VLBI Basics

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Technical Operations Workshop (TOW)
MIT Haystack Observatory
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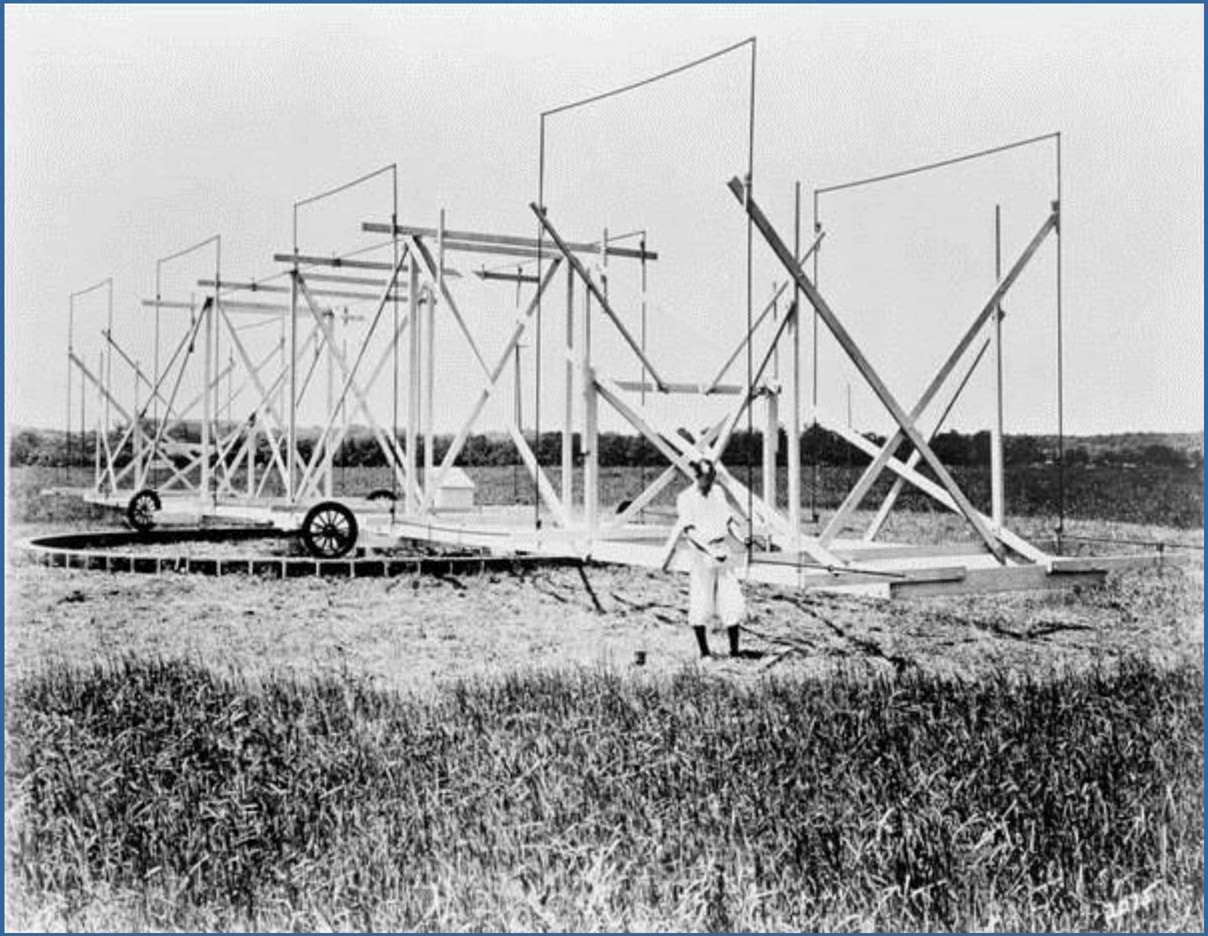
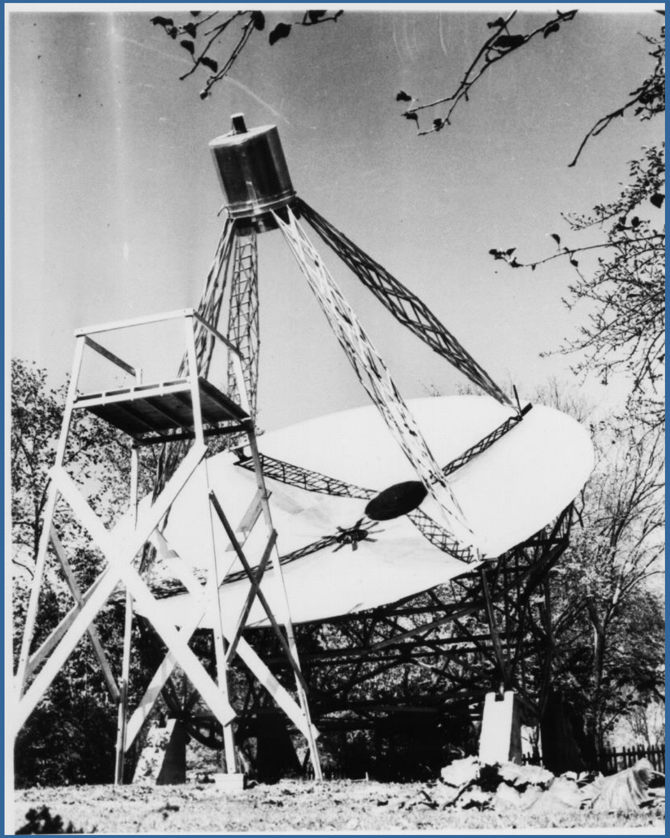
Karl Jansky’s radio antenna - 1931



(Bell Labs @ Holmdel, NJ)

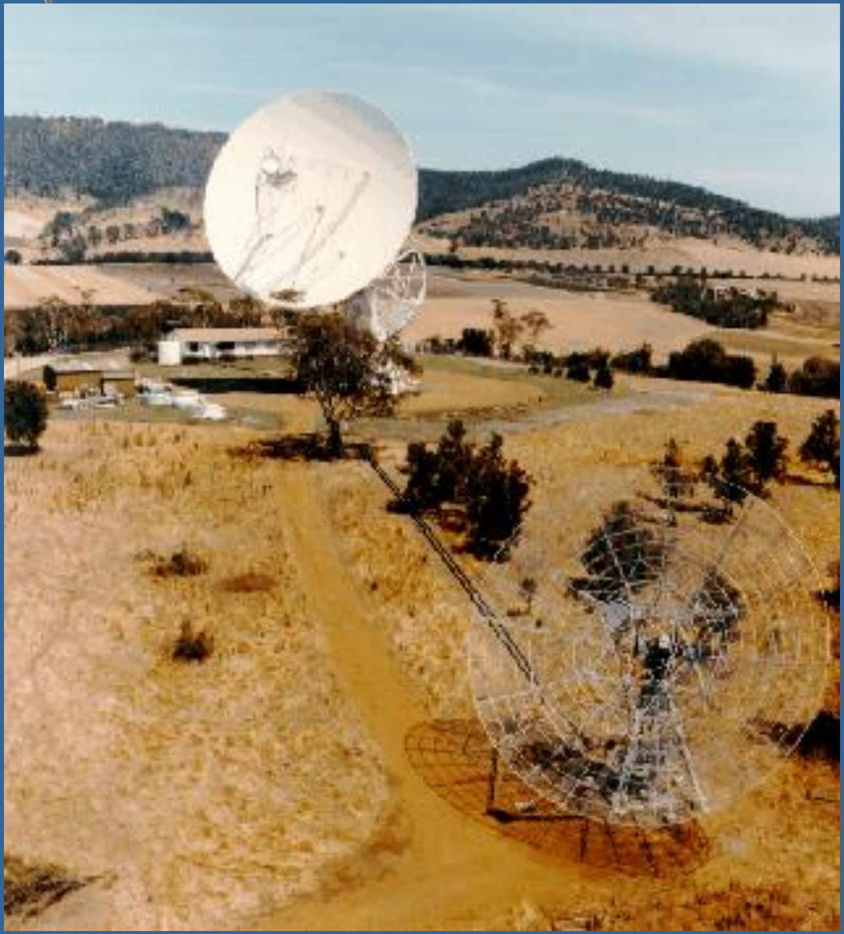
Grote Reber – radio astronomy pioneer & long-time Tasmania resident



1937 - Wheaton, IL

Grote Reber (1911-2002)

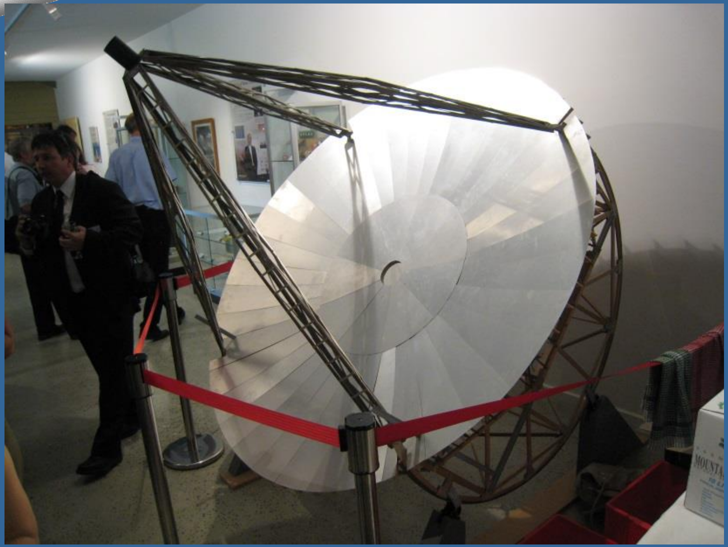
Mt. Pleasant Observatory – Cambridge, TAS

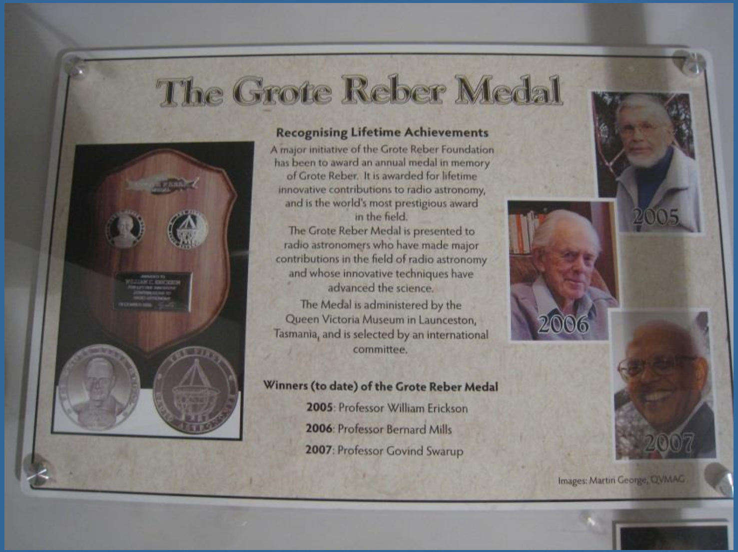


26m diameter (1985)
14m diameter (1981)

12m diameter (9 Feb 2010)

Grote Reber Museum at Mt. Pleasant Observatory





2005 Prof. William Erickson
2006 Prof. Bernard Mills
2007 Prof. Govind Swarup
2008 Dr. Sander Weinreb
2009 Dr. Barry Clark
2010 Dr. Alan E.E. Rogers
2011 Prof. Jocelyn Bell
2012 Prof. Nikolay Kardashev
2013 Prof. James Moran
2014 Prof. Ron Ekers

Since Galileo, observational astronomy has always had two goals

Resolution – what detail can we see in distant objects

Sensitivity – how well can we see dim objects

What determines sensitivity?

Sensitivity of any astronomy instrument is determined by:

- Amount of energy collected
  - Size & quality of the collecting area
  - Bandwidth of the energy spectrum
- Quietness of the receiving detectors

Only options to improve sensitivity are . . .

- Bigger antennas, but cost tends to go as D^2.7 (i.e. doubling antenna diameter raises price by ~x6!)
- Quieter receivers, but many receivers are already approaching quantum noise limits or are dominated by atmospheric noise
- Wider observing bandwidth
  - For most observations, sensitivity increases as square root of observed bandwidth
  - Increasing BW is usually the most cost-effective way to increase sensitivity

What determines resolution?

We are always held hostage to fundamental physics, which states…….

Angular Resolution is always approximately*

$$\frac{\lambda}{D} \text{ (radians)}$$

where

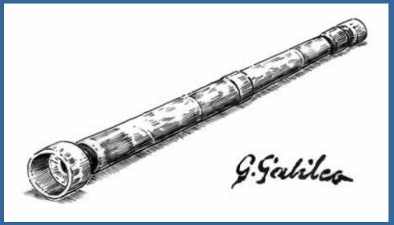
λ = wavelength

D = aperture size

* For a coherent aperture only; poorer for incoherent aperture

Optical-telescope resolutions

Human eye → $\frac{\lambda}{D}$ ~60 arcsec = 1 arcmin
(Sun diameter ~30 arcmin)



Galileo's telescope → $\frac{\lambda}{D}$ ~4 arcsec
(Jupiter diameter ~40 arcsec)

10cm optical telescope → $\frac{\lambda}{D}$ ~1 arcsec
(~2 km on moon)

10m optical telescope → $\frac{\lambda}{D}$ ~0.01 arcsec
(but limited to ~0.2 arcsec
by atmosphere)

Hubble telescope (2.4m) → $\frac{\lambda}{D}$ ~0.05 arcsec
(~100 m on moon)

Radio-telescope resolutions

100m telescope at λ=1cm → $\frac{\lambda}{D}$ ~20 arcsec
(Jupiter ~40 arcsec)

VLA (~35 km) at λ=1cm → $\frac{\lambda}{D}$~0.1 arcsec
(~2 km on moon;
~2 m at 5000 km)

10,000 km telescope at λ=1cm→ $\frac{\lambda}{D}$~200 micro-arcsec
(~40 cm on moon;
~5 mm at 5000 km)

5,000 km telescope at λ=1mm →$\frac{\lambda}{D}$~40 micro-arcsec
(~8 cm on moon;
~0.1 mm at 1000 km;
35 Sun diameters at 25,000 ly))

How do you build a really big telescope? Early attempts at radio interferometry

- Post-WWII: Radio-based connected-element interferometer to measure diameter of the sun and place an upper limit on size of Casseopeia A (Ryle et all, 1946, 1948, 1950), Australia
- Post-WWII: ‘Sea interferometer’ – antenna on cliff overlooking ocean receiving both direct and reflected waves from sun (McCready et al, 1947), Australia
- 1950s
  - •Simple 2 or 3-element low-frequency connected-element interferometers (CEIs) provided crude source sizes (Mills & Slee, 1953), Australia
  - •Bernard Mills built 2D cross array (aka ‘Mills Cross’), each arm ~500m long
  - •Early 50s: Jodrell Bank 1 km CEI
  - •Early 60s: Jodrell Bank CEI extended to 20km (1.5m wavelength)

First Very Long Baseline Interferometry (VLBI)

- 1965: Early discussion of using independent oscillators and tape recorders (Matveyenko, 1965), but unable to pursue in Russia
- 1965: Group at U of Florida first used VLBI to investigate Jupiter radio bursts (Carr et al, 1965)
  - 18MHz obs freq, 2.4 kHz BW, analog recorders, WWV signals used to steer station LOs
- Mid-60s: Enablers of first ‘modern’ VLBI
  - high-speed digital recorders and broadband analog recording systems became available
  - Atomic frequency standards were becoming available with sufficient stability (rubidium and hydrogen masers)
- 8 May 1967: First VLBI fringes on 220km baseline to Green Bank, WV using digital recording system (360kHz BW)
- 21 May 1967: First VLBI fringes on 3074km across Canada using analog recording system (4MHz BW)

Early geodetic VLBI

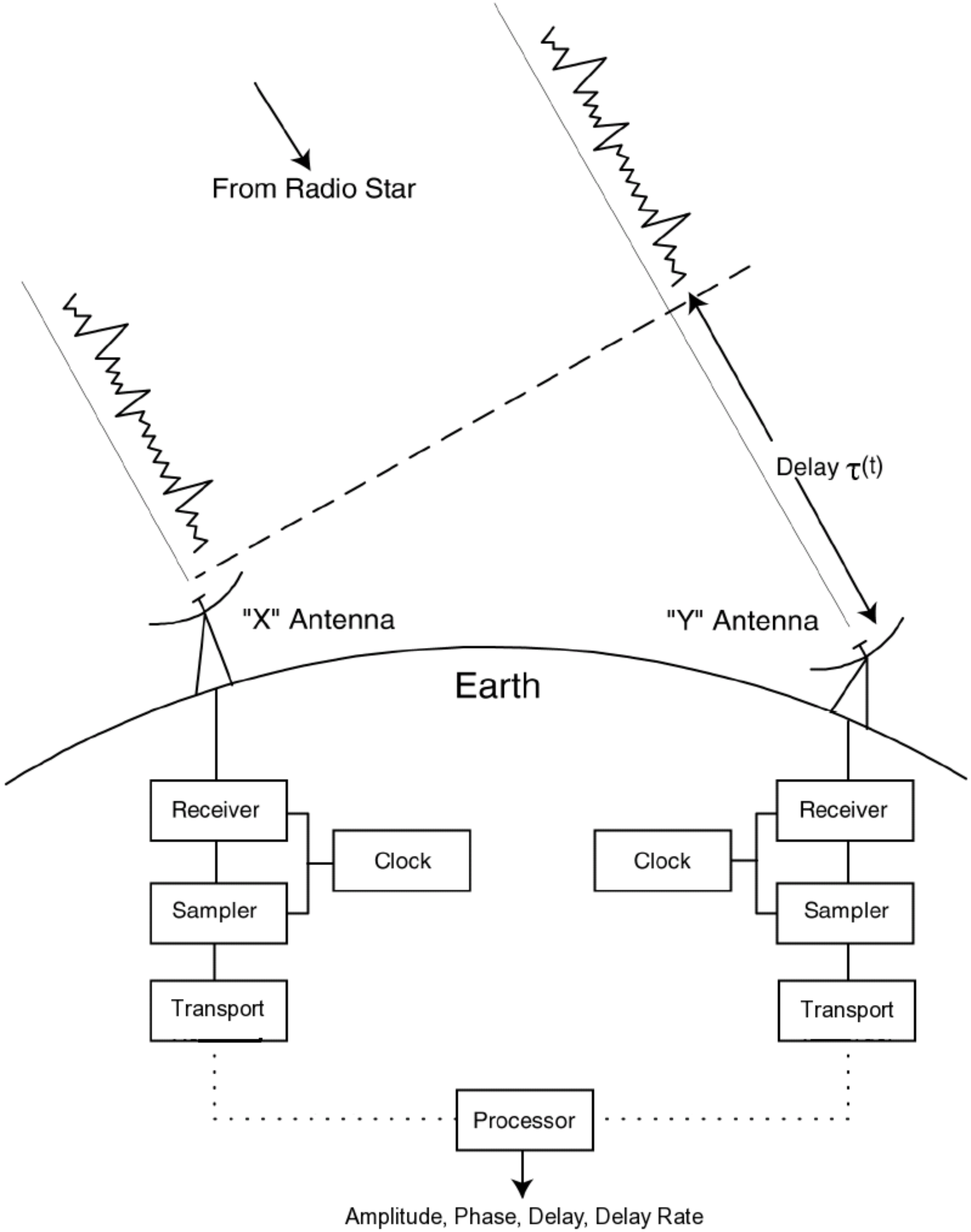
- Jul 1967: First suggestion that VLBI could make precise measurement of rotation period of Earth (T. Gold, Jul 1967)
- Aug 1967: First suggestion that VLBI could be used to measure light deflection by solar gravity field (Shapiro, Aug 1967)
- Late 1967: First suggestion that VLBI could be used for high-precision geodetic measurements (Shapiro, 1968)
- Apr 1968: First attempted geodetic-VLBI experiment
  - Haystack-to-NRAO 140’
  - Early H-maser frequency standard
  - ‘Switched-frequency’ bandwidth synthesis around 1660MHz; spanned bandwidth of ~40MHz
  - 360kHz recorded BW on Mark I, on reel-to-reel computer tape drive, 720 kbps
  - Processed on CDC3300 software correlator. No fringes!

Haystack CDC3300 software correlator (c1968)

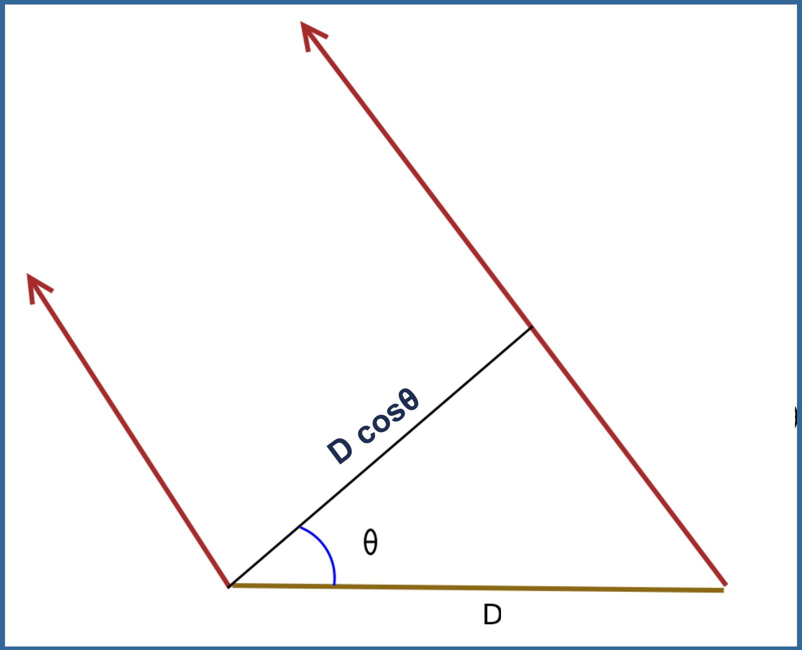
(Each 12" diameter/2400ft tape reel lasts 3 minutes & holds ~16MB of data!)

Early geodetic VLBI (continued)

- <u>Oct 1968</u>: First geodetic-VLBI experiment with fringes
  - –Part of larger GR light-bending experiment
  - –Haystack to Owens Valley, CA
  - –44MHz spanned BW around 7500MHz and around 1610MHz
  - –Frequency switch LOs
  - –Mark I recording system
  - –Fringes corrupted by solar corona and few good results
- <u>Jan 1969</u>: First 'successful' geodetic-VLBI experiment
  - –Haystack-to-NRAO 140'
  - –6-channel frequency switching over 110MHz around 1660MHz
  - –Parametric front-end amplifiers synchronously retuned with programmed bias voltage
  - –Mark I recording system
  - –Successful fringes!
  - –Positions of six radio source determined to better than 1 arcsec
  - –~<u>700km baseline length</u> determined to within <u>2m</u>, orientation to within <u>5m</u> – a real stop forward for the time!

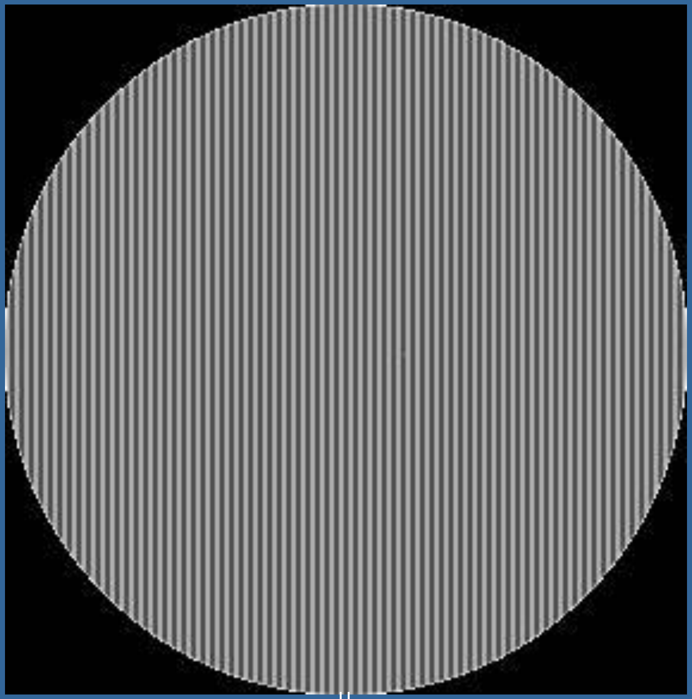

From Radio Star
Delay τ(t)
"X" Antenna
"Y" Antenna
Earth
Receiver
Clock
Sampler
Transport
Receiver
Clock
Sampler
Transport
Processor
Amplitude, Phase, Delay, Delay Rate

Interferometry

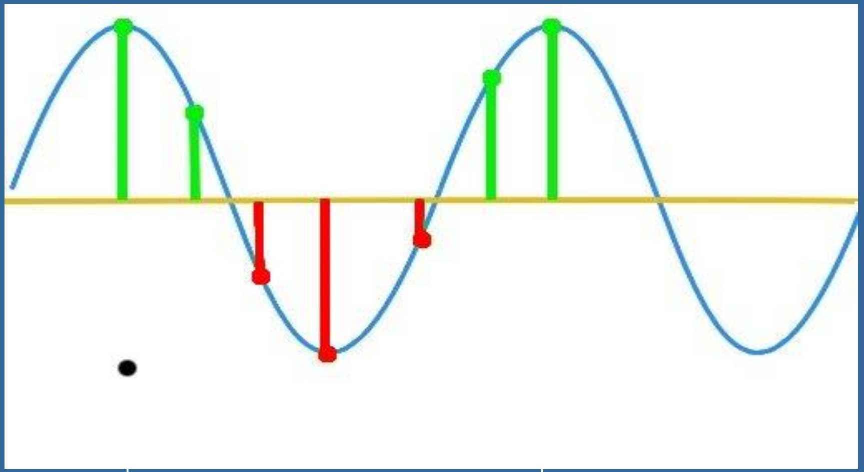


- As Source moves, response changes as cos (projection)
- Projected baseline =D*cos θ
- Fringe-pattern spacing on sky
  = λ/(projected baseline)
  = λ/(D*cos θ)

Point Source

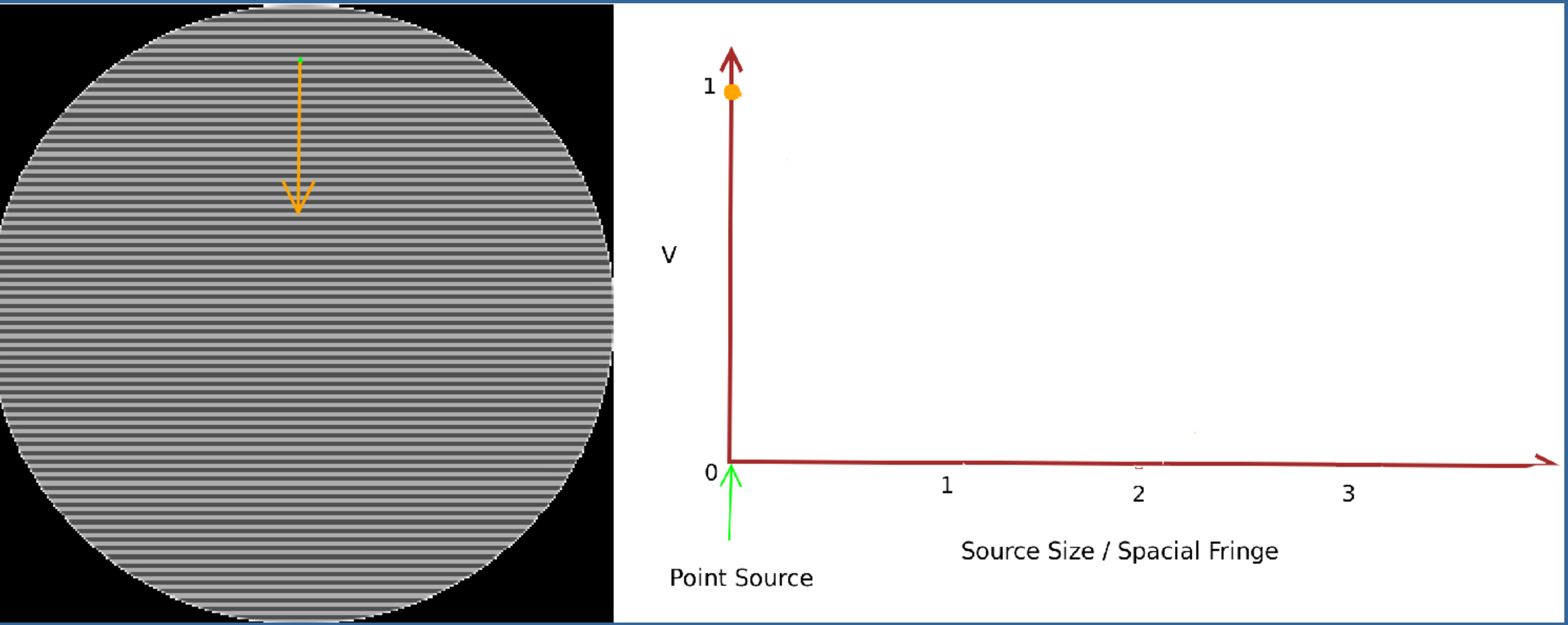


Fringe spacing
λ/(D*cos θ)

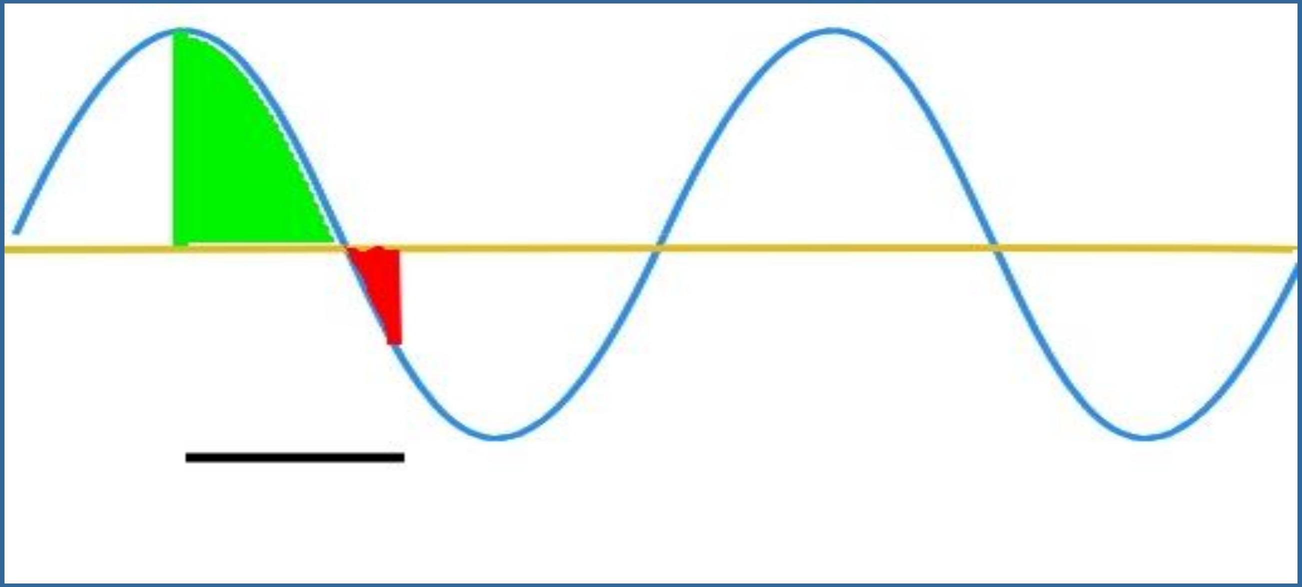


Fringe spacing
λ/(D*cos θ)

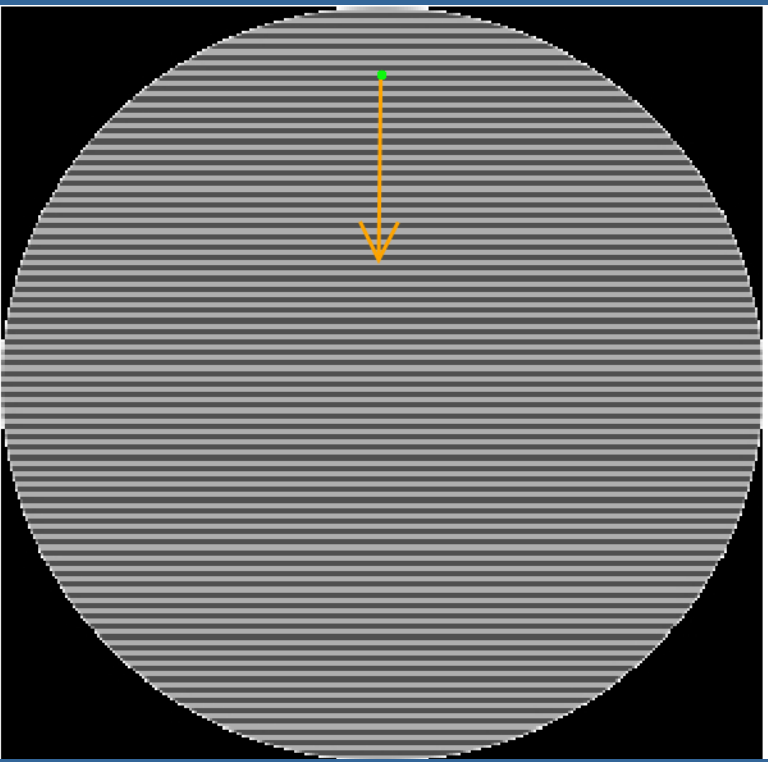
Point source

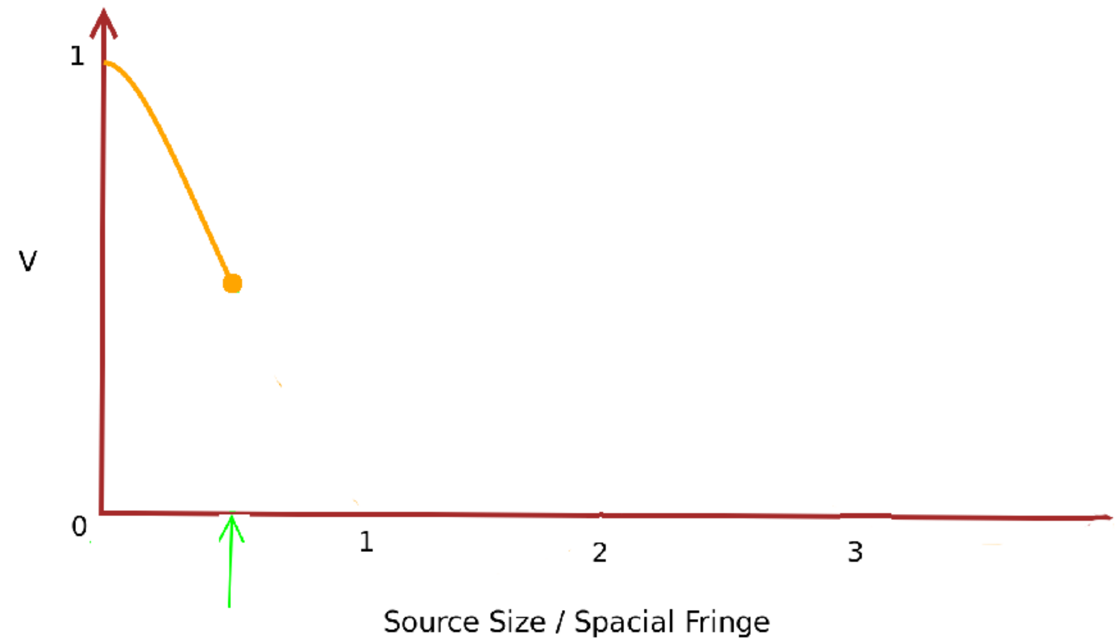


Extended Source

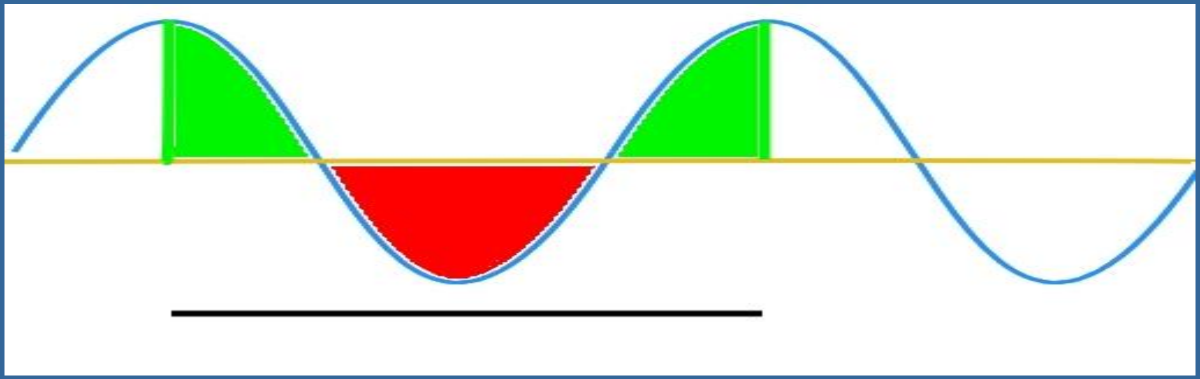


Extended Source

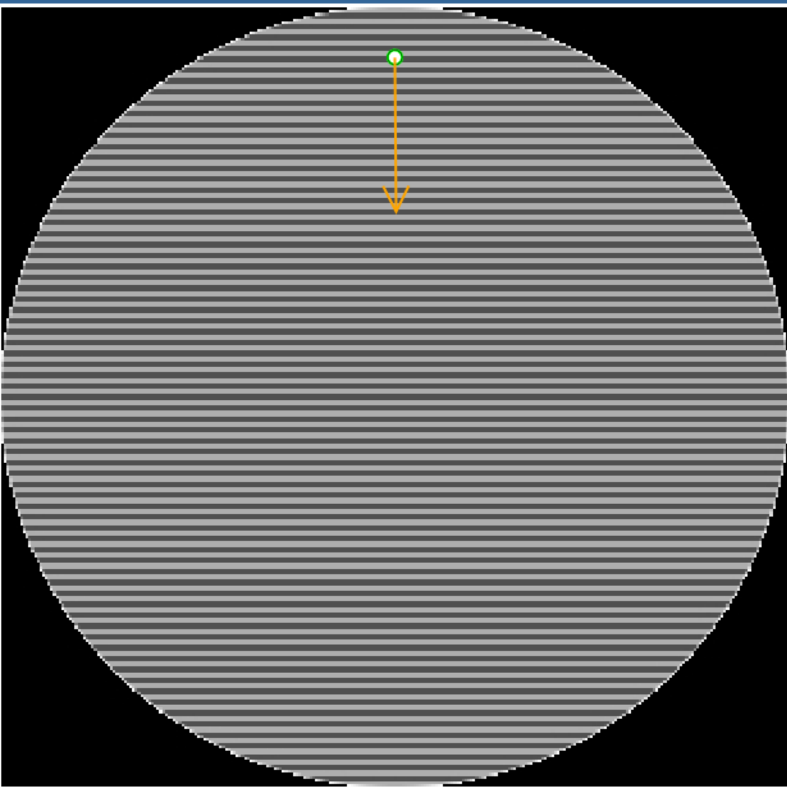


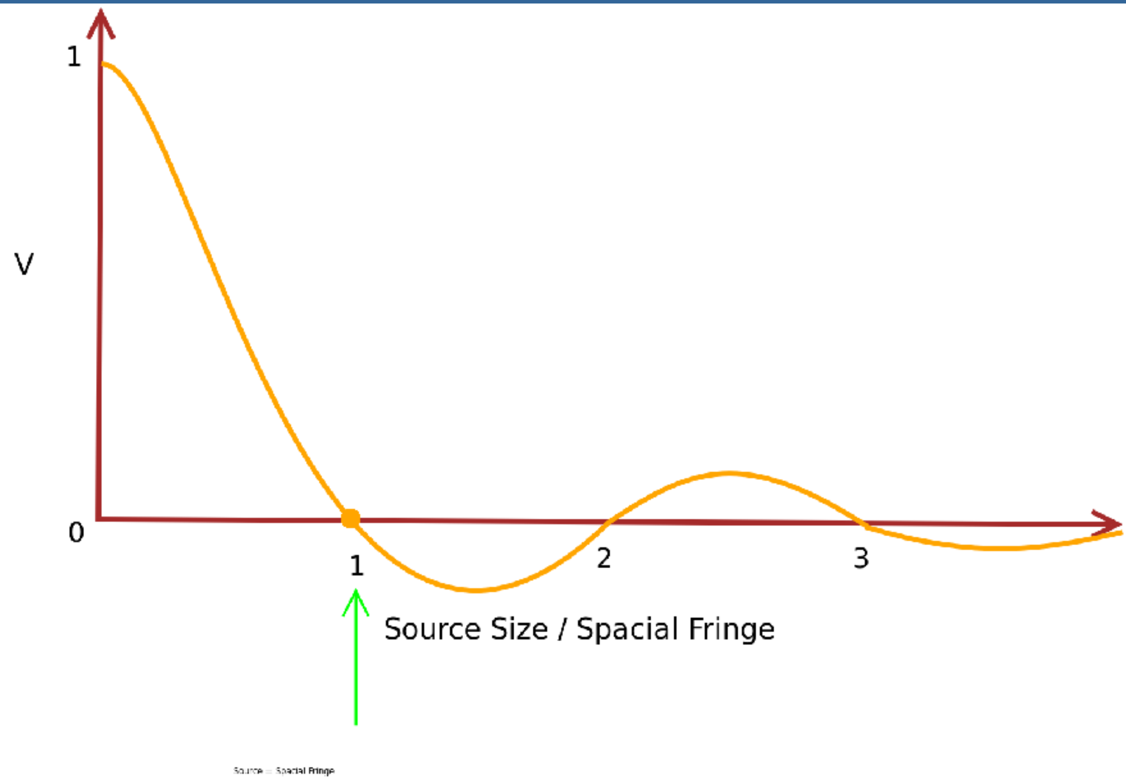


One Fringe Width

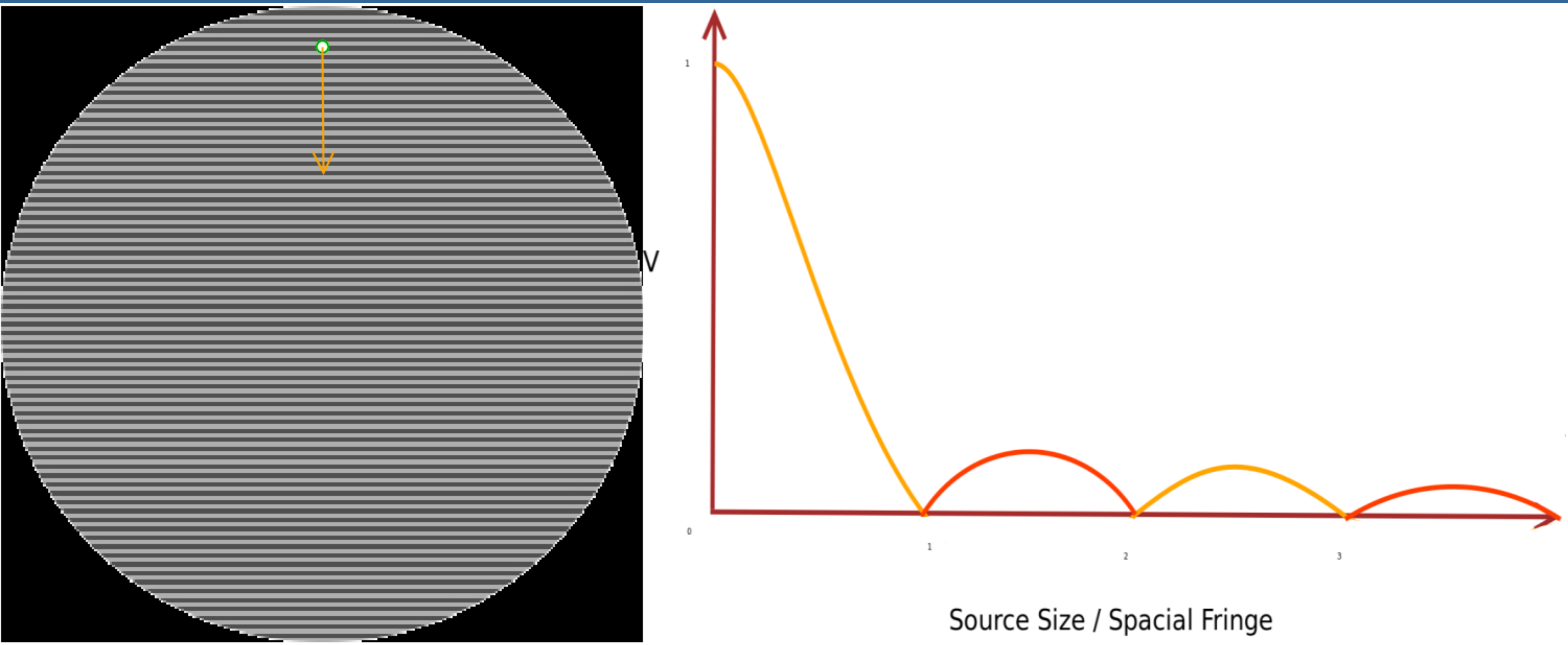


One Fringe Width





VLBI Response to Large Sources



Some Notes About Radio Sources-1

As we saw in the preceding slides, we require compact, bright radio sources for VLBI

Geodetic-VLBI has traditionally required sources that are nearly point-like, don’t change position, don’t change their shape, and don’t change their apparent center-of-brightness as a function of frequency.

These requirements are not always easy to meet!

VGOS, with its very wide bandwidth, is challenging geodetic-VLBI to relax some of these constraints in order to increase the number of suitable target sources.

Some Notes About Radio Sources-2

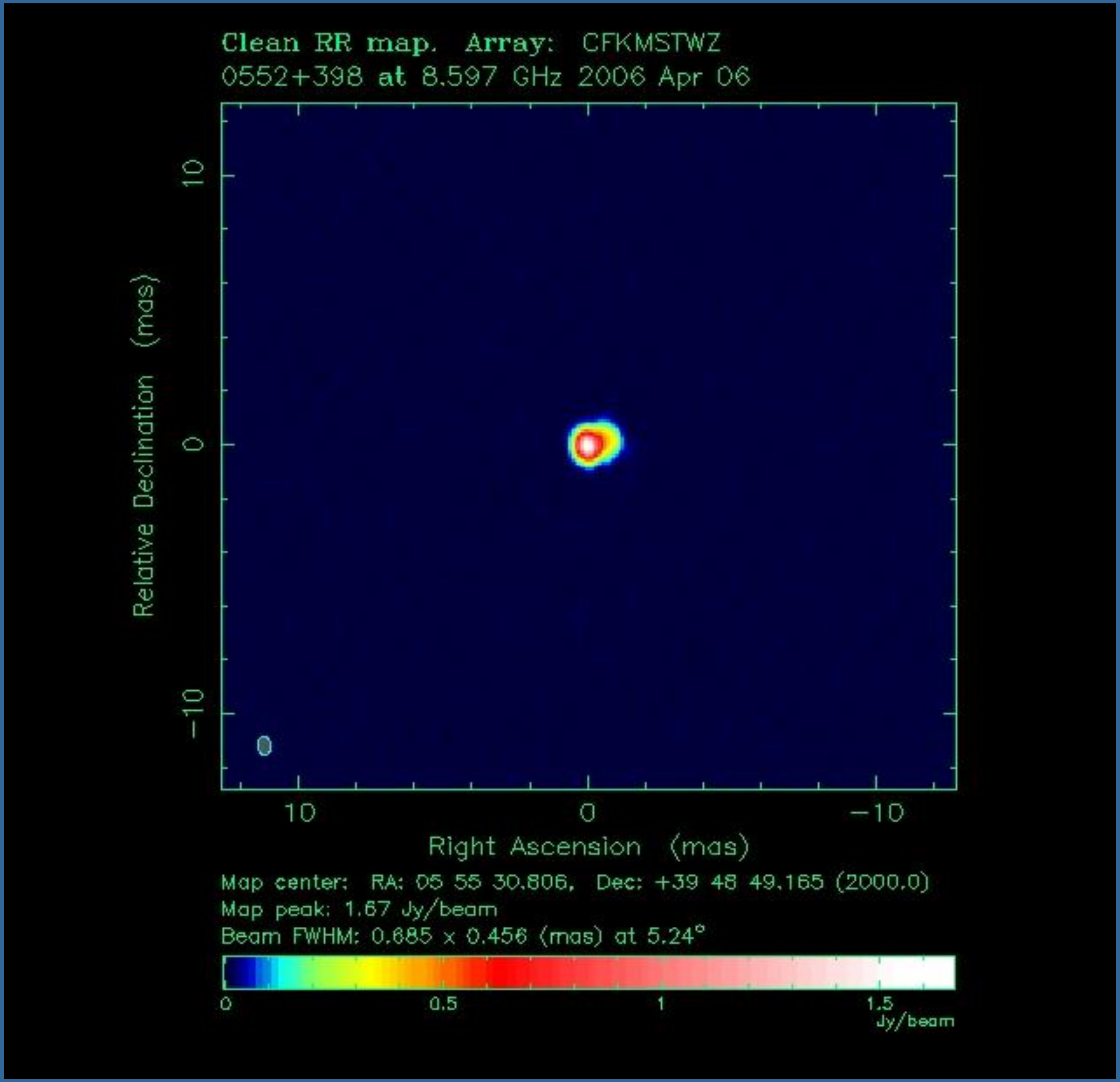
- Quasars are among the brightest radio sources in the sky, and they are very far away, so that they don’t appear to move as seen by us even if they have a large intrinsic motion.

- Some Quasars are very compact and show little source structure, but not many.

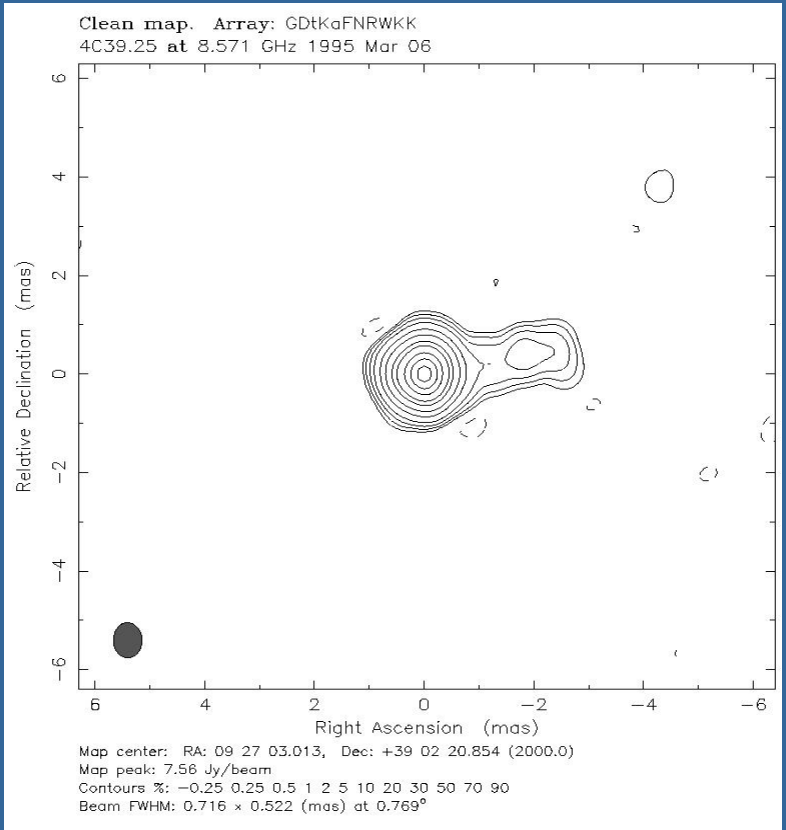
- Some Quasars are stable in brightness distribution and show the same brightness distribution as a function of frequency, but not many.

<u>The total number of available useful sources for current geodetic-VLBI capabilities is small - <~1000 over the sky; VGOS, with its improved sensitivity, should significantly improve the number of available sources</u>

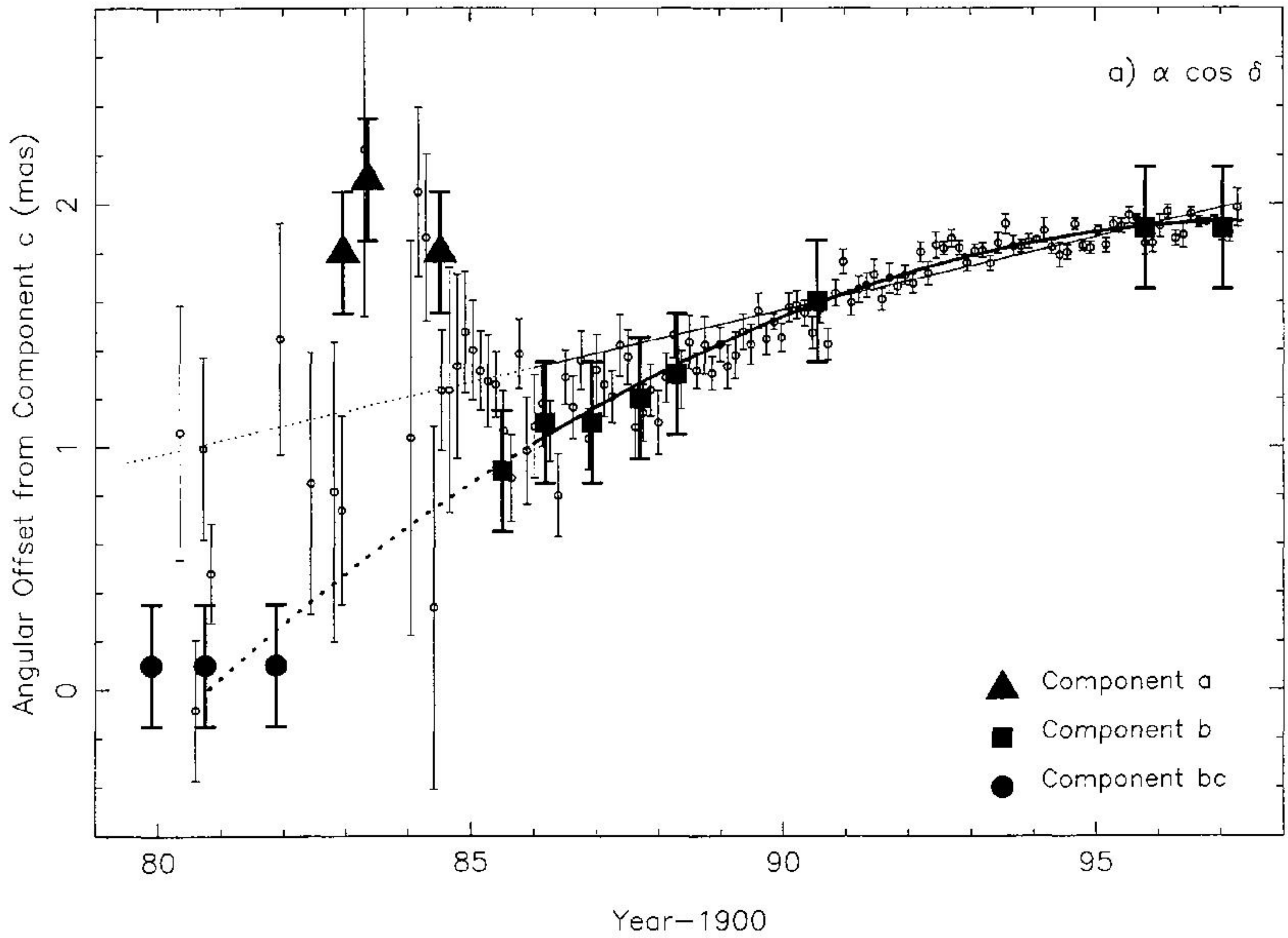
An example of a ‘good’ radio source



Example of a Questionable Source

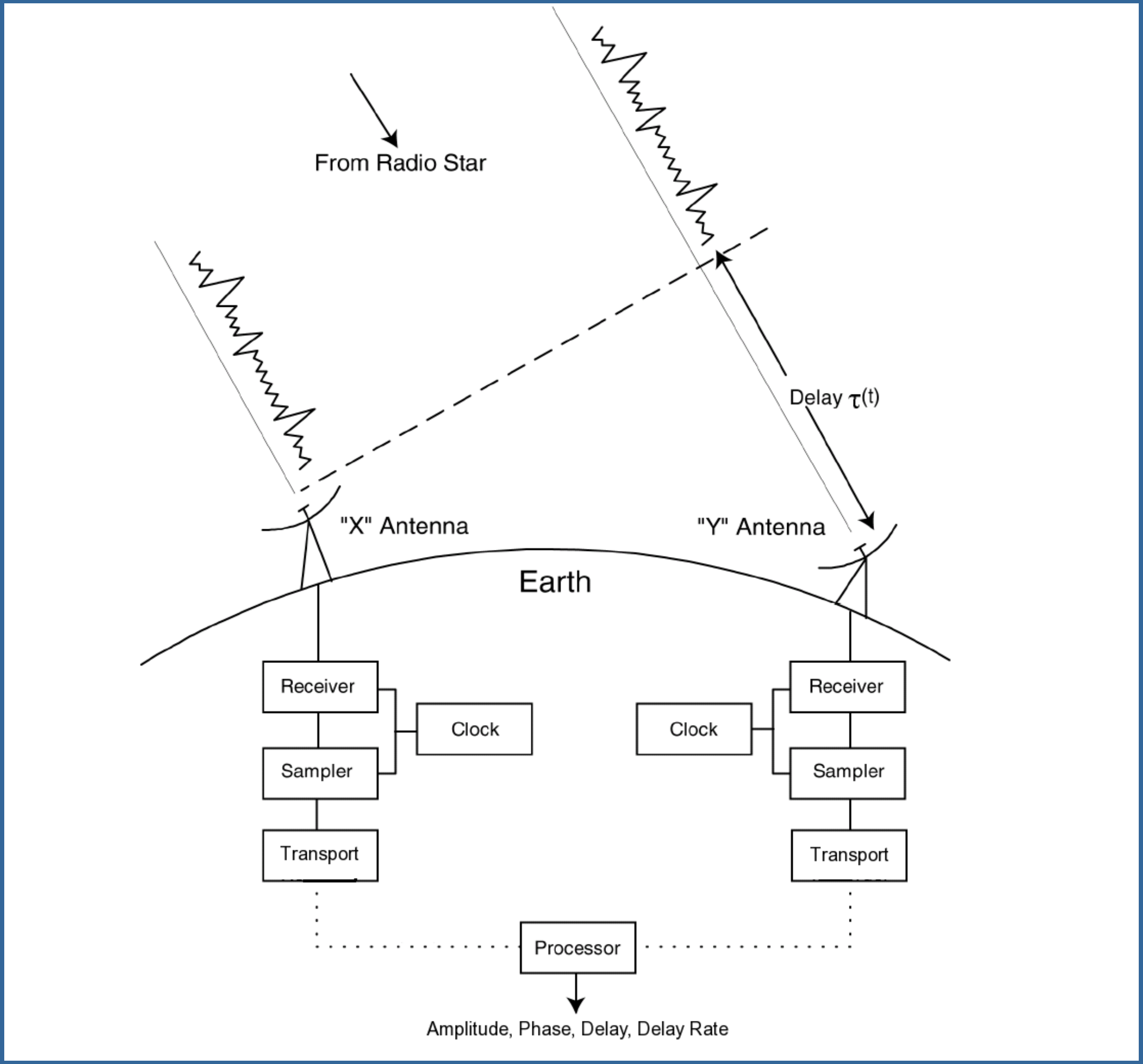


- Source is Extended
- Different baselines could give different results
- Source components change with time



a) α cos δ
Angular Offset from Component c (mas)
Year−1900
0
1
2
80
85
90
95
Component a
Component b
Component bc

Typical VLBI system



What do we need at a geodetic-VLBI station?

What Are We Observing?

- Noise from Quasars (our signal!)
- 3°K Cosmic Background
- Various noise sources in Beam
  - Unwanted background and foreground sources
  - Interstellar & intergalactic background noise
  - Thermal noise from Atmosphere and Ground
  - etc.
- Noise generated in the Observing System

What are we trying to measure?

We want to observe group delay (a time measurement)

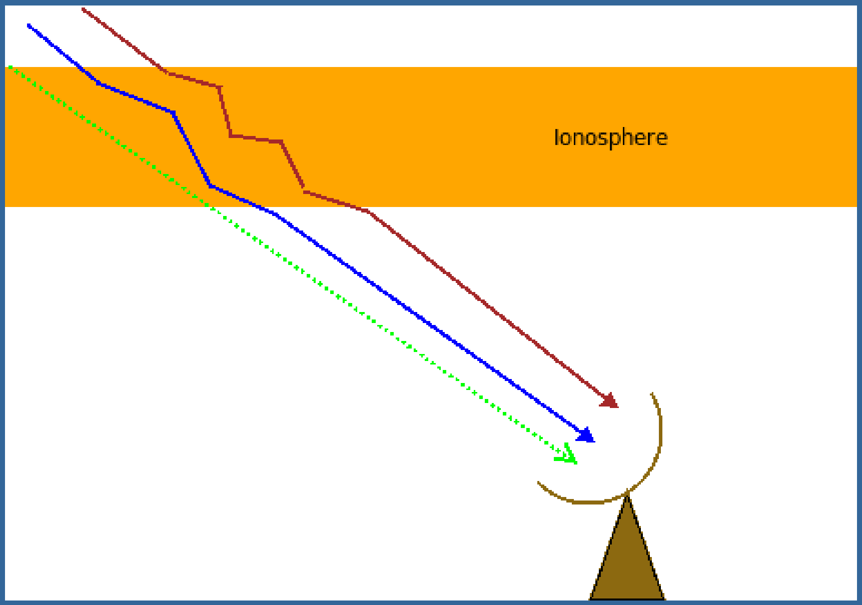
$$\text{Time resolution} \sim \frac{1}{\text{Spanned Bandwidth}}$$

This requires a wideband feed and receiver.

Station Requirements

- Wideband Feed and Receiver

We Also Have Observational Problems!



Ionospheric thickness is a function of both frequency and time, and can be measured by observing phase vs. frequency across a sufficient range of RF frequencies (particularly in S-band range)

Station Requirements

- Wideband Feed and Receiver
- Multi-Band system

System Equivalent Flux Density (Noise from Observing System and Background):

$$\text{SEFD (Jy)} = \frac{T_{sys}}{\eta_a \times A}$$

T_{sys} = System Temperature

η_a = Antenna efficiency

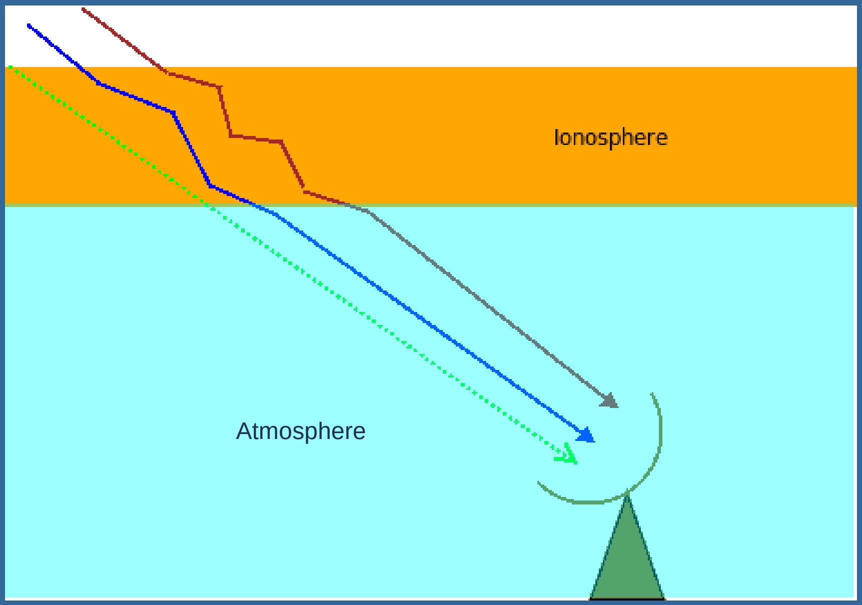
A = Antenna Area

Lower SEFD is Better

Station Requirements

- Wideband Feed and Receiver
- Multi-band system
- Low Noise Receiver
- Large, Efficient Dish

And another observational problem!



Atmospheric thickness is a function of time; best estimated by making frequenct low-elevation observations in many directions

Station Requirements

- Wideband Feed and Receiver
- Multi-band system
- Low Noise Receiver
- Large, Efficient Dish (also <u>fast</u> for geodetic-VLBI!)

Typical SEFDs for Geodetic radio telescopes are ~ 1000 Jy

This means that the power of the system noise by itself is equivalent to the observed power of a 1000Jy source.

But:

Sources are ~1 Jansky = 10^{-26} W/m^2 Hz

$$\frac{\text{Source Noise}}{\text{System Noise}} \sim 1/1000$$

Signal to Noise Ratio:

$$SNR = \frac{S * \sqrt{N}}{\sqrt{SEFD_1 * SEFD_2}}$$

S	=	Source Flux Density
$SEFD_i$	=	SEFD of station i
N	=	Number of samples

$$N = 2 * \Delta\nu * T$$

$\Delta\nu =$ Recorded Bandwidth $T =$ Timespan

So how do we get sufficient SNR for an observation?

To get S/N we need lots of recorded bandwidth:

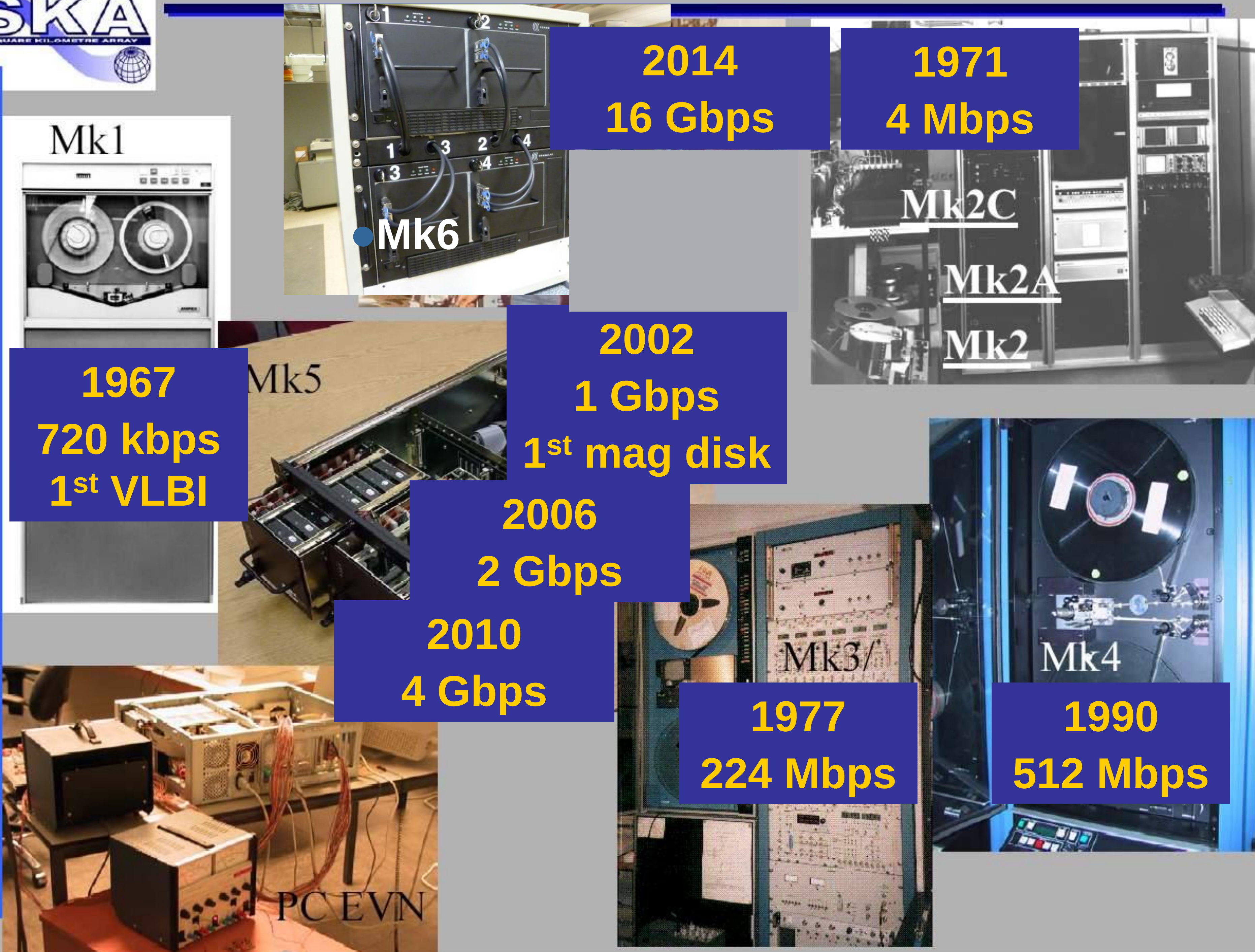
Sample rate = 2 x Bandwidth (Hz)
(so-called ‘Nyquist’ Sampling)

i.e. For 500MHz recorded bandwidth,
need 2Gbps sampled-data rate

For VGOS, recorded bandwidth is extending to 2-4GHz, requiring 8-16Gbps sampled-data rate

Station Requirements

- Wideband Feed and Receiver
- Multi-band system
- Low Noise Receiver
- Large, Efficient Dish (also <u>fast</u> for geodetic-VLBI!)
- High Speed Recording and/or Transport system



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

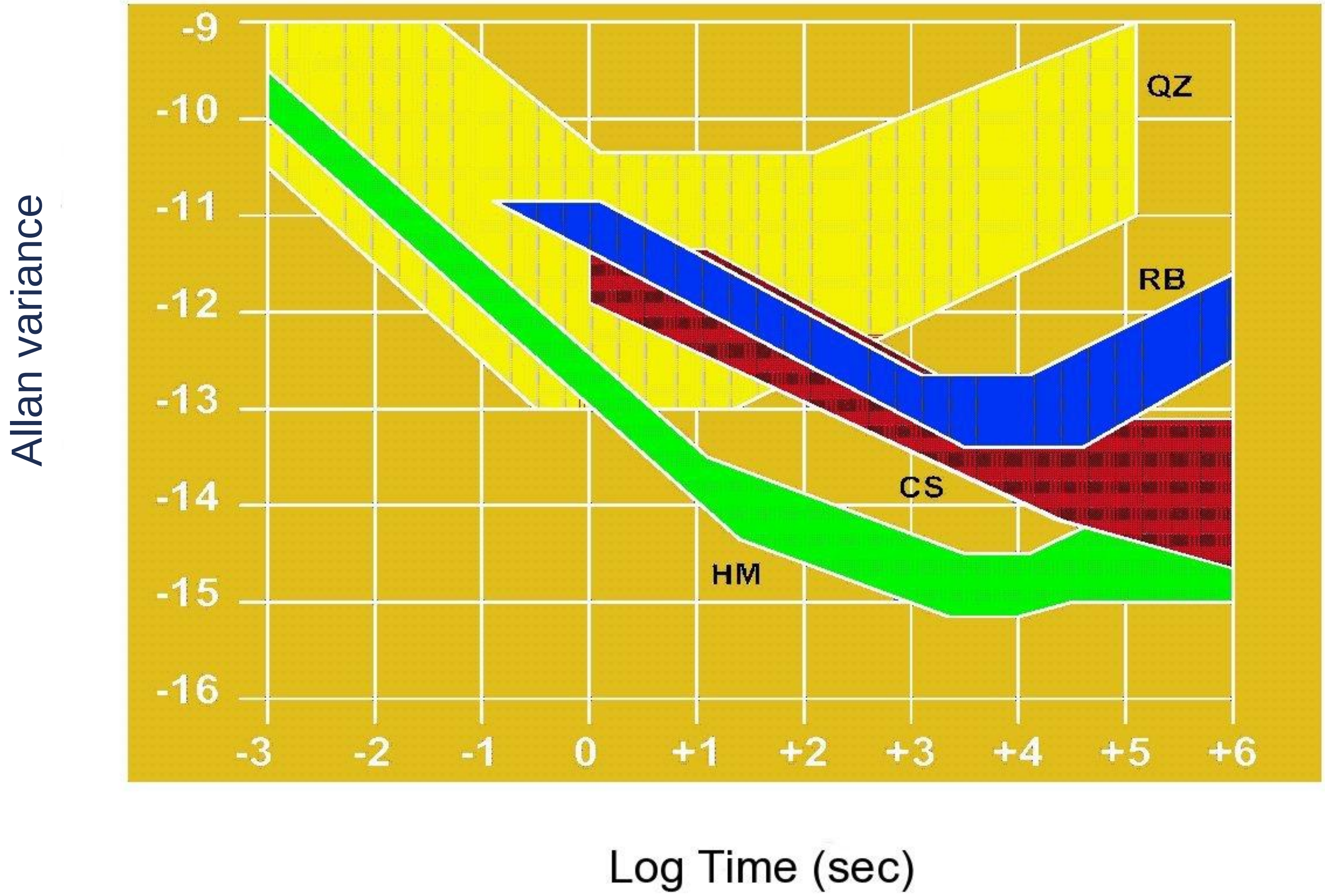
What about frequency-standard requirements?

We cannot (yet) distribute the Local Oscillator to all the stations with sufficient accuracy. So we need a local frequency standard good enough to maintain LO phase coherence between all stations.

How good?

At 10 GHz, one radian = 1.6×10^{-11} sec.   To maintain coherence over 1000 seconds we need a clock good to ~ 1 part in 10^{14}.

Stability of various frequency standards



Station Requirements

- Wideband Feed and Receiver
- Multi-band system
- Low Noise Receiver
- Large, Efficient Dish (also <u>fast</u> for geodetic-VLBI!)
- High Speed Recording and/or Transport system
- Hydrogen maser frequency standard

How good does time synchronization need to be?

For fringe-finding efficiency, correlators need station clocks synchronized to <~10 inverse channel-bandwidths.

For 64-MHz individual-channel bandwidths, this corresponds to <~200 nsec

This time accuracy can be achieved with proper GPS timing receivers.

Station Requirements

- Wideband Feed and Receiver
- Multi-band system
- Low Noise Receiver
- Large, Efficient Dish (also <u>fast</u> for geodetic-VLBI!)
- High Speed Recording and/or Transport system
- Hydrogen maser frequency standard
- Accurate time synchronization (easy with GPS)

We need to observe a <u>group delay</u> which is a time measurement. To do this accurately, we must make sure the delays in our observing system are calibrated across all observing bands.

To do this we have a instrumentation <u>calibration system</u> consisting of:

<u>Cable calibrator</u> → accurately measures group delay from maser to Receiver

<u>Phase calibrator</u> → removes instrumental phase biases

Station Requirements

- Wideband Feed and Receiver
- Multi-band system
- Low Noise Receiver
- Large, Efficient Dish
- High Speed Recording and/or Transport system
- Hydrogen maser clock
- Calibration system
  - Cable cal
  - Phase cal

What data are actually 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 nearly incompressible!

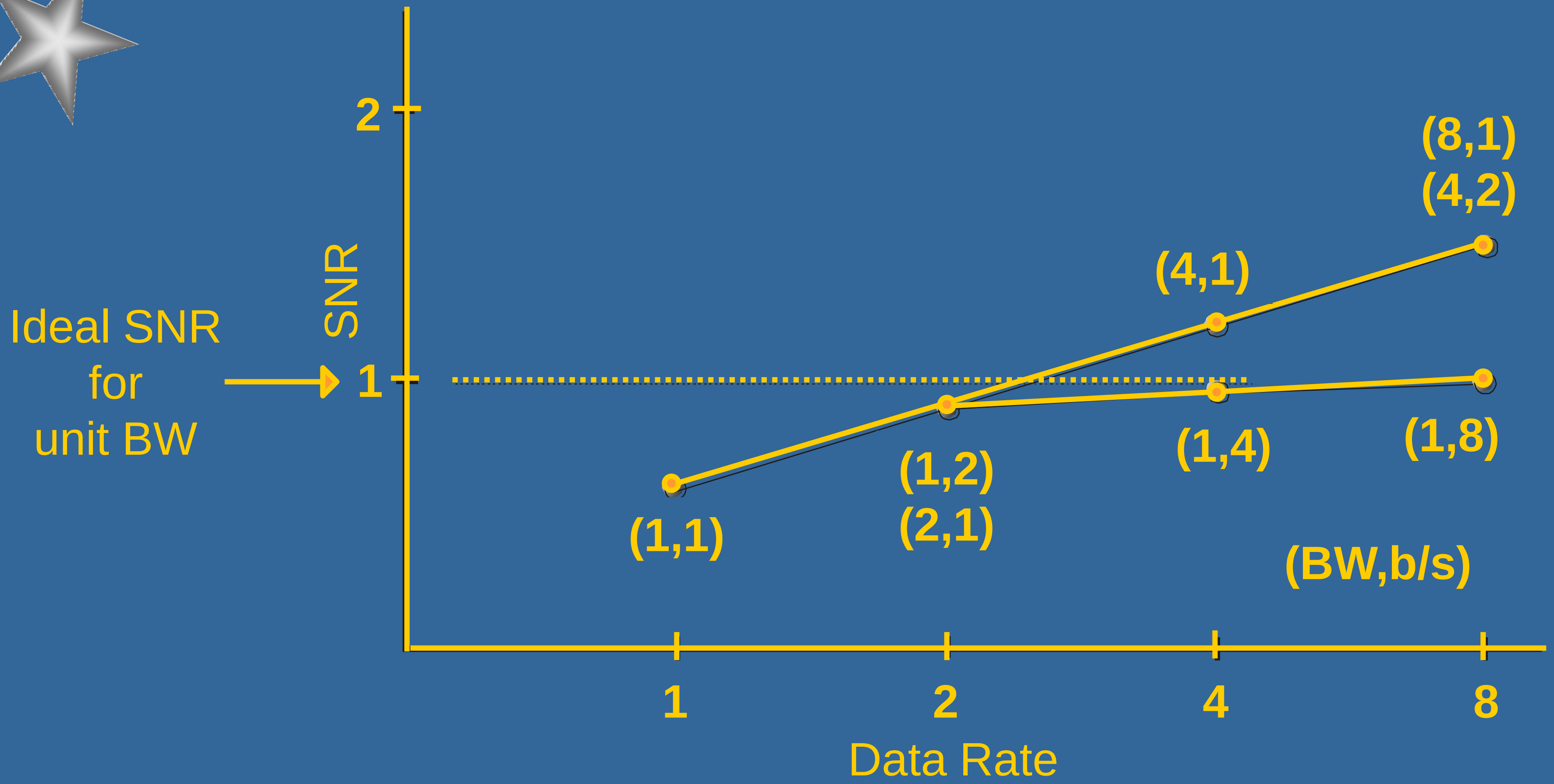
But also another important consequence:
If a small amount of data are lost,
it's usually no big deal!

Why only 1 or 2 bits/sample?

- **In 1960's John Van Vleck of Univ. of Wisconsin showed that:**
  - 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!!!
- **For VLBI:**

  If sampling at ∞ bits/sample produces an SNR of 1.0, then:
  - Sampling at 1 bit/sample produces an SNR of ~0.63 compared to ideal analog of 1.0
  - Sampling at 2 bits/sample produces an SNR of ~0.87 compared to ideal analog of 1.0
  - Recall: SNR increases as $\sqrt{BW}$ ↗

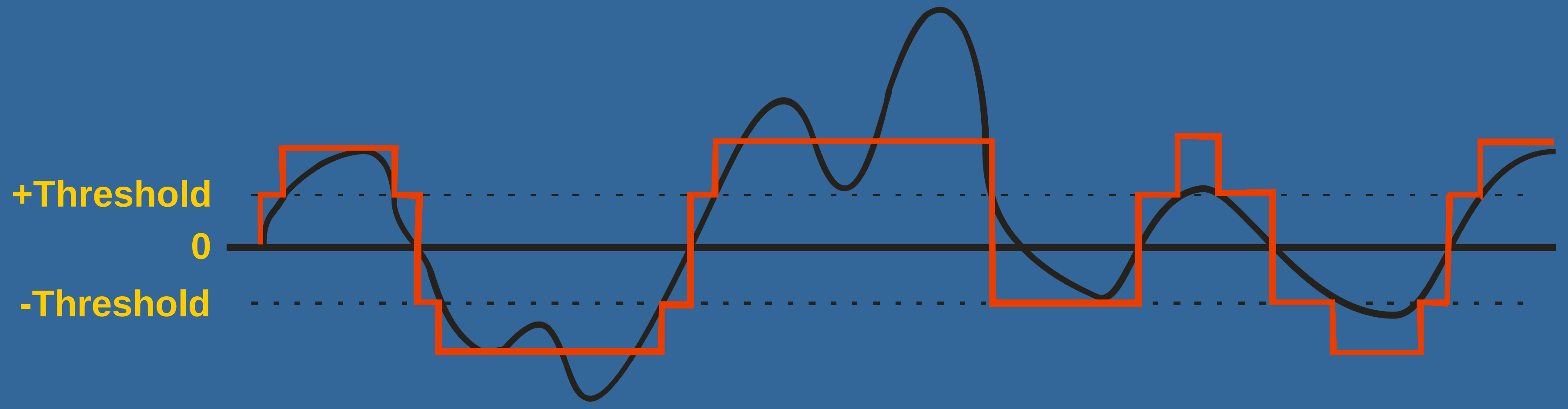
This is why only 1 or 2 bits/sample!

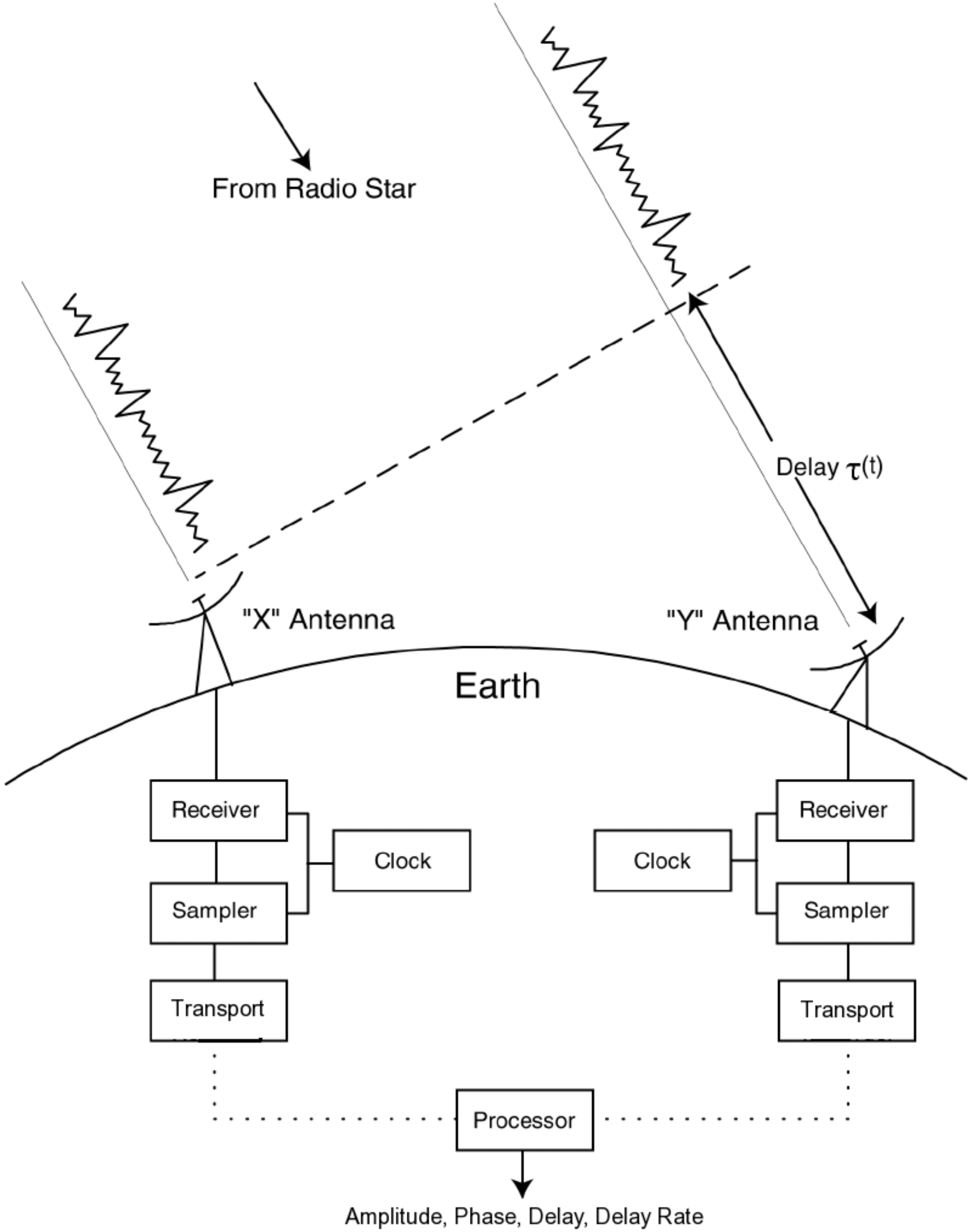


Note that SNR goes up faster by increasing BW than by increasing #bits/sample

Conclusion: To maximize SNR when data-rate is constrained, it is best to increase the BW!

Example of sampling a waveform at 2 bits/sample




From Radio Star
Delay τ(t)
"X" Antenna
"Y" Antenna
Earth
Receiver
Clock
Sampler
Transport
Receiver
Clock
Sampler
Transport
Processor
Amplitude, Phase, Delay, Delay Rate

Combining Radio Telescopes Into an Array

We have incredibly faint noise sources being observed by 1000X-noisier observing systems.

We have limited ability to expand the bandwidth (sampler/recorder limitations)

We must have limited integration times (clock behavior, recorder limits); for geo-VLBI, must move rapidly around the sky

Question:
How are observations from individual stations combined to form a large, Earth-sized array?

Correlator Mathematical Magic

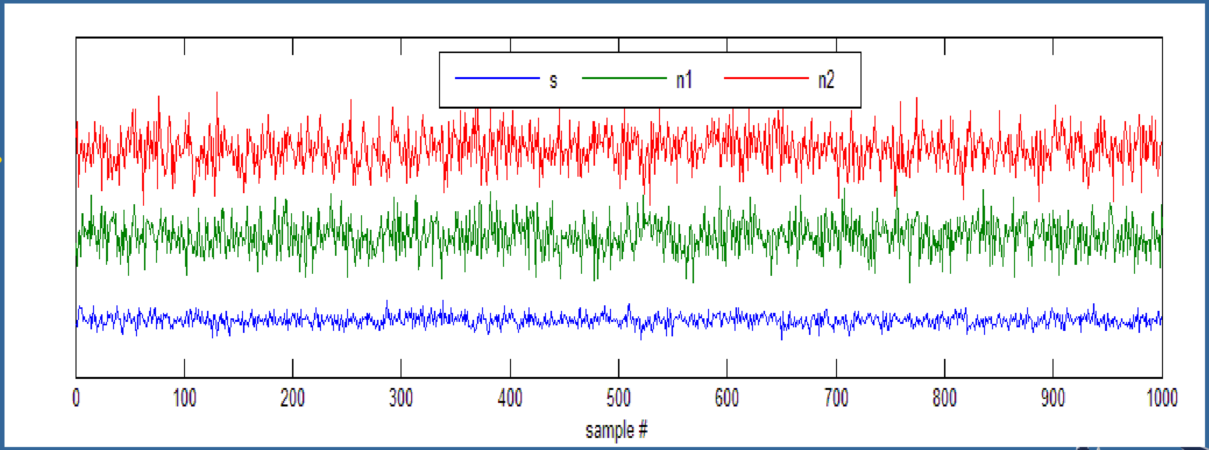
Cross-correlation of weak signals in noise

Let s(t) be a weak astronomical signal, and $n_1(t)$ and $n_2(t)$ be noise signals at sites 1 & 2

Receiver 1 noise $n_1(t)$

Receiver 2 noise $n_2(t)$

Signal s(t)



Cross-correlation of weak signals (cont'd)

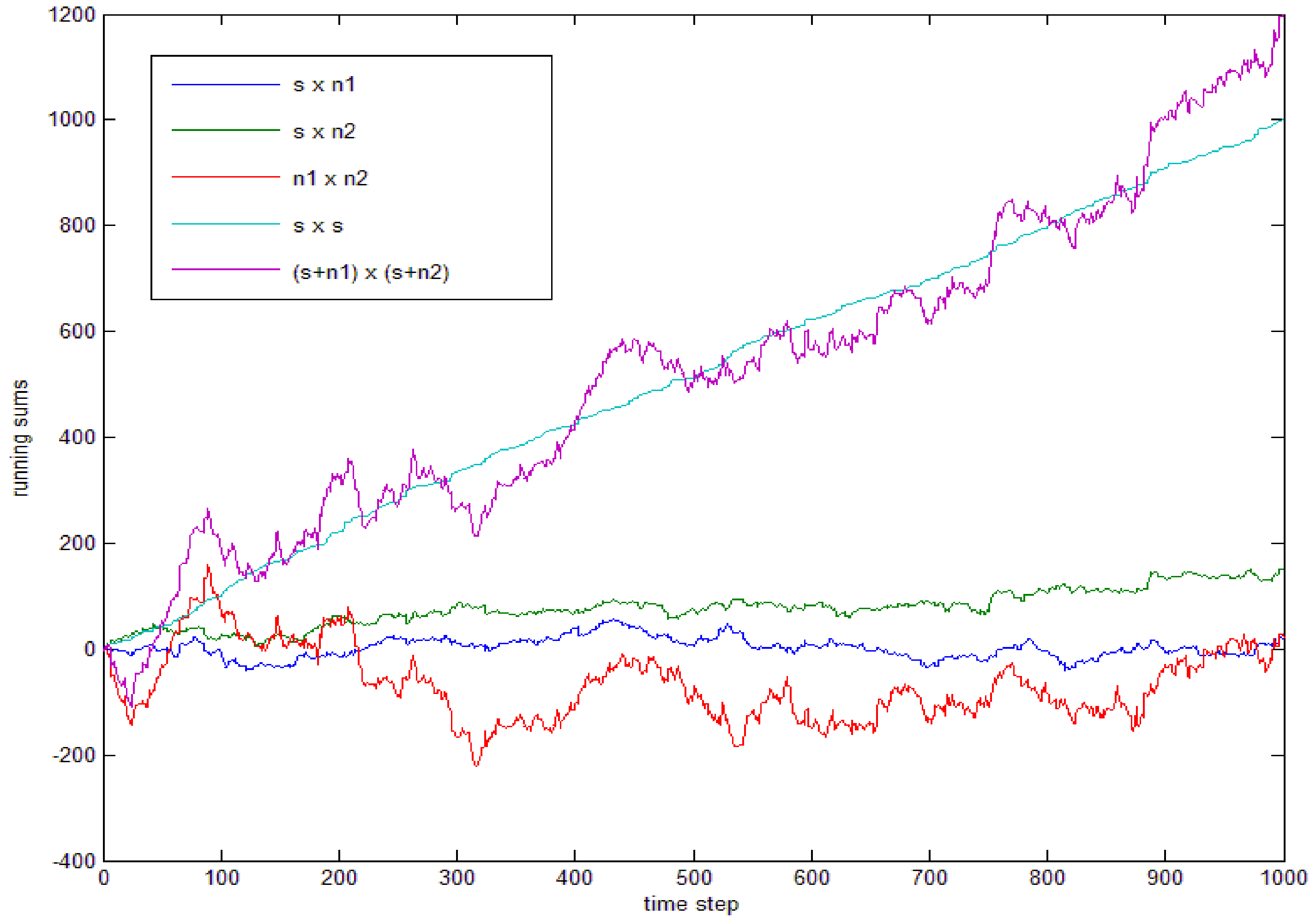
Product of signals is:

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

In actuality, life is more complicated due to Earth rotation:

- Time-of-arrival difference continually changes
- Differential Doppler shift continually changes

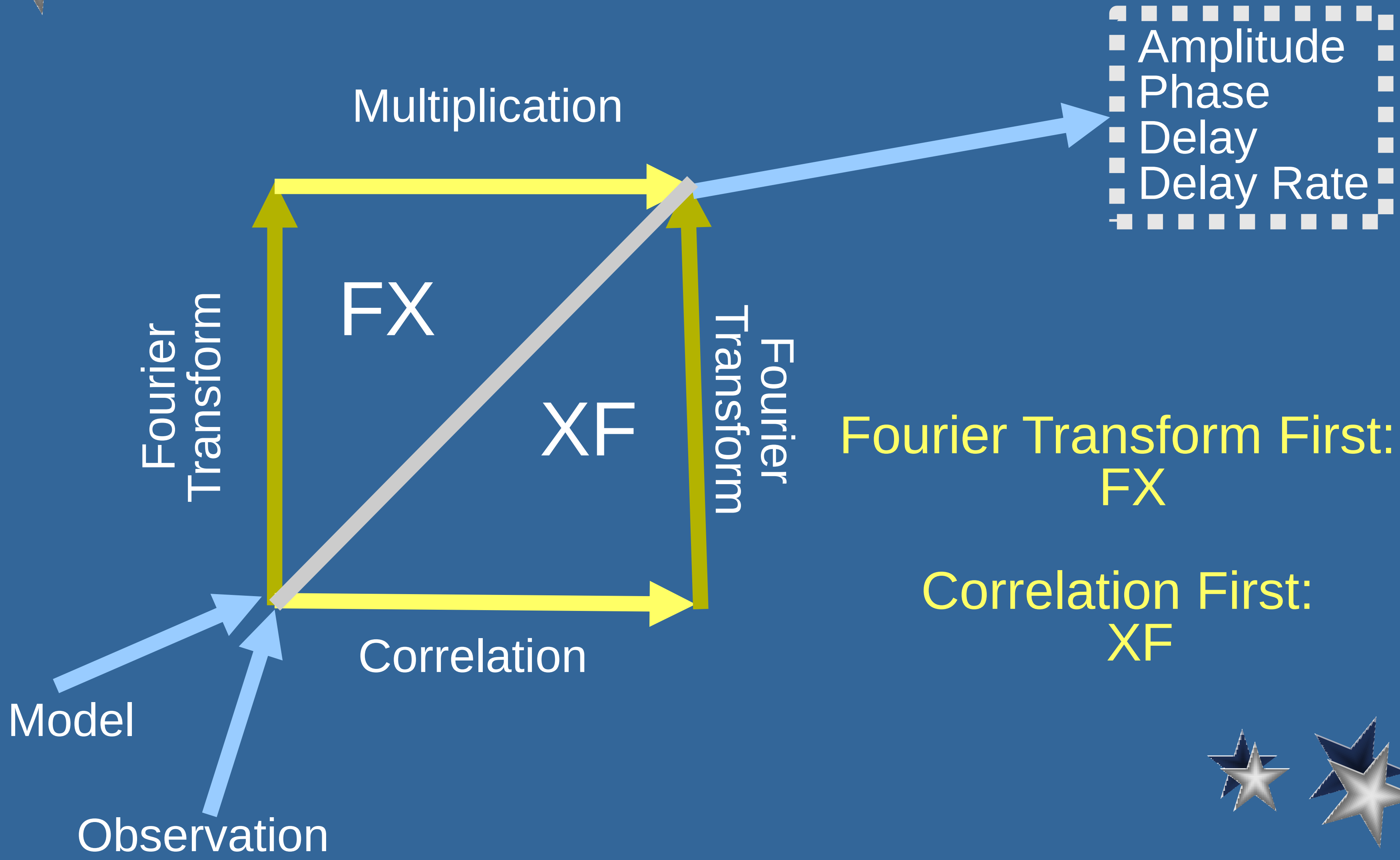
Correlation components



Combining the Observations – 1
Two Kinds of Mathematical Magic

- Fourier Transforms
  - Method of extracting frequency information from data
  - Efficient Fast Fourier Transforms are particularly suitable for computer applications
- Correlation
  - Pulls weak signals out of stronger background
  - Same technique is used in GNSS and CDMA cell phones

Combining the Observations – 2
Two Flavors of Processors



Fourier Transform First:
FX

Correlation First:
XF

Why are they called “Correlators”?

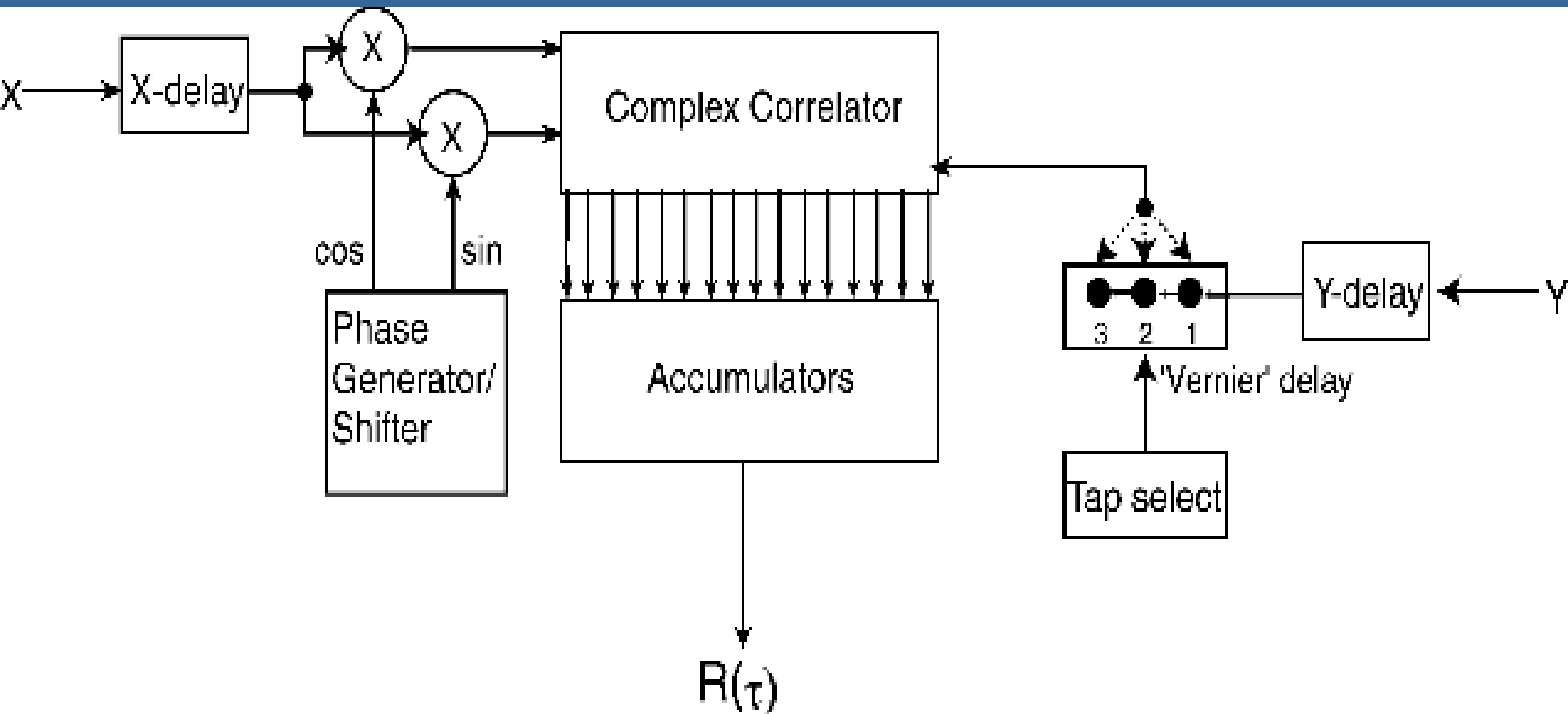
- If we had a very high snr pulses, we could just difference the arrival times
- Unfortunately, quasar signals are noise-like and ~10^3 weaker than the noise in our receiving systems
- The correlator allows us to magically pull this weak signal out of the noise and measure its delay (and rate and phase) between two sites

Correlator Details

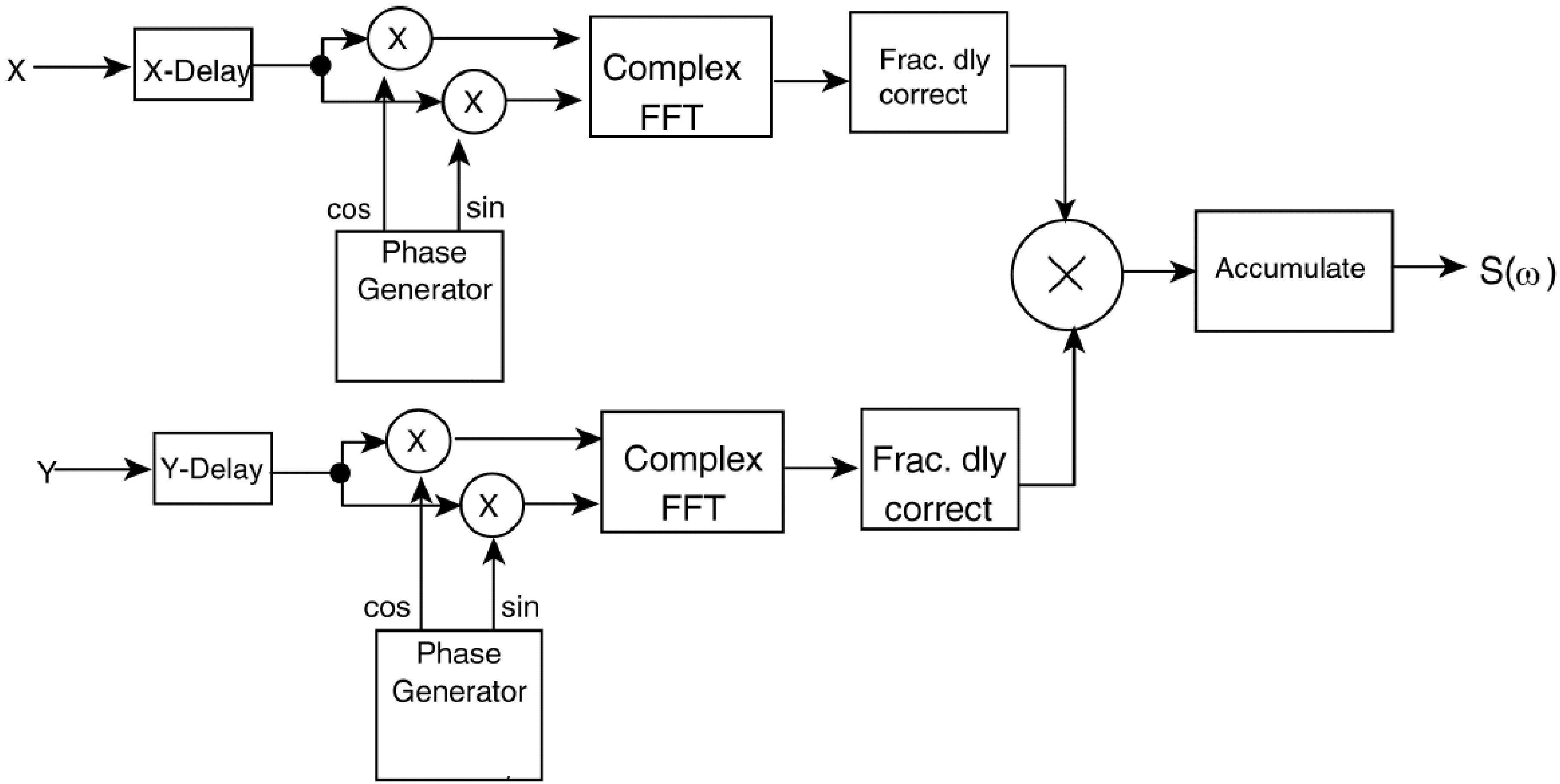
If correlation is done at the original RF frequency, a delay model by itself would produce the correct Doppler shift

Since we process at baseband, we need to have separate delay and phase models

XF Correlator Channel



FX Correlator Channel



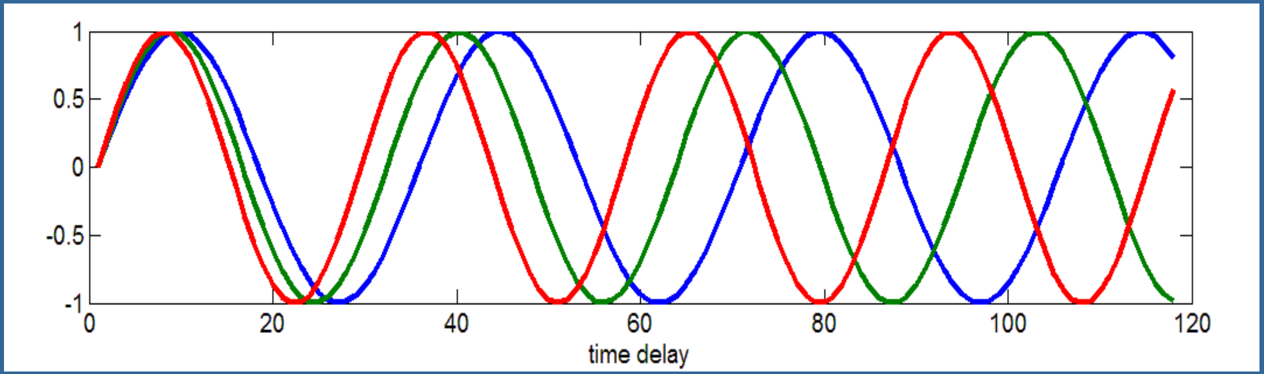
- We now must combine the channels into one solution.
- To do this we use a technique called bandwidth synthesis

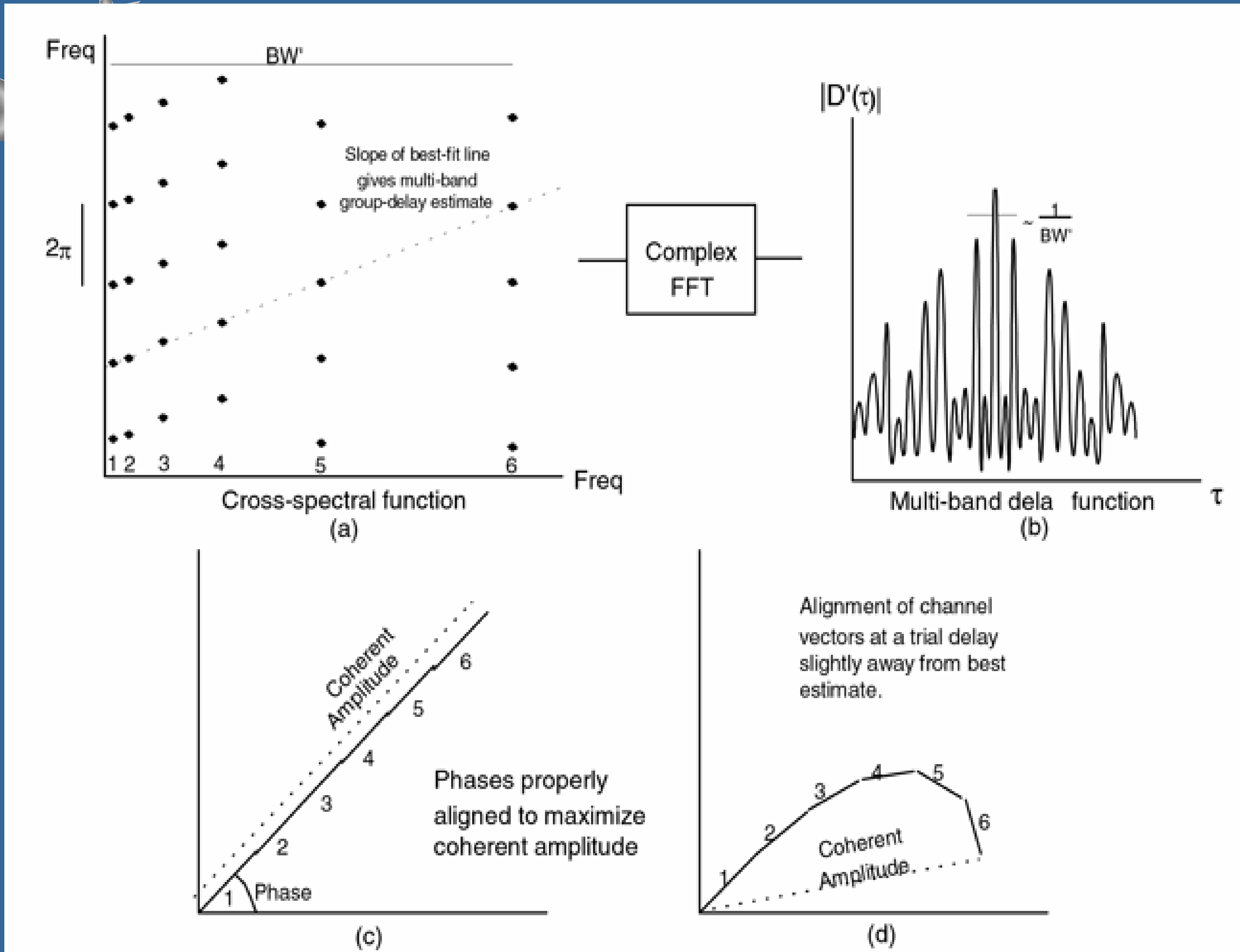
Bandwidth Synthesis

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

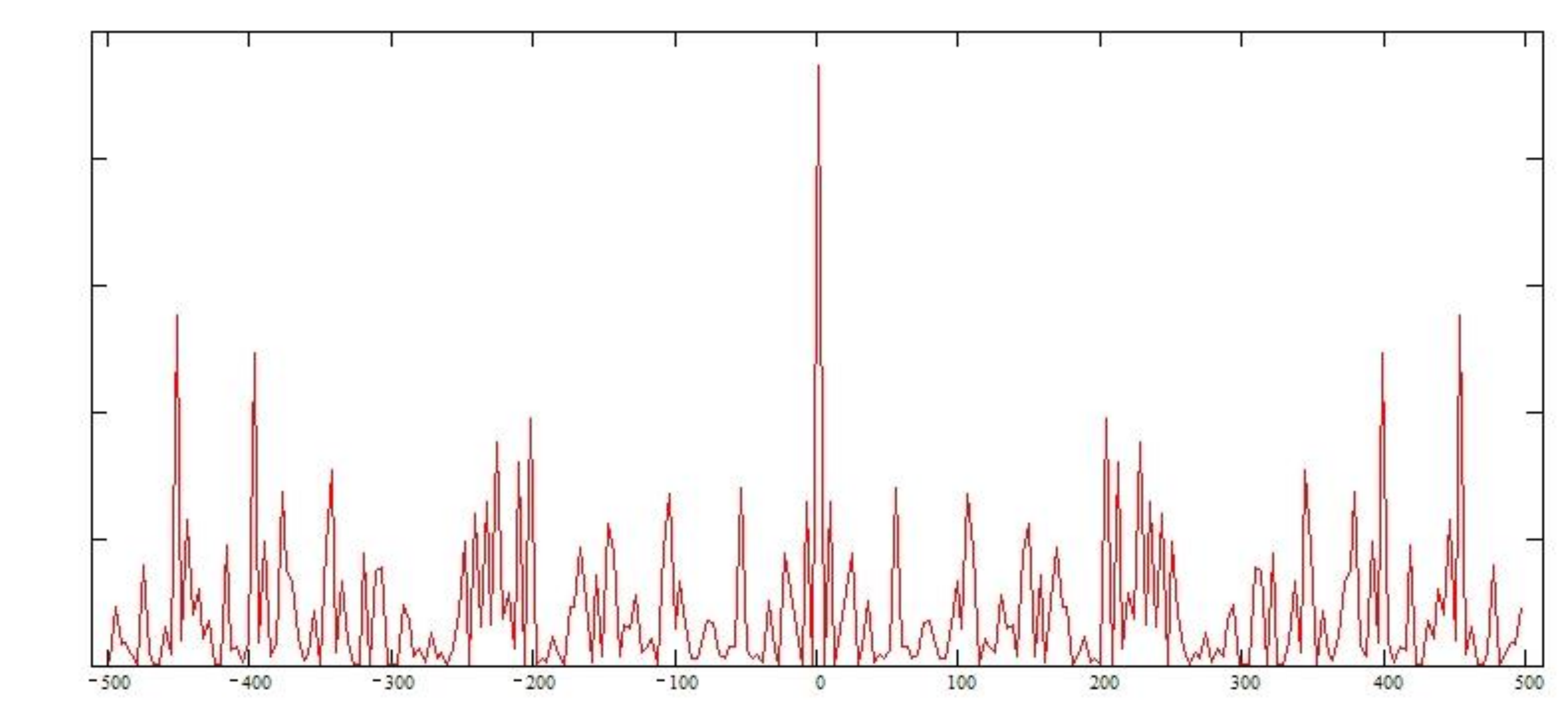
First, we must measure the observed fringe-phase difference for each of the observed frequency channels:

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



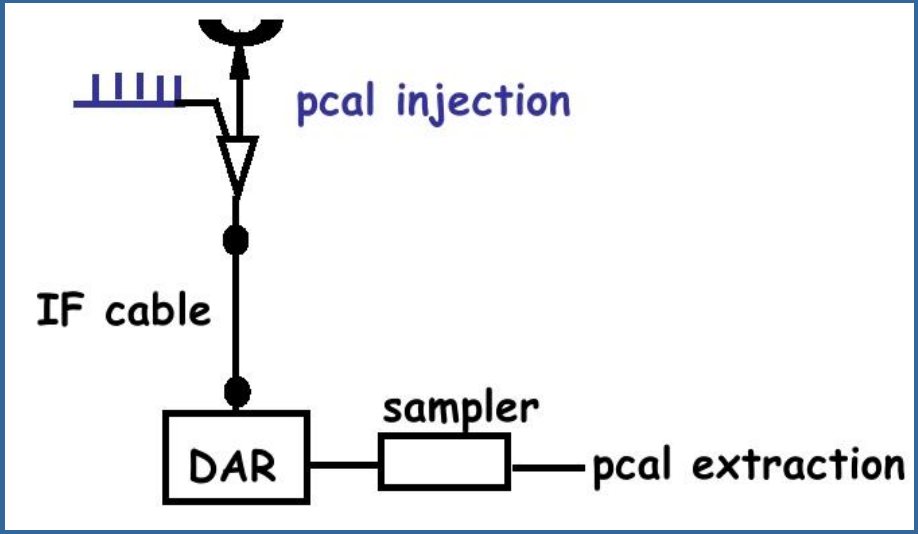

Freq
BW'
Slope of best-fit line
gives multi-band
group-delay estimate
2π
1 2 3 4 5 6
Freq
Cross-spectral function
(a)
Complex
FFT
|D'(τ)|
~ 1/BW'
τ
Multi-band dela function
(b)
Coherent
Amplitude
1 2 3 4 5 6
Phase
Phases properly
aligned to maximize
coherent amplitude
(c)
Alignment of channel
vectors at a trial delay
slightly away from best
estimate.
1 2 3 4 5 6
Coherent
Amplitude
(d)

Assuming a reasonable SNR (>~10), the height of the correct delay-function peak above other peaks depends on the RF-frequency spacing between observing channels



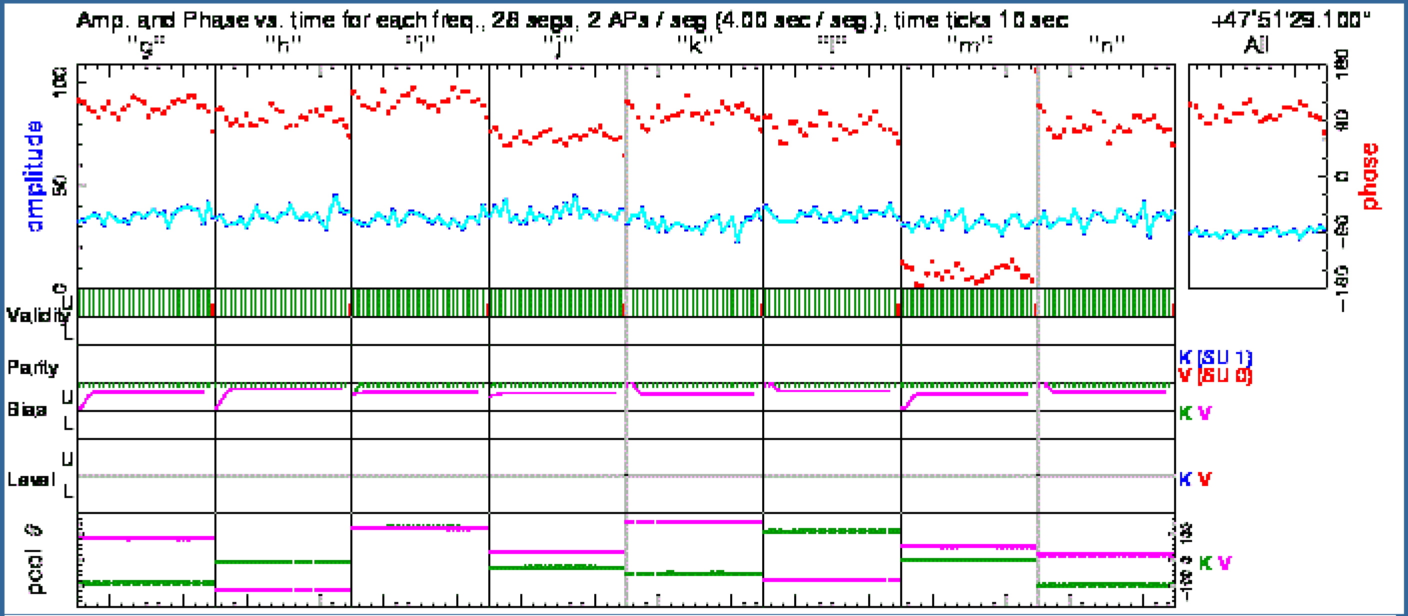
Better delay functions result from non-redundant frequency spacings between channels (for example: 0,1,4,6)

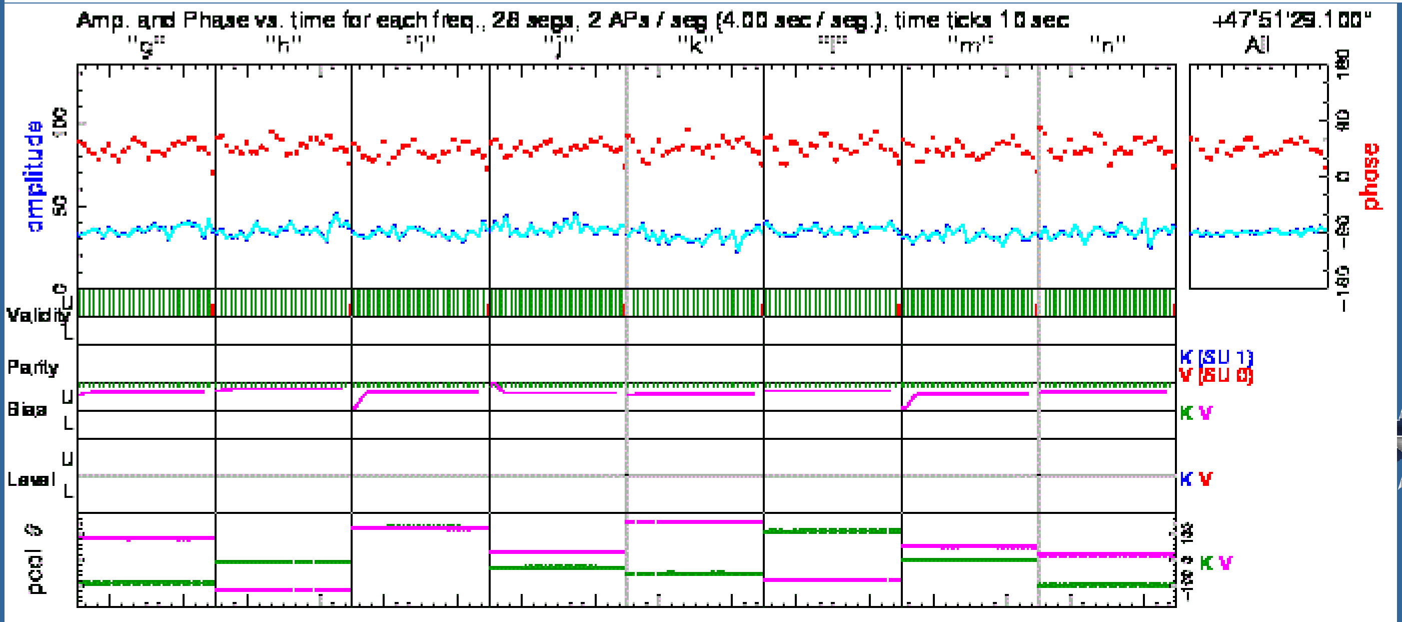
Optimizing Coherence among BBC channels



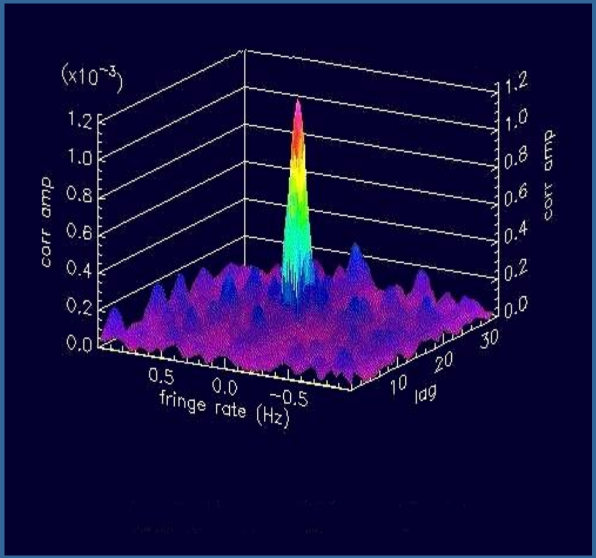
- In addition to the linear phase change due to frequency, there is a contribution to each channel's phase from the instrumentation
- e.g. the filters in each BBC have slightly different delays
- The phase cal subsystem injects tones into the front end every MHz with the same phase (at the start of each second).
- The correlator detects each tone, and adjusts the phase of the corresponding channel.

Phase-cal aligns the channels:





The Final Result : Fringes!



Observables for each baseline-scan:

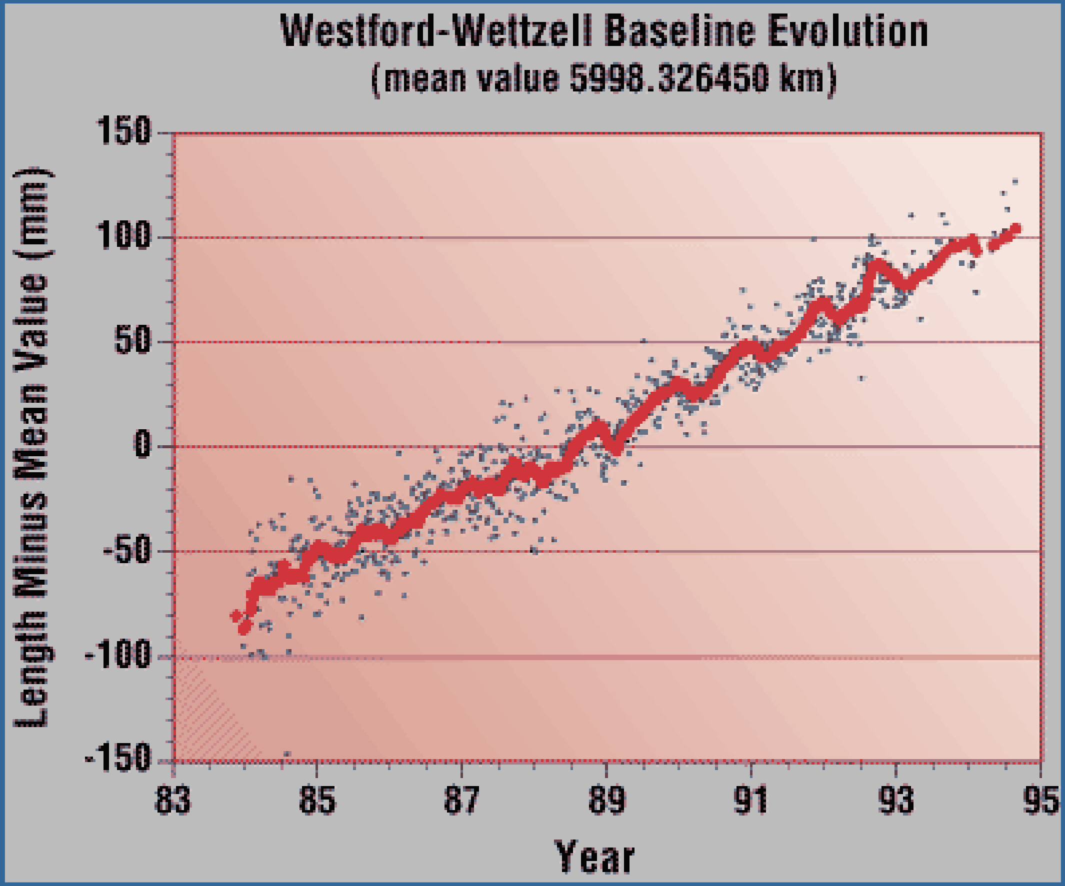
Correlation Amplitude
Correlation Phase (generally 2π ambiguous)
Total Group Delay
Total Delay-Rate

And, of course, these observables must be carefully tied to a precise UT epoch.

But that’s not the end!

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

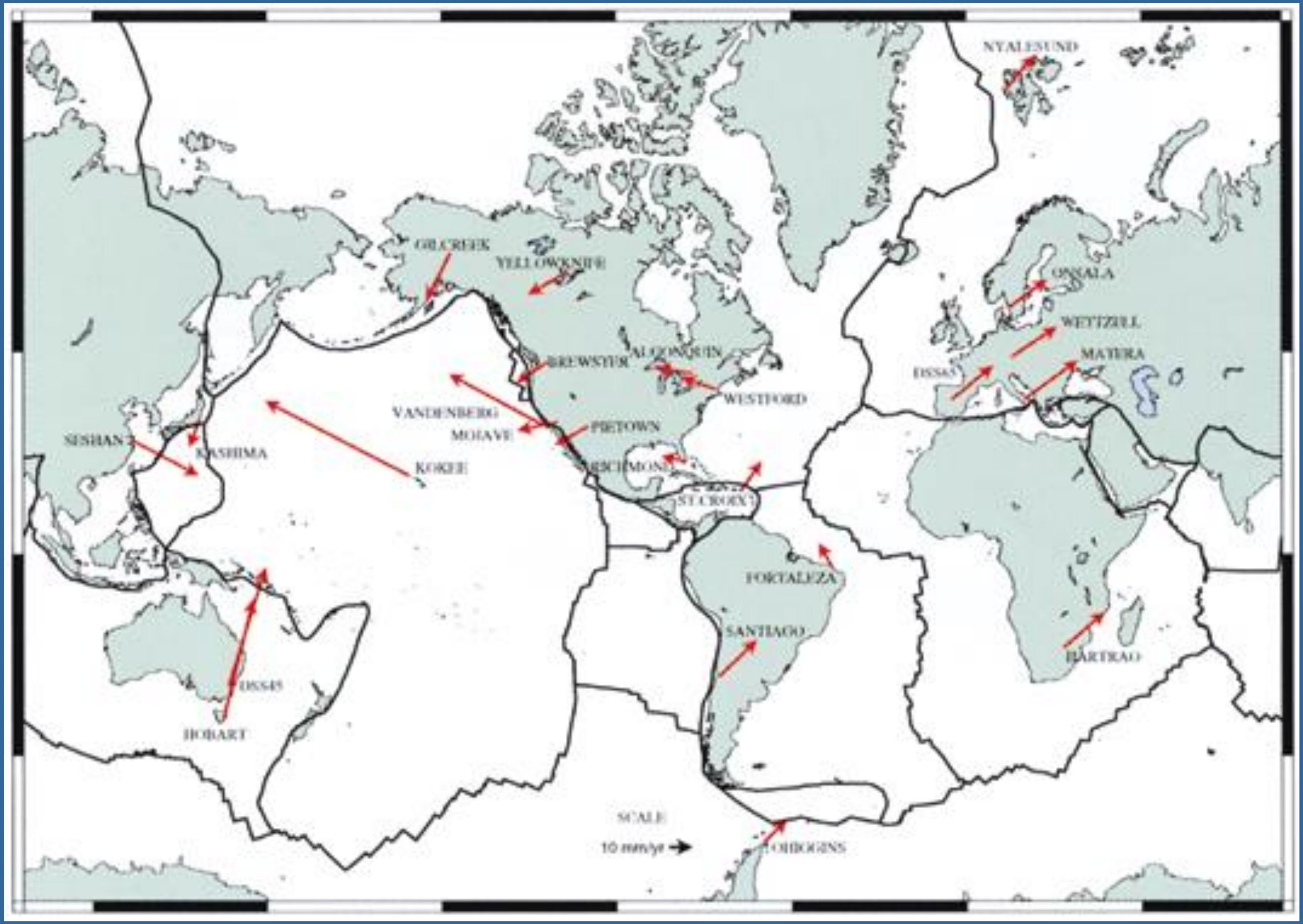
Continental Drift from VLBI



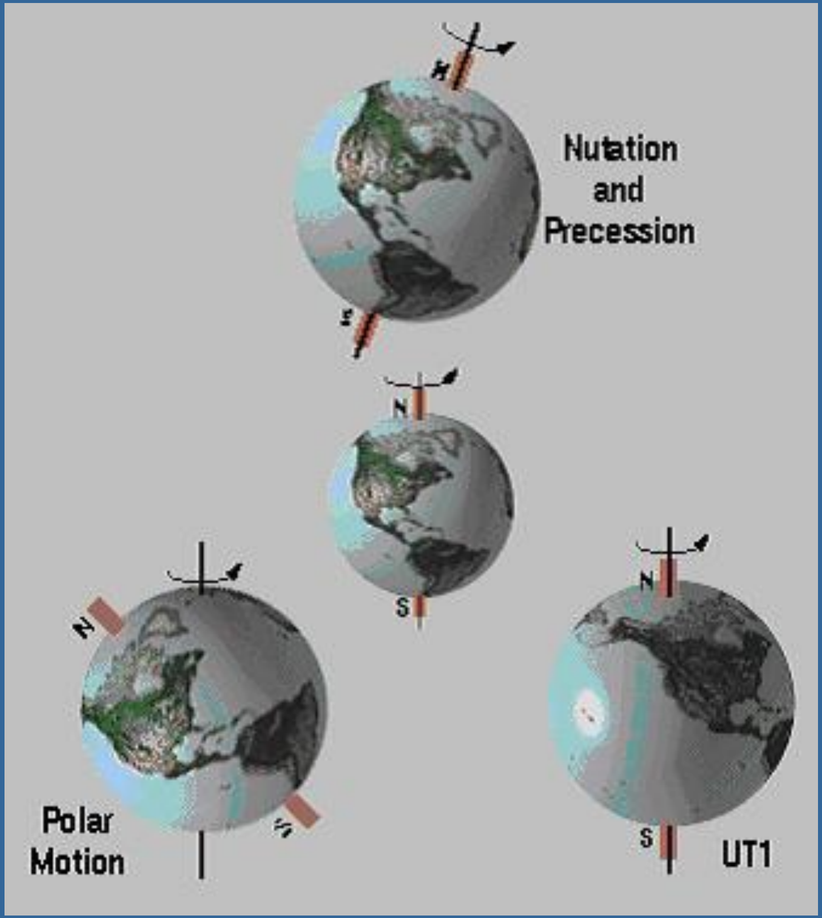
Motions of the Earth's crust:

- Displacements due to earthquakes
- Plate tectonic motions

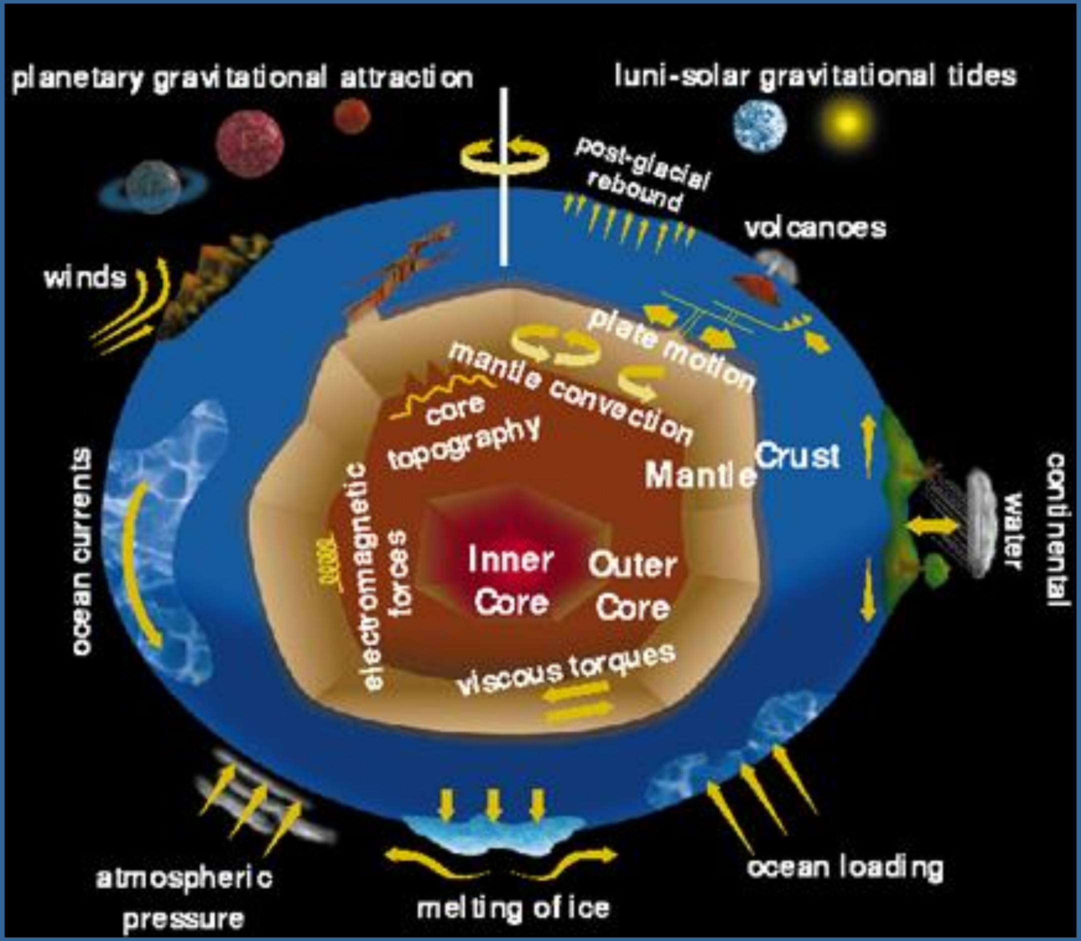
Tectonic Plate Motion



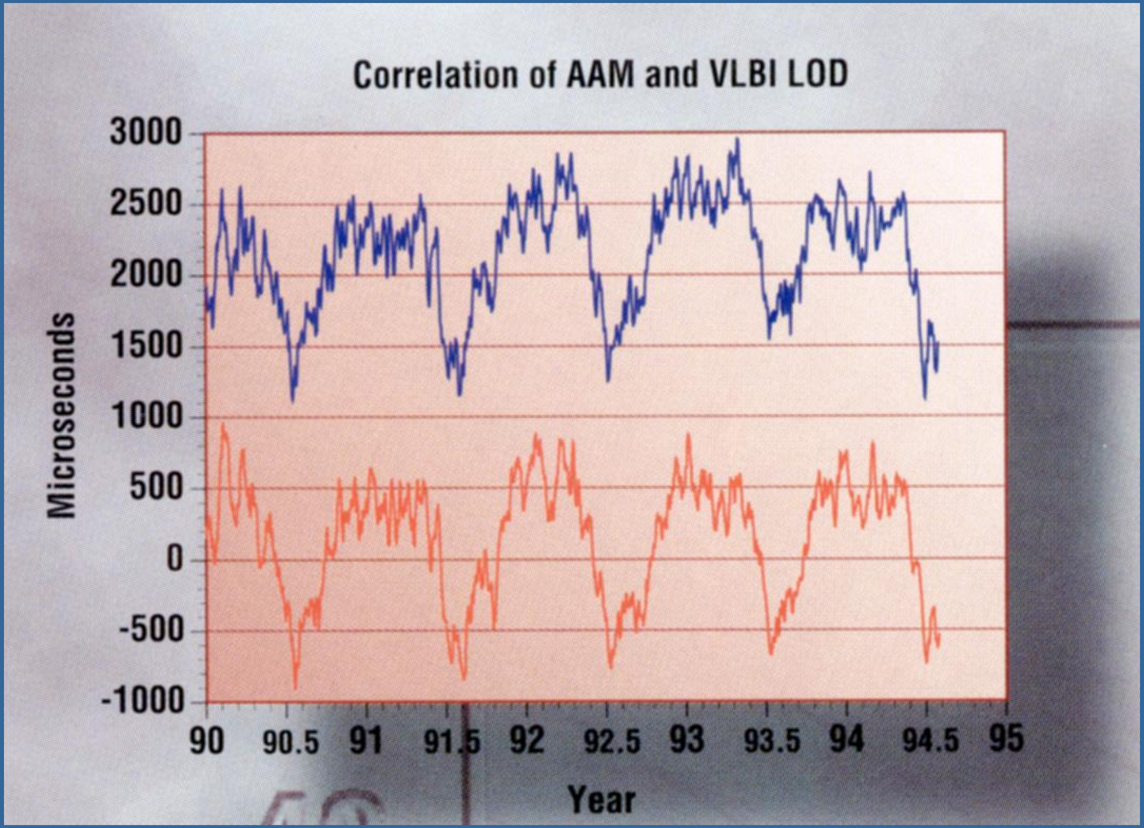
The wiggles and wobbles of the Earth in the reference frame of the distant quasars



The breathing, living Earth itself

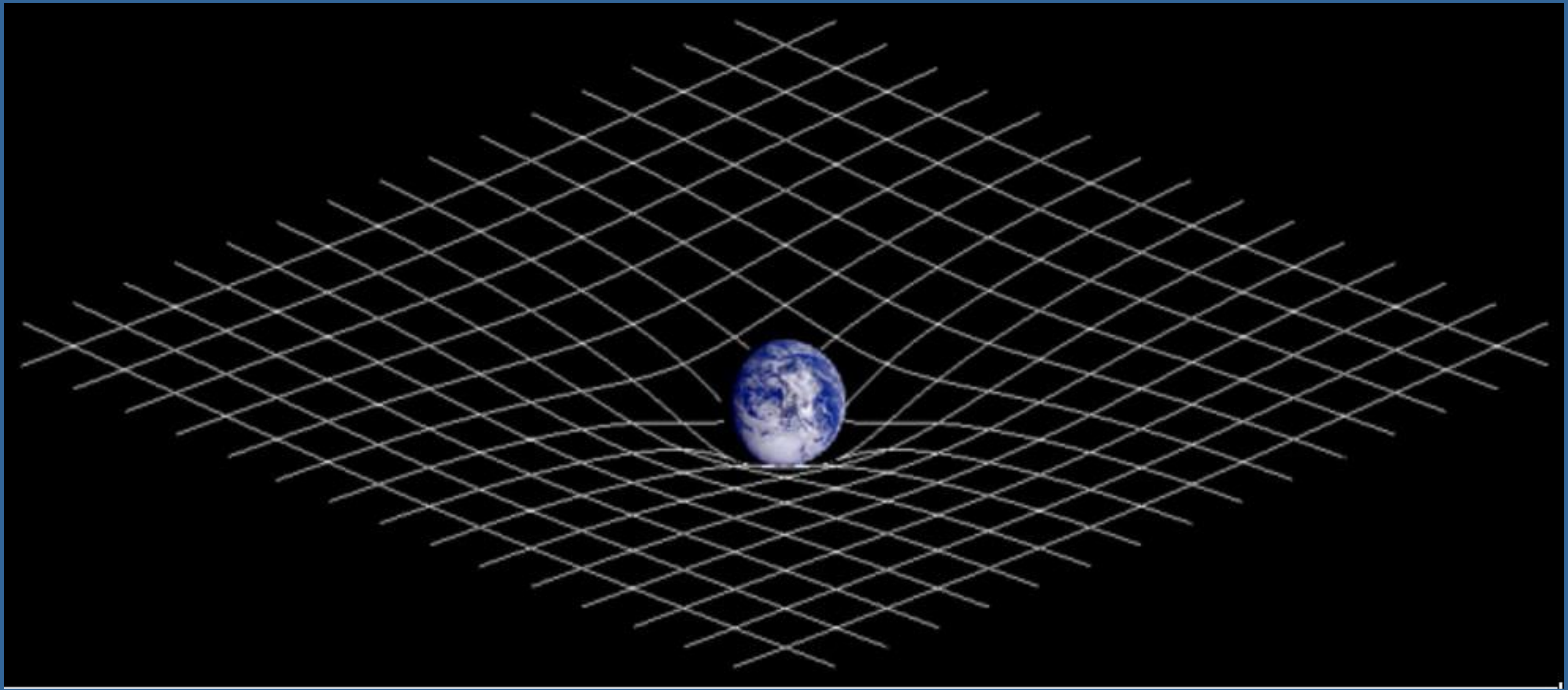


Atmospheric Angular Momentum & Length of Day



- The Sun drives Earth's weather patterns
- Weather patterns drive AAM
- Angular momentum is exchanged between the atmosphere and the solid Earth

Space-time effects of General Relativity



- The apparent position of stars is affected by the gravitational environment through which their radio waves pass

Accurately modeling all of these effects is essential to successful geodetic-VLBI

Without a highly sophisticated model of the Earth's various wiggles, wobbles and internal deformations, it would be impossible to extract meaningful conclusions from the raw correlated observables.

But is another story for another time that is best told by the data-analysis experts!

Many thanks to those from whom I lifted material:

Chris Beaudoin
Alessandra Bertarini
Roger Cappallo
Tom Clark
Dave Hall
Kerry Kingham
Arno Mueskins
Arthur Niell
Mike Titus

Thank you!

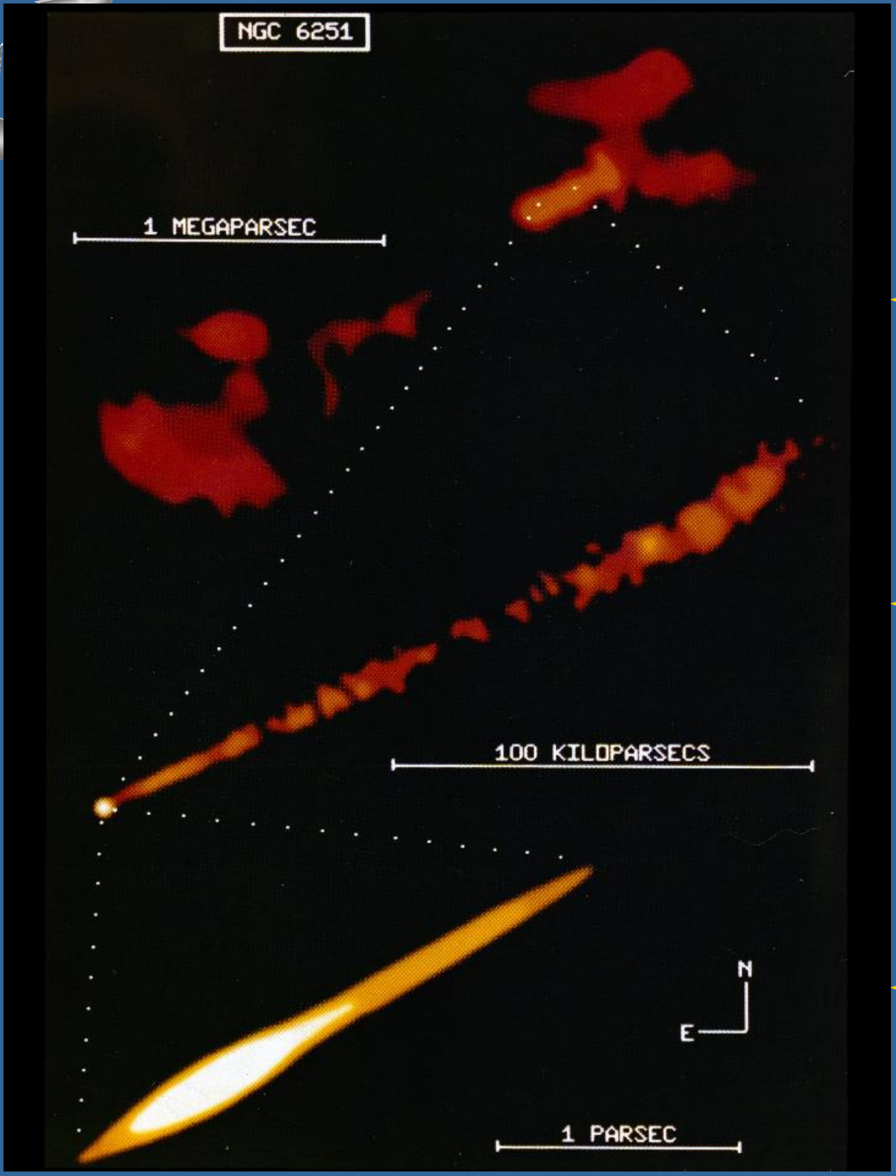
Extra Slides

VLBI for Astronomy

- Highest-resolution technique available to astronomers (or anyone else!) – tens of micro arcseconds
- Allows detailed studies of the most distant objects – quasars, gravitational lenses, GRBs, as well as black hole at center of Milky Way

NGC6251

Distance 350 Mly = 107 Mpc



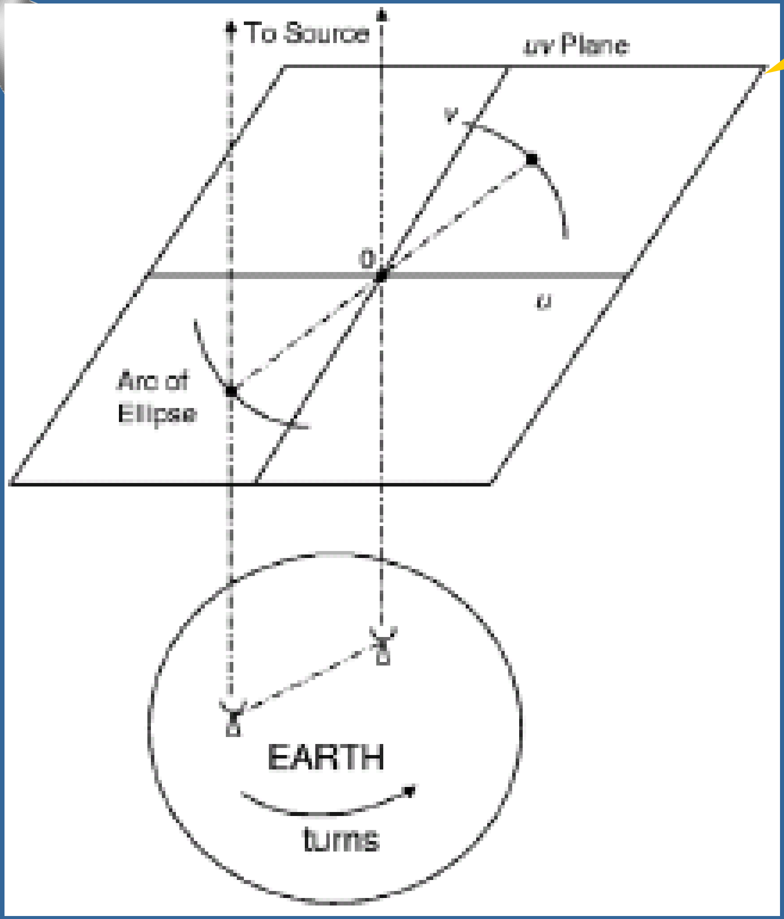
Single radio telescope image (1 Mpc → 0.5 deg)

VLA image (100 kpc → 3 arcmin)

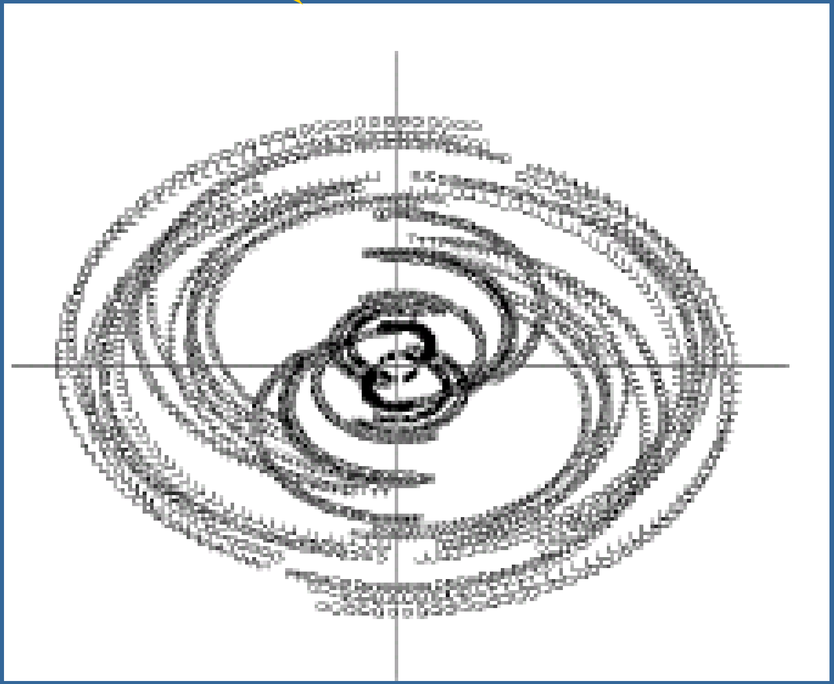
VLBI image (1 pc → 2 milli-arcsec)

Magnification ratio of 1,000,000!

Earth-Rotation Aperture synthesis



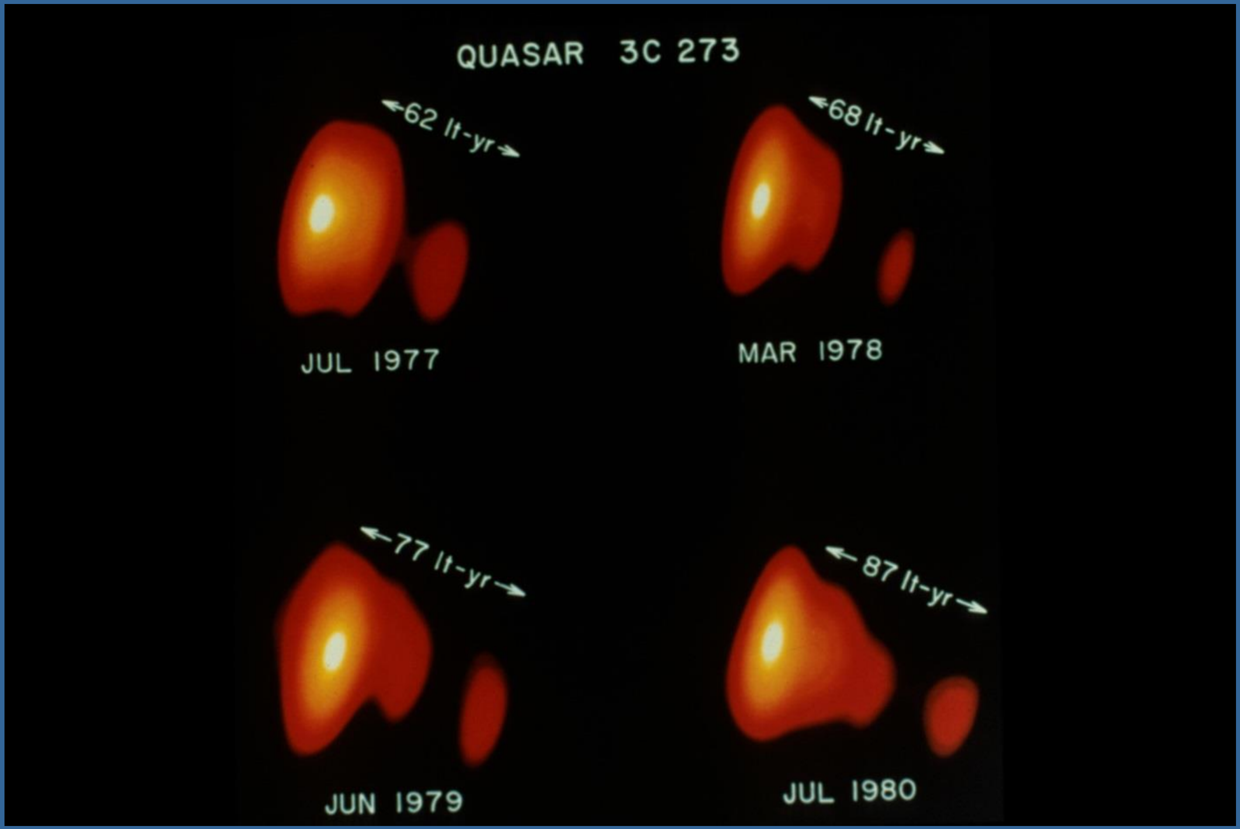
‘Virtual antenna’ aperture



As the Earth turns, each antenna pair creates an ellipse in the aperture of the Earth-size ‘virtual antenna’; many such ellipses from different antenna pairs help to ‘fill’ the virtual antenna aperture

“Superluminal motion“ in Quasar 3C273

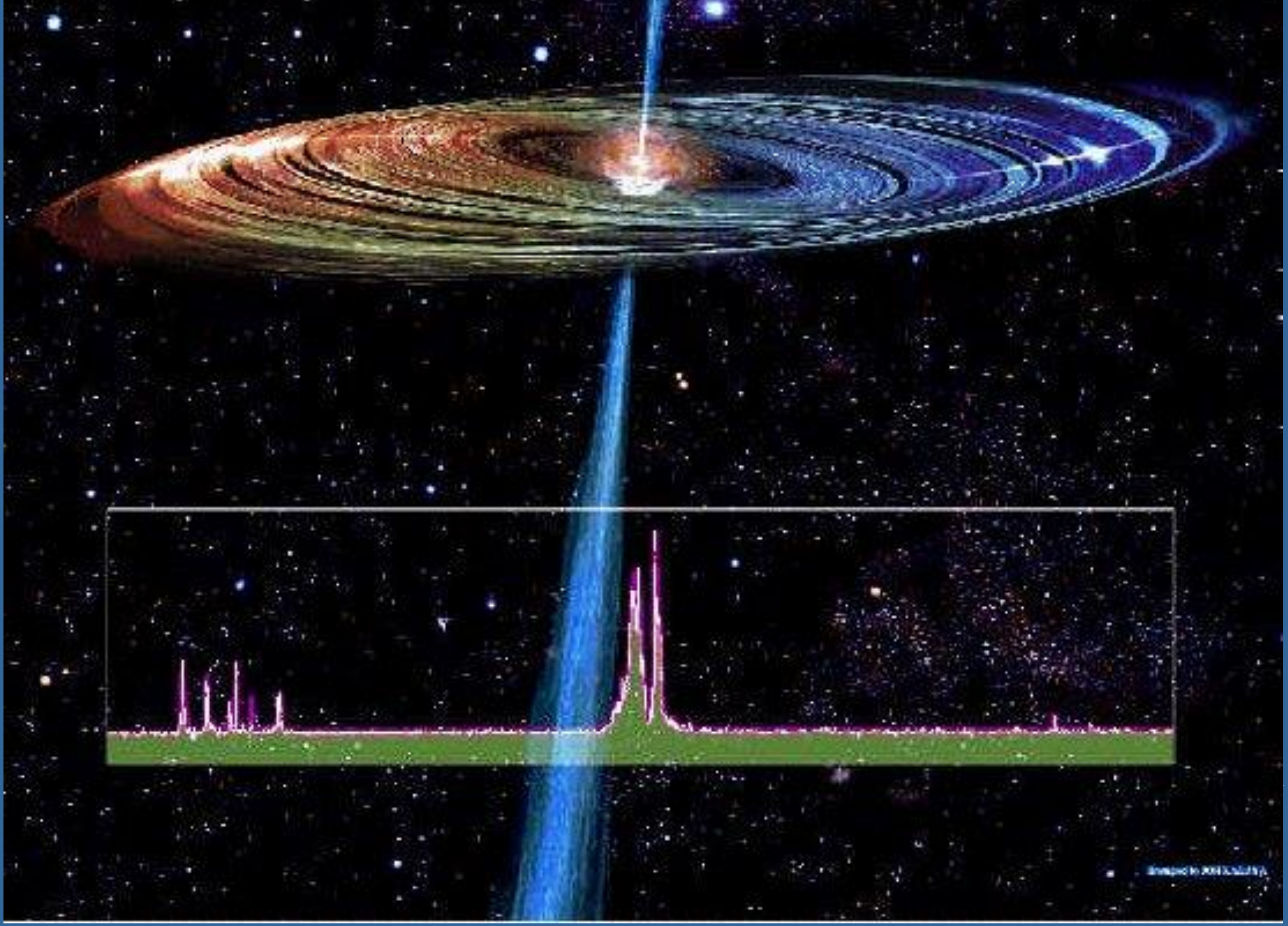
(Distance 2000 Mly = 600 Mpc)



Apparent motion faster than the speed of light!

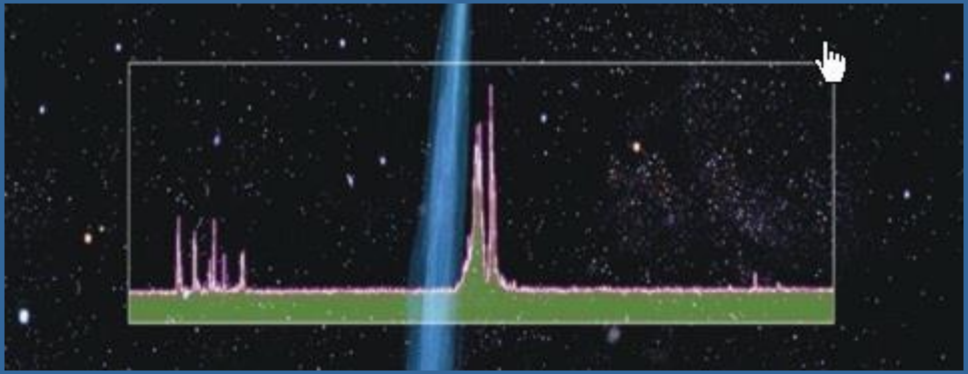
Galaxy NGC4258

- evidence of a massive block hole at center with a mass of ~36 million solar masses!
- distance is ~20 Mlight-yrs



On the trail of a massive black hole – NGC4258

-

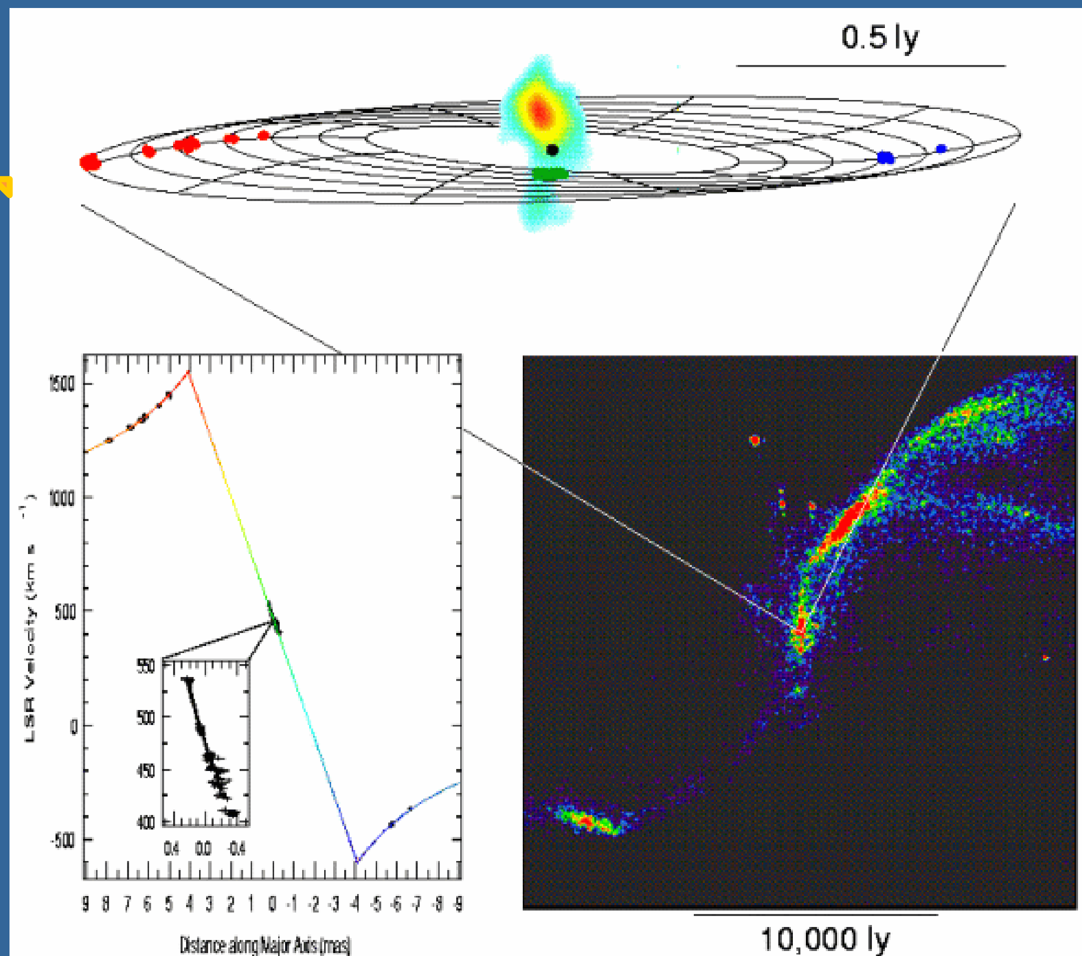


First hint was this spectra showing $H2O$ maser lines:
- Red-shifted lines receding at 1300 km/sec
- Blue-shifted lines receding at -400 km/sec
- Center receding at 500 km/sec

Galaxy NGC4258

- evidence of a massive block hole at center with a mass of ~40 million solar masses and rotating at up to 3 million km/h!
- distance is ~23.5 Mly measured by VLBI, 25 to 27 Mly by traditional Cepheid-variable distance

H_2O masers



Getting to the Event Horizon: The Galactic Center

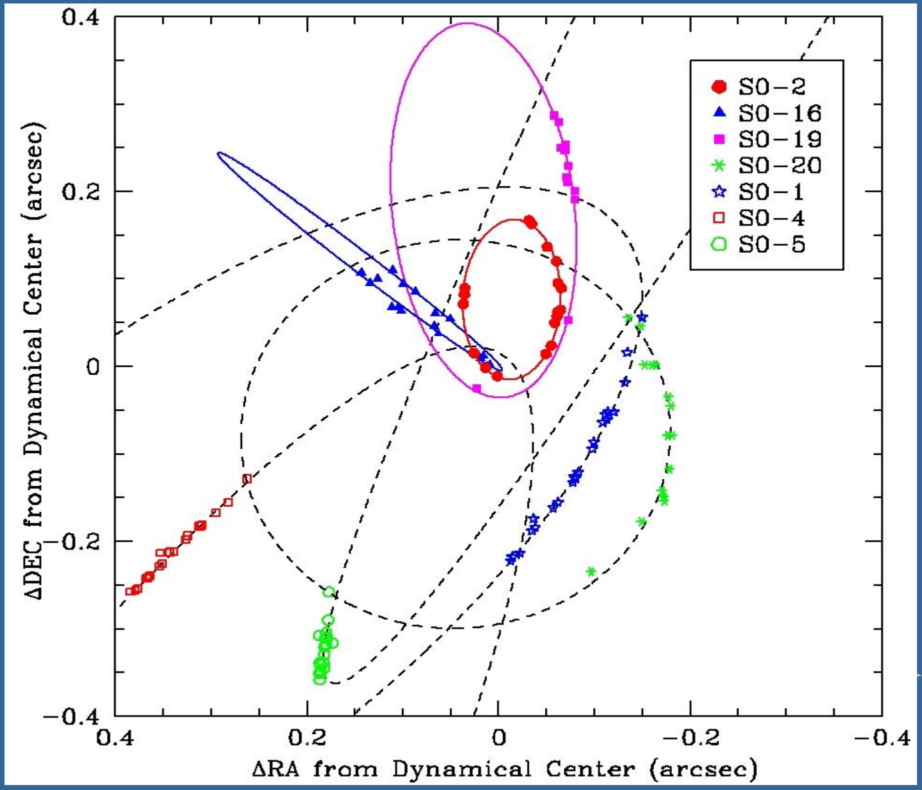
The SgrA* radio source marks the position of a super massive black hole (~4M solar masses) in the Galactic Center:

proper motion of SgrA* is small, and we see surrounding stars orbiting unseen mass.

Ghez et al 2005

- Measuring orbits of surrounding stars tells us that mass of black hole is 4M solar masses!

- 1-mm wavelength VLBI was deployed to try to put limits on size of black hole



VLBI at mm/sub-mm wavelength

- Allows highest resolutions ever achieved (tens of micro-arcseconds)
- mm/sub-mm wavelengths allow penetration of dust and gas around target objects that longer radio waves cannot penetrate
- Sources tend to be very weak;
  requires highest BW and data rate to achieve sufficient SNR
- Atmosphere limits coherence to 10-30 seconds
- Technically extremely challenging

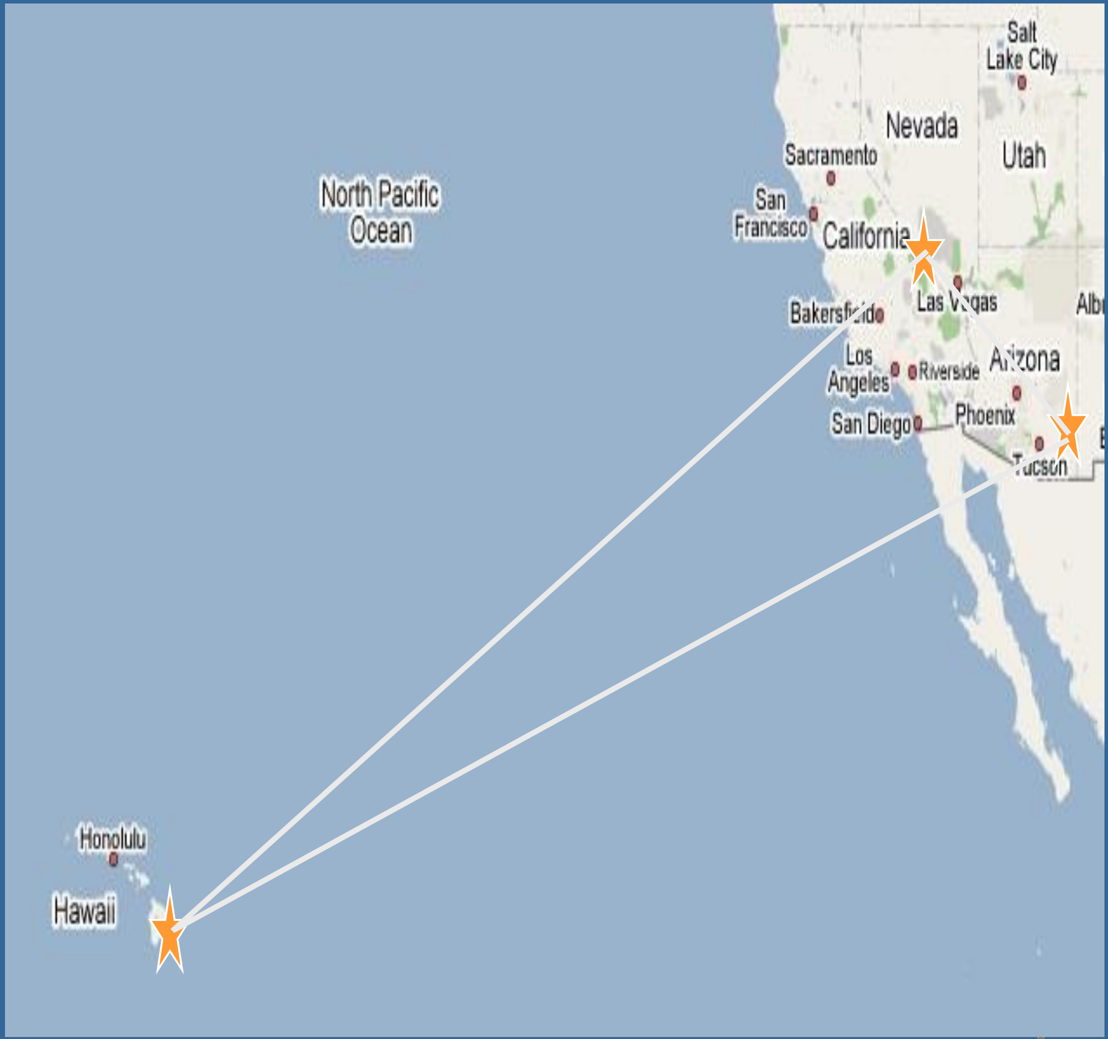
A big prize is understanding the black hole at the center of our galaxy!

230GHz VLBI: April 2007
SMTO, JCMT/SMA, CARMA

- First successful 3-station 230 GHz (1mm wavelength) VLBI observations

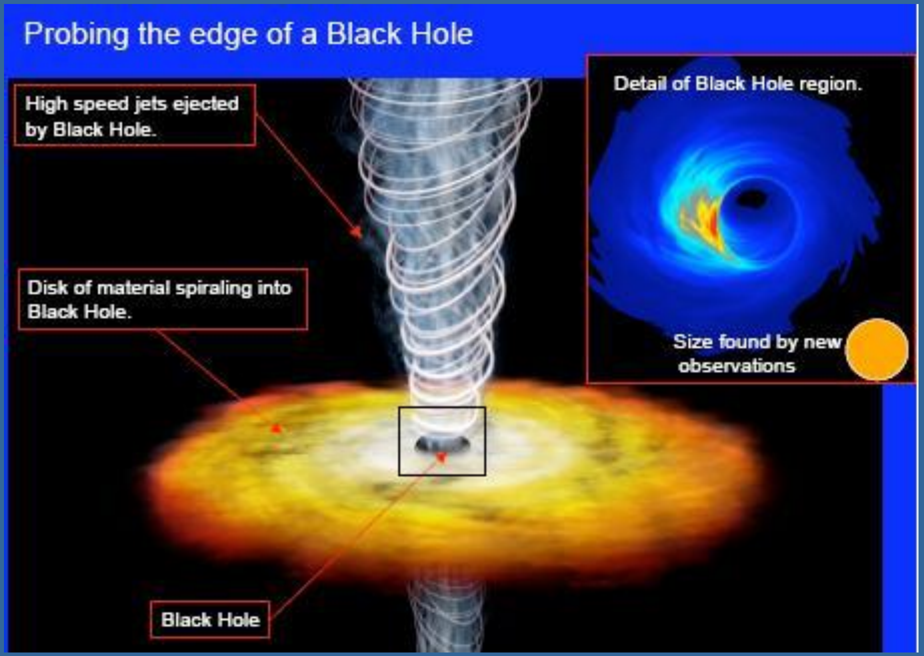
- Resolution on baselines to Hawaii is ~40 microarcsec; highest resolution ever achieved

- Extremely difficult observations



Results of SgrA* Observations

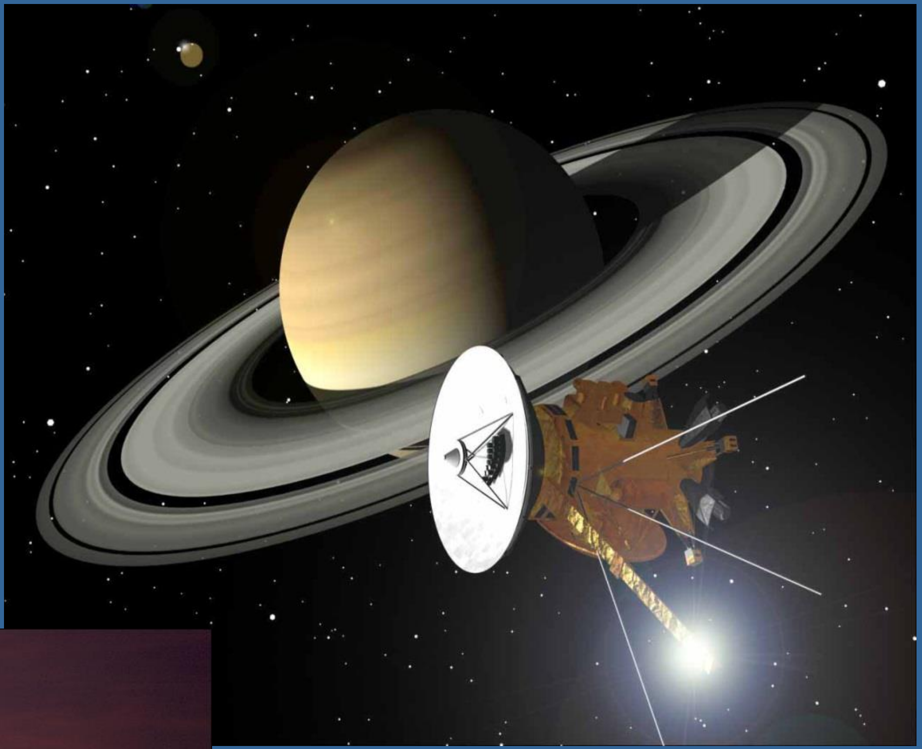
- Established a radius upper limit of ~5 times the event-horizon radius (~1/3 Sun-Earth distance)
- Probably seeing emitting material circling closely around black hole
- Results have generated intense interest; more observations planned



Differential VLBI for Deep Space Tracking

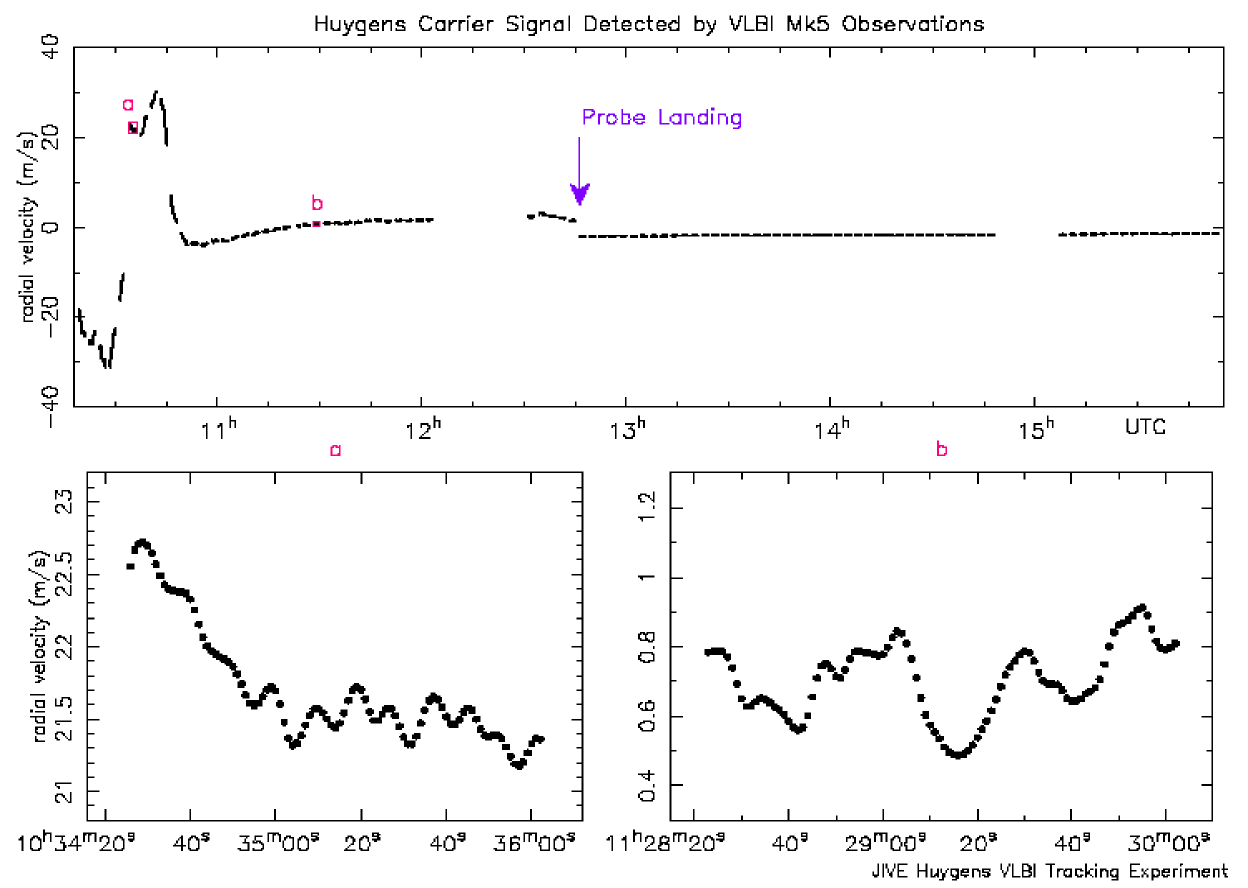
- Track spacecraft in 2-dimensions on the sky by measuring difference position to nearby (usually very weak) quasar
- Along with traditional round-trip delay to spacecraft, gives 3D position
- Abandoned by NASA in 1980's; reinstated after losing two spacecraft on Mars
- Also saved the day for the Huygen's probe to Saturn's moon Titan

Cassini-Huygens probe to Saturn
(14 January 2005)



⟸ Huygens probe parachuting to Titan

VLBI Saved the Day!



Differential VLBI, along with Earth-based Doppler, tracked probe in 3D as it fell

(courtesy JIVE)

TANDEM – Return to Titan c. 2015

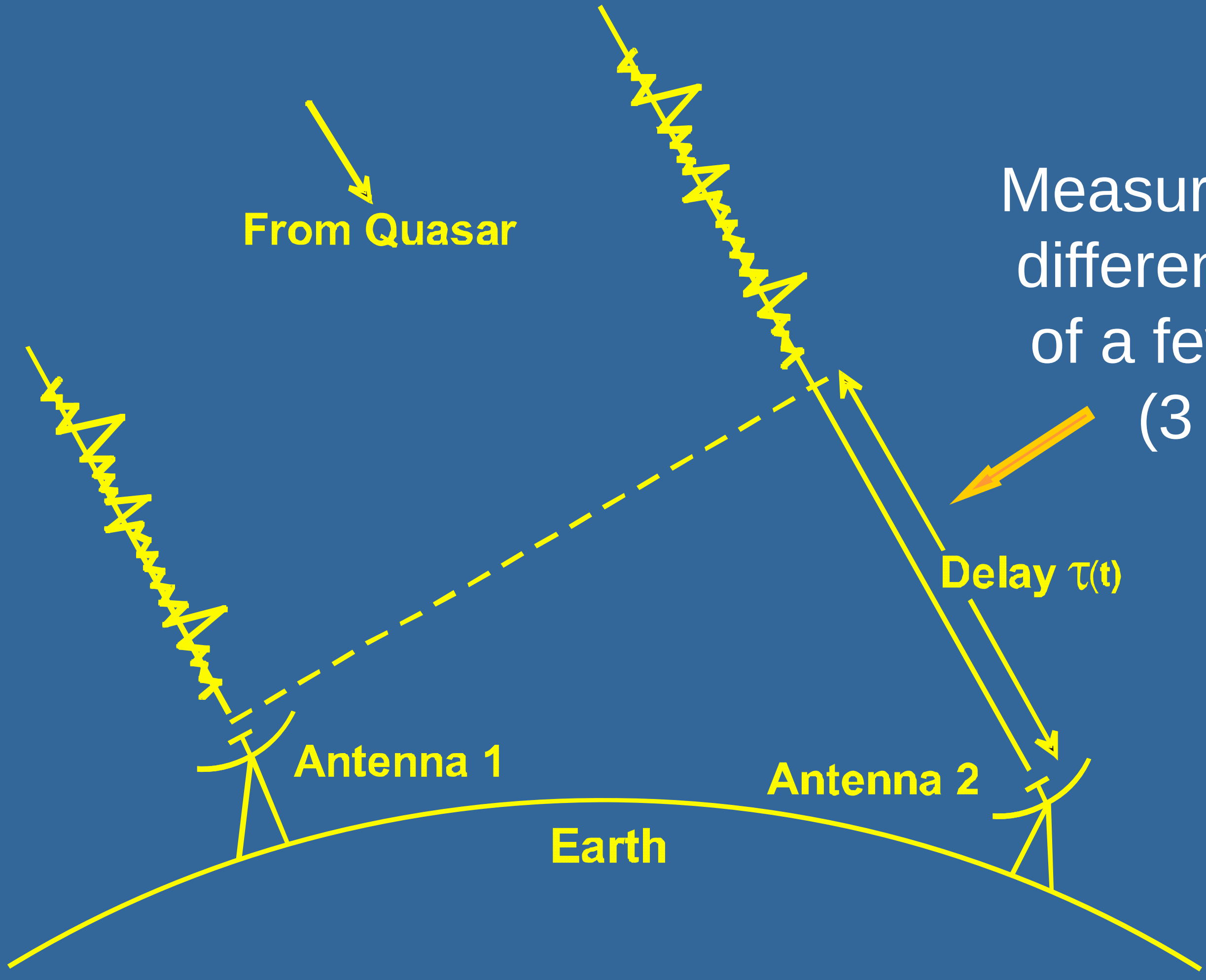
Proposal: Float a long-lived balloon in the atmosphere of Titan, the largest moon of Saturn

Requirement: Dynamically measure the position of the balloon to within ~10m in near-real-time

VLBI for Geodesy

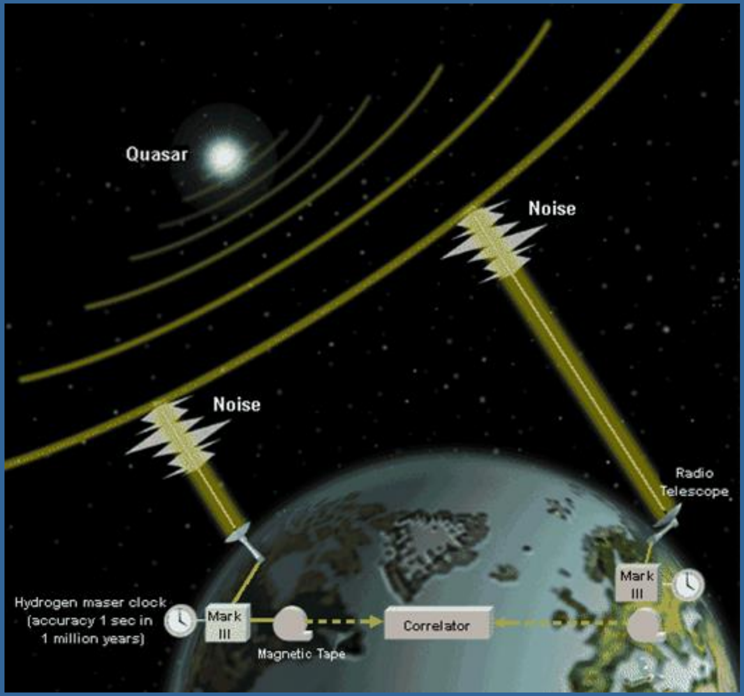
- Highest precision (few <u>mm</u>) technique available for global tectonic measurements
- Earth-rotation measurements important for military/civilian navigation
- Fundamental calibration for GPS constellation within Celestial Ref Frame
- Highest spatial and time resolution of Earth's motion in space for the study of Earth's interior

Principle of Geodetic VLBI



Measure time-of-arrival difference to accuracy of a few picoseconds (3 ps =1 mm)

Complications!



The Earth and the universe are messy places:

- atmosphere
- ionosphere
- wobbling Earth
- stormy Sun
- inter-stellar and inter-galactic media
- changing source structures

VLBI2010 Project

Project goals:

- measure global antenna positions to 1mm accuracy in 24 hrs
- measure motions to 0.1mm/yr
- continuous monitoring of Earth's orientation in space
- <24 hrs from data taking to results
- 20 to 40 stations worldwide

~20 countries participating

VLBI2010 – major sources of error

Random errors:

- atmosphere variability (including water vapor content)
- clock drifts and instabilities
- signal-to-noise ratio of observations

Systematic errors:

- source structure
- instrumentation deficiencies
- antenna deformation
- site instability

VLBI2010 – how to fight these errors

Random errors:

- atmosphere variability
  - ► *move antenna rapidly around sky to sample as quickly as possible*
- clock drifts and instabilities
  - ► *use high-quality H-maser frequency standards*
- signal-to-noise ratio of observations
  - ► *observe wider bandwidths with quieter receivers*

Systematic errors:

- source structure
- instrumentation deficiencies
- antenna deformation
- site instability

All of these applications benefit from increased sensitivity

- **Astronomy**
  - Number of accessible sources increases exponentially as detection limits improve; can look further back in time
  - Increased sensitivity → lower noise → better images
- **Geodesy and geophysics**
  - Better distribution of available point-like sources over the sky improves quality of Celestial Reference Frame
- **Deep-space tracking**
  - Allows finding weak references sources nearer to spacecraft sky position to improve tracking accuracy

Now let's talk a bit about the nuts and bolts of VLBI

- **The hallmarks of VLBI:**
  - A push for utmost sensitivity;
    Increased sensitivity → lower noise → better measurements
  - Ultra-stable clocks and frequency sources;
    particularly for geodetic-VLBI and short-wavelength VLBI
  - Massive amounts of data to be collected and processed

What data are actually recorded?

Answer: It is just precisely timed samples of pure noise
− pure white, Gaussian noise!

Interesting fact: Normally, the voltage signal is sampled with only 1 or 2 bits/sample

Big consequence: It is essentially incompressible!

But also another important consequence:
If a small amount of data are lost,
it's usually no big deal!

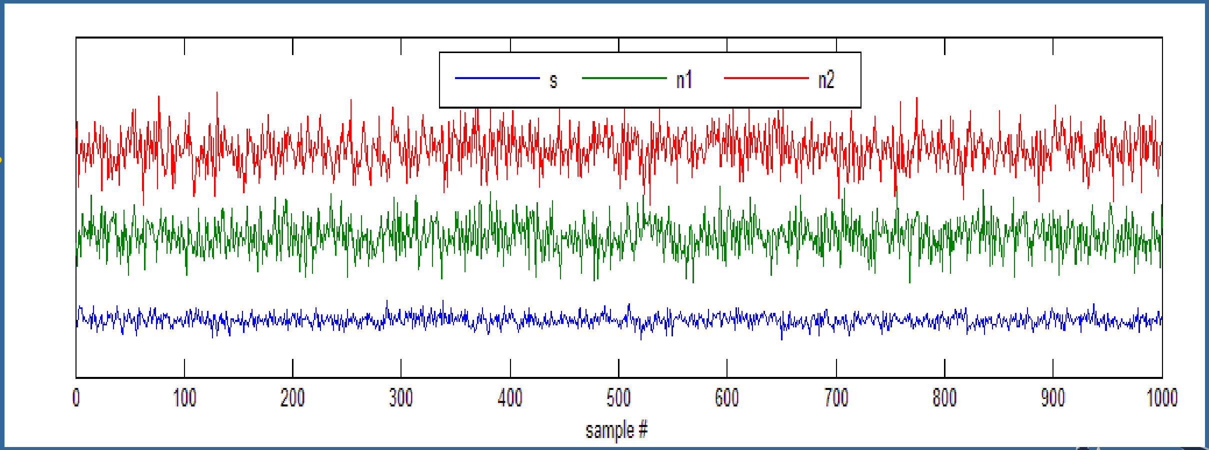
Cross-correlation of weak signals in noise

Let s(t) be a weak astronomical signal, and $n_1(t)$ and $n_2(t)$ be noise signals at sites 1 & 2

Receiver 1 noise $n_1(t)$ →

Receiver 2 noise $n_2(t)$ →

Signal s(t) →



Cross-correlation of weak signals (cont'd)

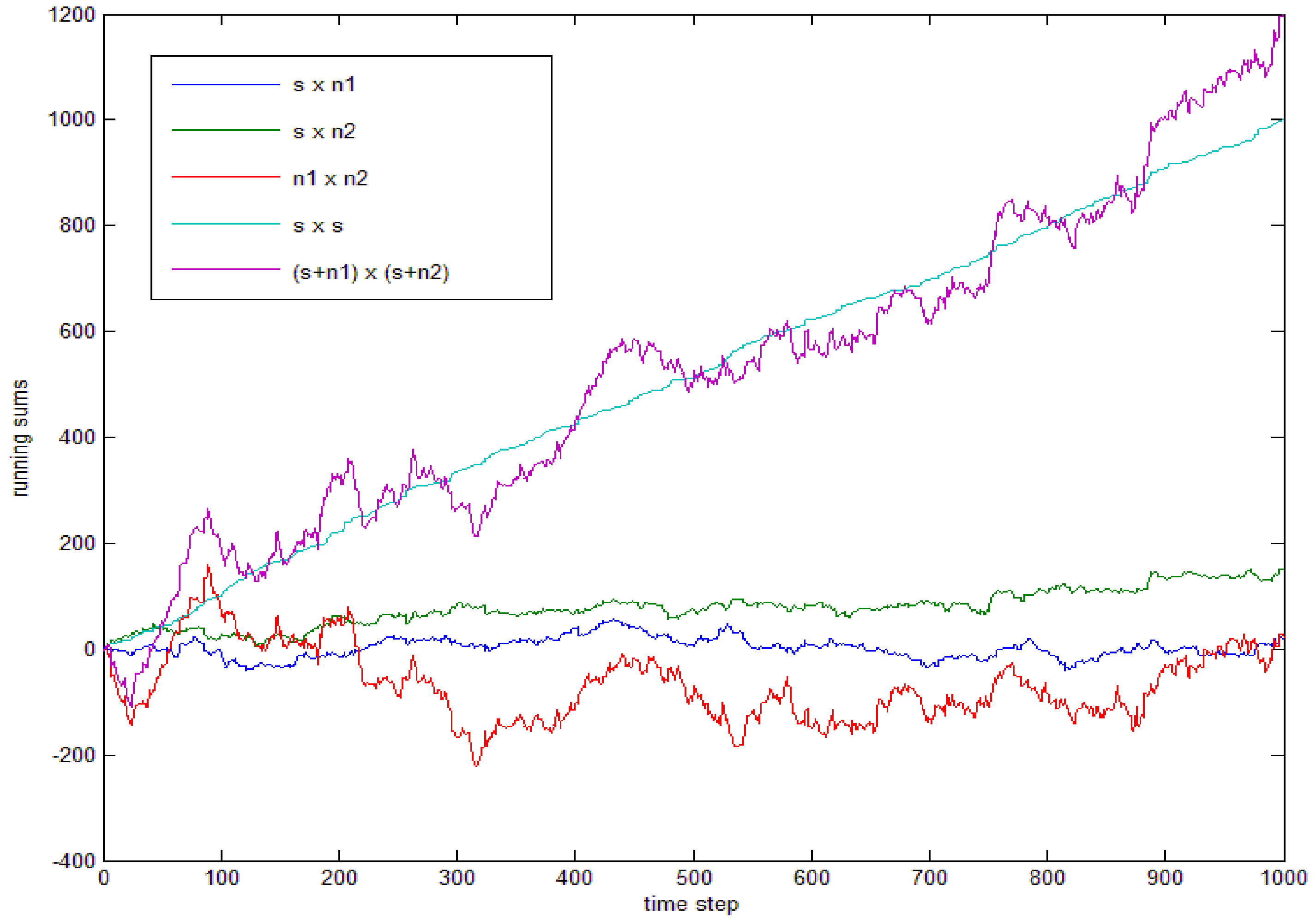
Product of signals is:

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

In actuality, life is more complicated due to Earth rotation:

- Time-of-arrival difference continually changes
- Differential Doppler shift continually changes

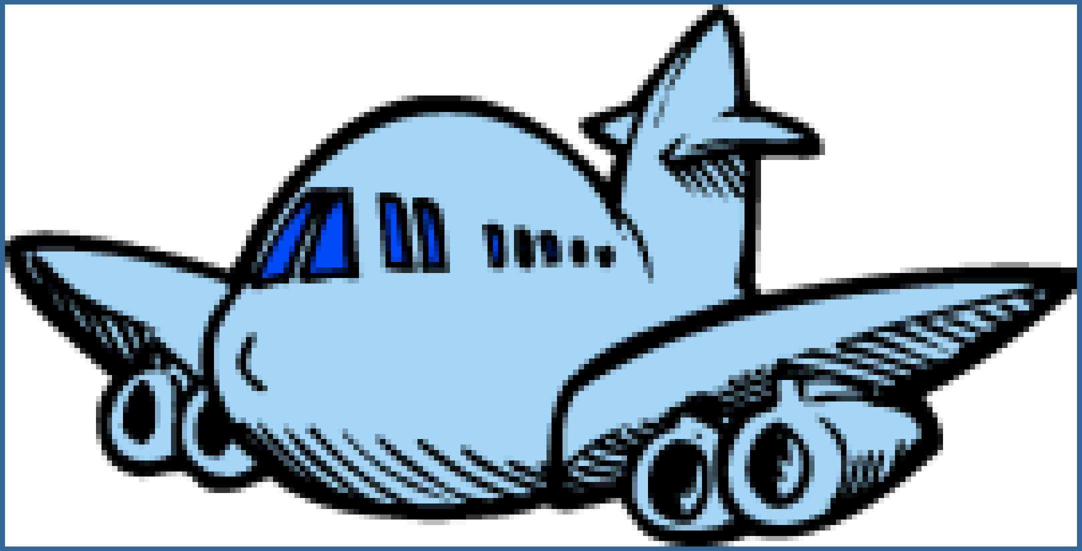
Correlation components



VLBI Data Rates and Volume – not for the faint of heart!

- **Astronomy experiments at 1-4 Gbps/station, 4 to 20 stations**
  - ~5-40 TB/station/day
  - Global 10-station experiment @ 4 Gbps/station → up to ~400 TB/day
  - Single 10-day experiment can produce up to ~4 PB
- **Higher data rates (8-32 Gbps) are already on the horizon; higher data rates → more sensitivity**
- **Available disk supply can support only few days of observations at these rates**
- **All pairwise telescope combinations must usually be cross-correlated**

Traditionally, these data have been shipped to a central processing facility



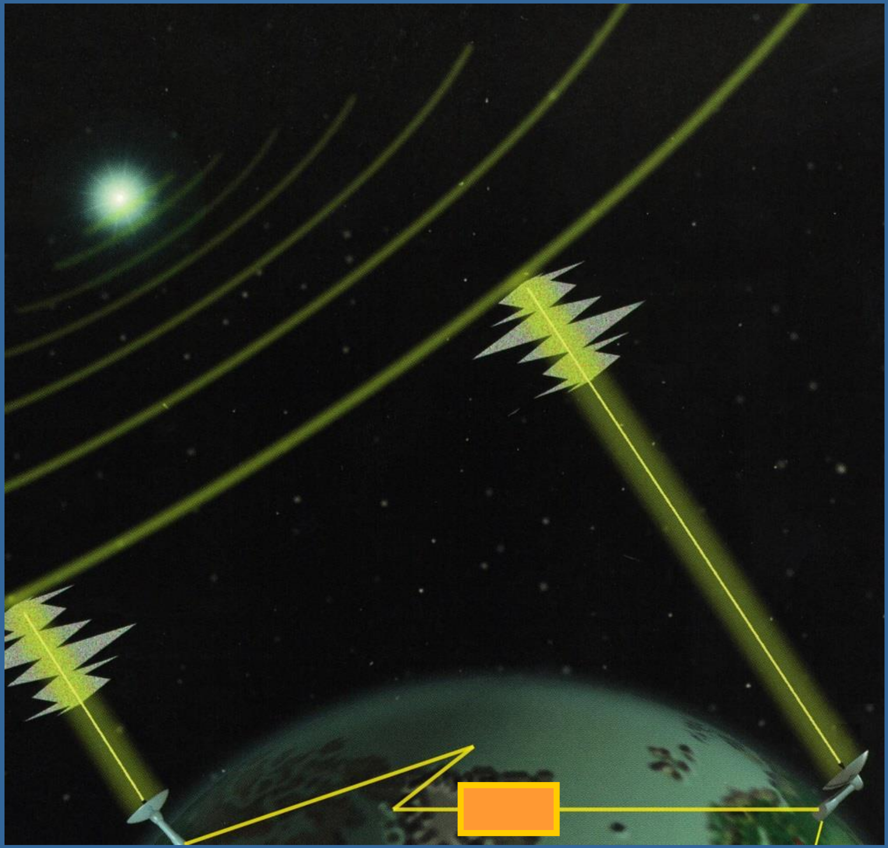
….but that takes time and ties up large amounts of expensive media

Enter ‘e-VLBI’:
Electronic Transmission of VLBI Data

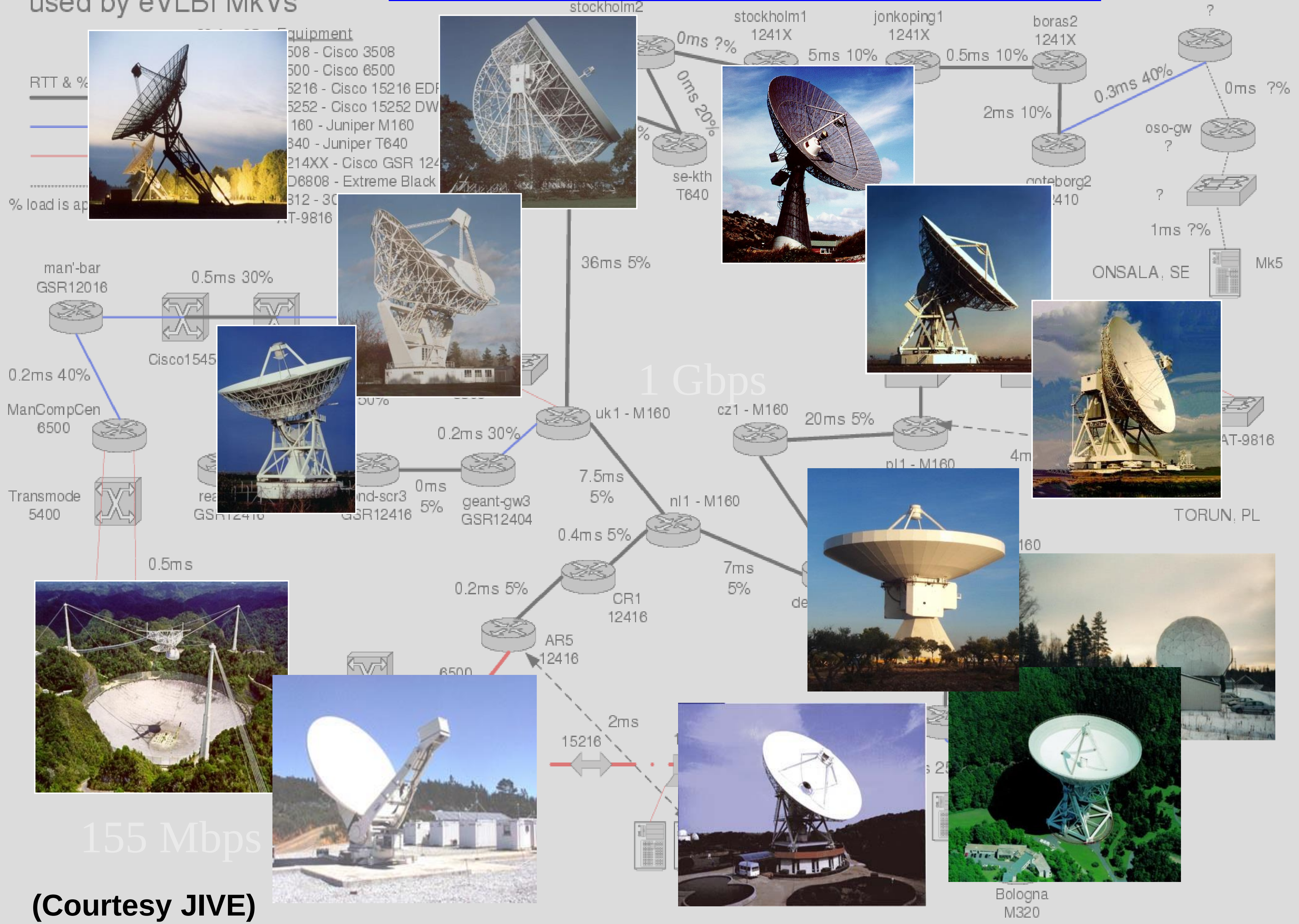
Of course, not a new idea, but only recently becoming somewhat practical and economical

- **1977** – Canadian’s used a satellite to transmit data in real-time from Green Bank, WV to Algonquin, Canada at 20 Mbps (pretty impressive for the time!)
- **1979** – Haystack developed near-real time correlation using data transmitted at 1200 bps over POTS using computer modems
- **Mid-1990’s** – Japanese developed dedicated 4-station network around Tokyo operating at 256 Mbps over dedicated fiber-optic links

Recently, for the first time, global high-speed fiber connections open the possibility of high-bandwidth VLBI data transmission in real-time or near-real-time!

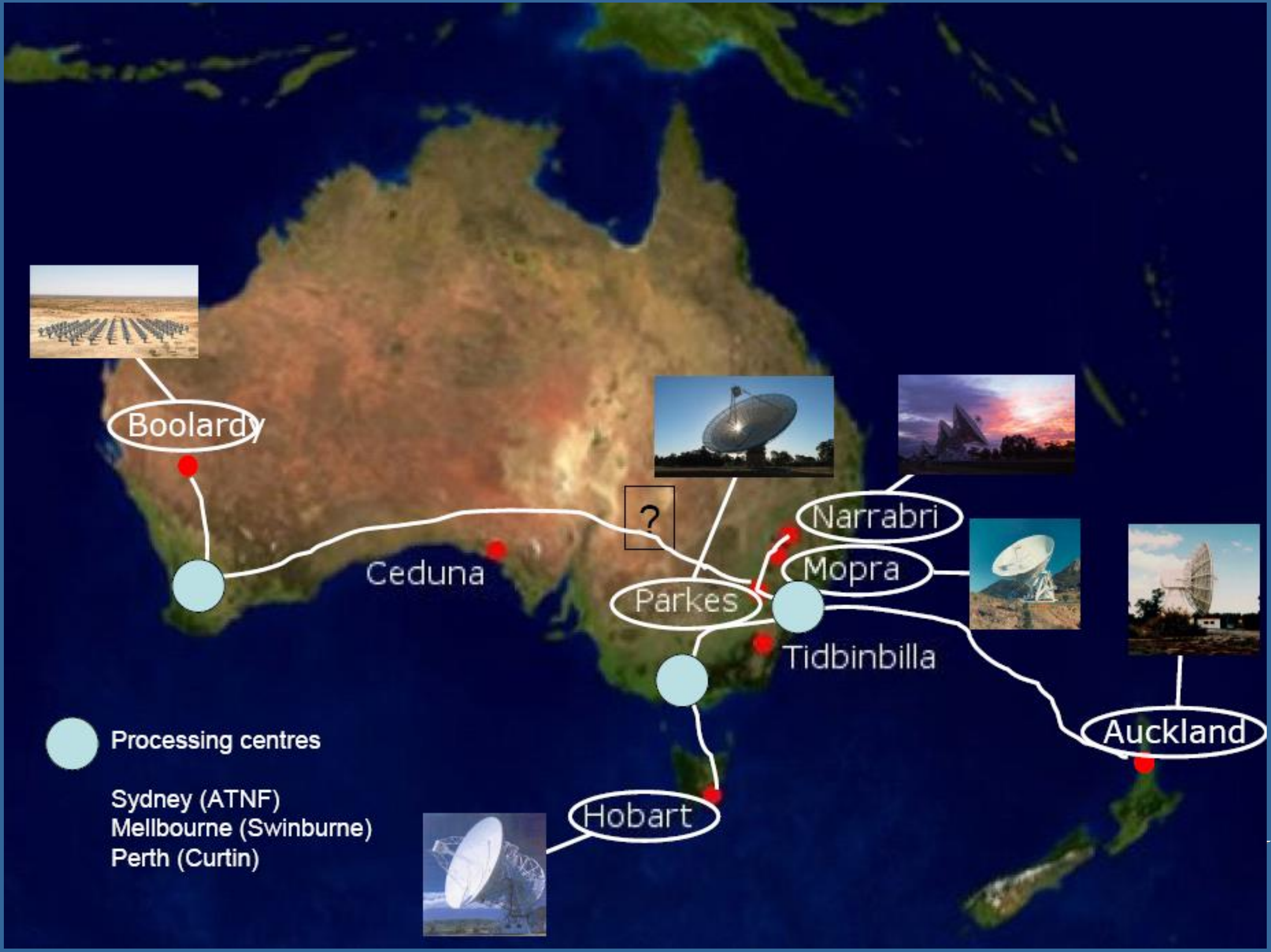


Europe is connecting

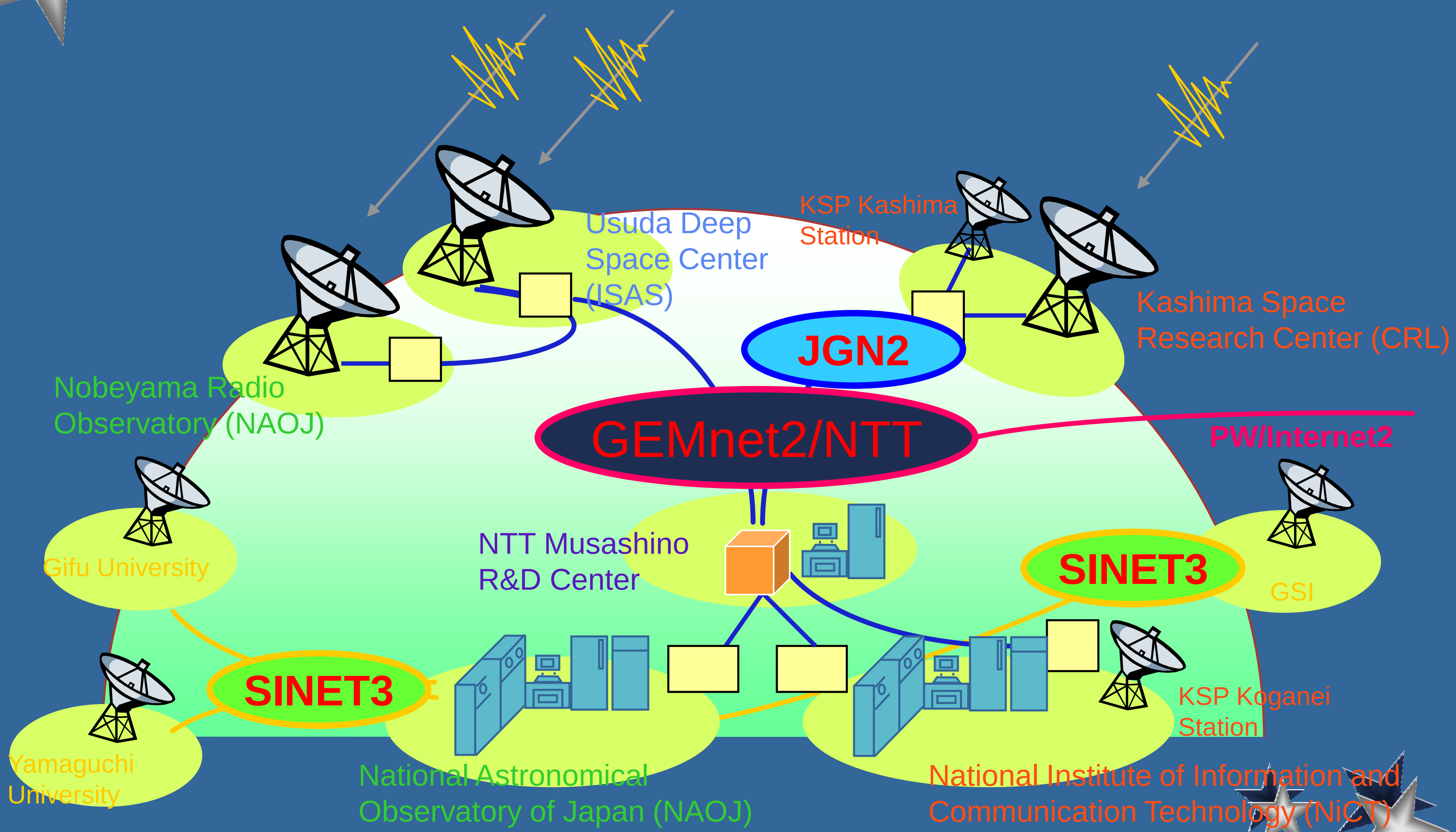


(Courtesy JIVE)

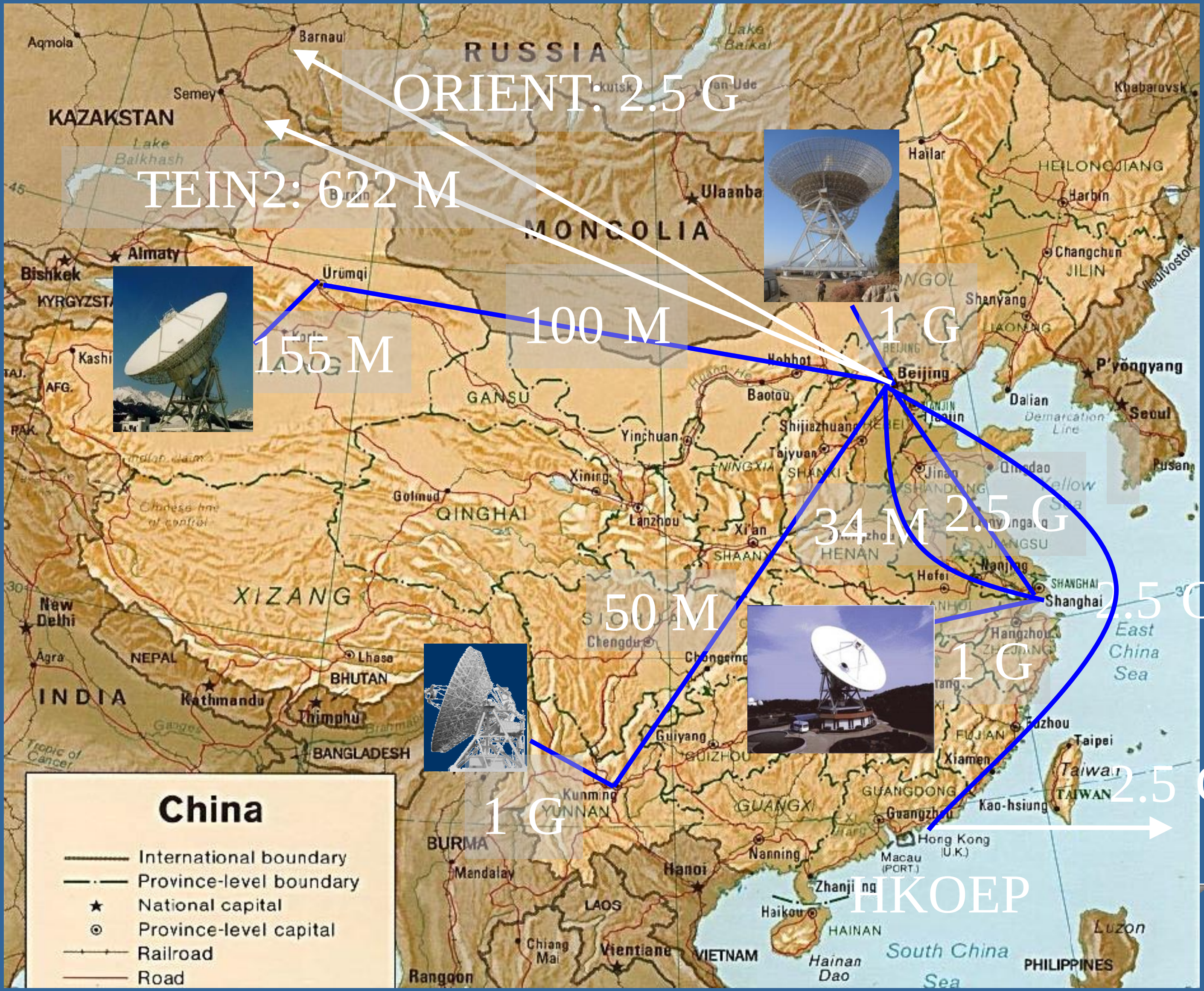
Australia is in process of connecting stations at 10 Gbps



Japan already has many of its telescopes connected at high speeds

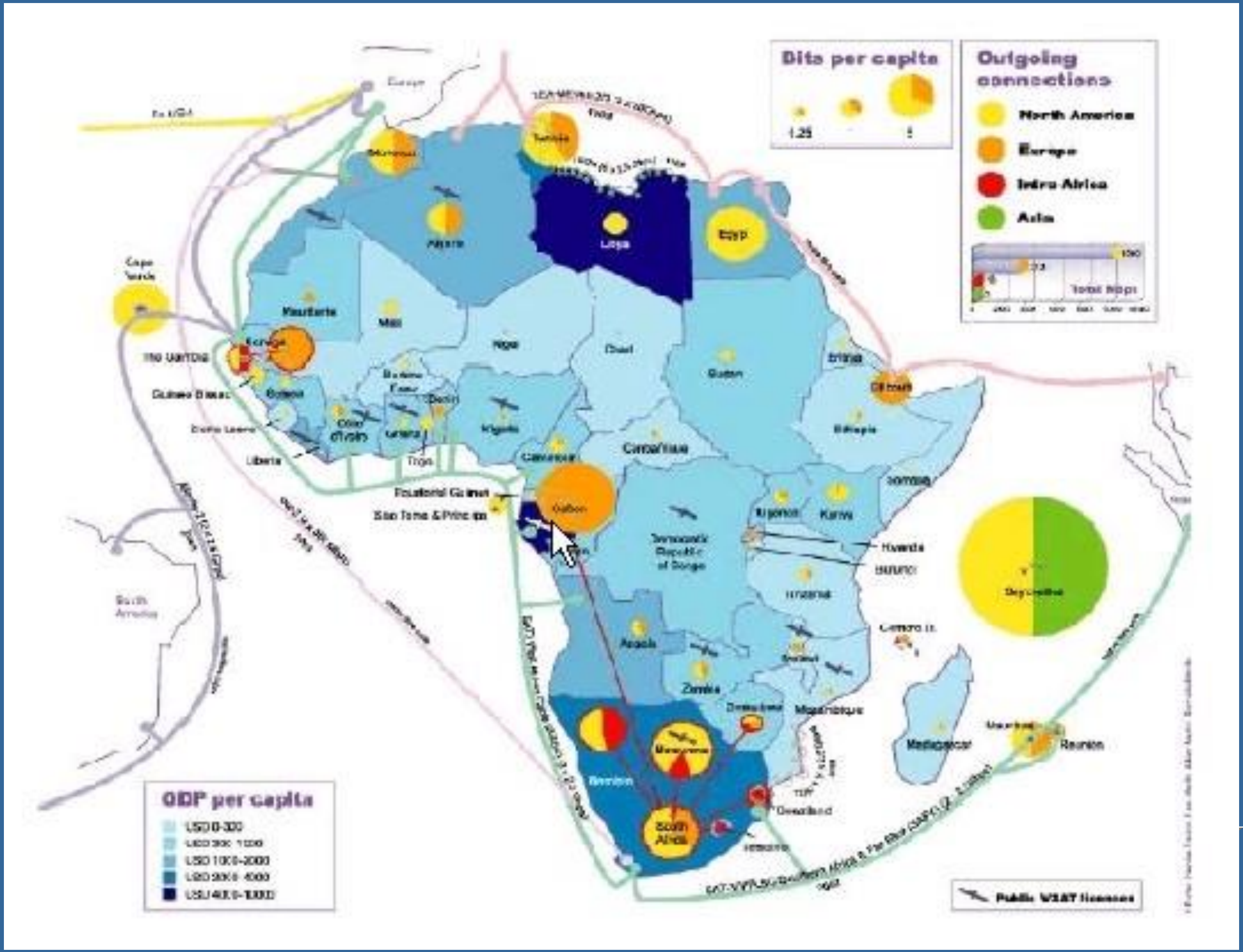


China connections are increasing

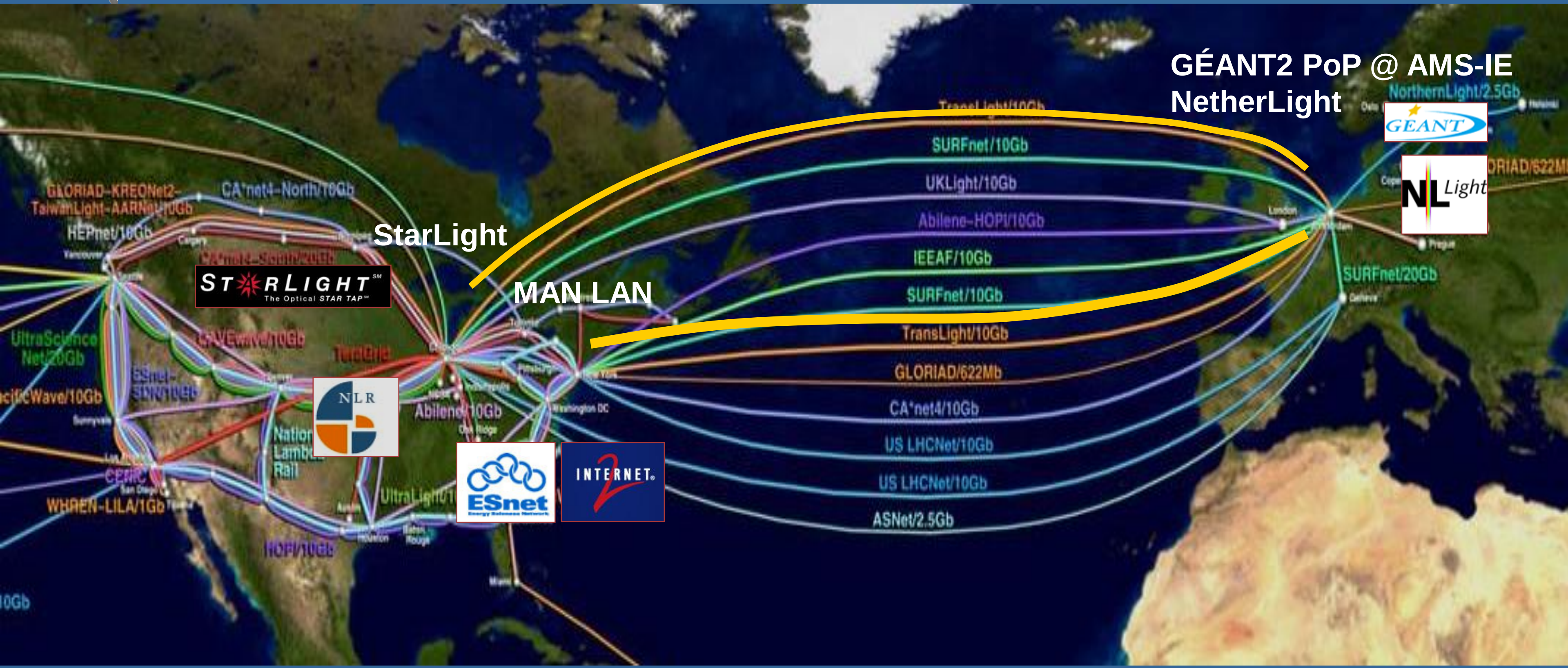


Some links available to South America and improving

Africa is very poorly connected (some connection to S. Africa)

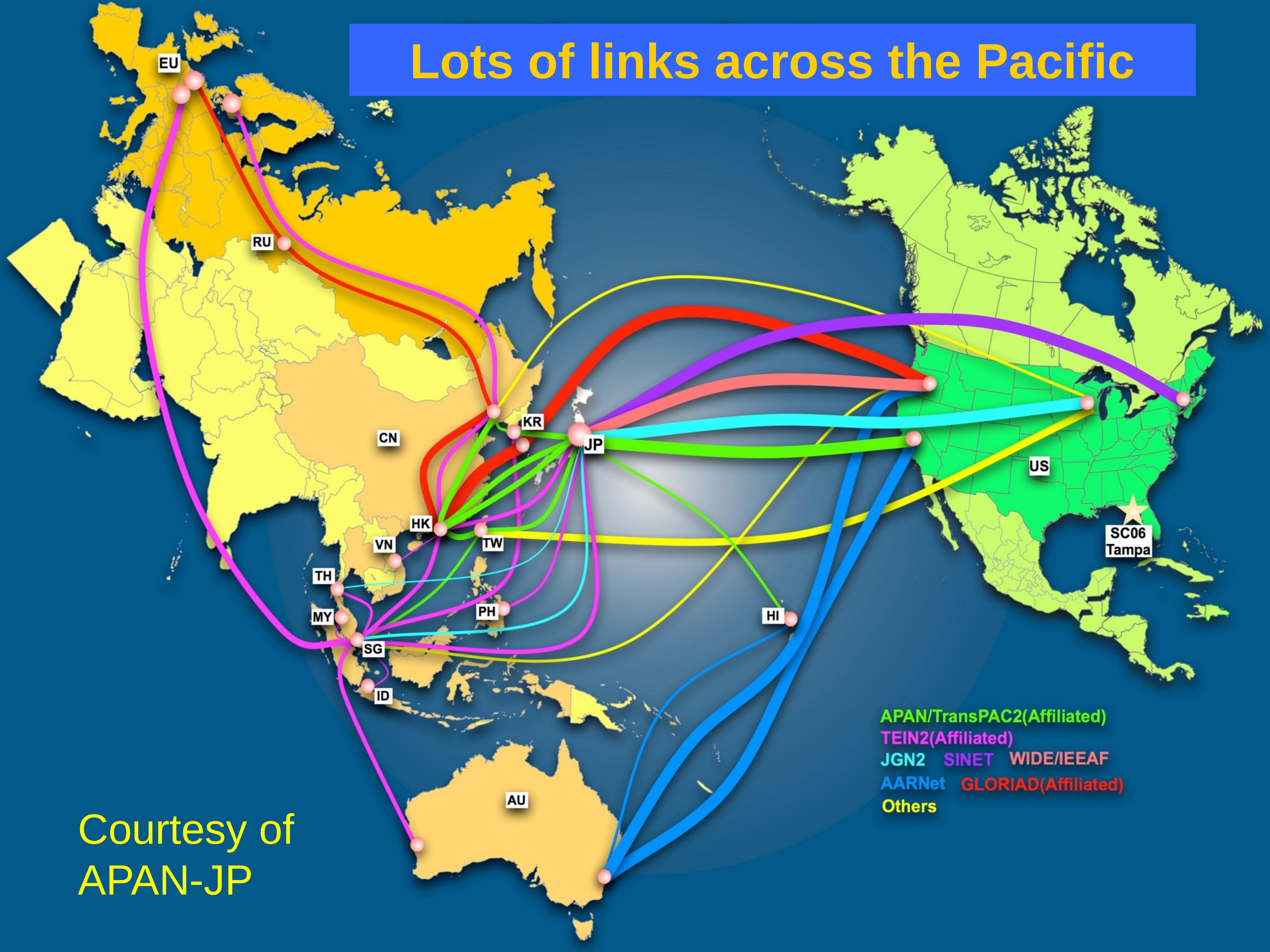


Lots of links across the Atlantic



www.startap.net/translight

Lots of links across the Pacific



Courtesy of
APAN-JP

The ‘Last-mile’ problem

Many of the world’s radio telescope were deliberately built in remote locations!

As a result, most of the world’s telescopes are <u>not</u> well connected

Direct fiber cost is relatively low– $60/fiber-km in 80-fiber bundle

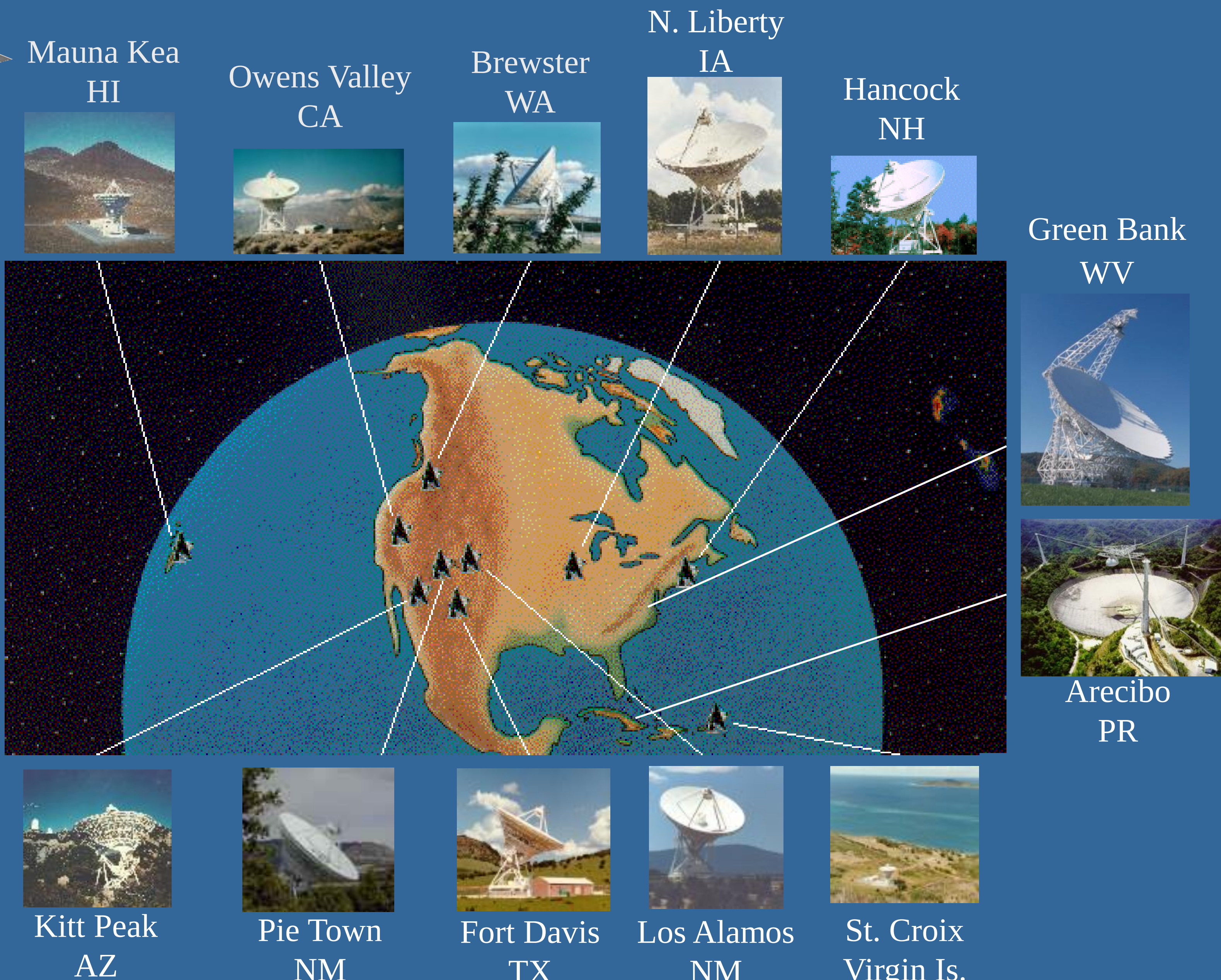
<u>But</u> –

Europe: >$20/m (or any populous wide-area)

U.S.: >$10m (in simplest desert environment)

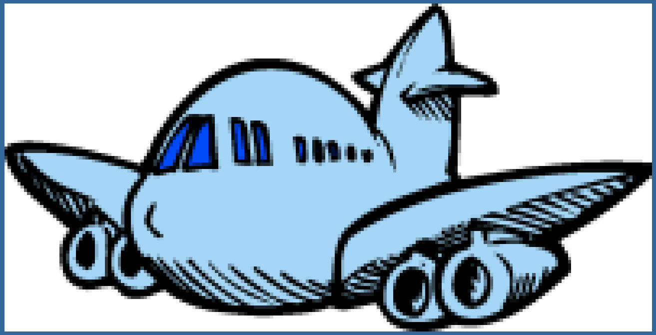
The upside: there is developing a lot of momentum and support from the greater networking community to get the job done!

VLBA – The World’s Only Full-Time VLBI Array



Only Arecibo is connected; no current plans for others

The e-VLBI challenger –
a B747 loaded with recorded digital media!



Payload: 140 tons ≈ 140,000 1-TB disks = 140 PB
Based on 24-hr flight time, bandwidth is ~10 Tb/sec!
This is 1000x faster than a 10 Gbps link!

In 1970, with 12" open-reel computer tape at 800 bpi,
a B747 could carry only 1.5 TB; bandwidth ~140 Mbps!
This is 3000x faster than a 56 kbps link available at the time.

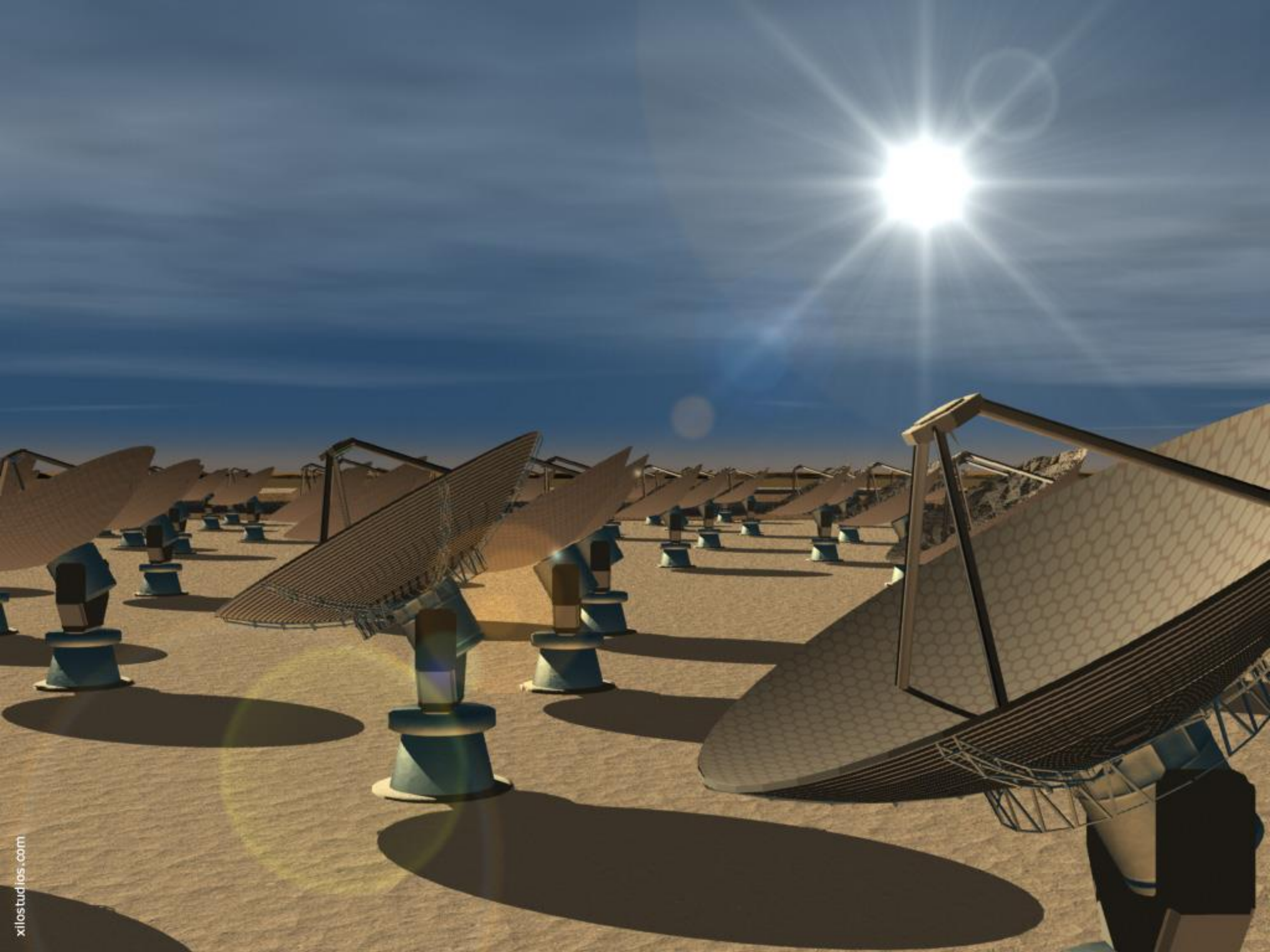
The Big Challenge:
When will e-VLBI catch up to a B747?!

What lies in the future for VLBI?

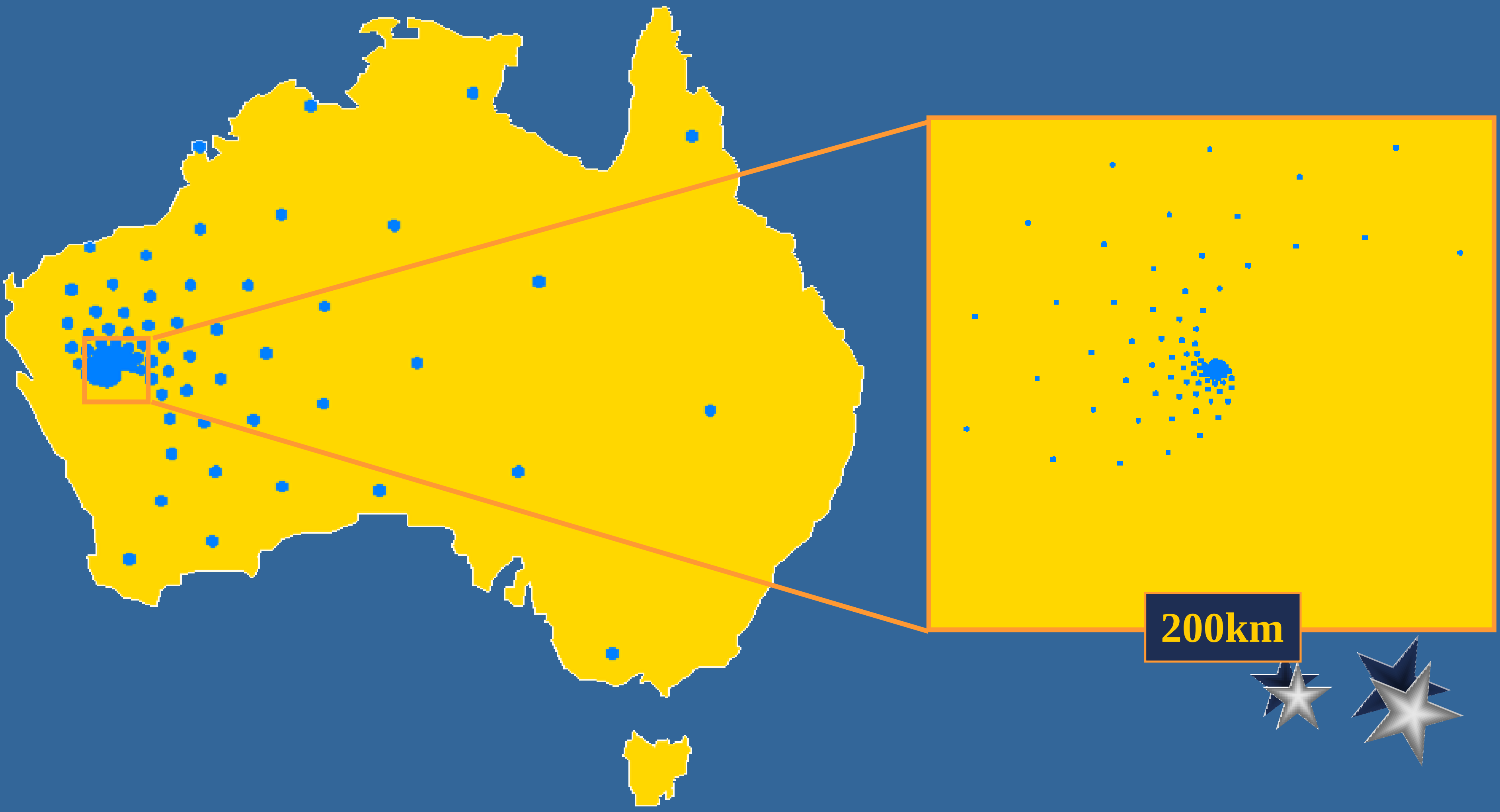
- Astronomy: Push to mm and sub-mm wavelengths to see deeper and more clearly
- Geodesy: Global 1-mm measurement accuracy
- Higher data rates – climbing on towards 10-100 Gbps/station
- New global radio-telescope arrays with unprecedented size and sensitivity
- New deep-space applications

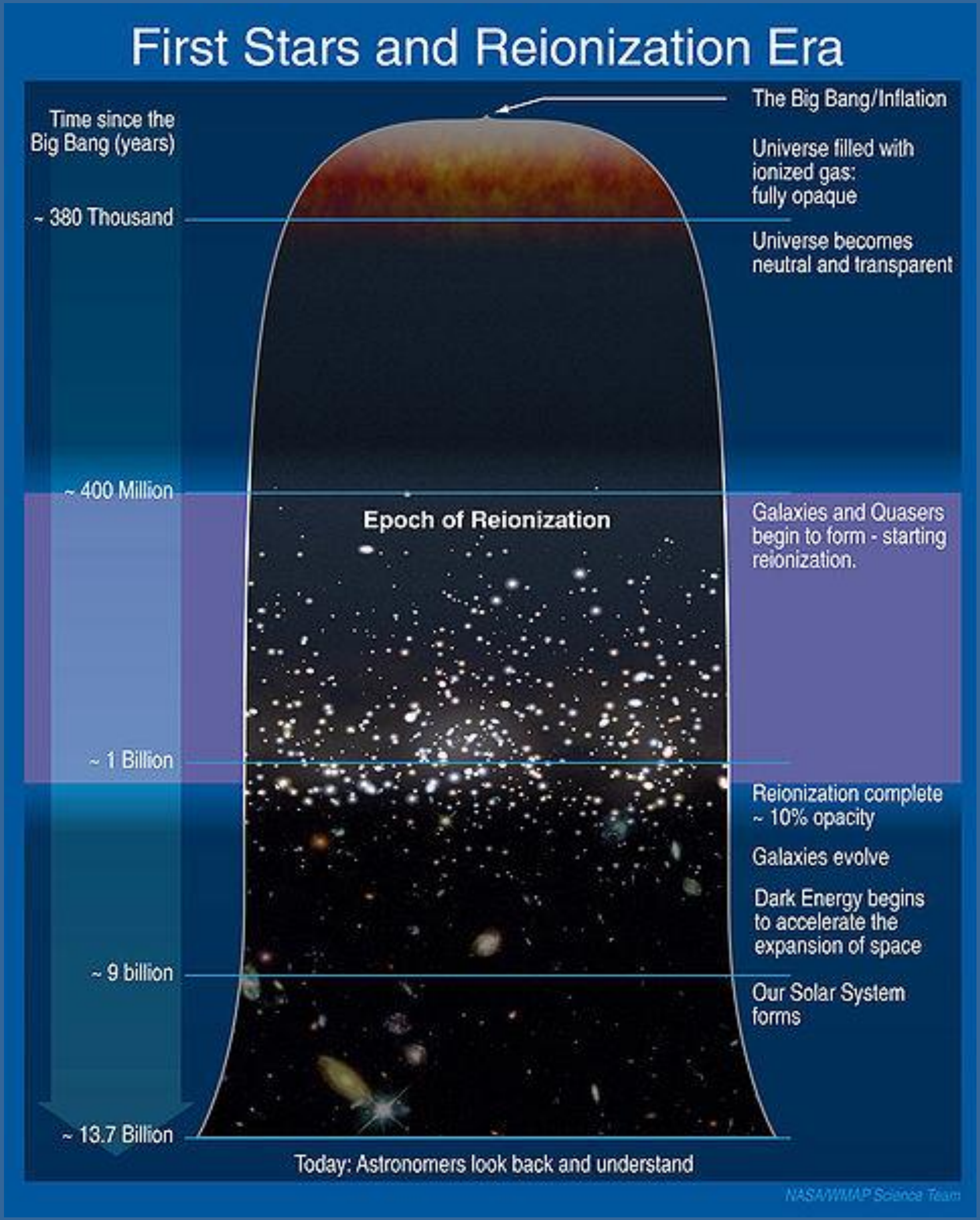
SKA Key Specifications

- Collecting area of order 1 million square meters, array of ~5000 dishes each ~12m in diameter
- Antennas are highly concentrated in the central 5km, and further distributed in stations at distances up to at least 3000km
- Individual antennas are connected via wide-band fibre links (100 Gbit/s) to a central data processor (10-100 Pflop/s) – order 1 Pb/sec total date rate
- Large international project - Cost $2-5B
- Build in stages over next 10-15 years

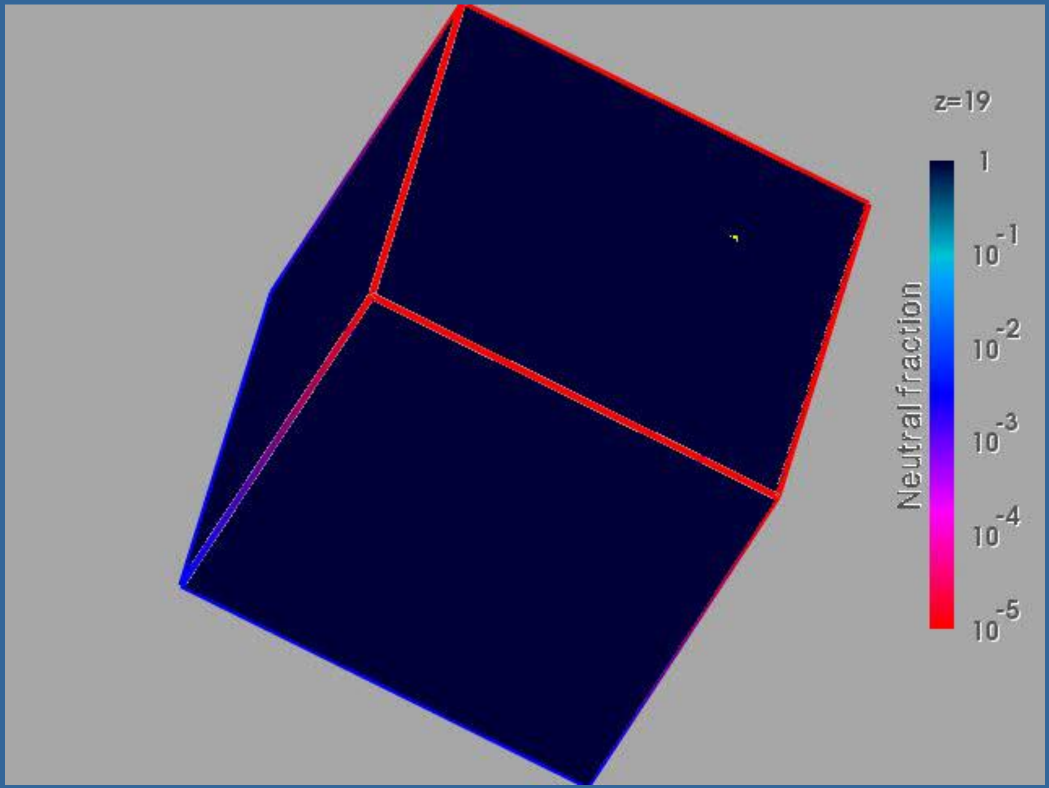

xilostudios.com

SKA configuration Western Australia example




First Stars and Reionization Era
Time since the Big Bang (years)
~ 380 Thousand
~ 400 Million
~ 1 Billion
~ 9 billion
~ 13.7 Billion
The Big Bang/Inflation
Universe filled with ionized gas: fully opaque
Universe becomes neutral and transparent
Epoch of Reionization
Galaxies and Quasers begin to form - starting reionization.
Reionization complete ~ 10% opacity
Galaxies evolve
Dark Energy begins to accelerate the expansion of space
Our Solar System forms
Today: Astronomers look back and understand
NASA/WMAP Science Team

A model of the evolution of the early universe



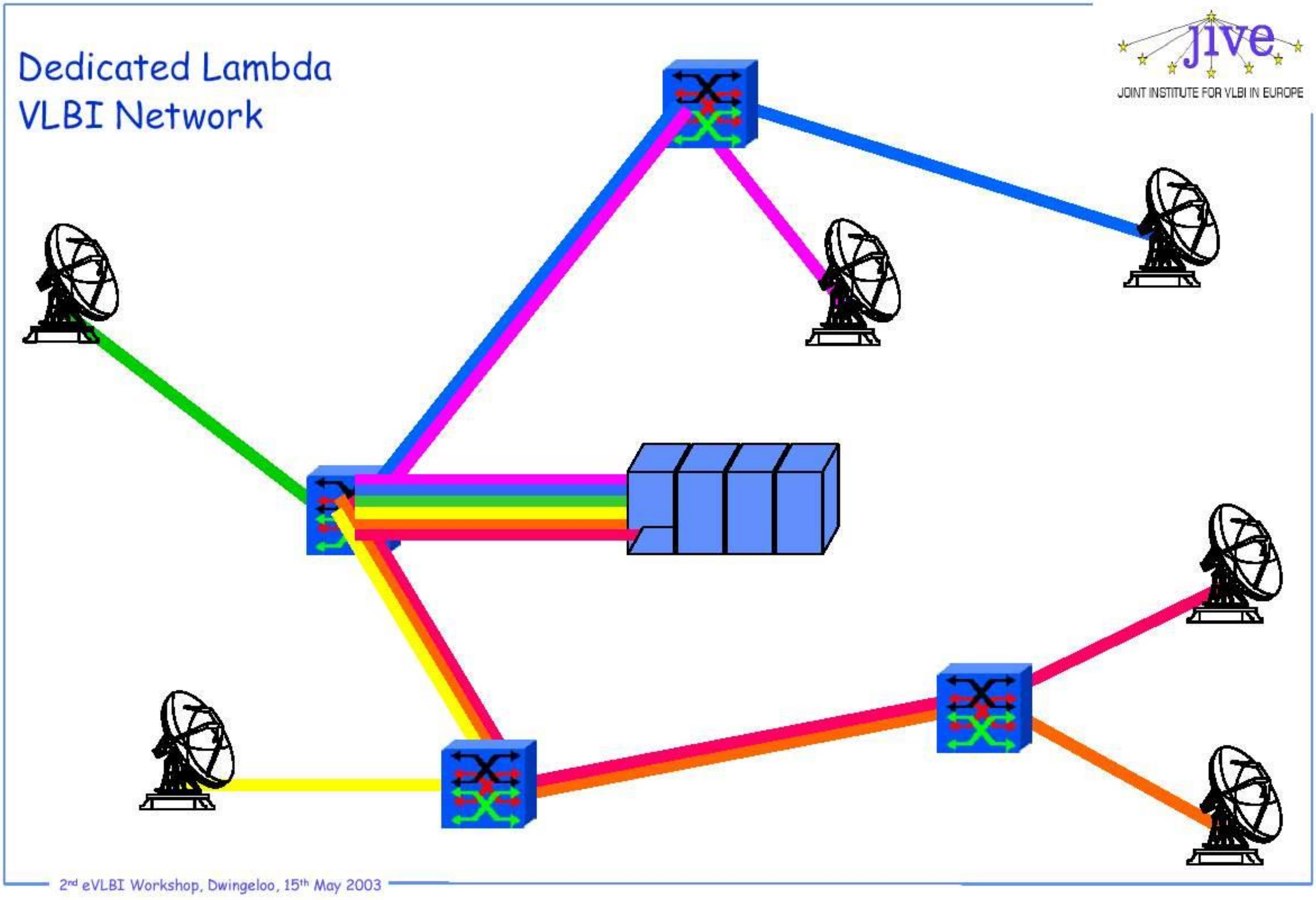
The End

Thanks for your attention!

Impact of e-VLBI Program

- Opens new doors for astronomical and geophysical research.
- Represents an excellent match between modern Information Technology and a real science need.
- Motivates the development of a new shared-network protocol that will benefit other similar applications.
- Drives an innovative IT research application and fosters a strong international science collaboration.

EVN Future Vision




K3

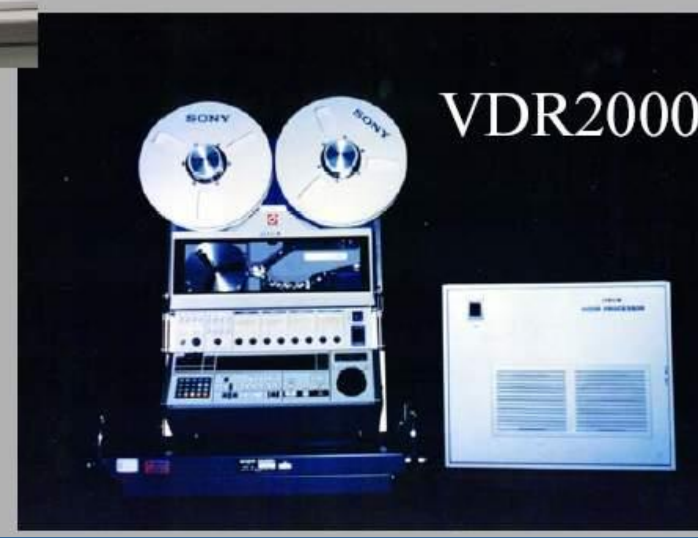

K4/VSOP

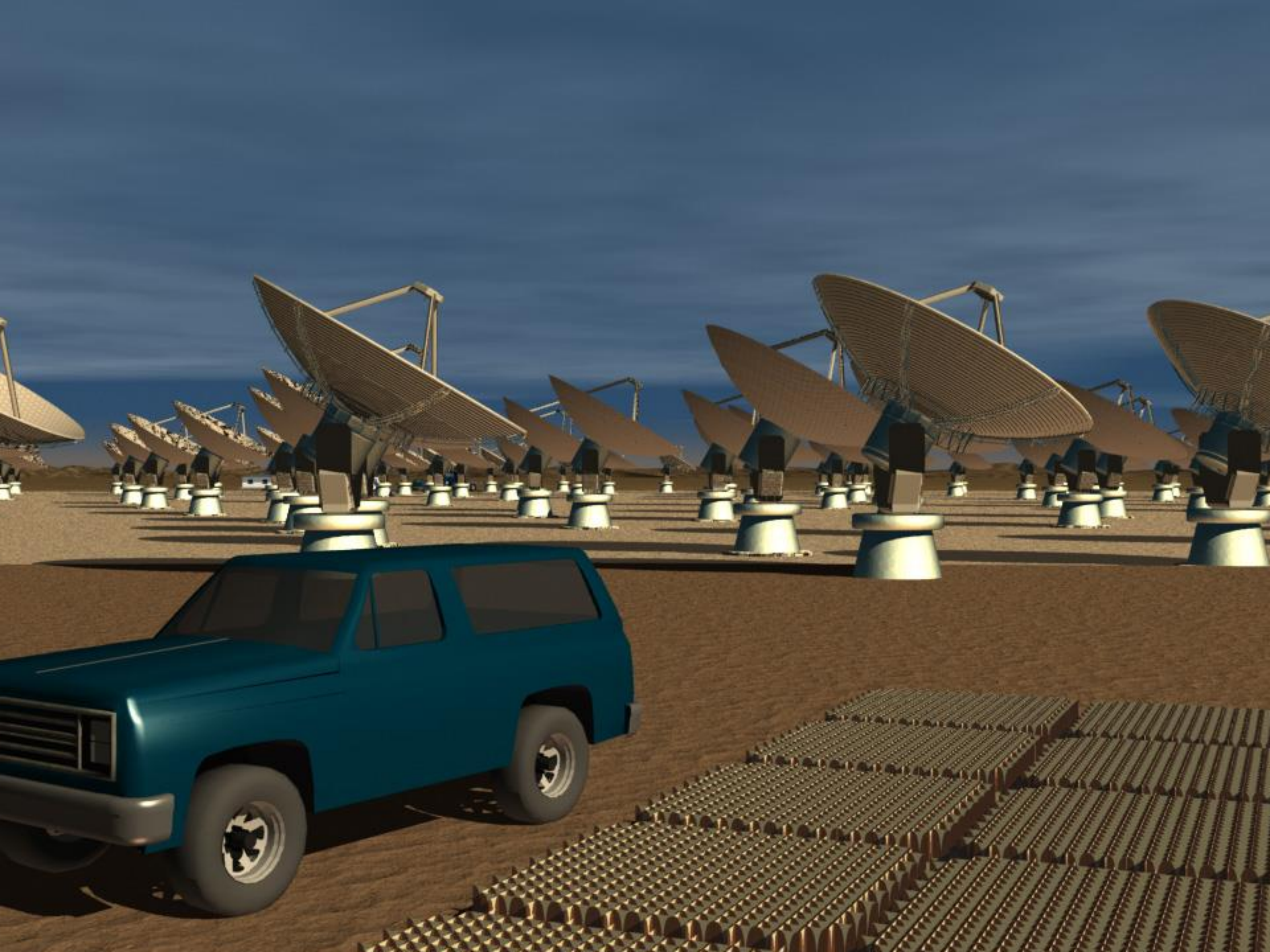

PCVLBI


K5

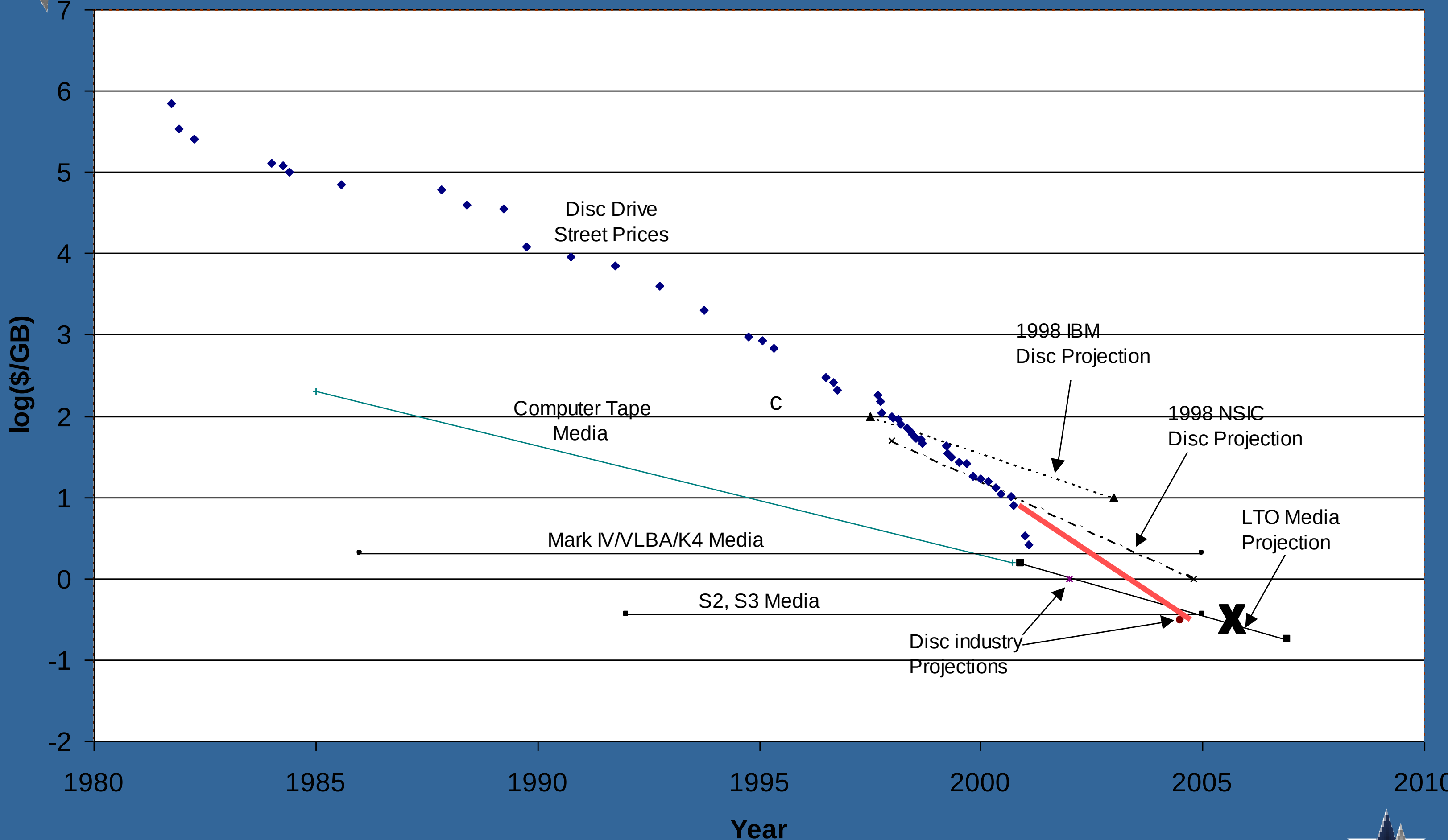

K1


GBR2000


VDR2000




Australia


7
6
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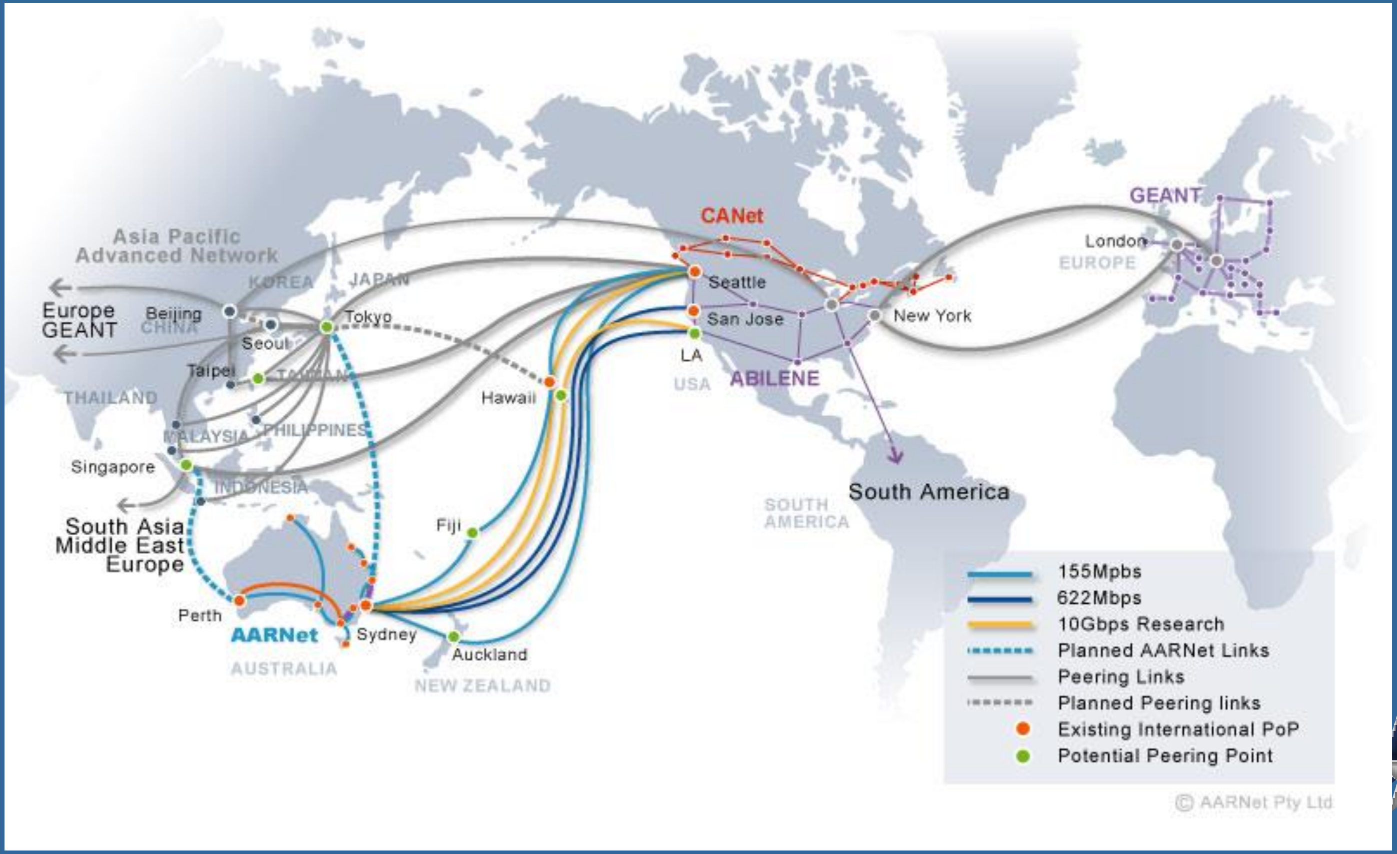
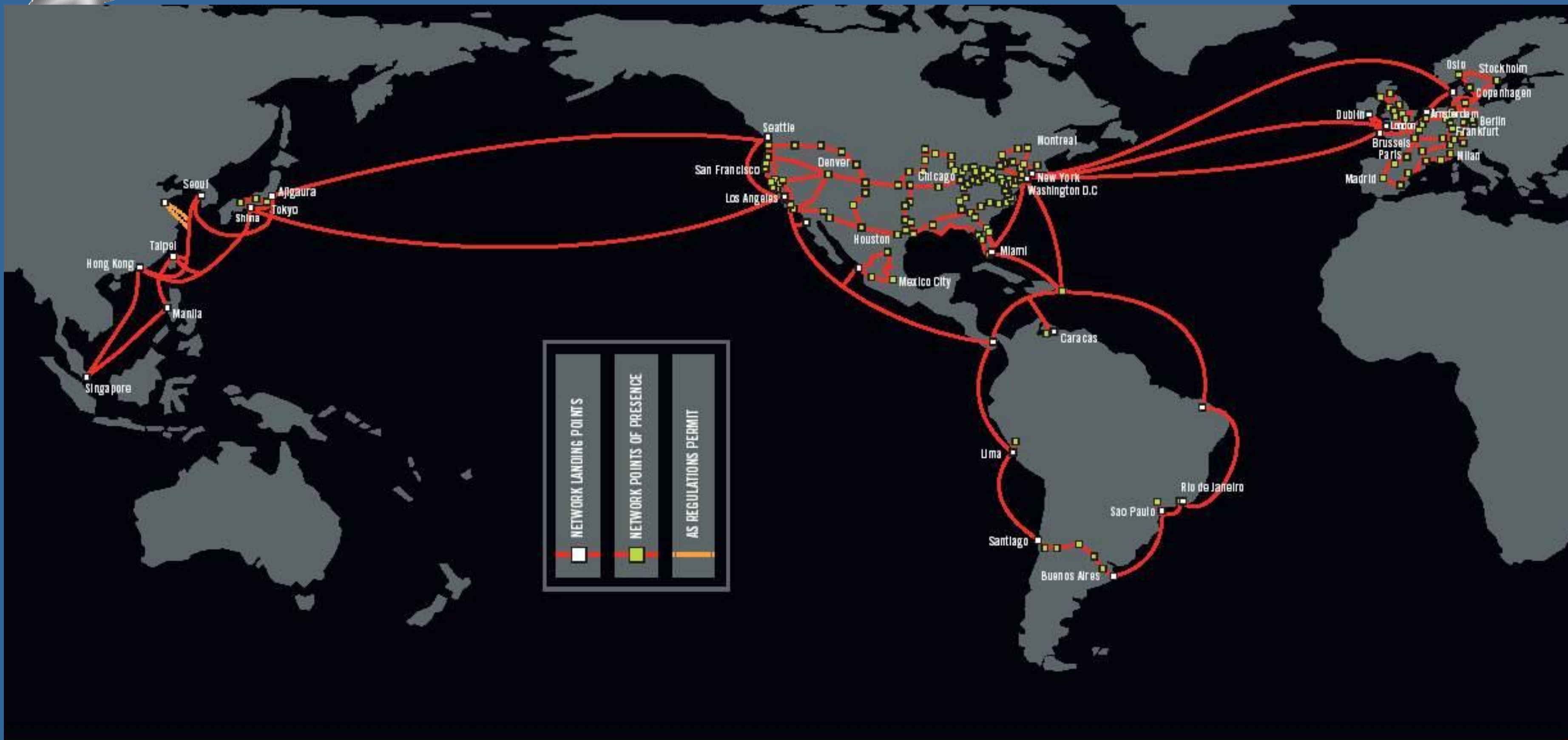
log($/GB)
1980
1985
1990
1995
2000
2005
2010
Year
Disc Drive
Street Prices
1998 IBM
Disc Projection
Computer Tape
Media
C
1998 NSIC
Disc Projection
LTO Media
Projection
Mark IV/VLBA/K4 Media
S2, S3 Media
X
Disc industry
Projections

Australian connection





GLOBAL CROSSING NETWORK

Global Crossing®

Conclusions

- e-VLBI is riding an unprecedented wave of global network connectivity and networking community enthusiasm
- But….there are many e-VLBI challenges!
- 10-100 Gbps/antenna is technically possible with e-VLBI
- Haystack is moving aggressively to exploit these new technologies

What are molecules good for?

Detections - recent one - “glycoaldehyde” (sugar)

Probes - measure temperature, density, chemistry

Kinematics - velocities - doppler effect