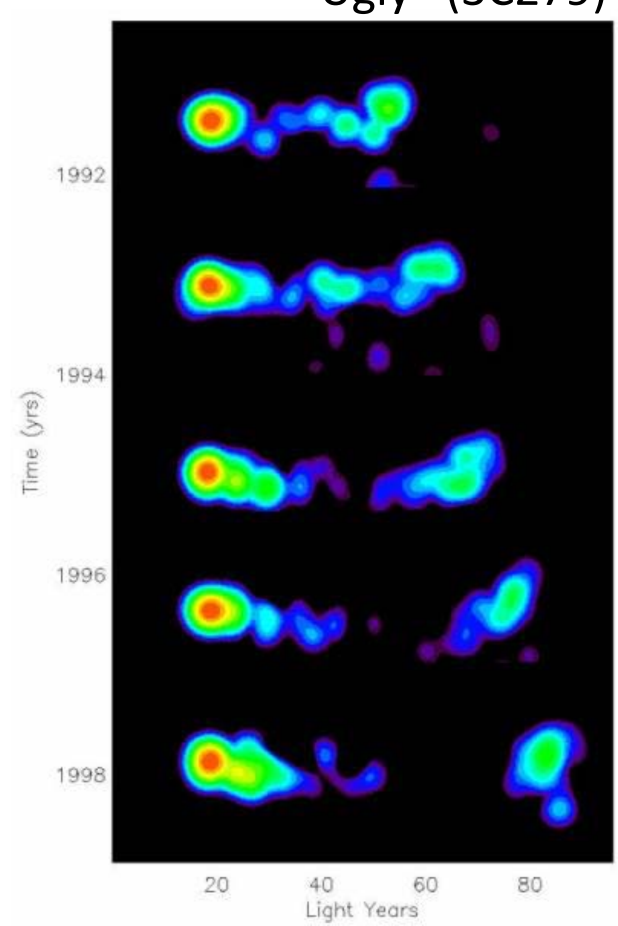
Geodetic VLBI radio sources

- 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)



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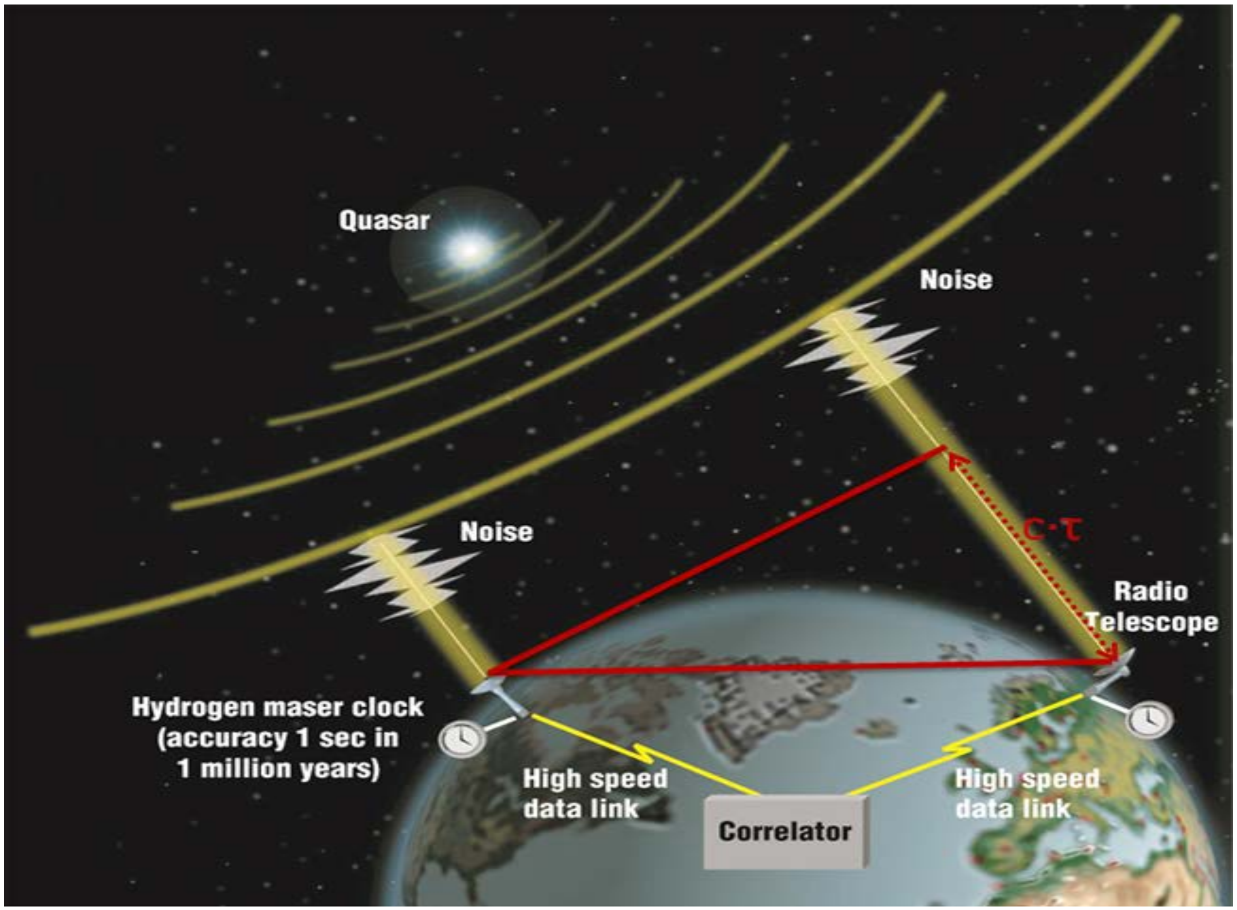
Principle of (geodetic) VLBI

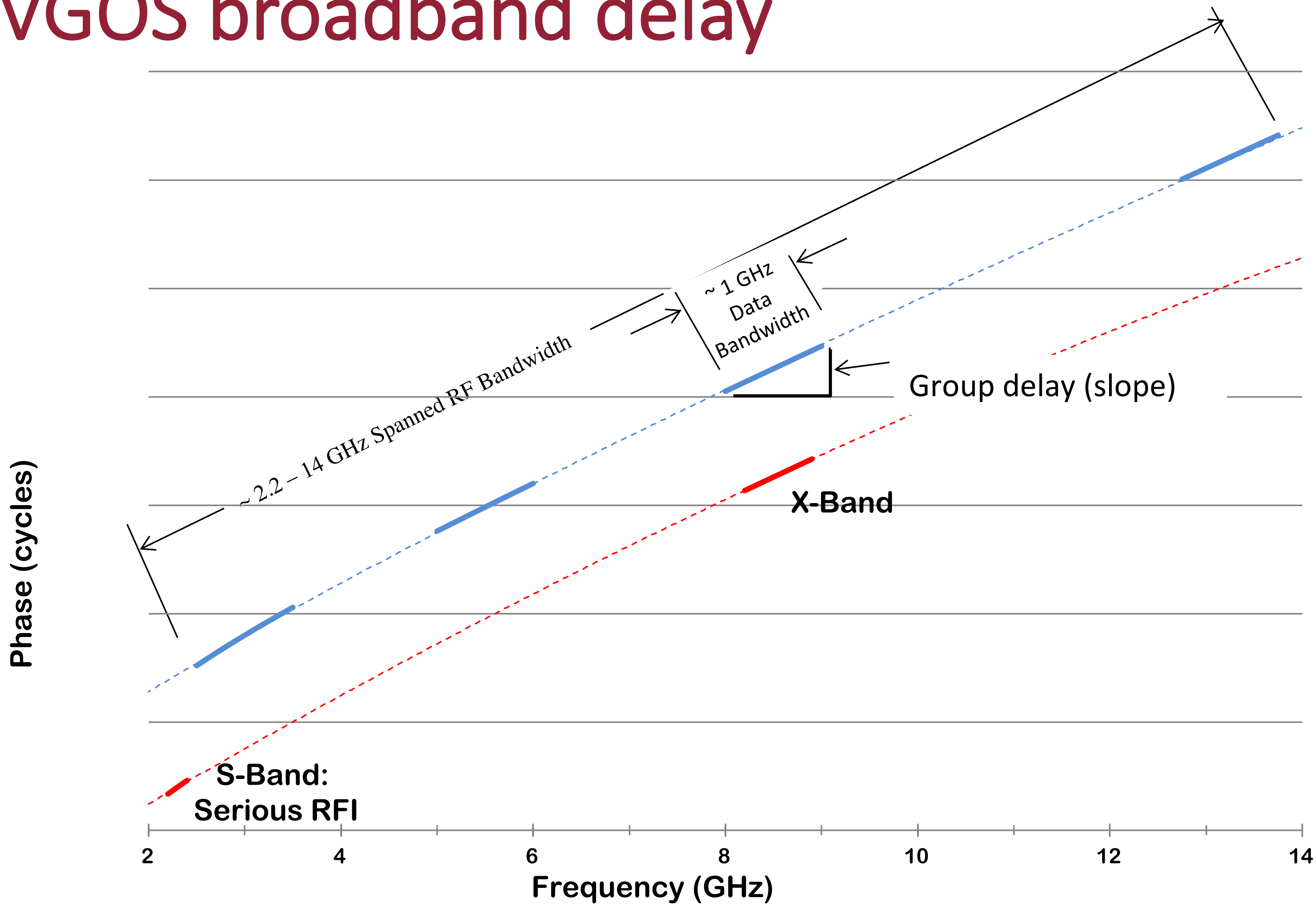


- Measure time-of-arrival difference (delay) accurately
- mm-level positioning requires delay precision of a few picoseconds (3 ps = 1 mm)

VLBI station requirements

- Observing "noise" from quasars (contaminated by various noise sources)
- Measuring a (group) delay (a time measurement) whose resolution 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



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

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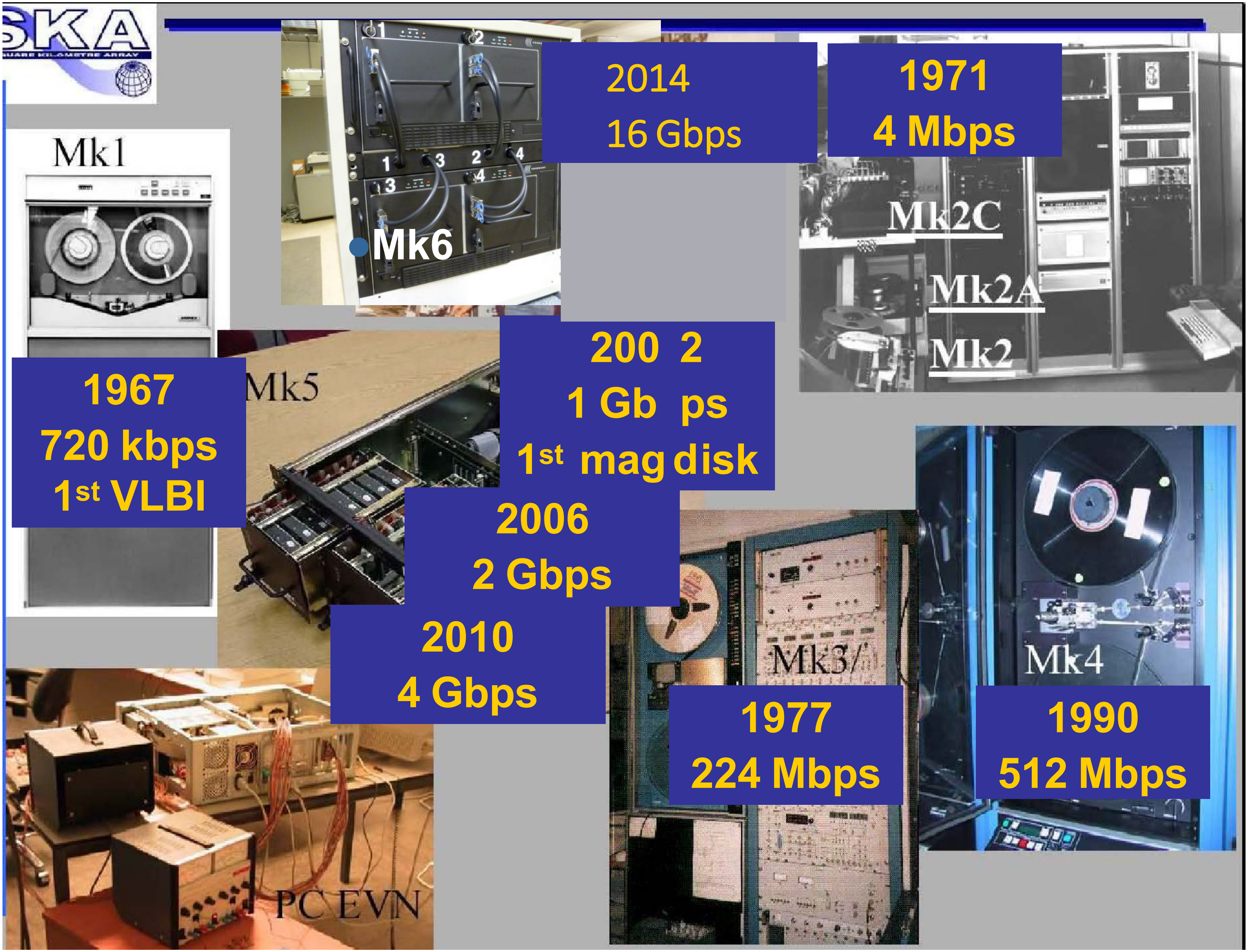

SKA
Mk6
2014
16 Gbps
1971
4 Mbps
Mk1
Mk2C
Mk2A
Mk2
1967
720 kbps
1st VLBI
Mk5
2002
1 Gbps
1st mag disk
2006
2 Gbps
2010
4 Gbps
Mk3/
Mk4
1977
224 Mbps
1990
512 Mbps
PC EVN

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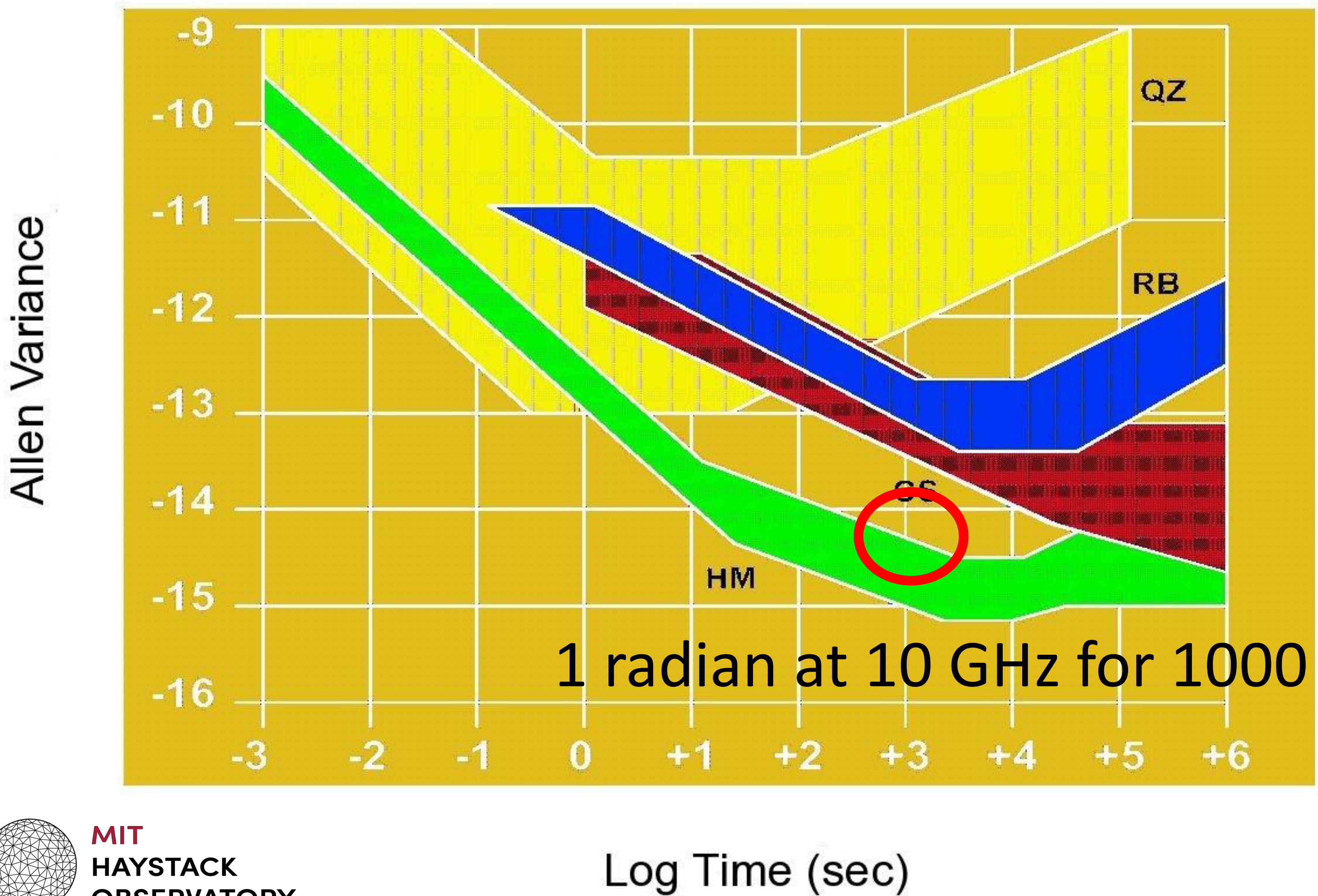
  - Hydrogen maser frequency standards

Stability of various frequency standards



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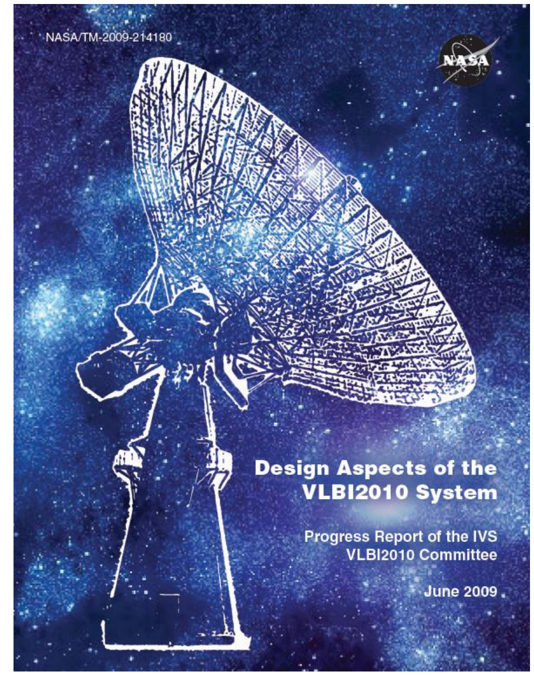
  - Antennas that are large, efficient, and fast (atmosphere)
  - High-speed recording for high SNR via large bandwidth (Nyquist)
  - Hydrogen maser frequency standards
  - Accurate time synchronization (to ~300 nsec with GPS time)
  - Instrumental calibrations (cable delays and phase calibration)

Legacy-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



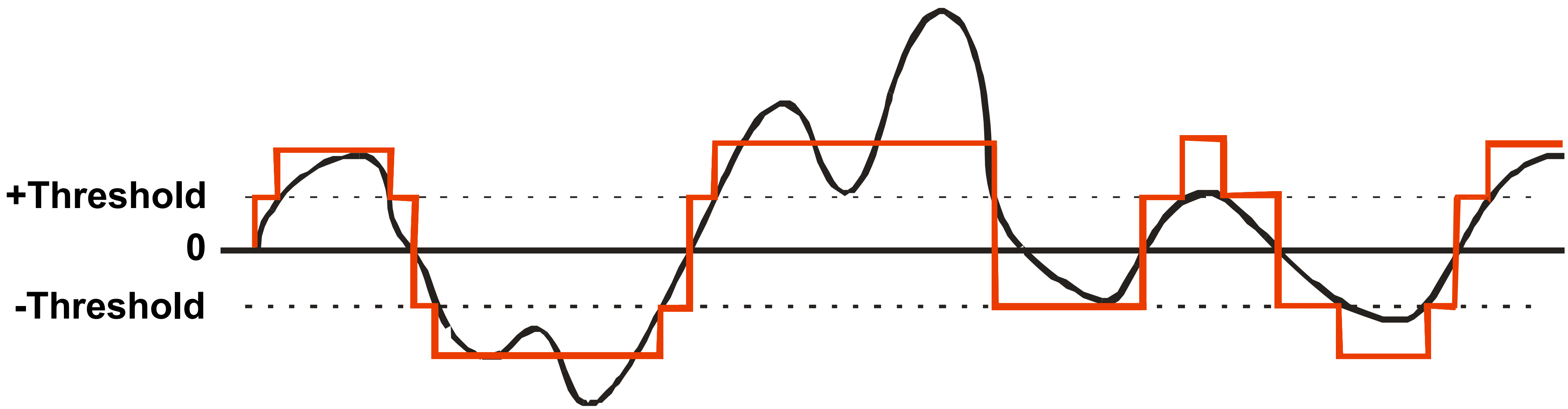
ftp://ivscc.gsfc.nasa.gov/pub/misc/V2C/TM-2009-214180.pdf

What data are recorded?

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

Build an array from individual telescopes

- To summarize:

  - Incredibly faint noise sources are observed by systems that are 1000x noisier

  - Limited ability to expand the bandwidth (sampler/recorder limitations)

  - Short integration times (clock behavior, recorder limits, fast moving antennas in VLBI geodesy)

Correlator

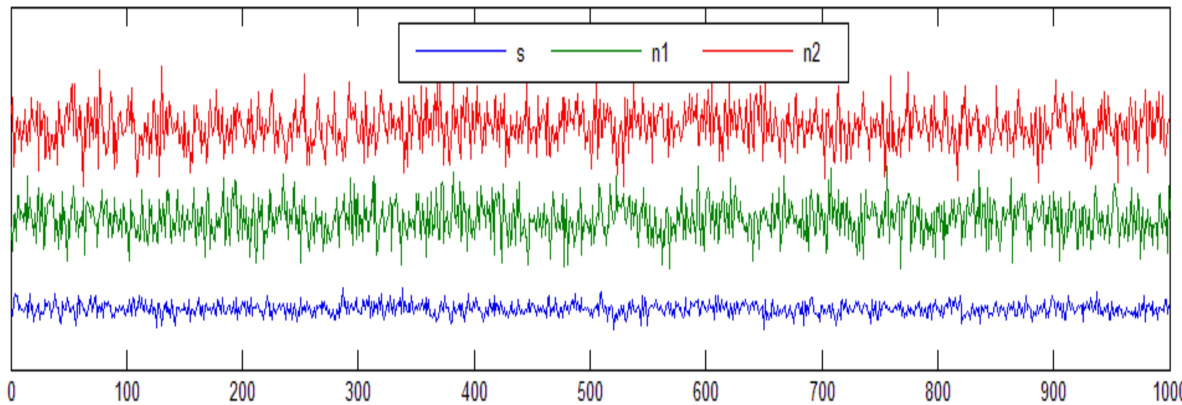
- Multiplies and accumulates noisy signals from the individual telescopes to pull the signal from the noise, thus forming a large Earth-size array

Cross-correlation of weak signal

Receiver 1 noise $n_1(t)$

Receiver 2 noise $n_2(t)$

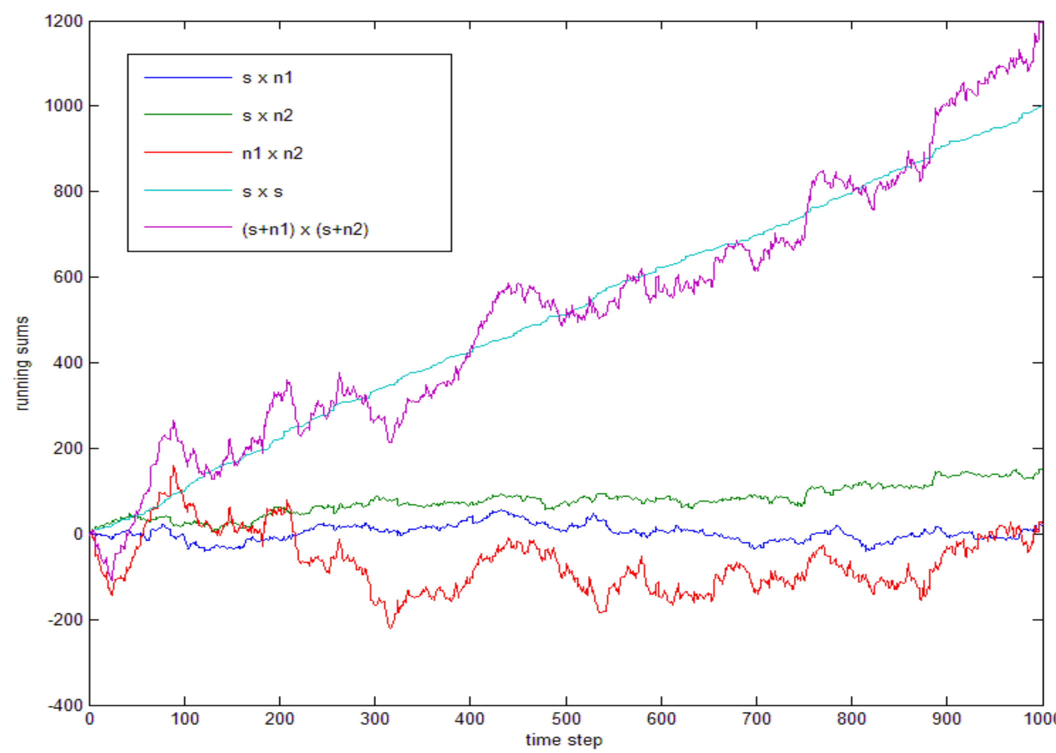
Signal s(t)



Correlation is product and accumulation

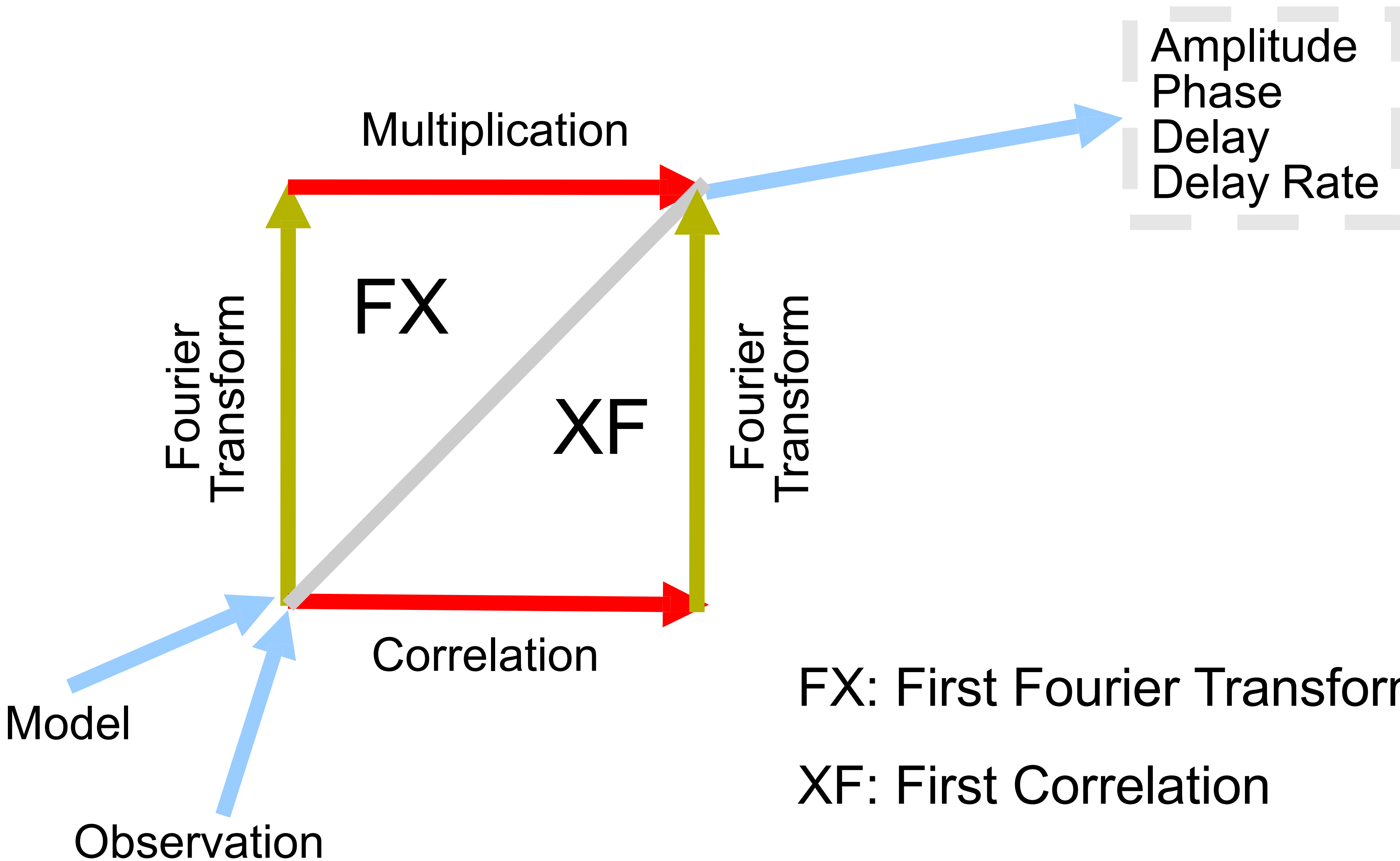
$(s + n_1)(s + n_2) =$

$s^2 + n_1 s + n_2 s + n_1 n_2$



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

Correlators: two flavors of processors

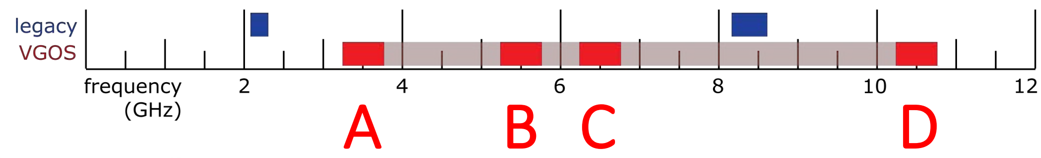


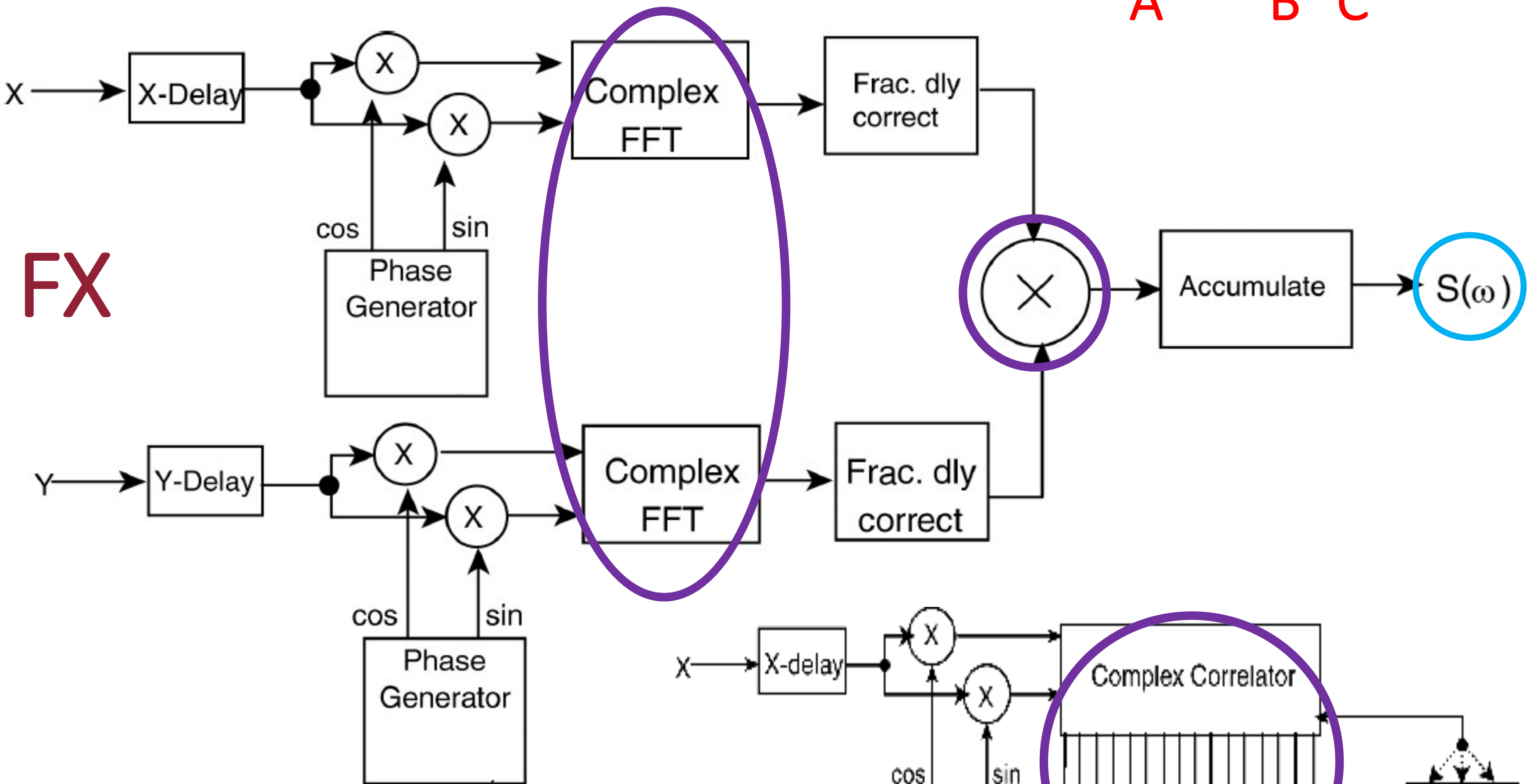
FX: First Fourier Transform

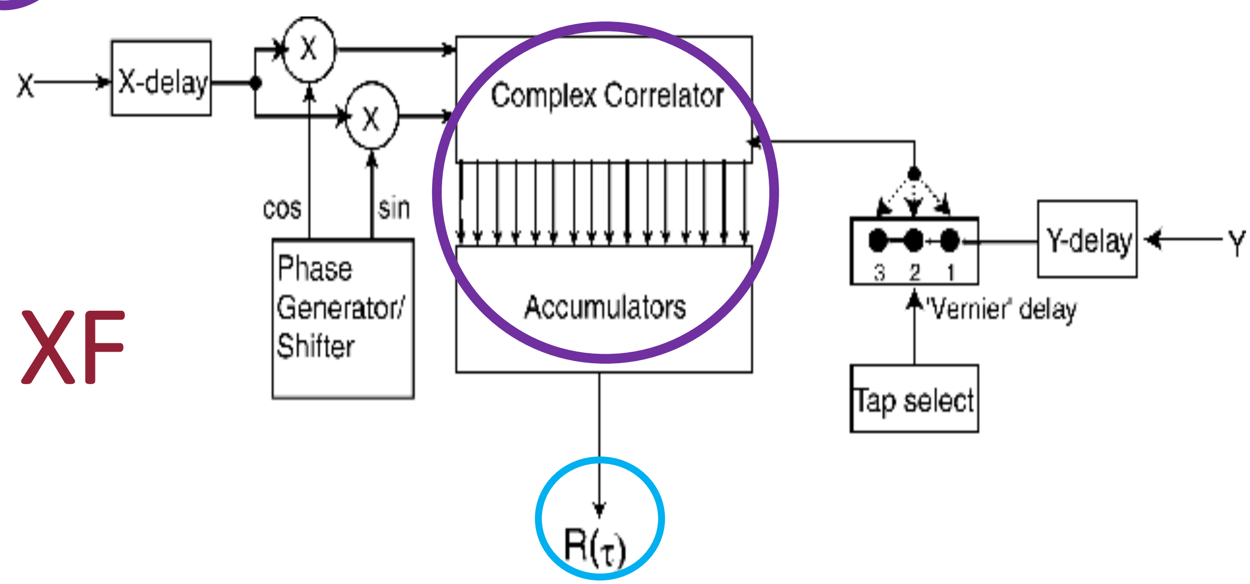
XF: First Correlation

Correlator channel

VGOS: 8 channels/band x 4 bands







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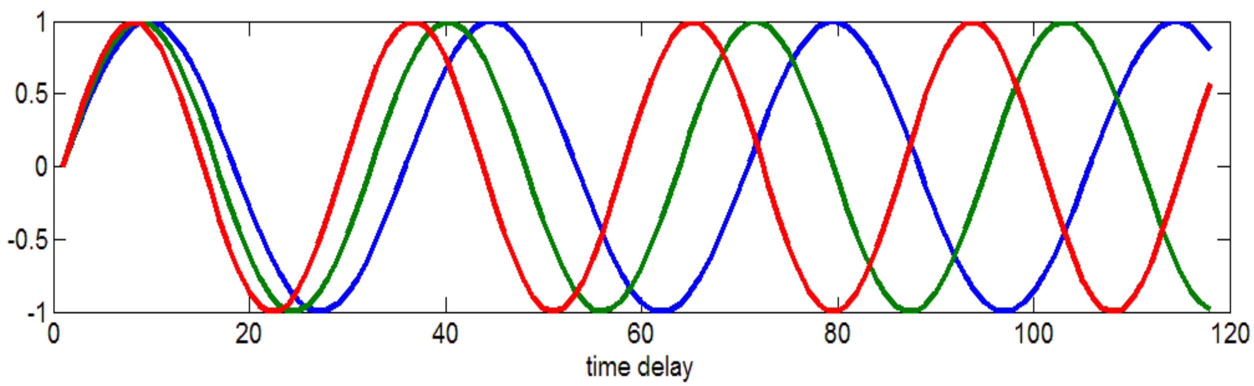
Combine channels: “Bandwidth Synthesis”

The goal is to measure the group delay, defined as $d\theta/d\omega$

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:



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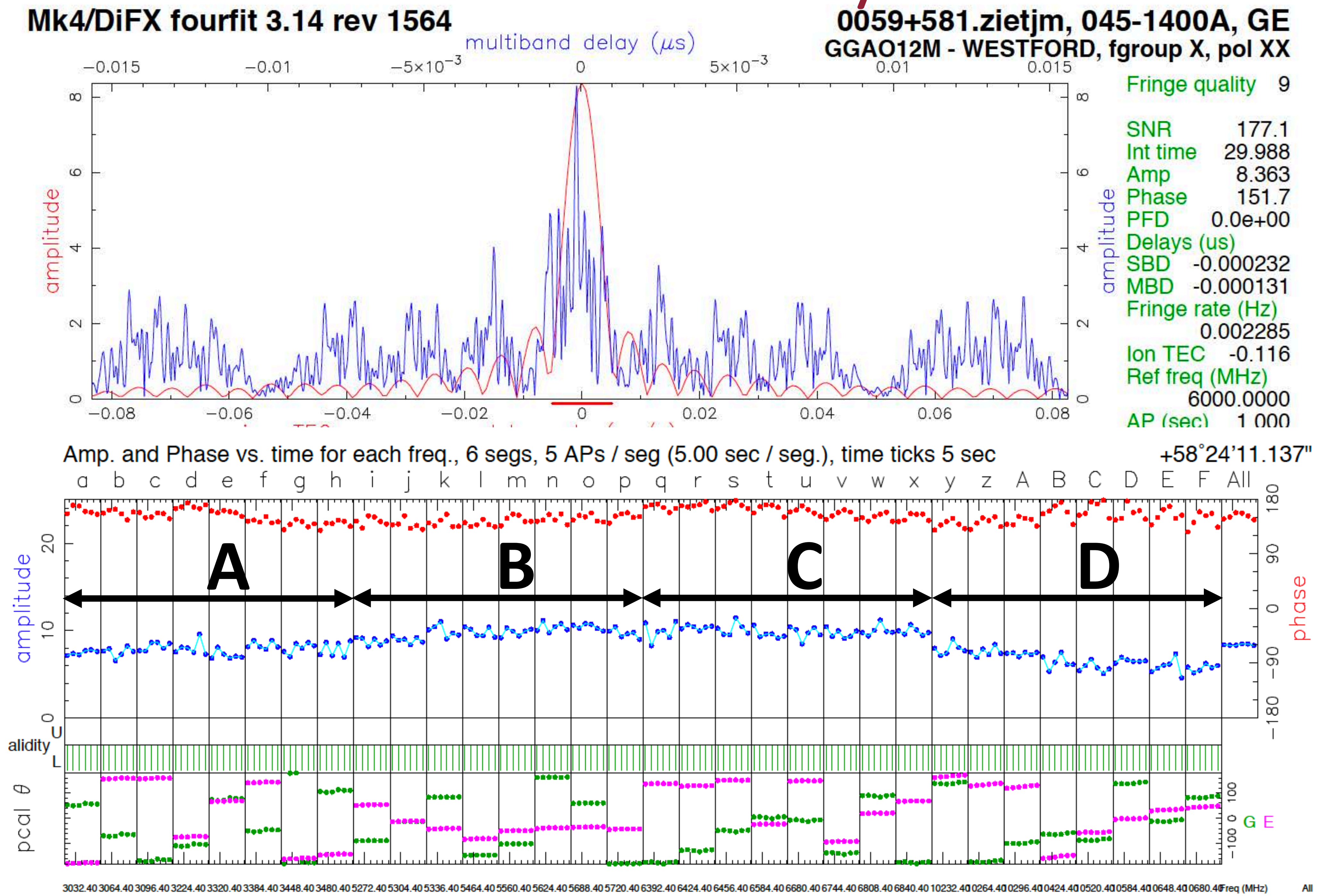
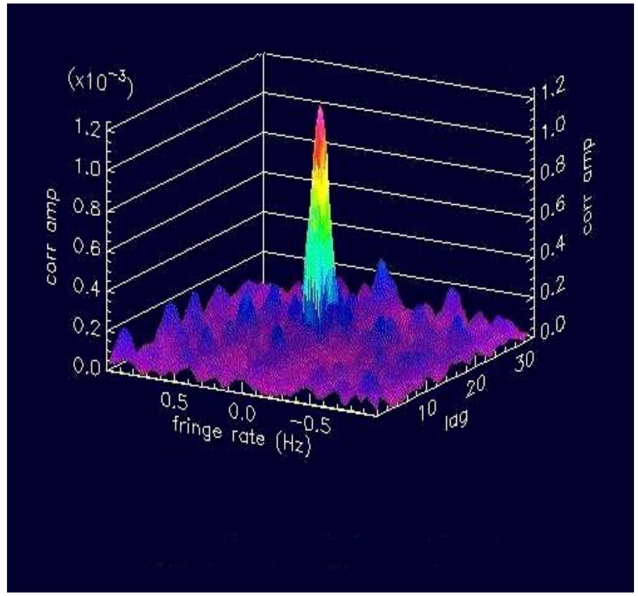
Multiband delay



The final result: FRINGES!!!



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

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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

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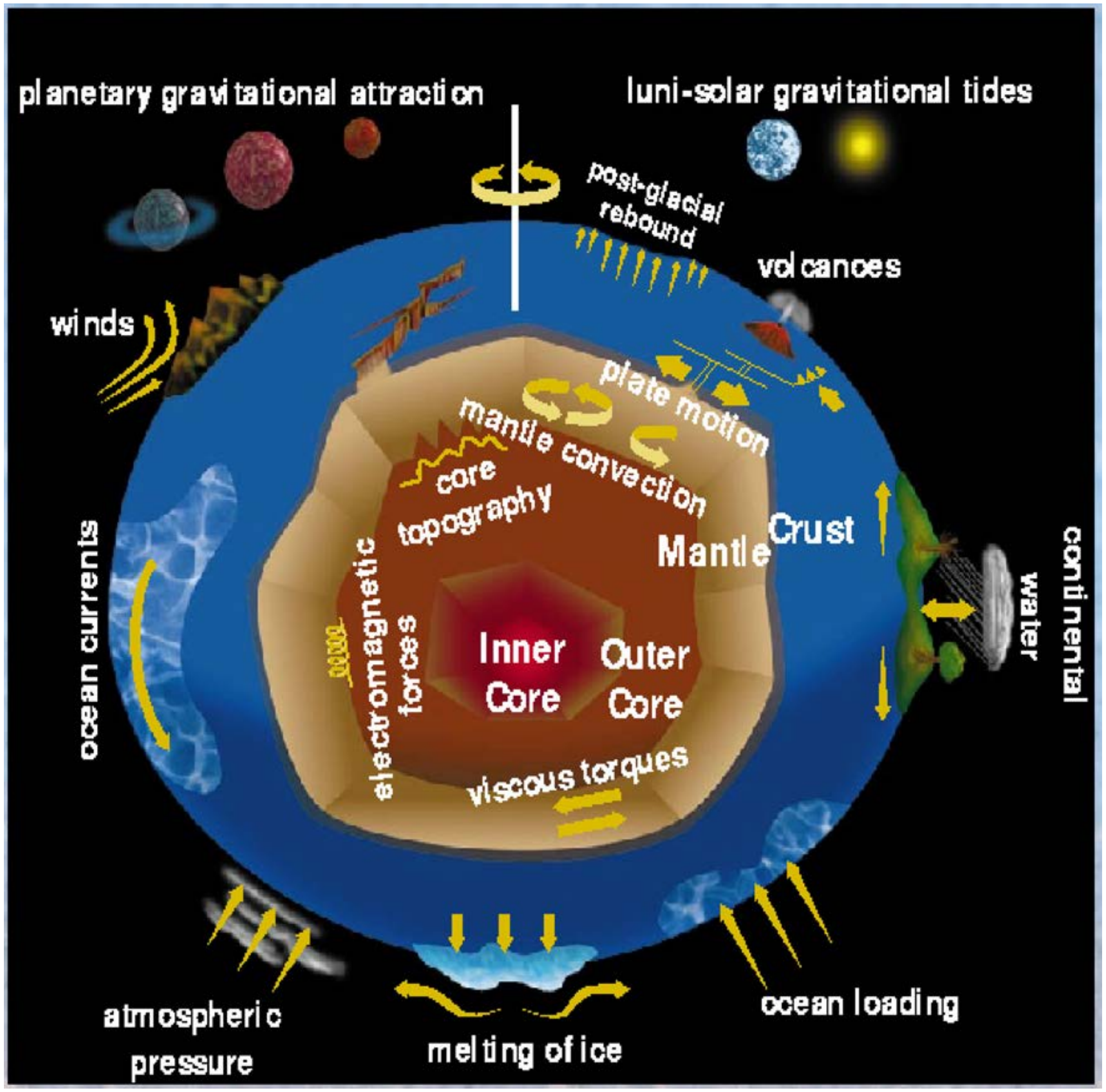
Living on a dynamic Earth



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

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

Adapted from Sovers et al., 1998

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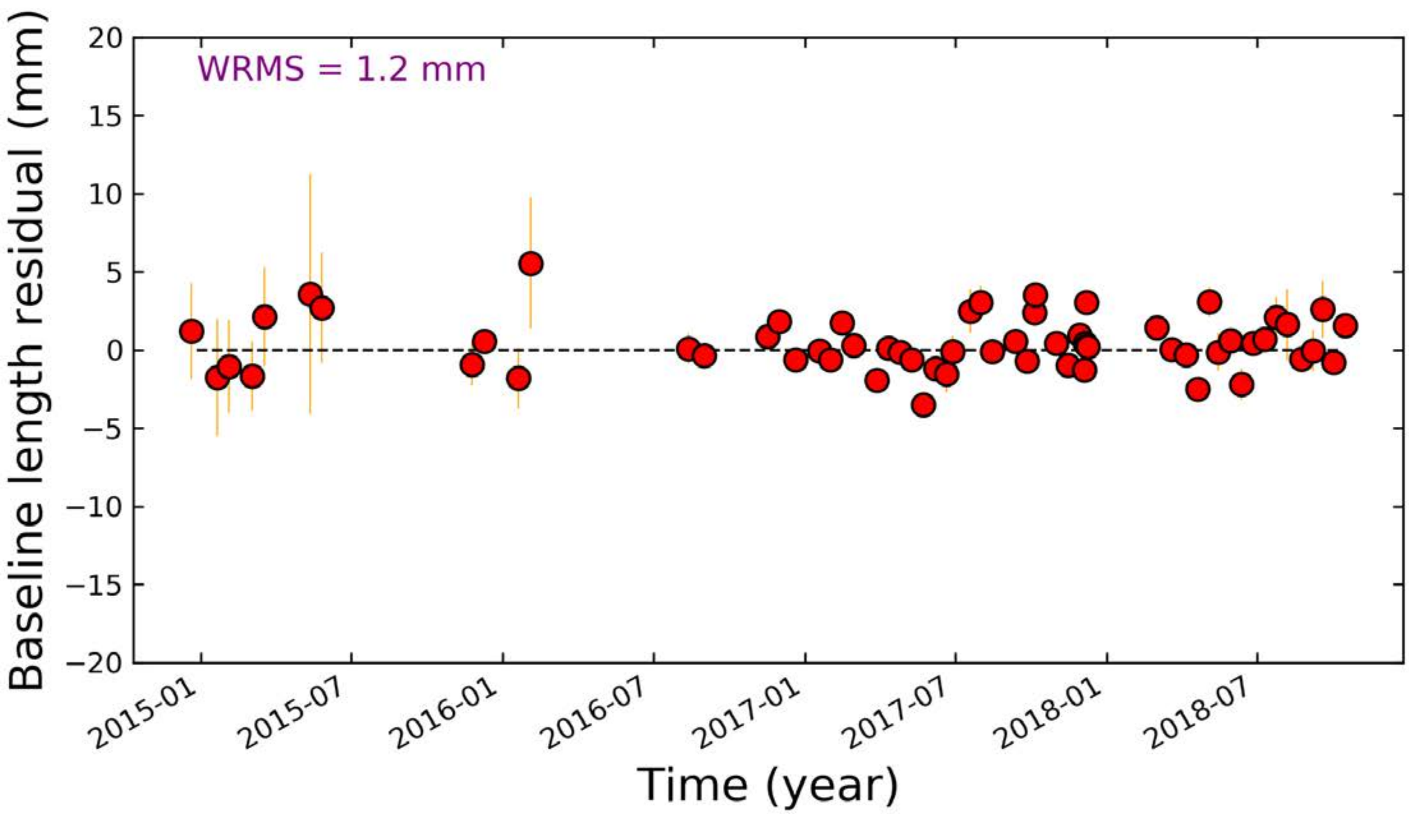
VGOS positioning precision assessment

4 cm



~4 years

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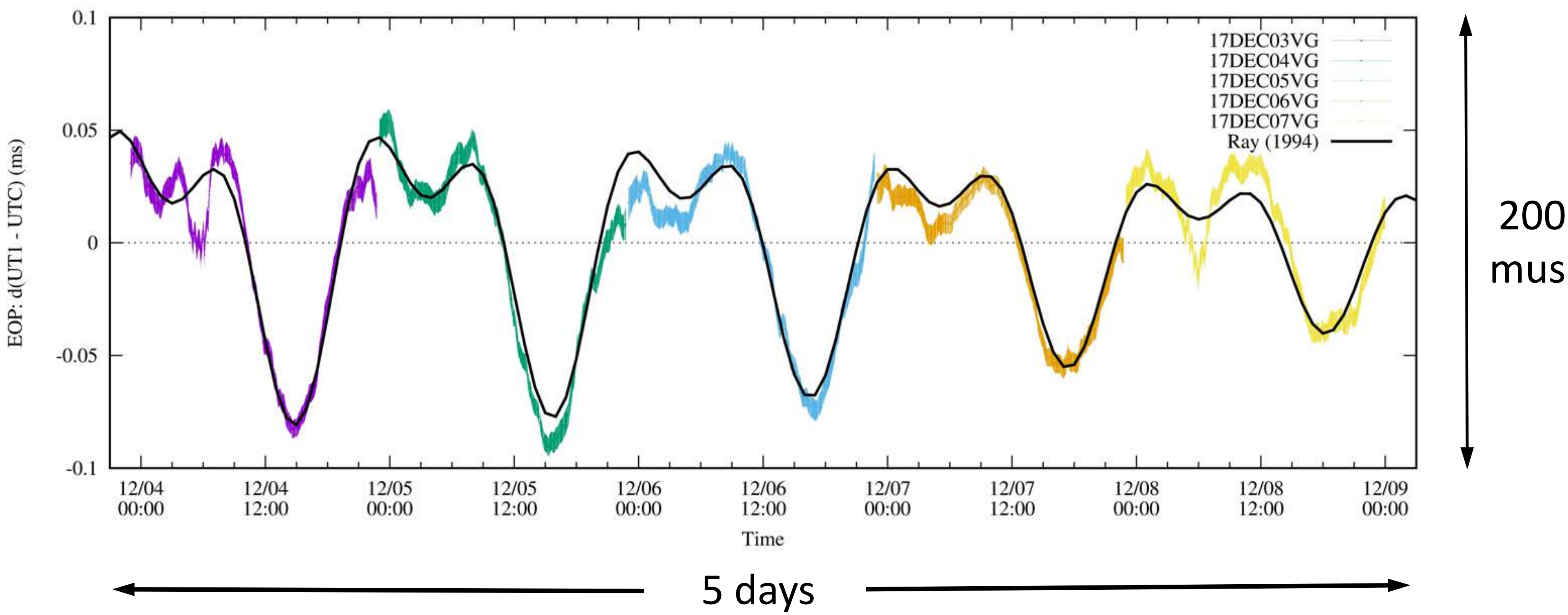
UT1 estimates, VGOS vs. model

Sub-diurnal ocean tide variations



More by S. Bolotin later in the week

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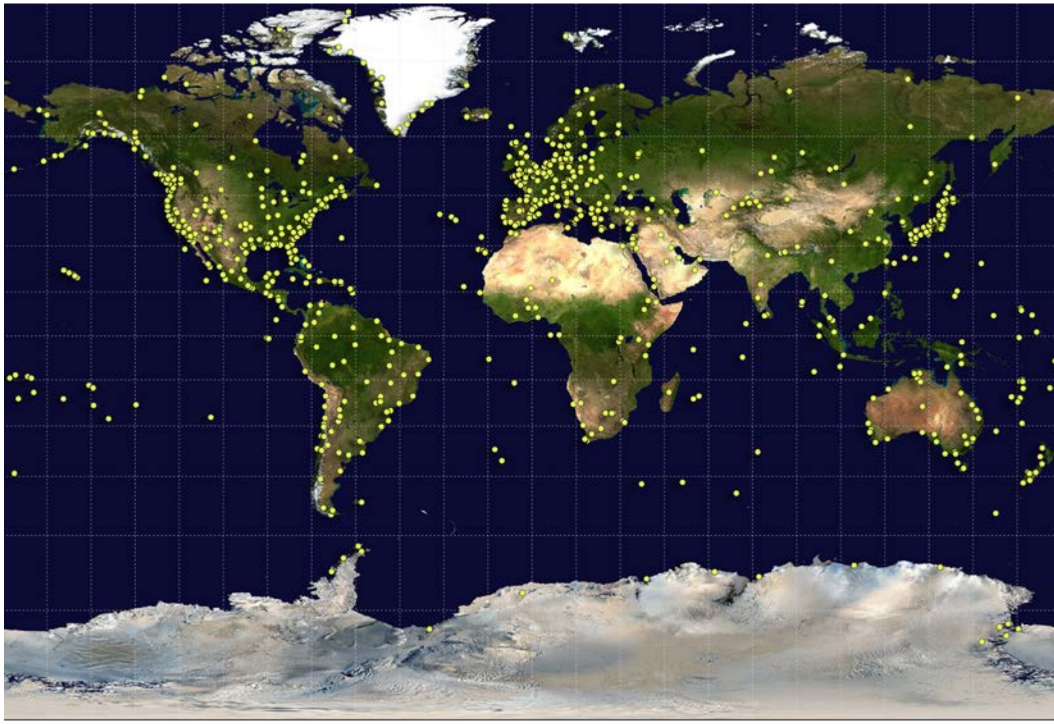
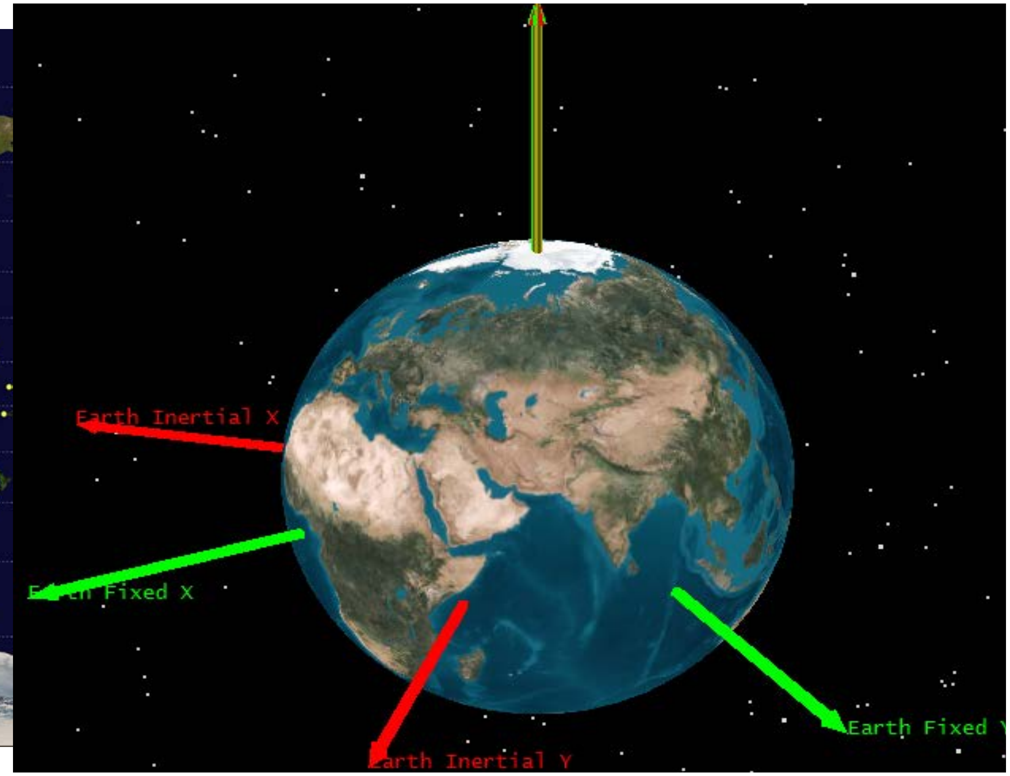
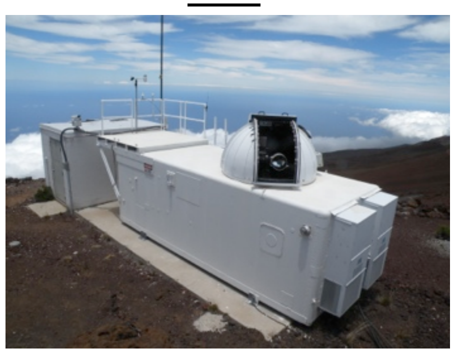
Terrestrial Reference Frames and EOP





VLBI	SLR	GNSS	DORIS
			

And that's pretty much it for today

Have all a productive and a holly jolly TOW!

Thank you