VLBI Basics

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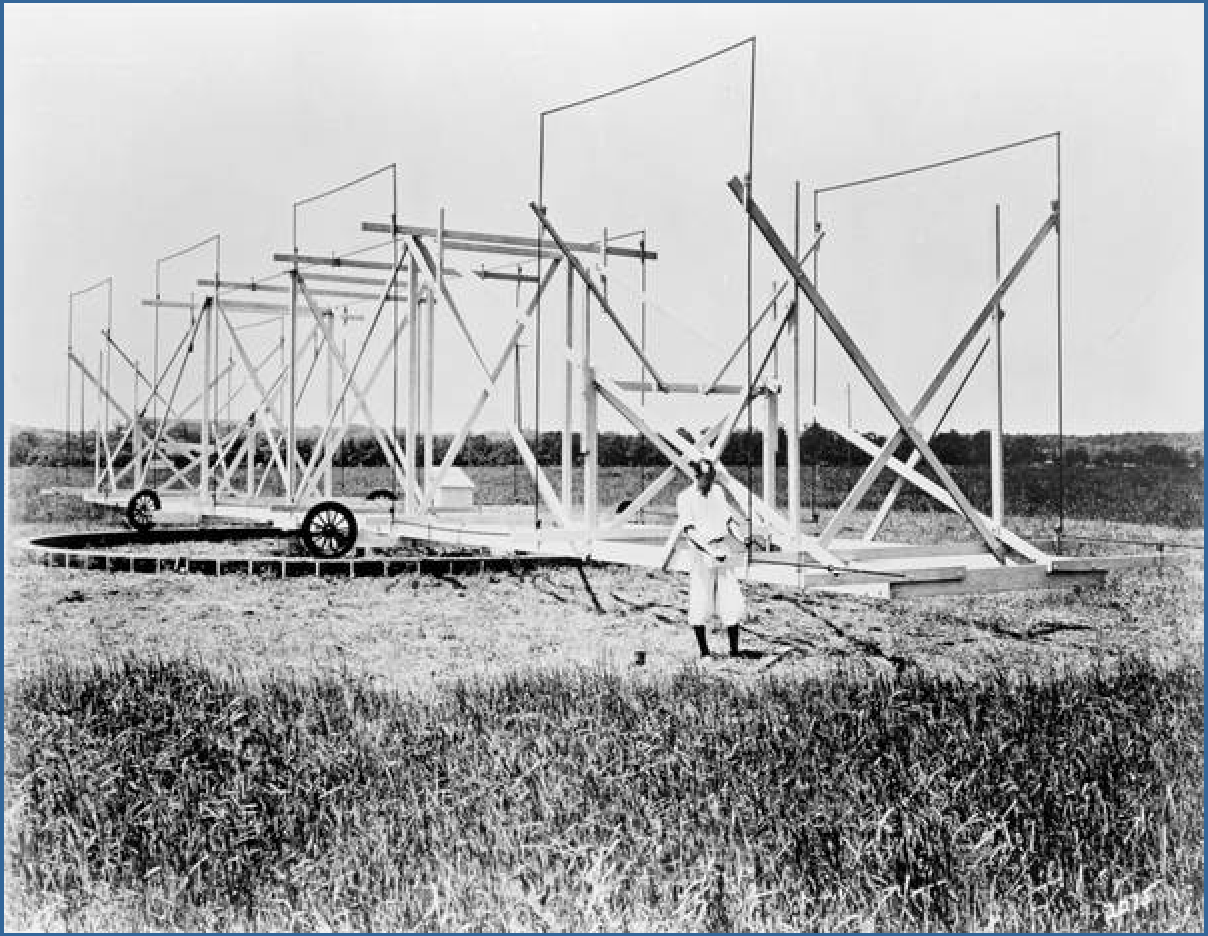
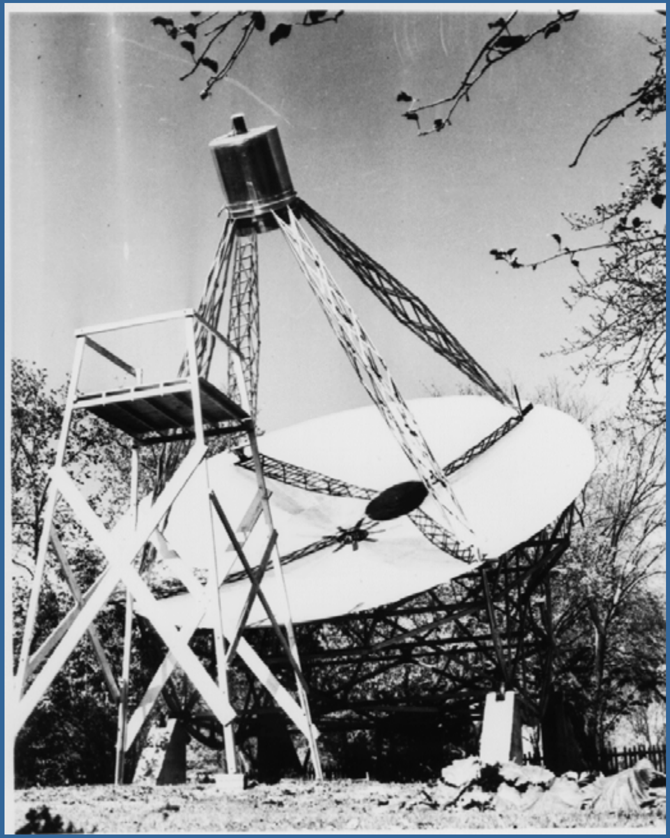
Technical Operations Workshop (TOW)
MIT Haystack Observatory
6 May 2013

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)

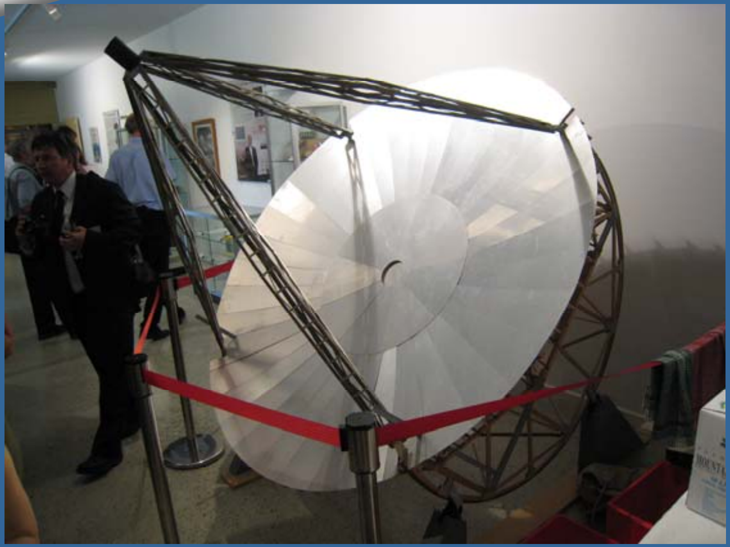
Mt. Pleasant Observatory – Cambridge, TAS

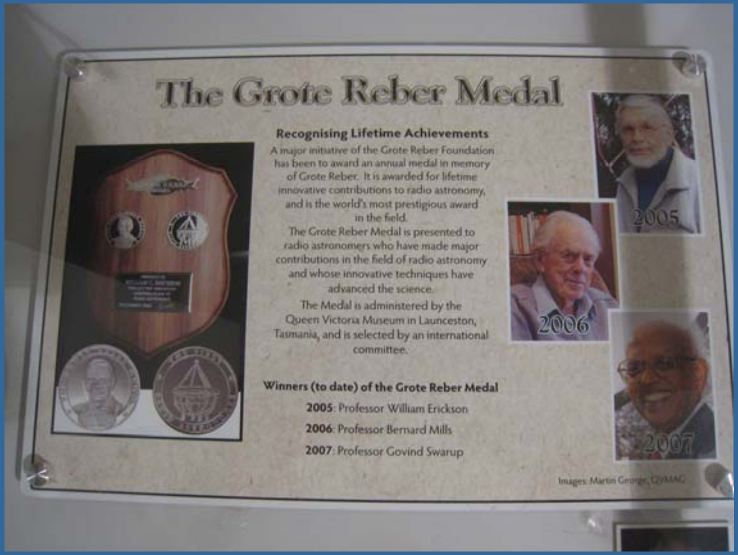
26m diameter (1985)

14m diameter (1981)

12m diameter (9 Feb 2010)

Grote Reber Museum at Mt. Pleasant Observatory



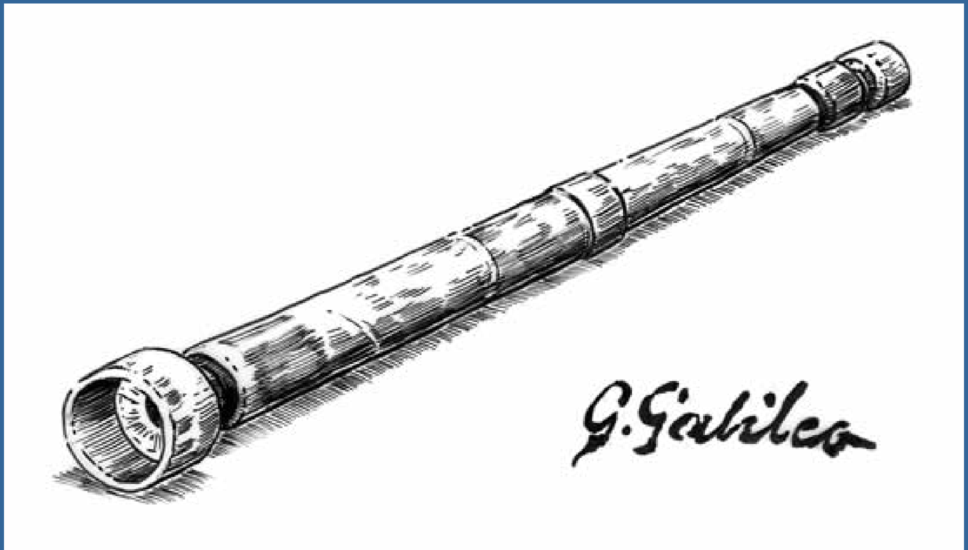


2005 Prof. William Erickson
2006 Prof. Bernard Mills
2007 Prof. Govind Swarup
2008 Dr. Sander Weinreb
2009 Dr. Barry Clark
2010 Dr. Alan E.E. Rogers
2011 Prof. Jocelyn Bell
2012 Prof. Nikolay Kardashev
2013 Prof. James Moran

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 of the collecting area (aperture size)
  - Bandwidth of the energy spectrum
- Quietness of the receiving detectors

What determines resolution?

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

Angular Resolution is always approximately*

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

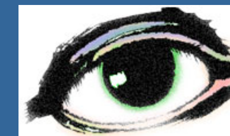
where

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 Michelson Interferometers to diameter of the sun and determine location of place 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)

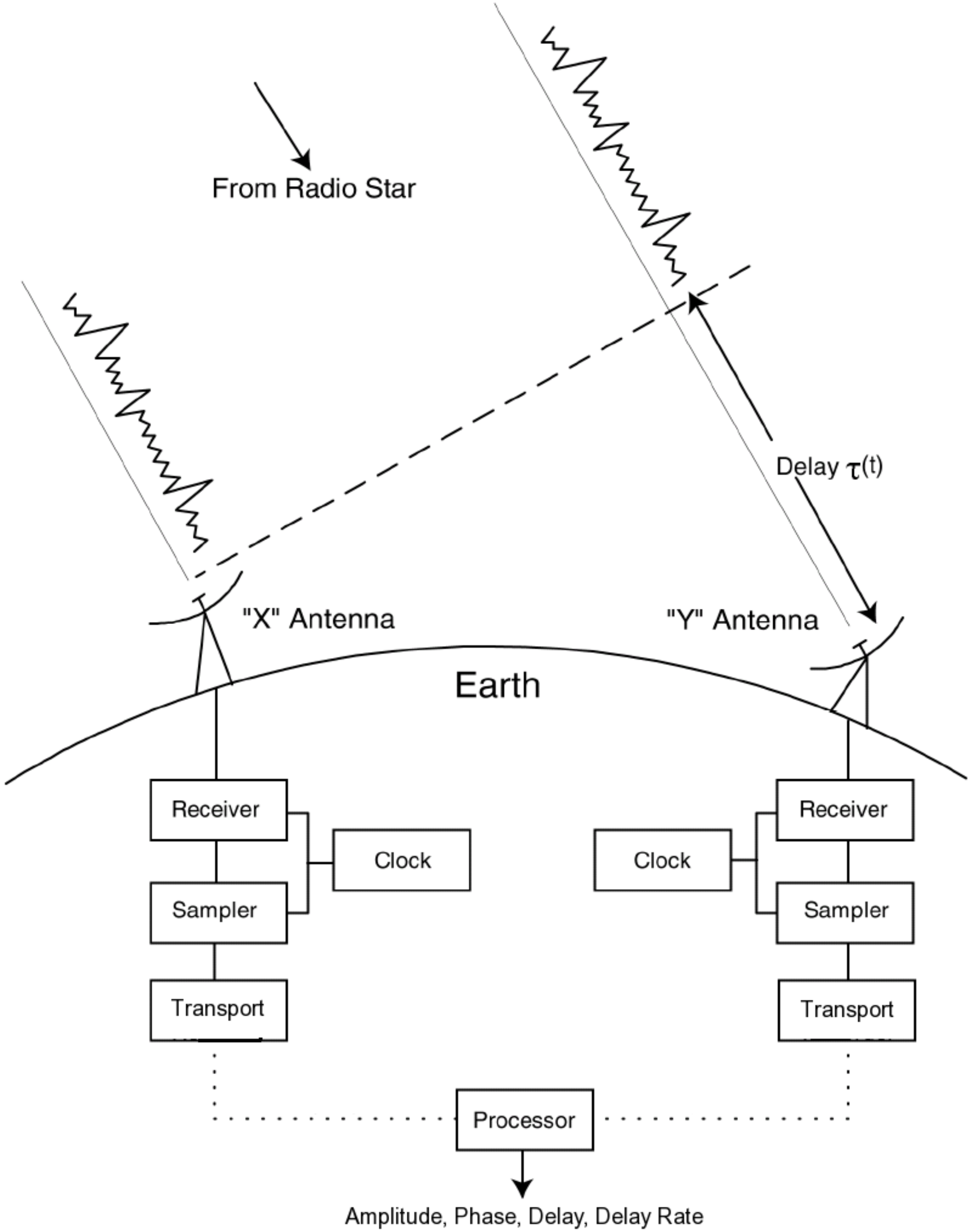
Early geodetic VLBI

- 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!

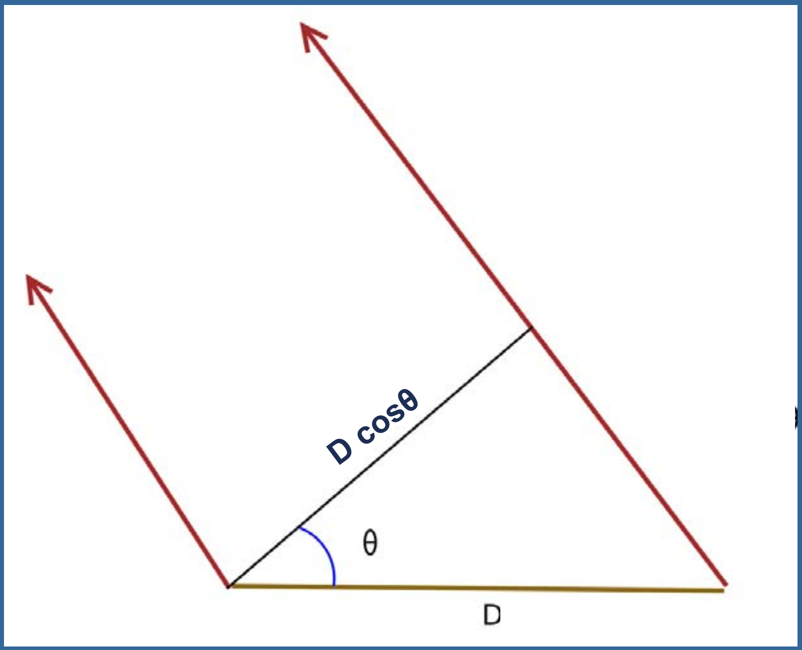
Haystack CDC330 software correlator (c1968)

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!

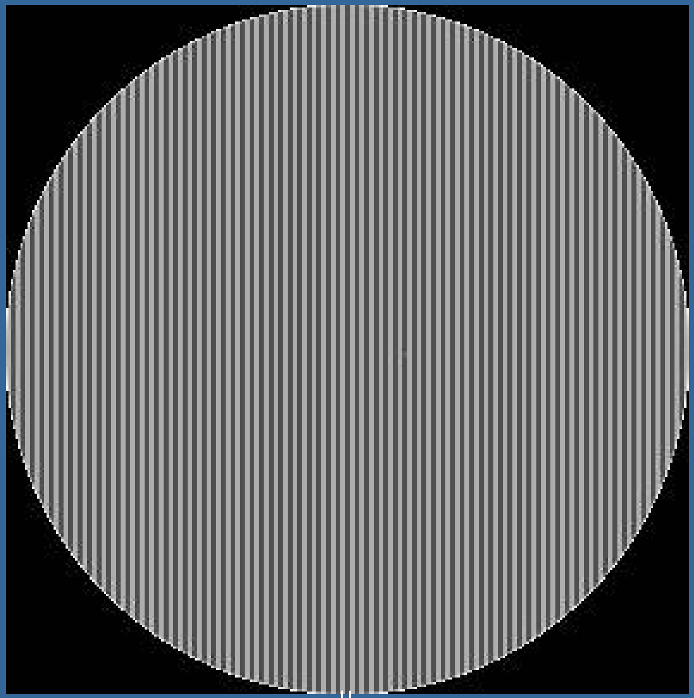

From Radio Star
Delay τ(t)
"X" Antenna
"Y" Antenna
Earth
Receiver
Clock
Sampler
Transport
Receiver
Clock
Sampler
Transport
Processor
Amplitude, Phase, Delay, Delay Rate

Interferometry

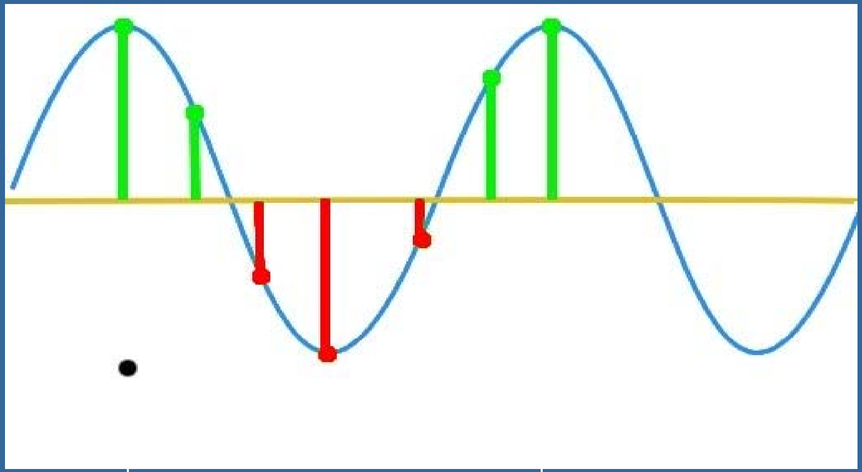


- As Source moves, response changes as cos (projection)
- Projected baseline =D*cos θ
- Fringe-pattern spacing on sky
  = λ/(projected baseline)
  = λ/(D*cos θ)

Point Source

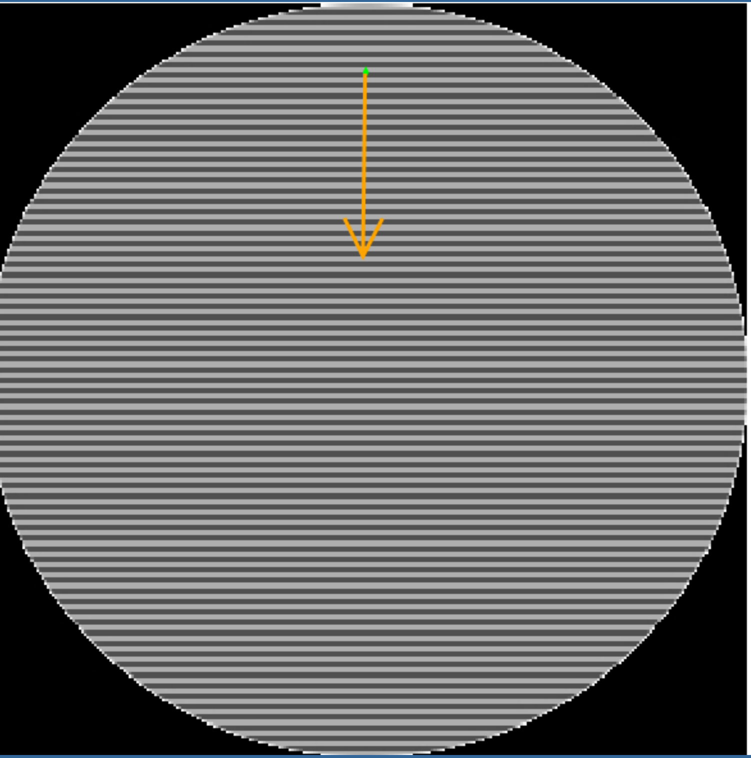


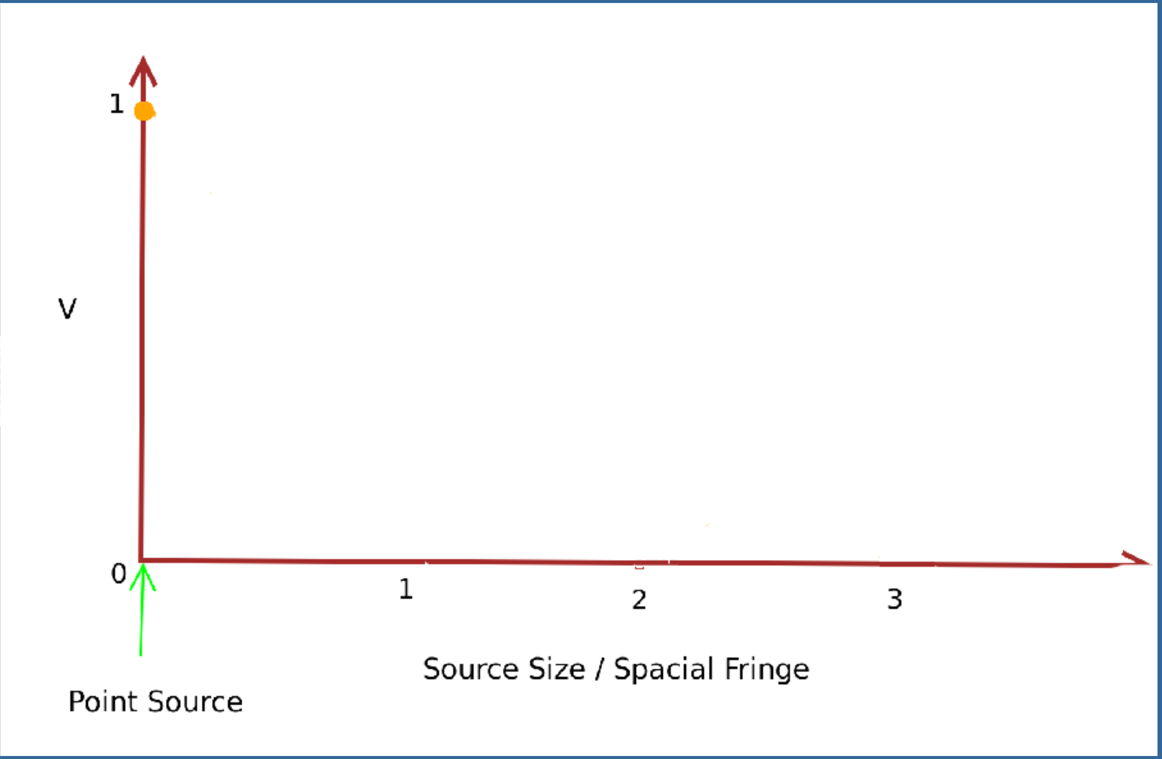
Fringe spacing
λ/(D*cos θ)



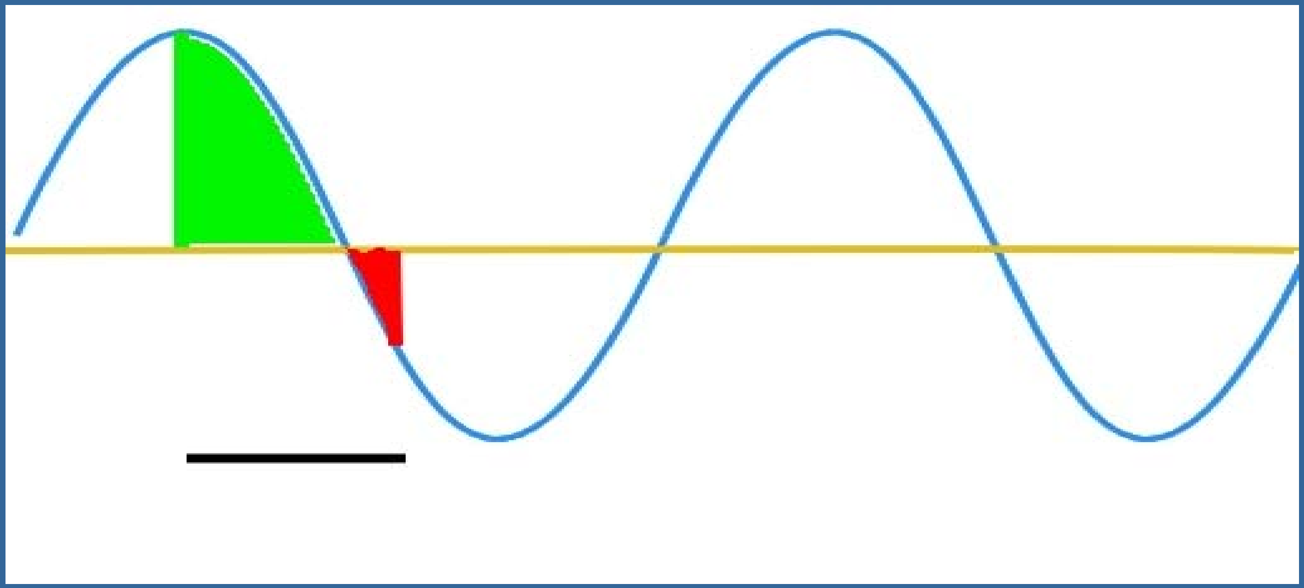
Fringe spacing
λ/(D*cos θ)

Point source

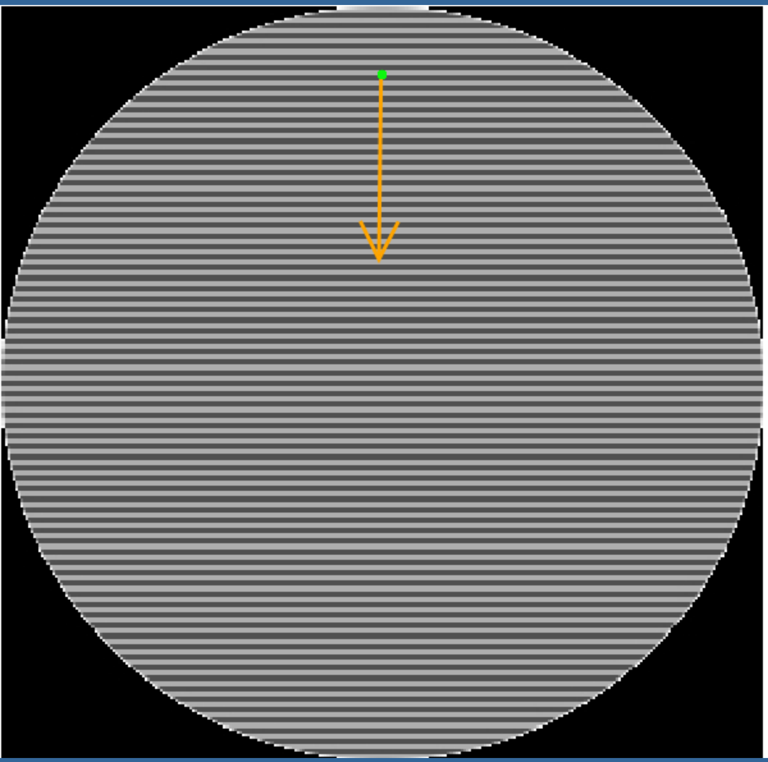


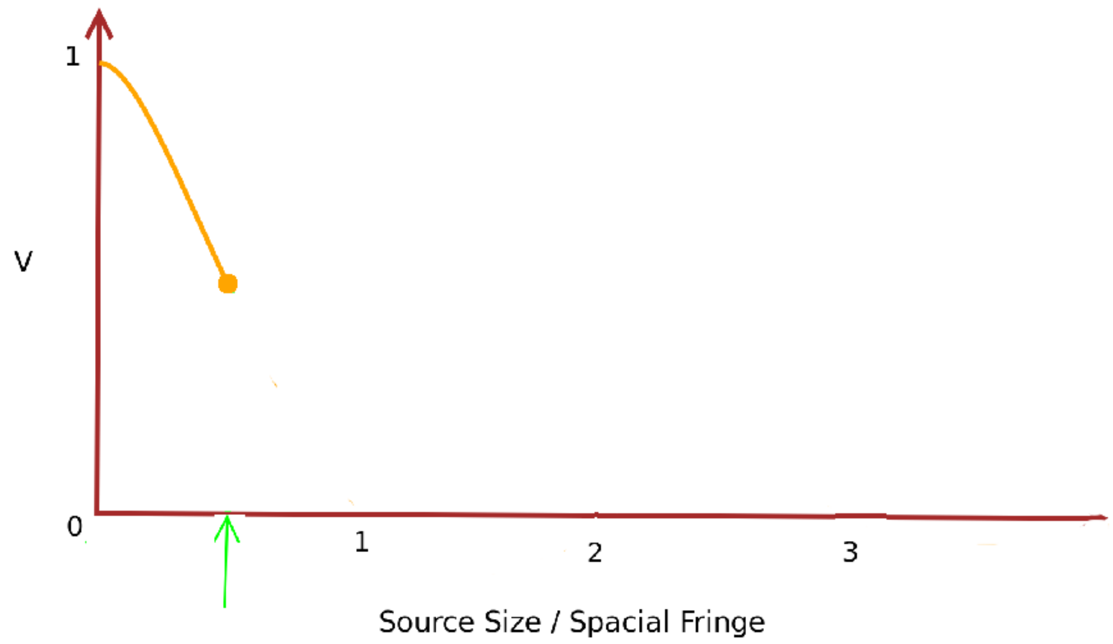


Extended Source

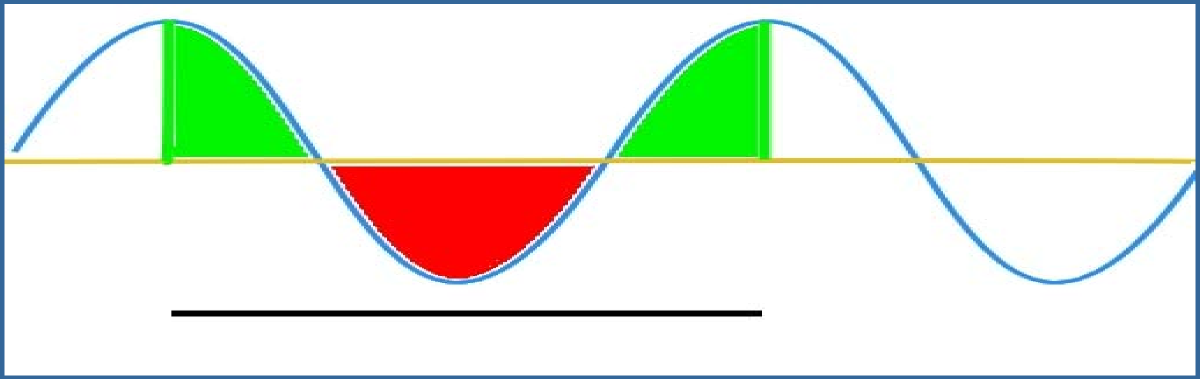


Extended Source

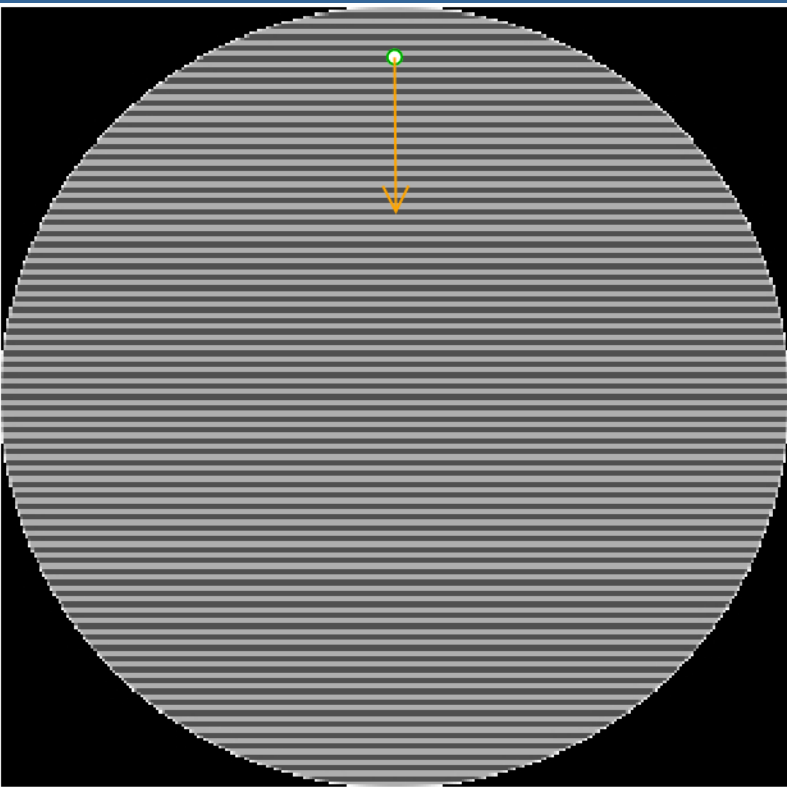


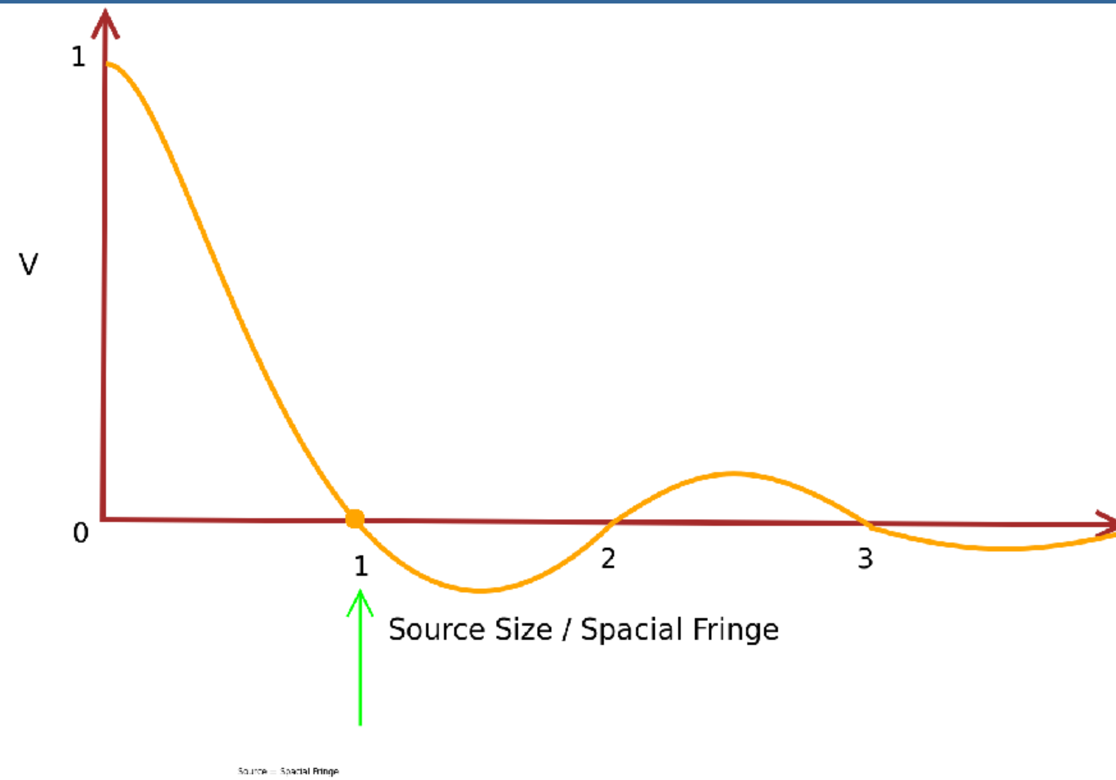


One Fringe Width

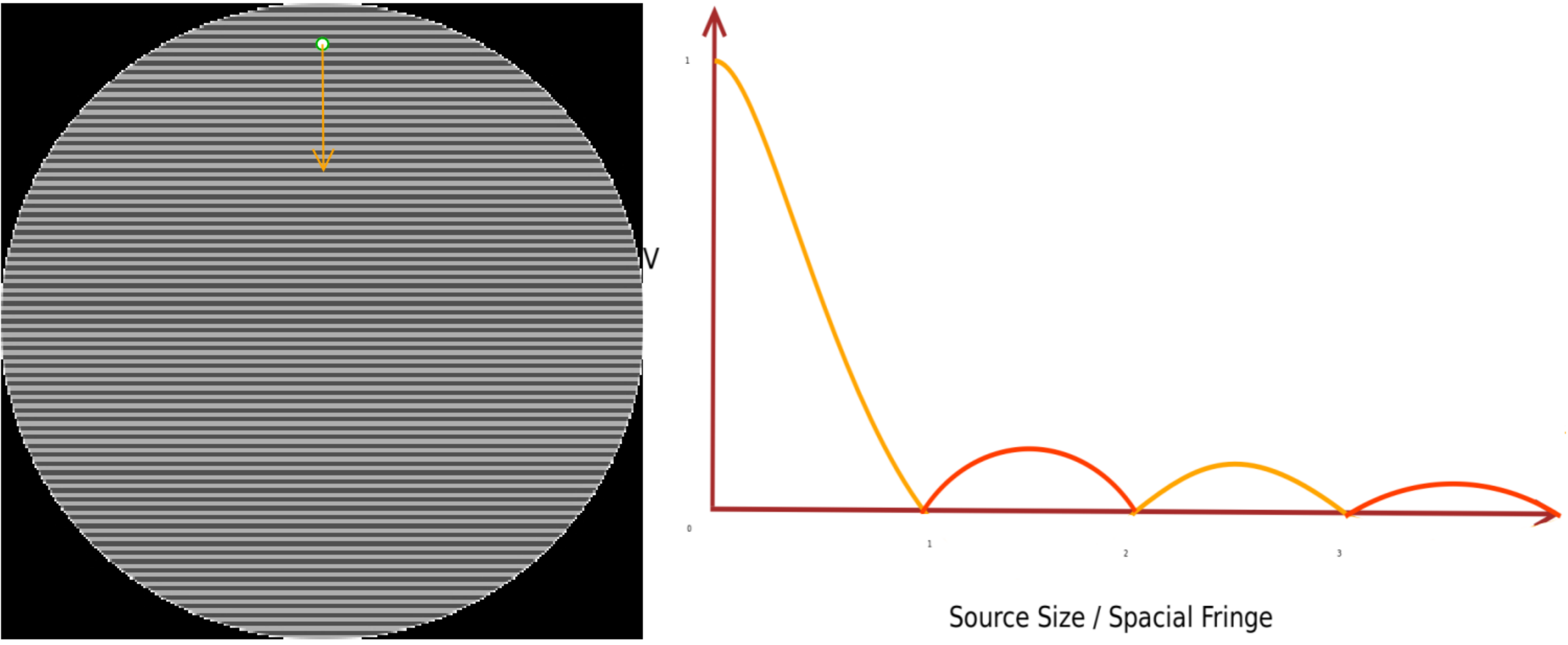


One Fringe Width





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

We also are trying to measure positions accurately. For this we require sources that don't move, 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!

Some Notes About Radio Sources-2

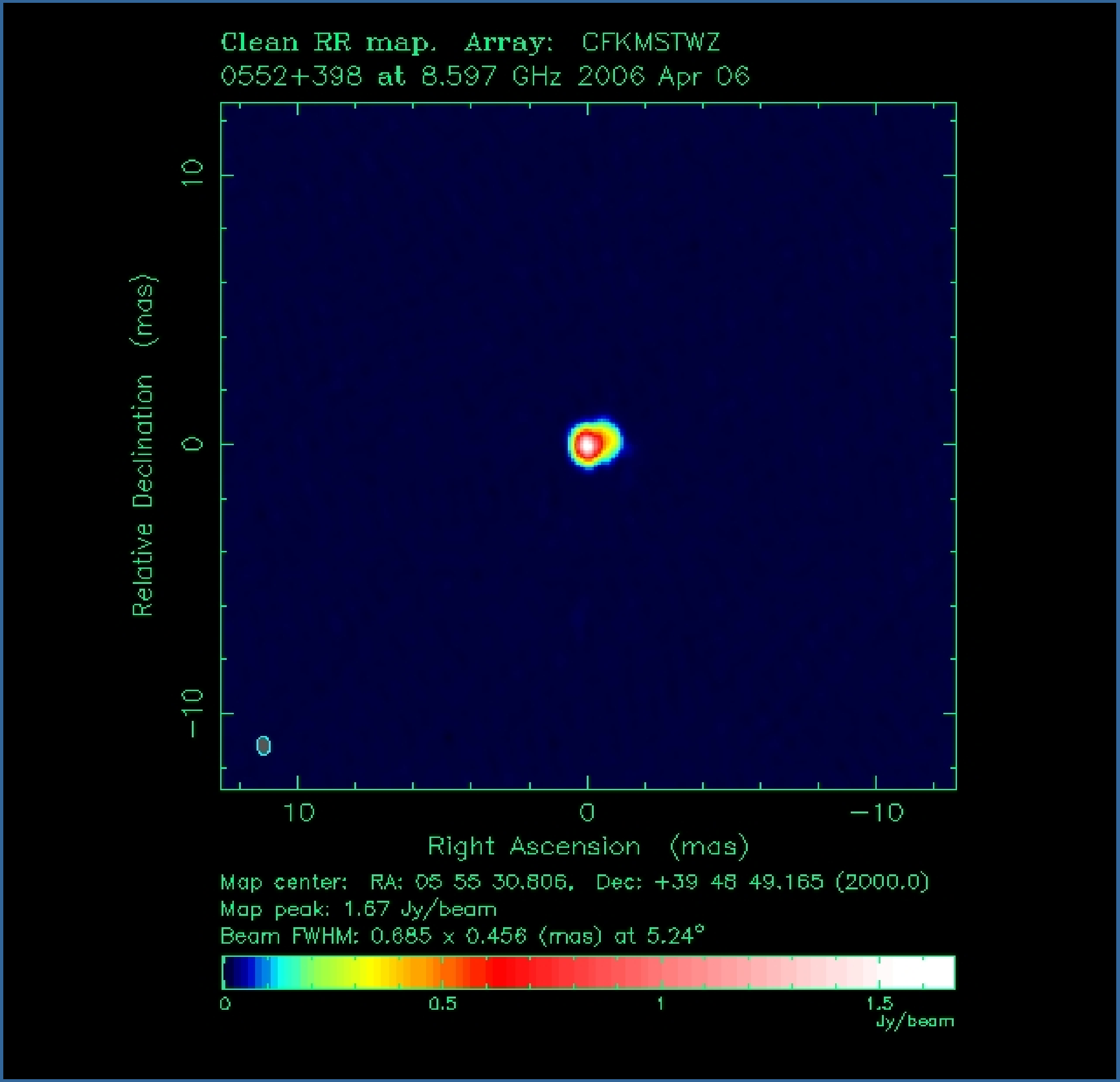
Quasars are among the brightest radio sources in the sky, and they are very far away, so that they don't appear to move as seen by us even if they have a large intrinsic motion.

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

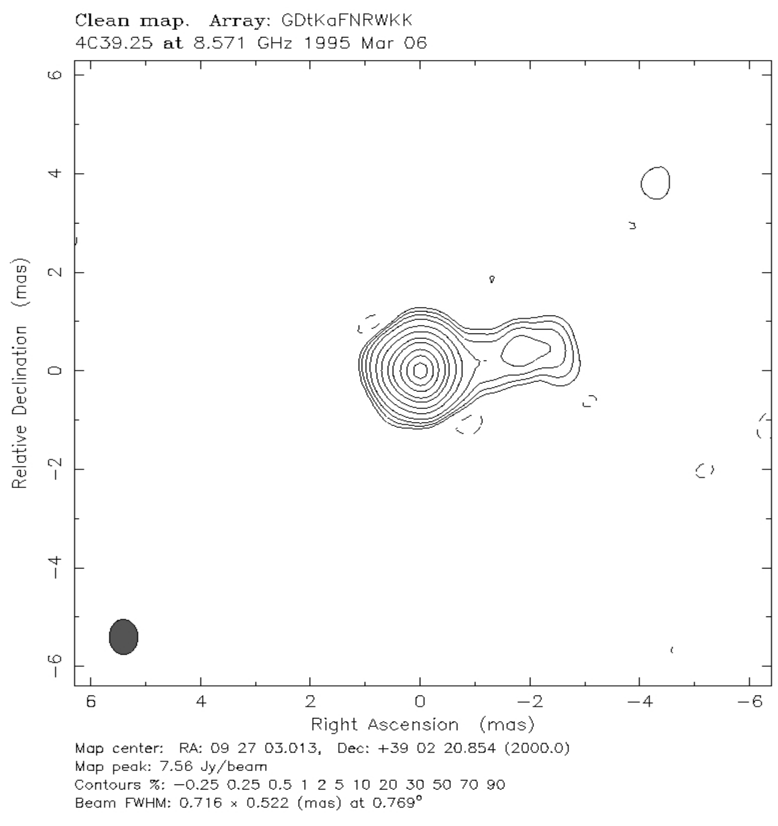
Some Quasars are stable in brightness distribution and show same brightness distribution as a function of frequency, but not many.

The Total number of available useful sources is small, < 1000 over the sky (for current typical geodetic-VLBI systems)

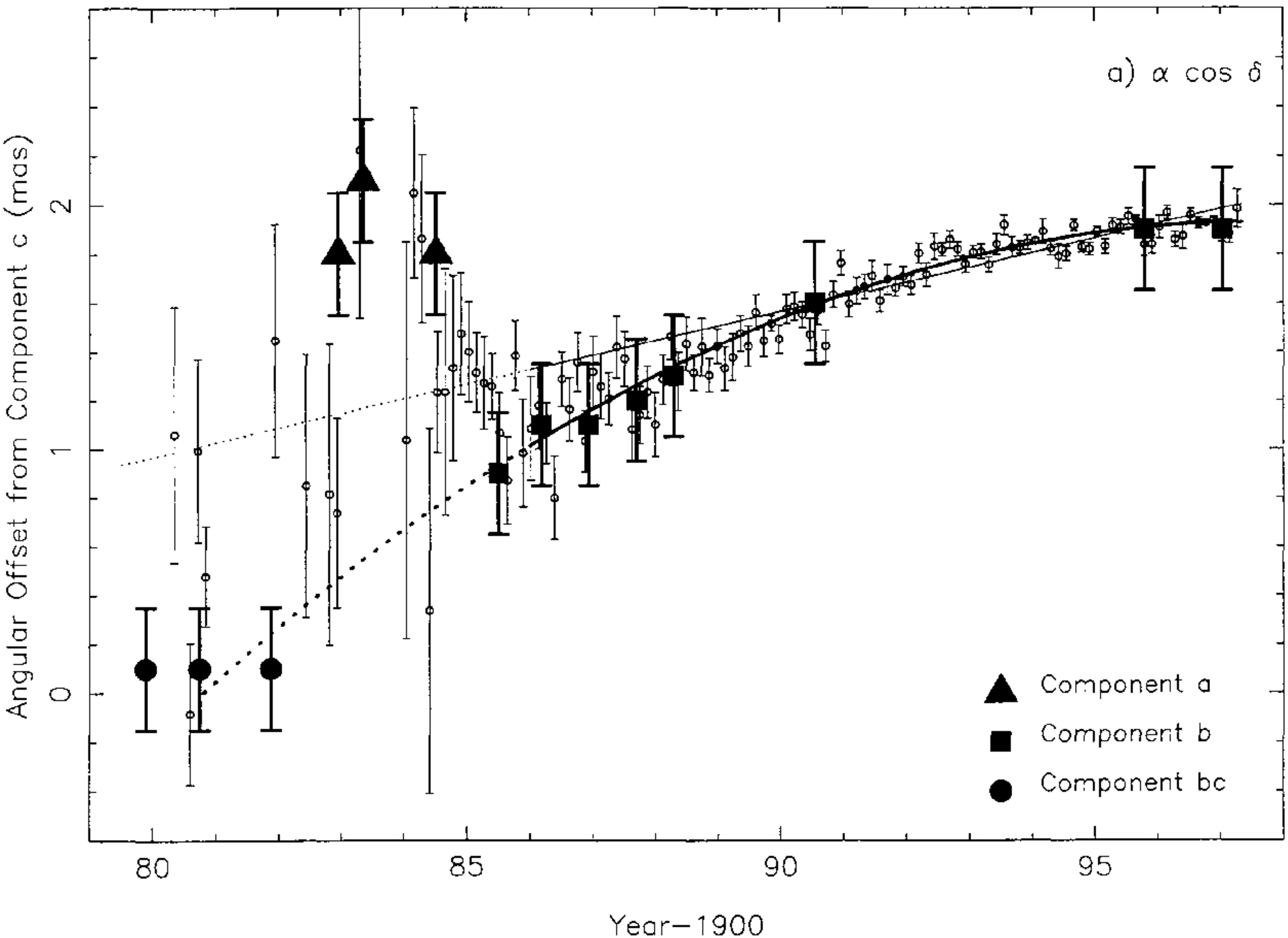
An example of a 'good' radio source



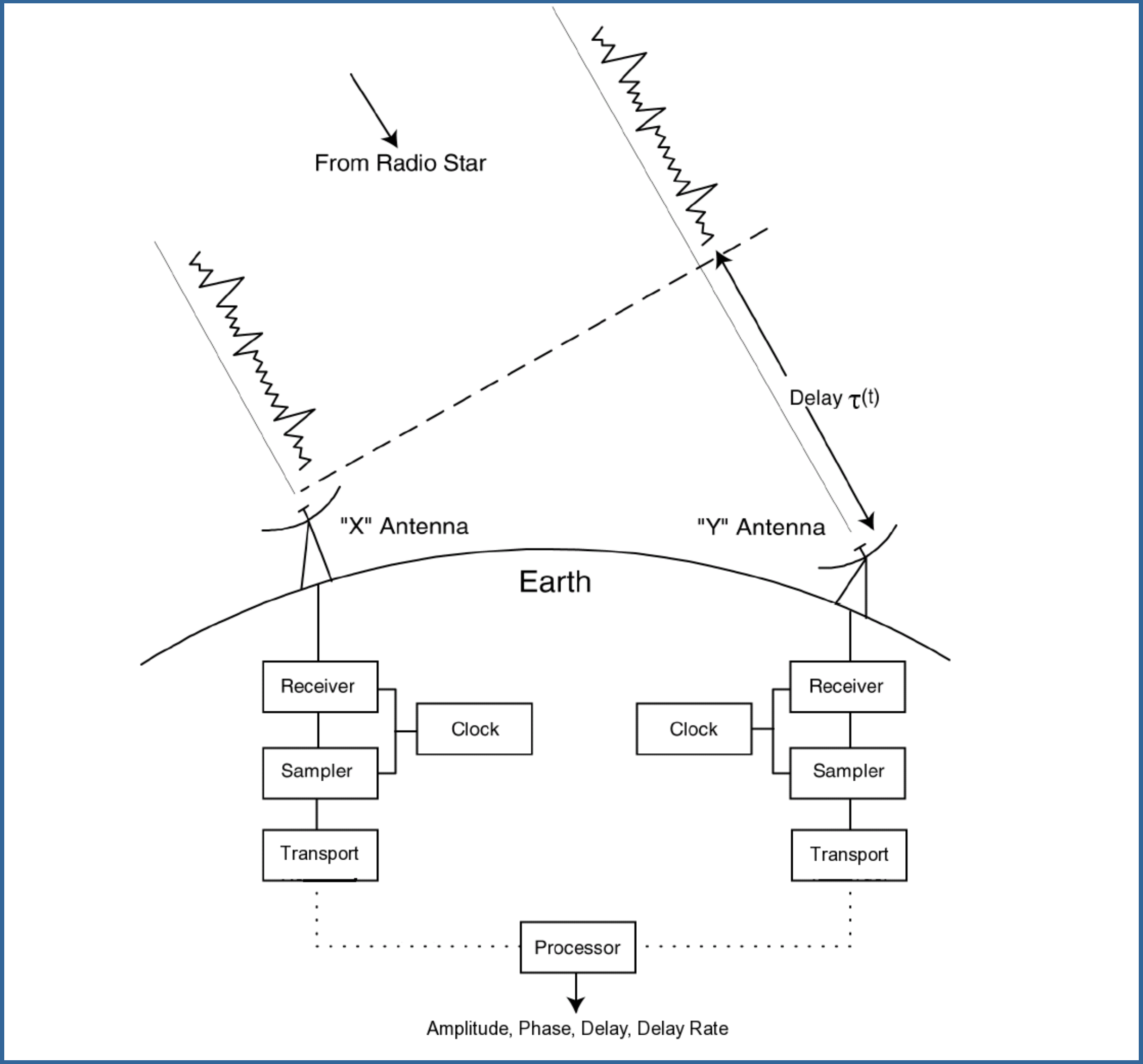
Example of a Questionable Source



- 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
Component a
Component b
Component bc
0
1
2
80
85
90
95

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 medium
  - 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)

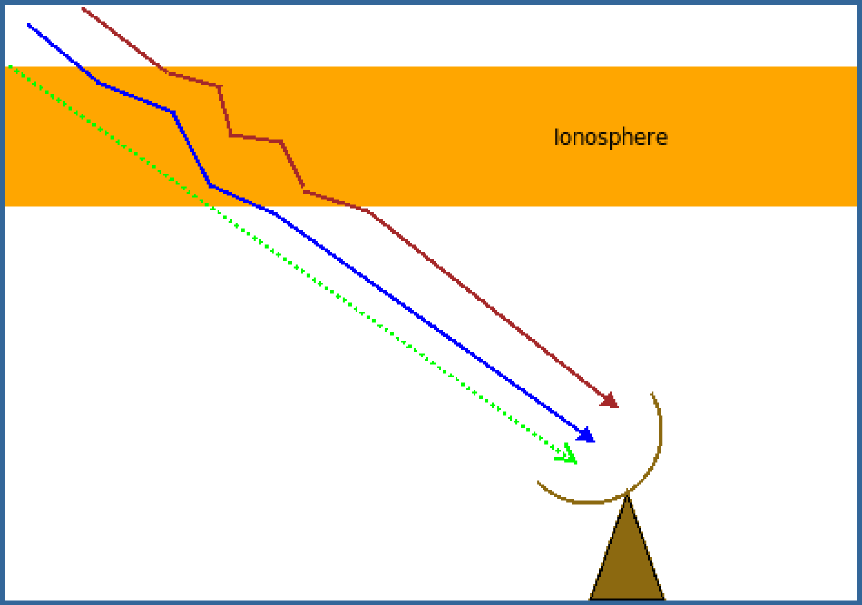
$$\text{Time resolution} = \frac{1}{\text{Spanned Bandwidth}}$$

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

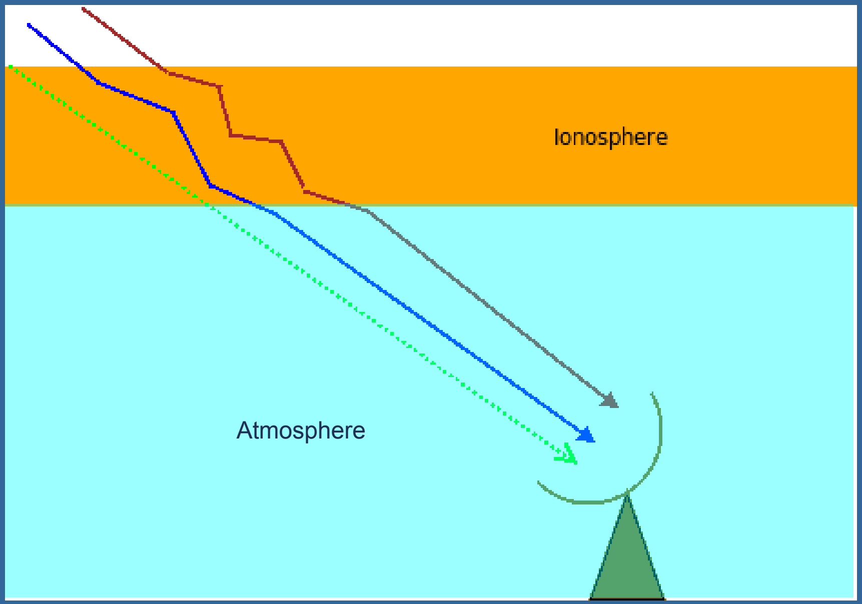
A = Antenna Area

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 frequency low-elevation observations in all 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?

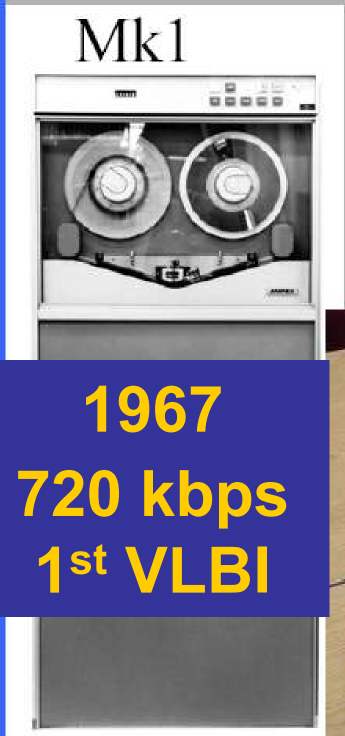
To get S/N we need lots of recorded bandwidth:

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

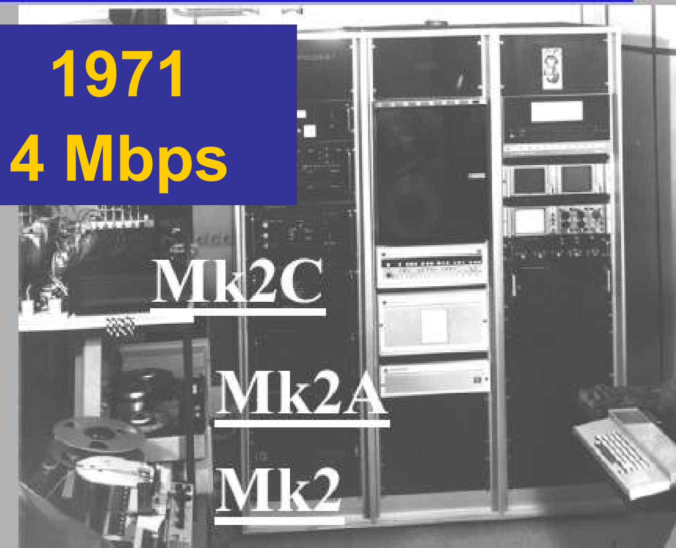
i.e. For 500 MHz recorded bandwidth, need 1Gs/s

Station Requirements

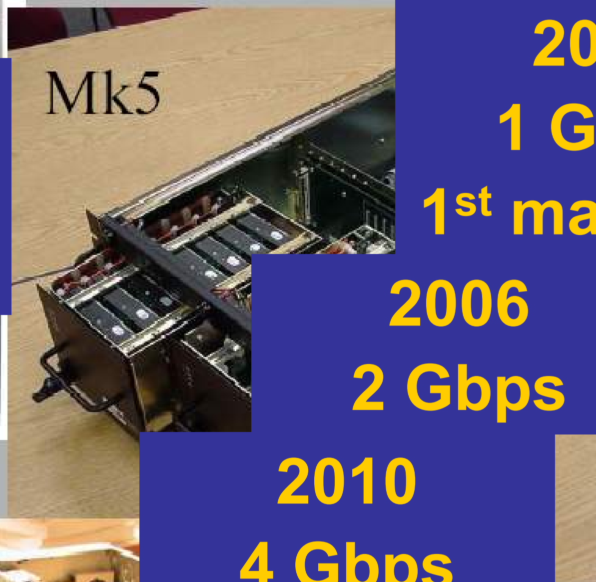
- Wideband Feed and Receiver
- Multi-band system
- Low Noise Receiver
- Large, Efficient Dish (also fast for geodetic-VLBI!)
- High Speed Recording and/or Transport system



1967
720 kbps
1st VLBI



1971
4 Mbps

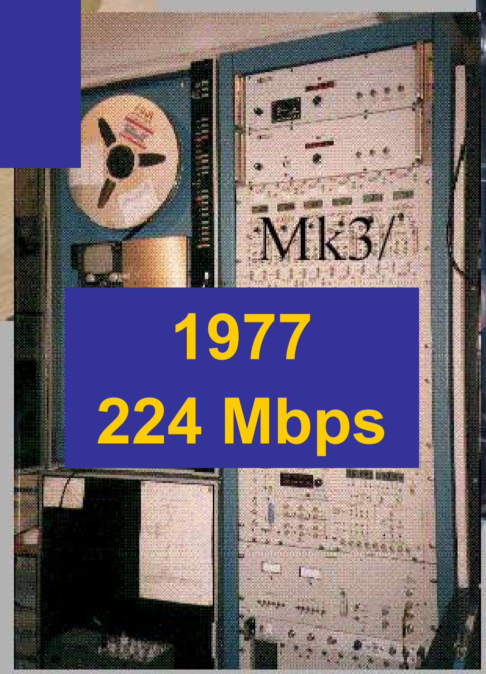


2002
1 Gbps
1st mag disk

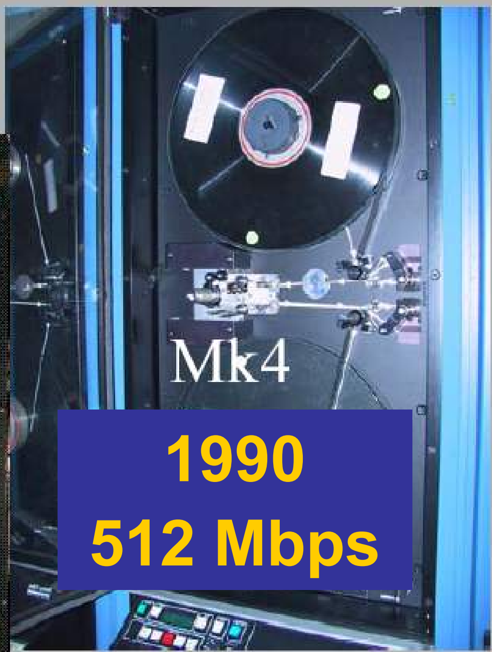
2006
2 Gbps

2010
4 Gbps

2012
16 Gbps



1977
224 Mbps



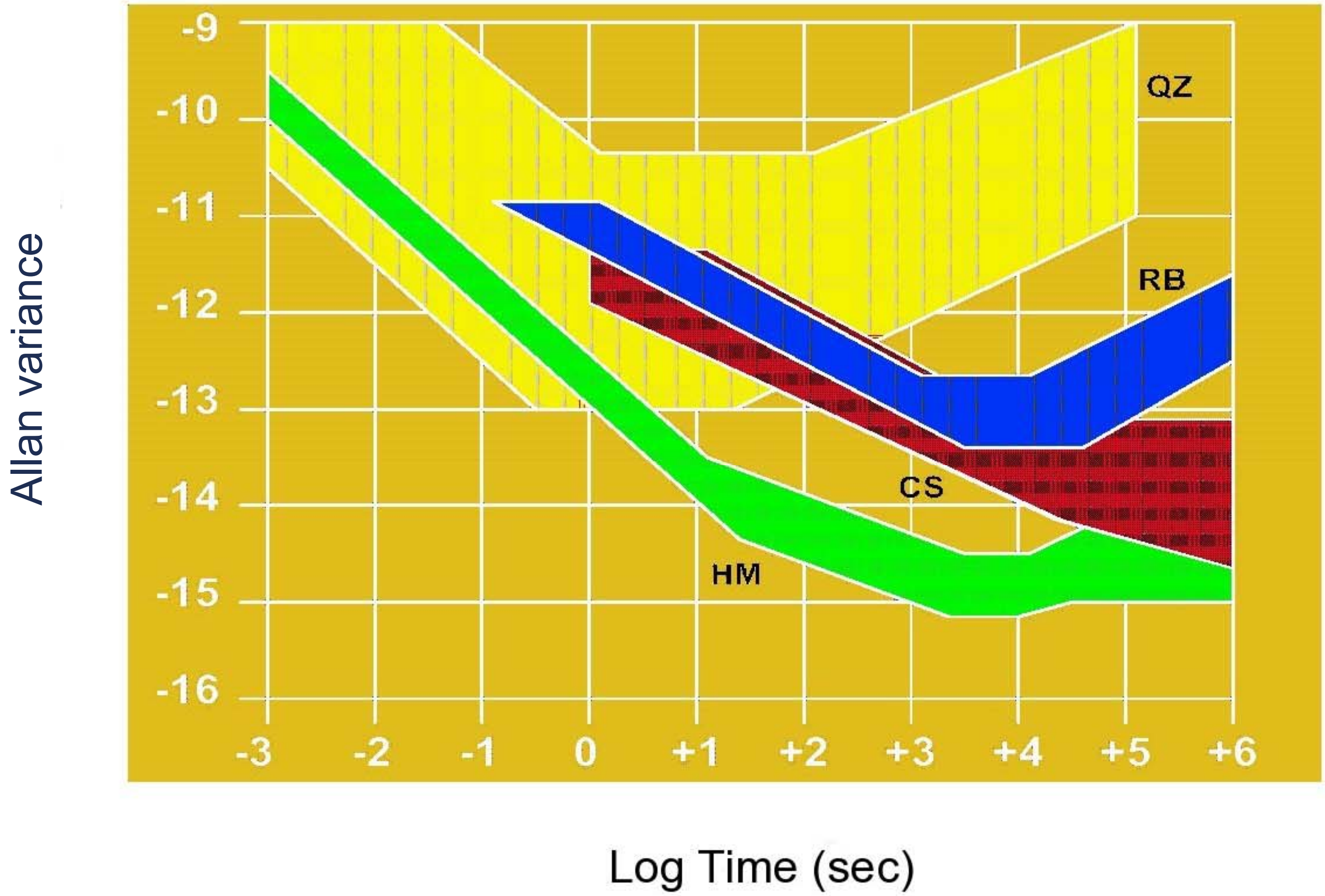
1990
512 Mbps

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}.


Allan variance
-9
-10
-11
-12
-13
-14
-15
-16
-3
-2
-1
0
+1
+2
+3
+4
+5
+6
QZ
RB
CS
HM
Log Time (sec)

Station Requirements

- Wideband Feed and Receiver
- Multi-band system
- Low Noise Receiver
- Large, Efficient Dish (also fast 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 easily 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 group delay 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 calibration system consisting of:

Cable calibrator → accurately measures group delay from maser to Receiver

Phase calibrator → 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!

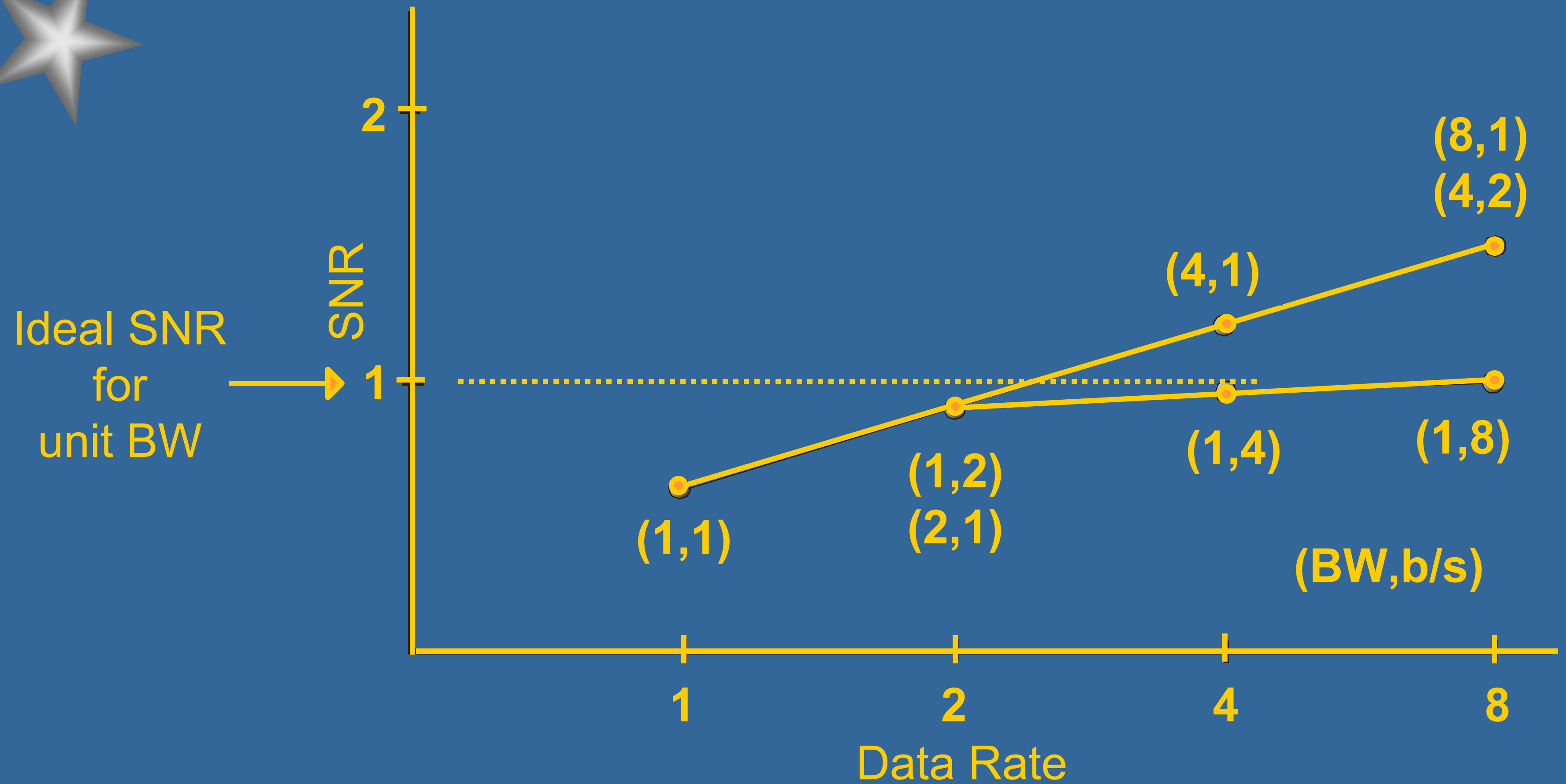
But also another important consequence:
If a small amount of data are lost, it's usually no big deal!

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 $\sqrt{BW}$

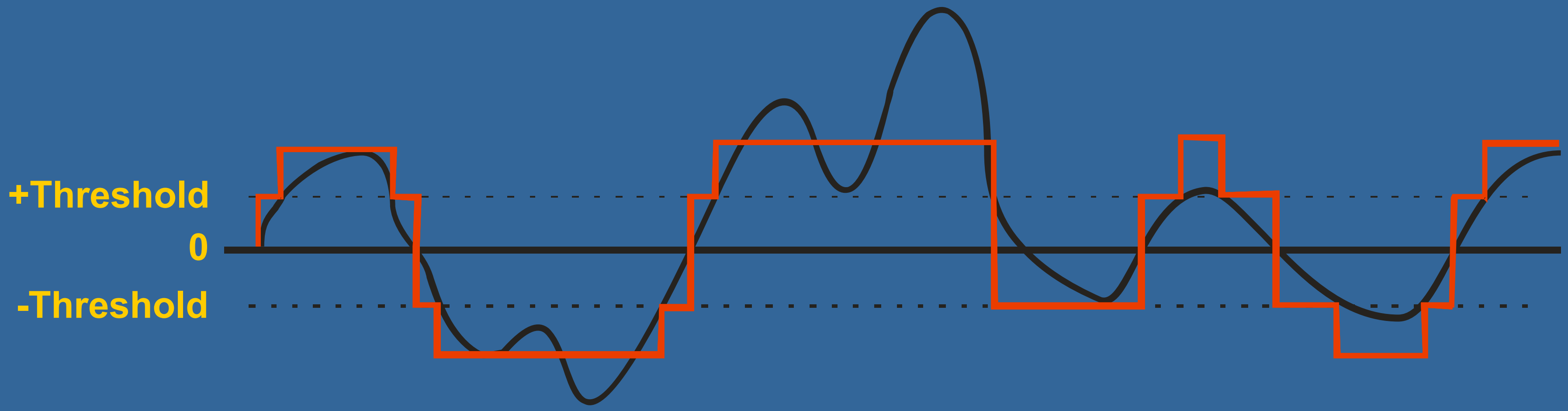
This is why only 1 or 2 bits/sample!

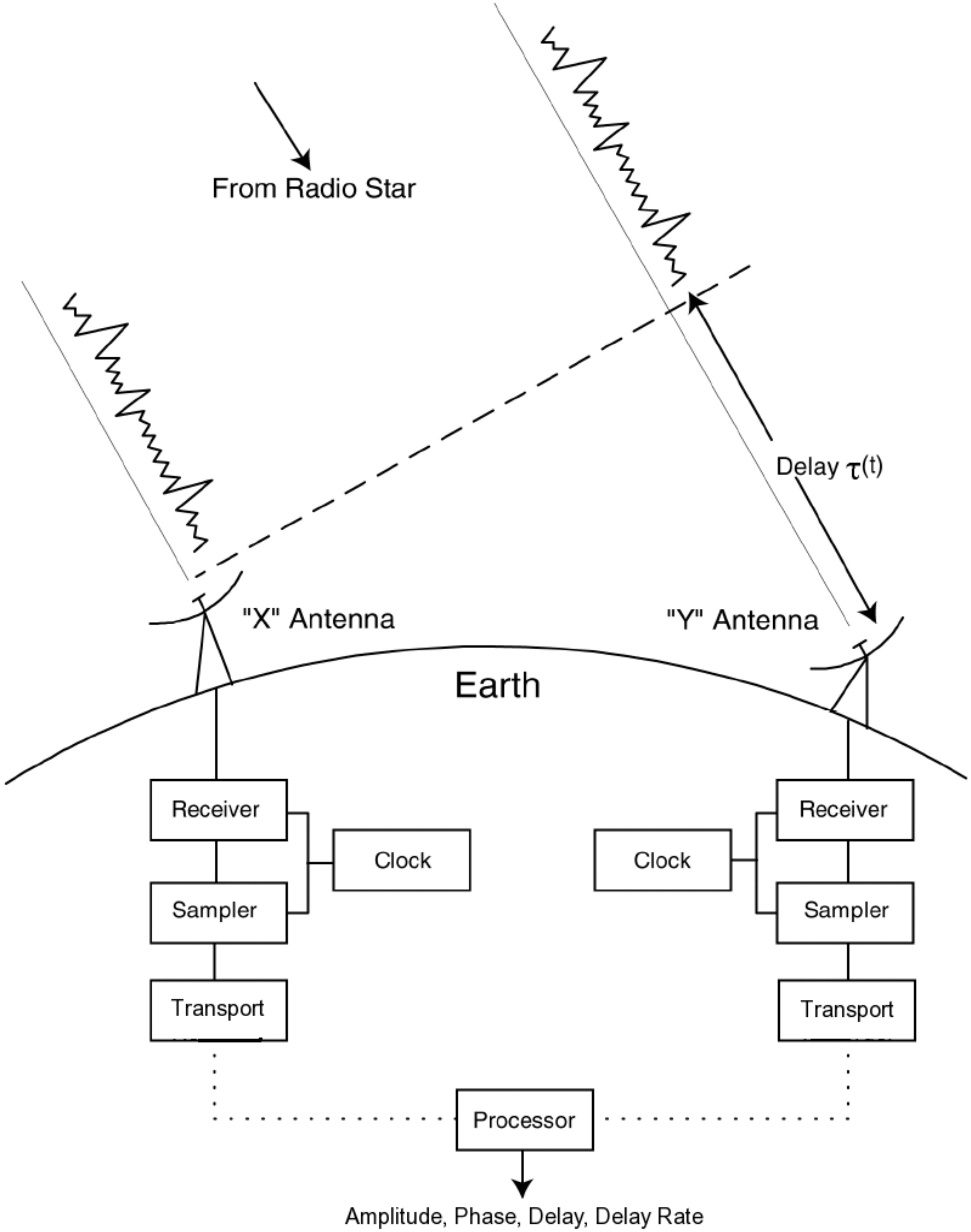


Note that SNR goes up faster by increasing BW than by increasing #bits/sample

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 1000 X noisier observing systems.

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

We have limited integration times (clock behavior, recorder limits)

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

Correlator Mathematical Magic

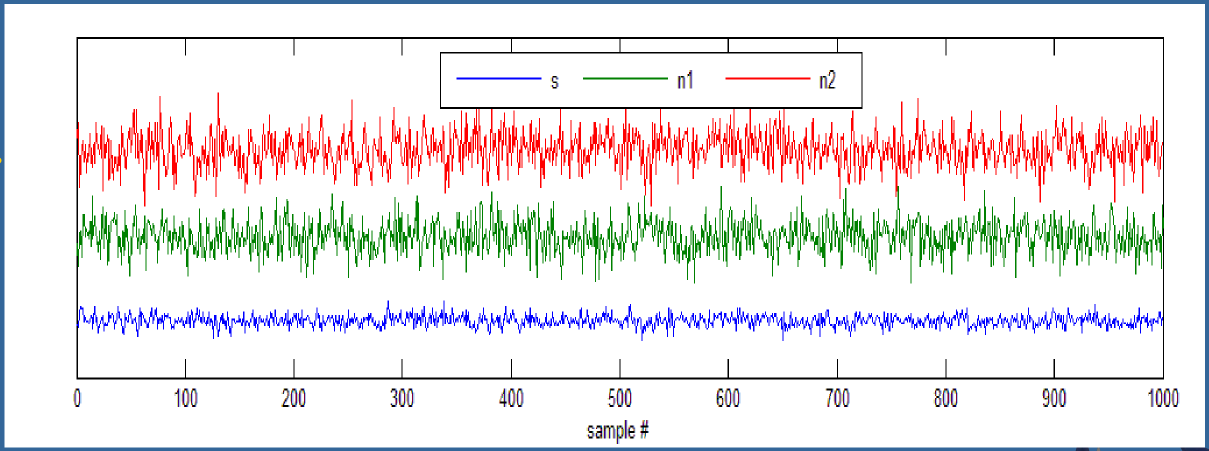
Cross-correlation of weak signals in noise

- 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) →



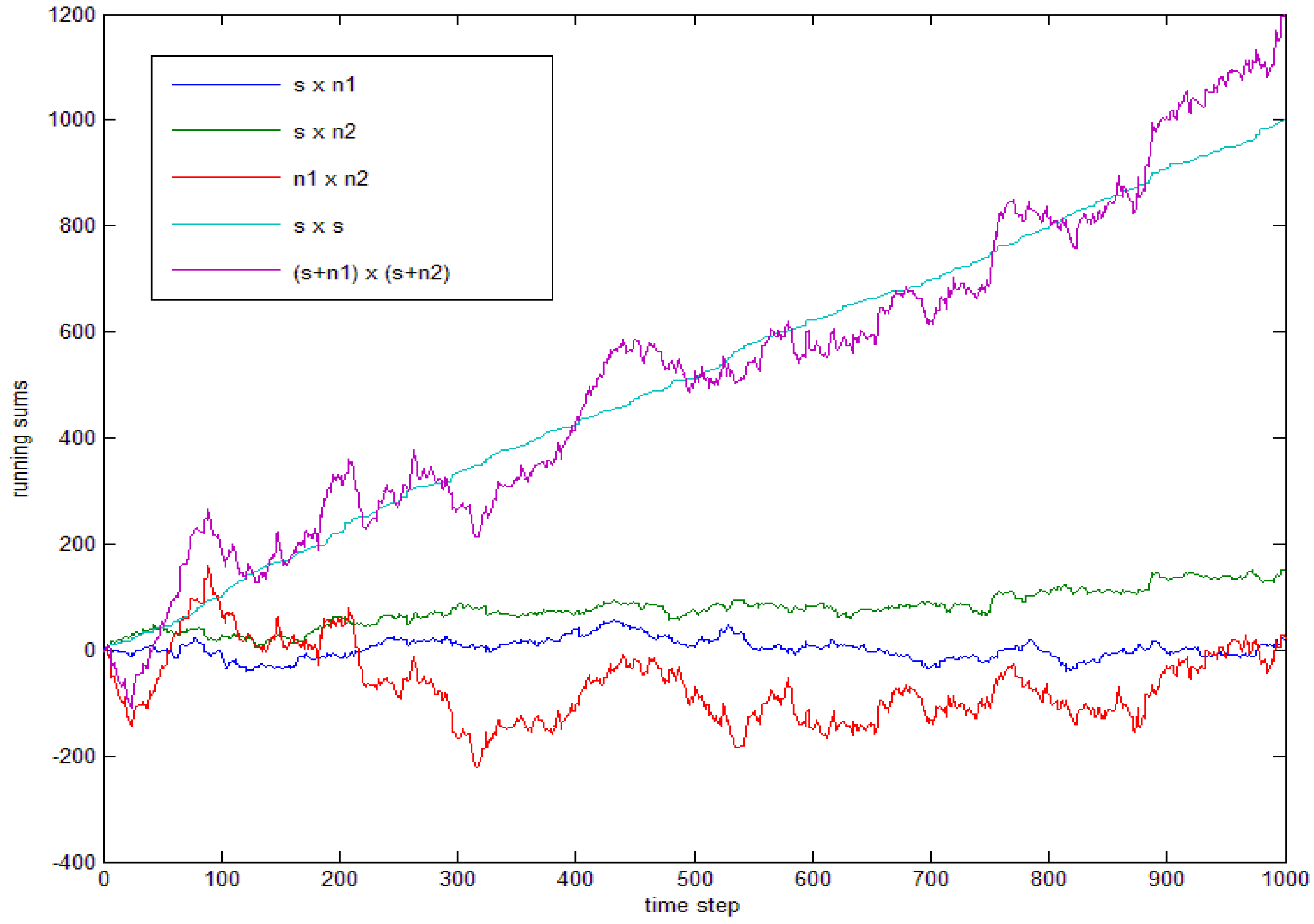
Cross-correlation of weak signals (cont'd)

- 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

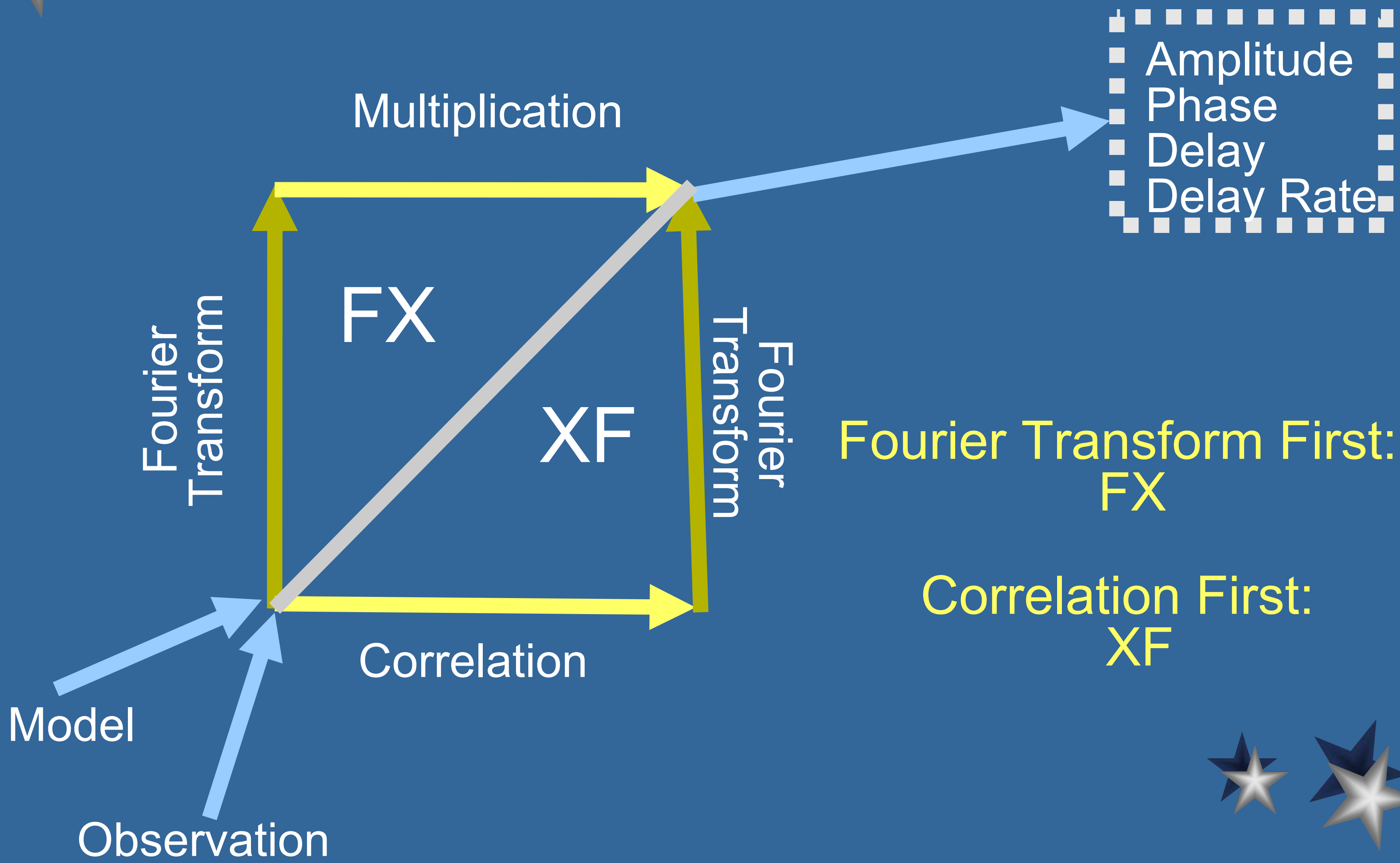
Correlation components



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

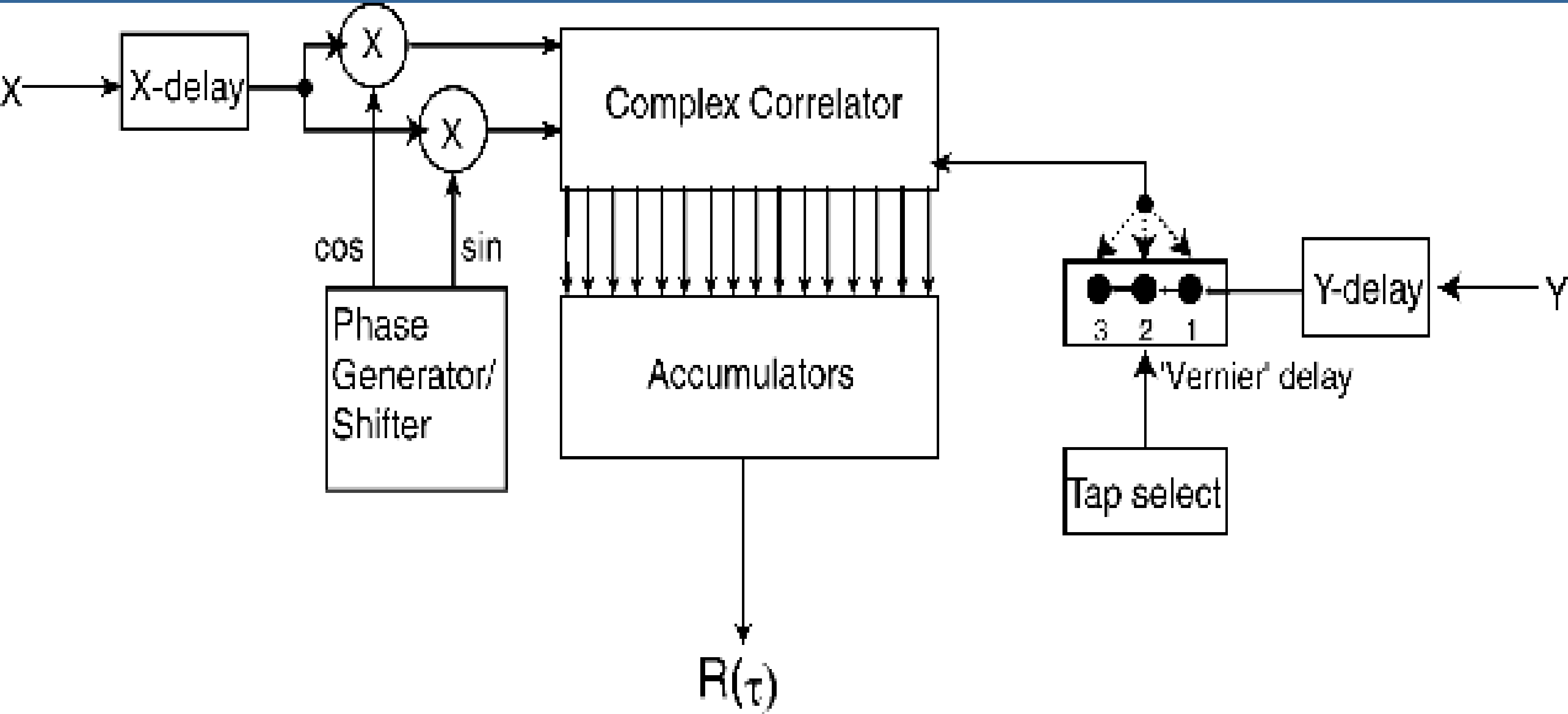
Why are they called "Correlators"?

- If we have a high snr, we could just difference the arrival times (e.g. pulse)
- Unfortunately, quasar signals are ~10^3 weaker than the noise in our best 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

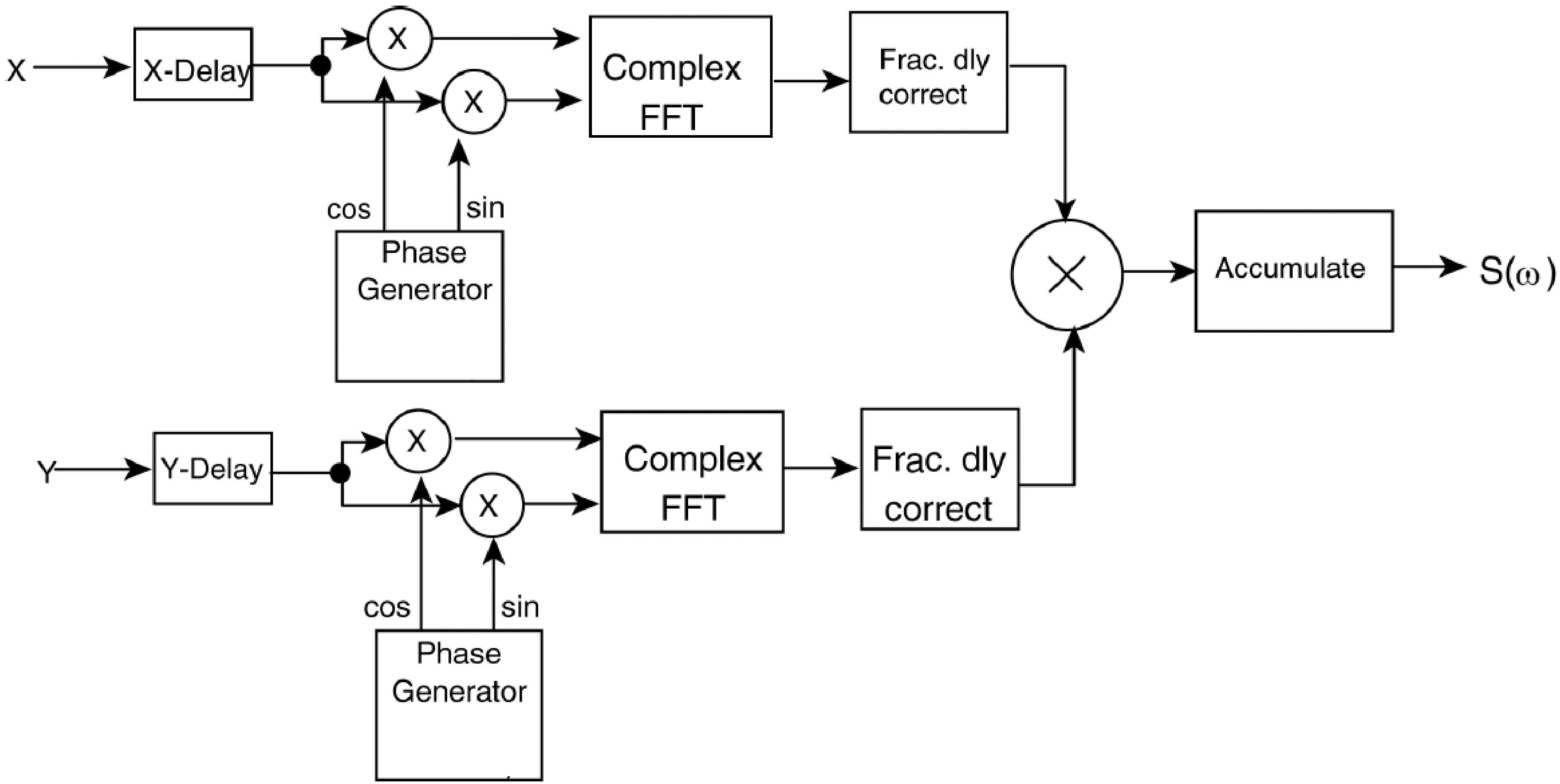
Correlator Details

- If done at the original RF, 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



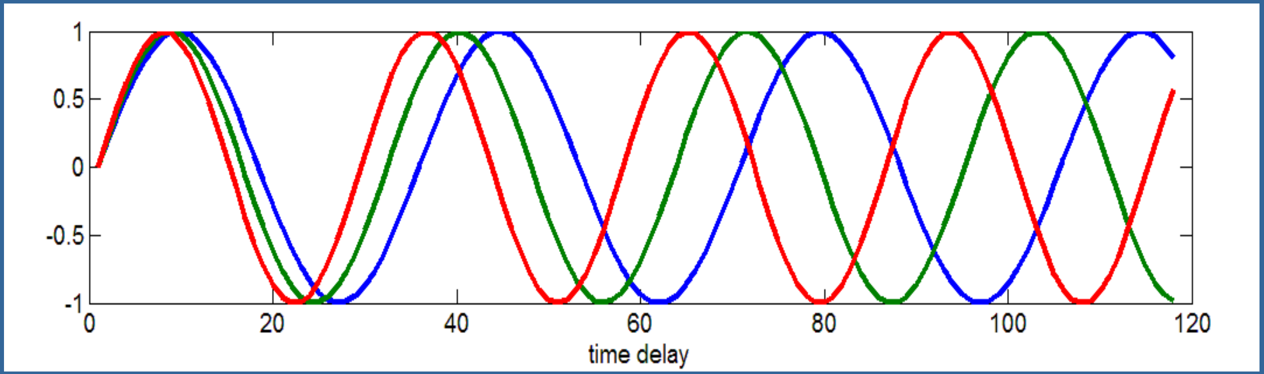
FX Correlator Channel

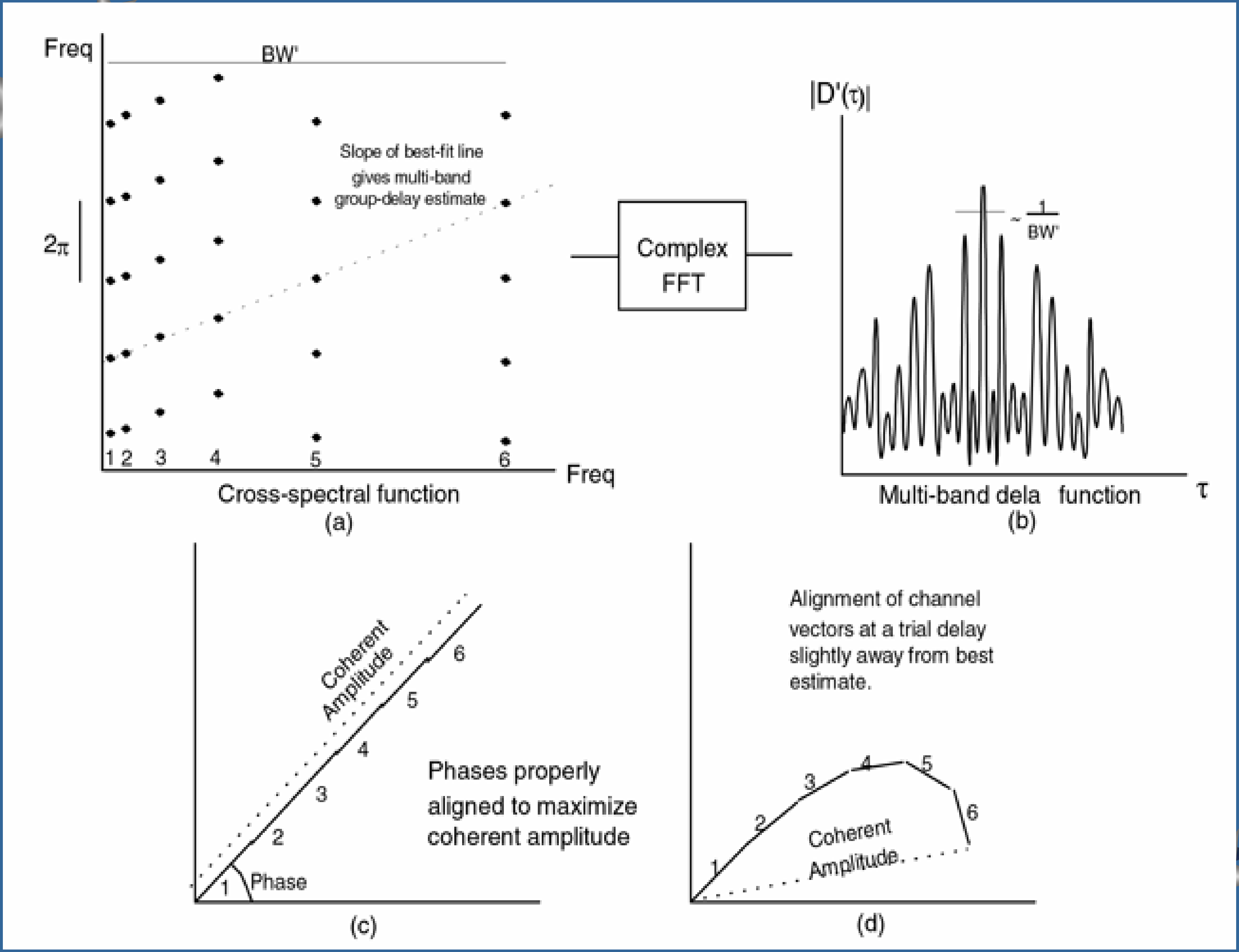


- We now must combine the channels into one solution.
- To do this we use a technique called bandwidth synthesis

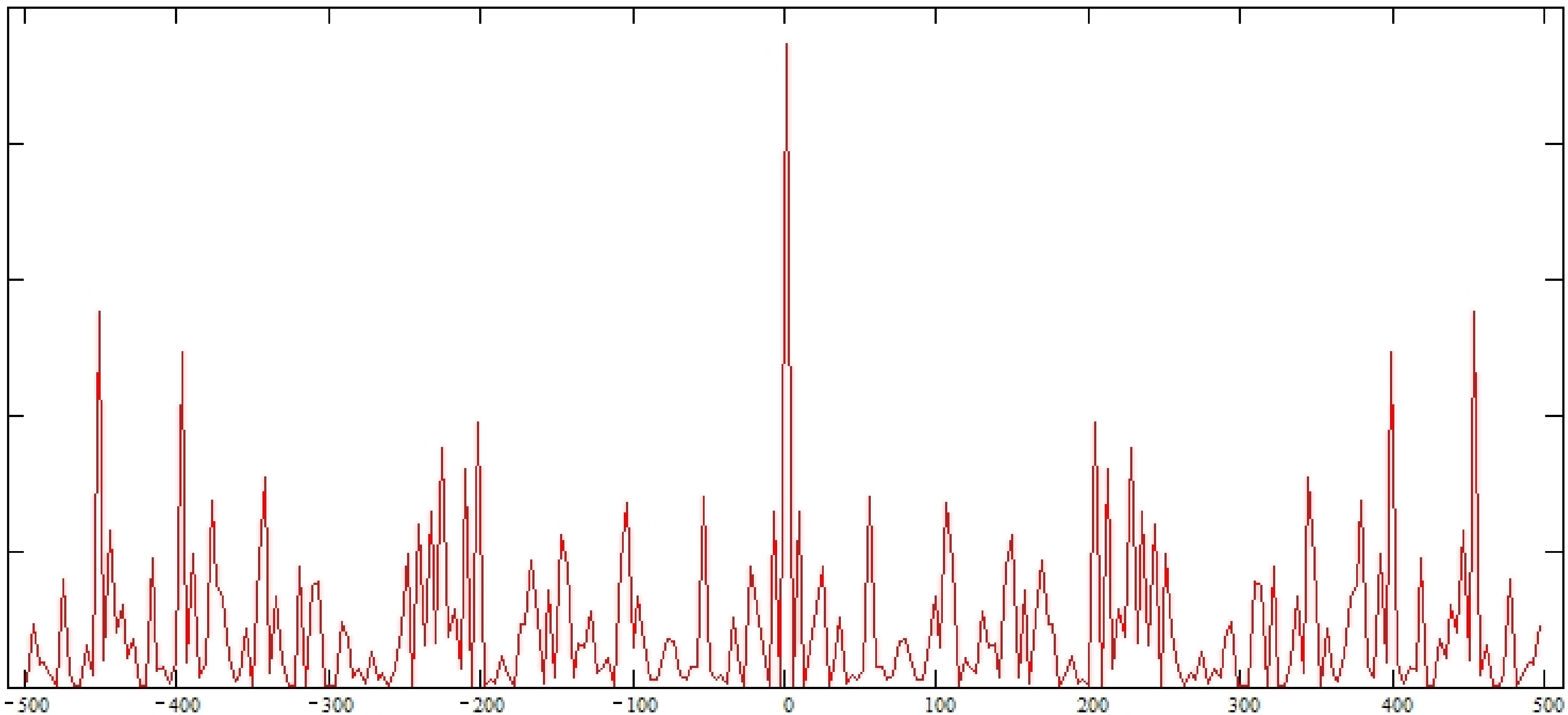
Bandwidth Synthesis

- The goal is to measure the group delay, which is defined as 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, so the greater time-rate change in phase:



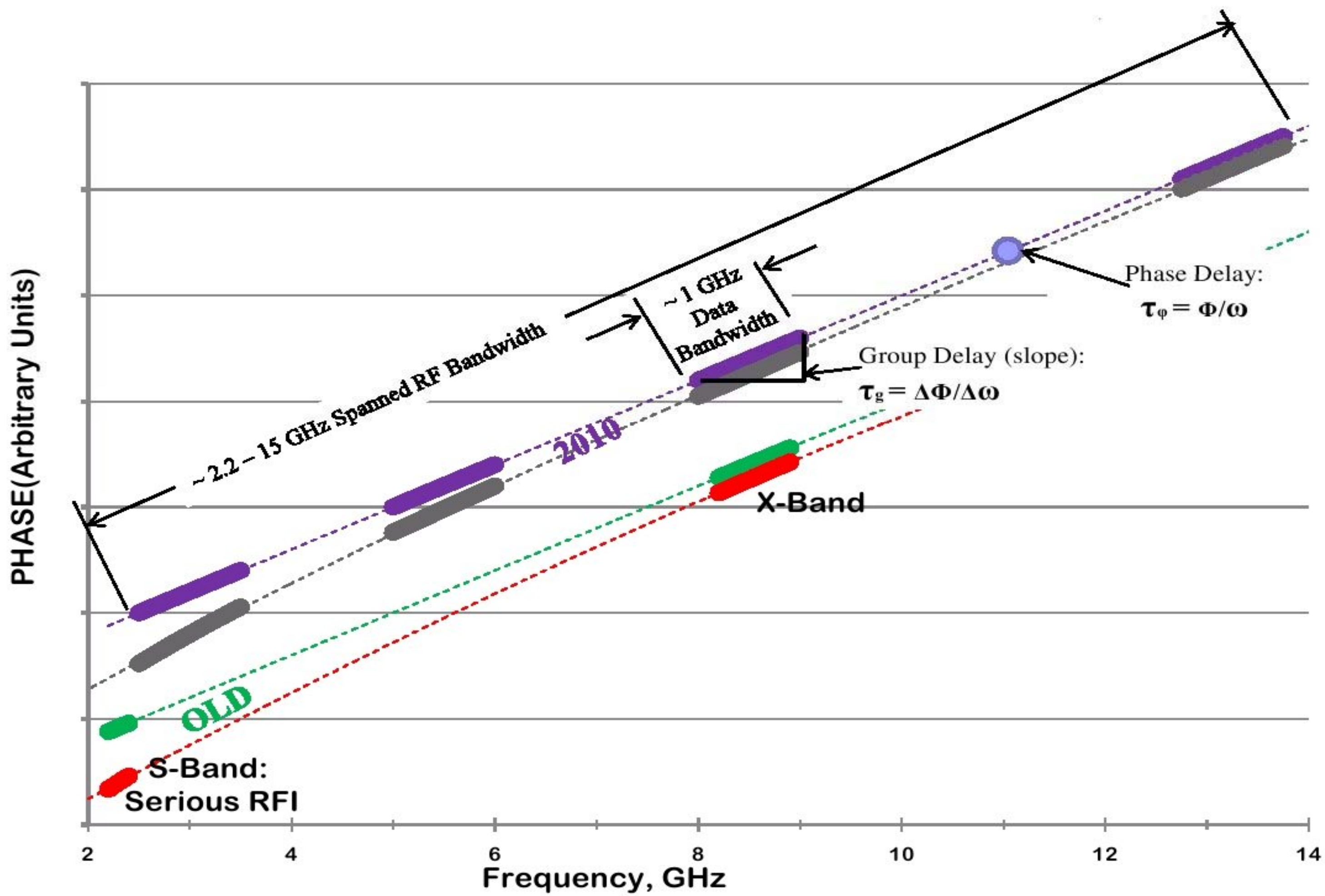

Freq
BW'
Slope of best-fit line gives multi-band group-delay estimate
2π
1 2 3 4 5 6
Freq
Cross-spectral function
(a)
Complex FFT
|D'(τ)|
~ 1/BW'
Multi-band dela function
τ
(b)
Coherent Amplitude
6
5
4
3
2
1
Phase
Phases properly aligned to maximize coherent amplitude
(c)
Alignment of channel vectors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

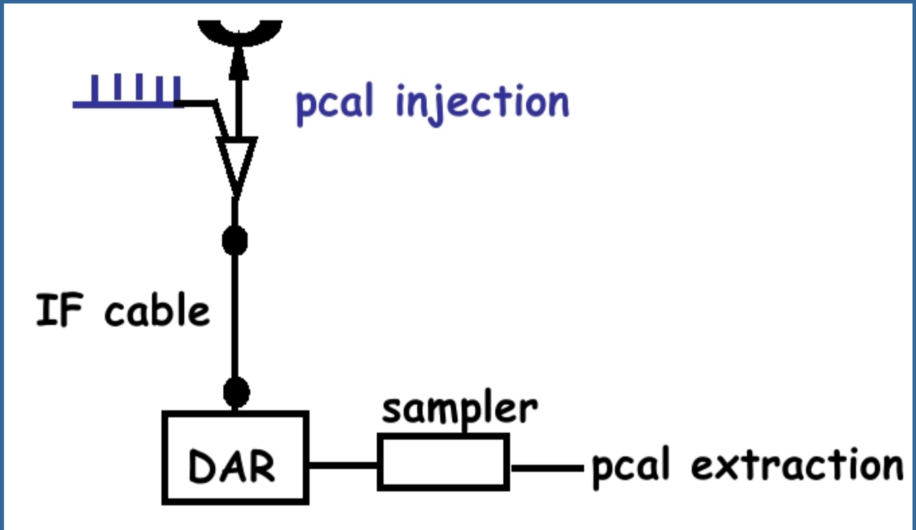


Better delay functions result from non-redundant frequency spacings between channels (for example: 0,1,4,6)

Extreme Bandwidth Synthesis: "Broadband Delay" (i.e. VLBI2010)

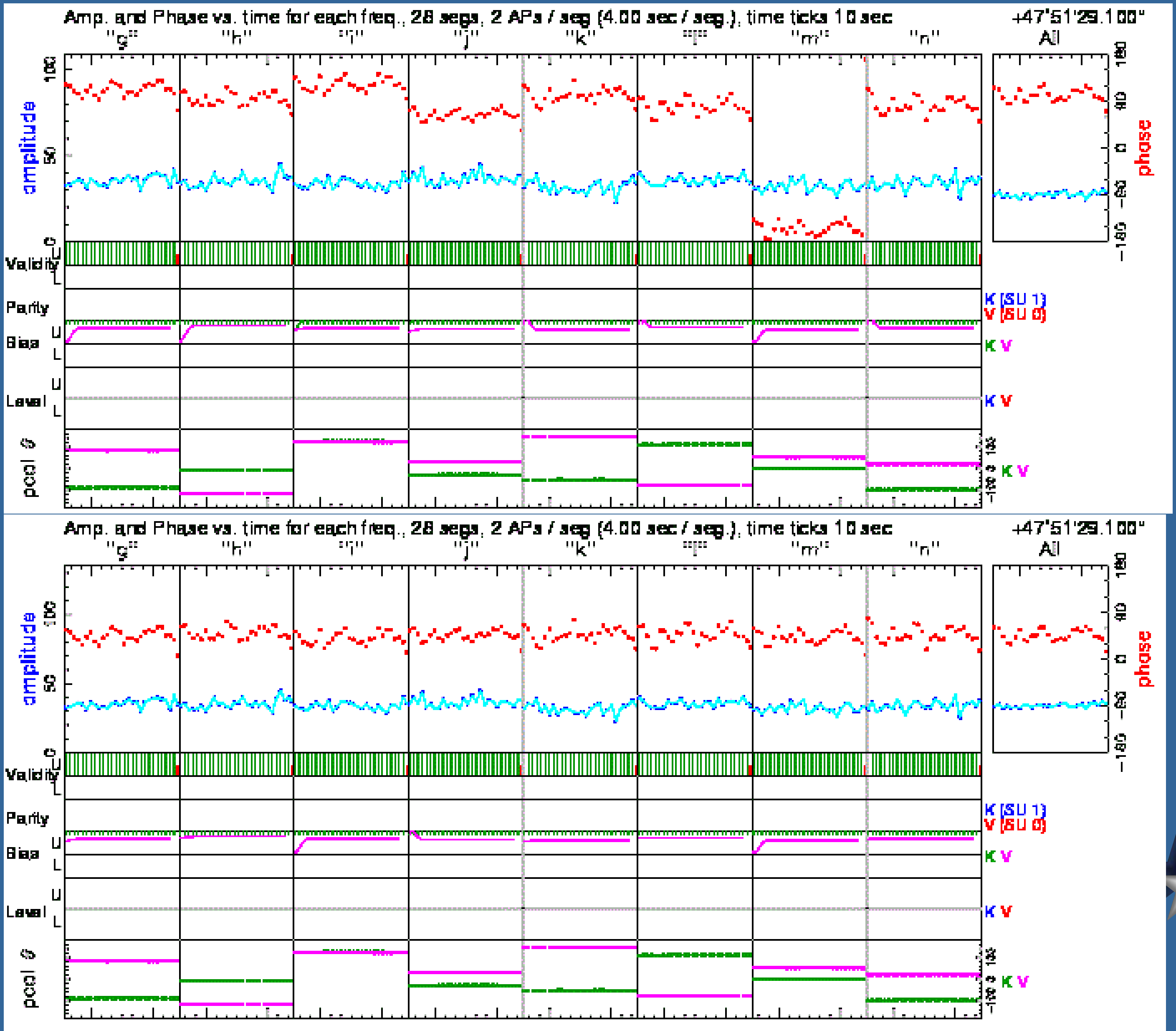


Optimizing Coherence among BBC channels

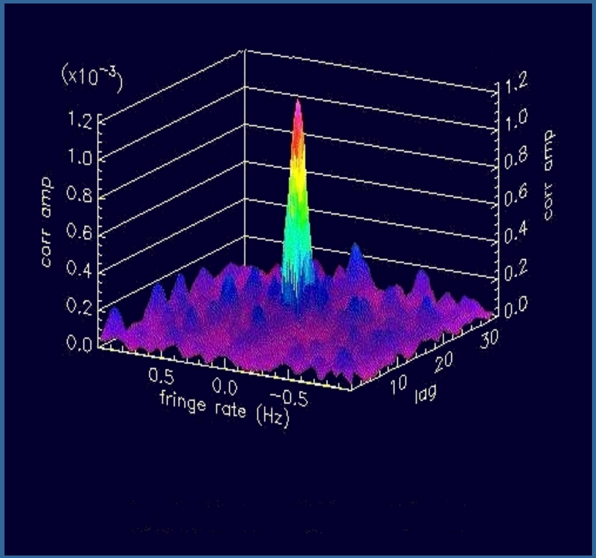


- In addition to the linear phase change due to frequency, there is a contribution to each channel's phase from the instrumentation
- e.g. the filters in each BBC have slightly different delays
- The phase cal subsystem injects tones into the front end every MHz with the same phase (at the start of each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

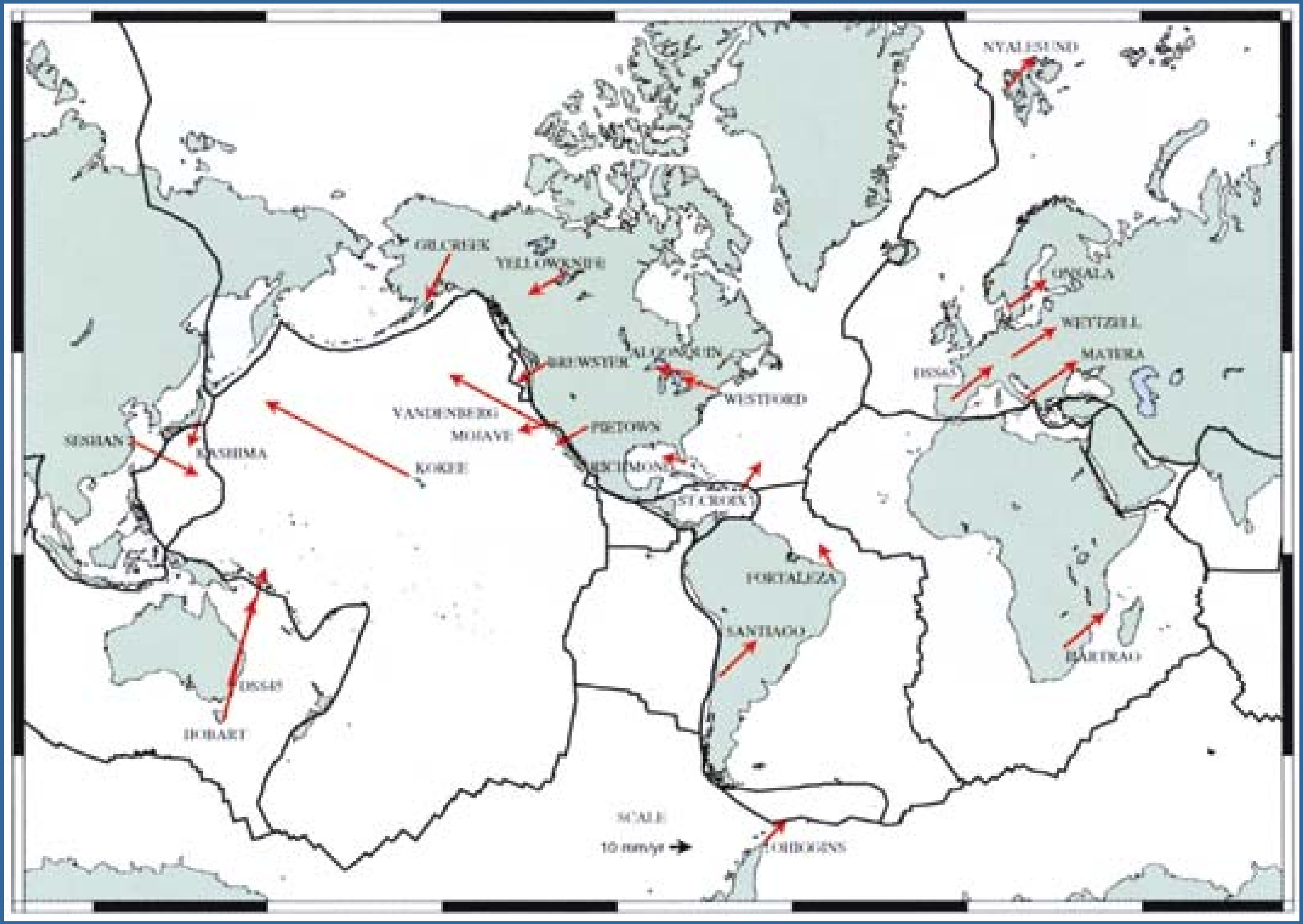
Correlation Amplitude
Correlation Phase (generally 2π ambiguous)
Total Group Delay
Total Delay-Rate

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

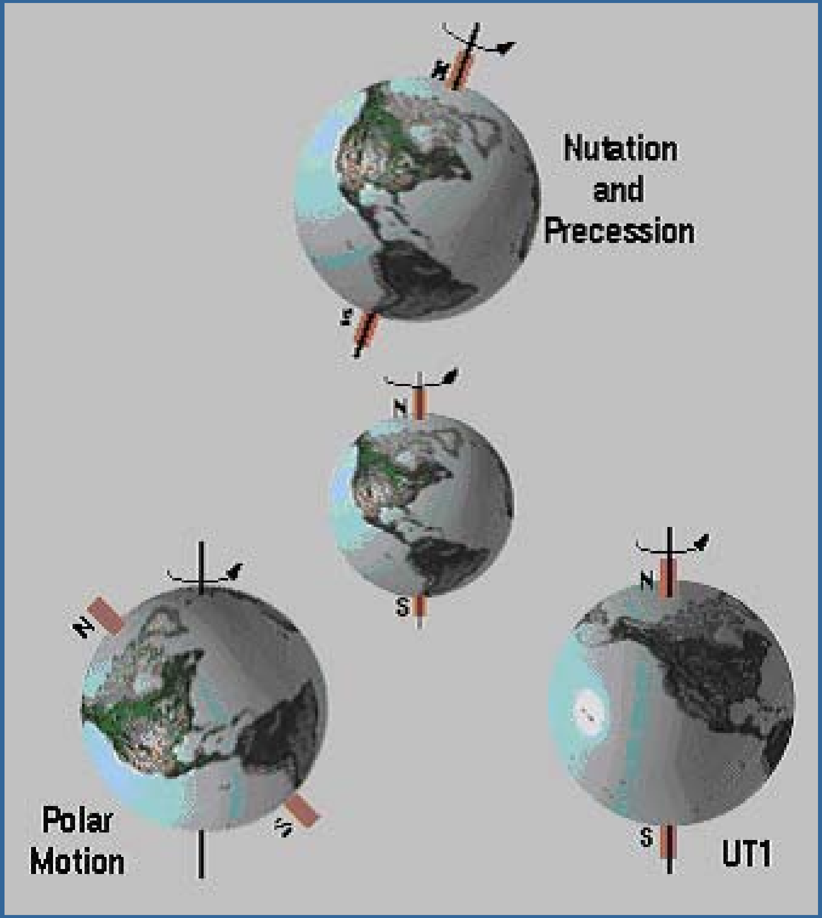
But that’s not the end!

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

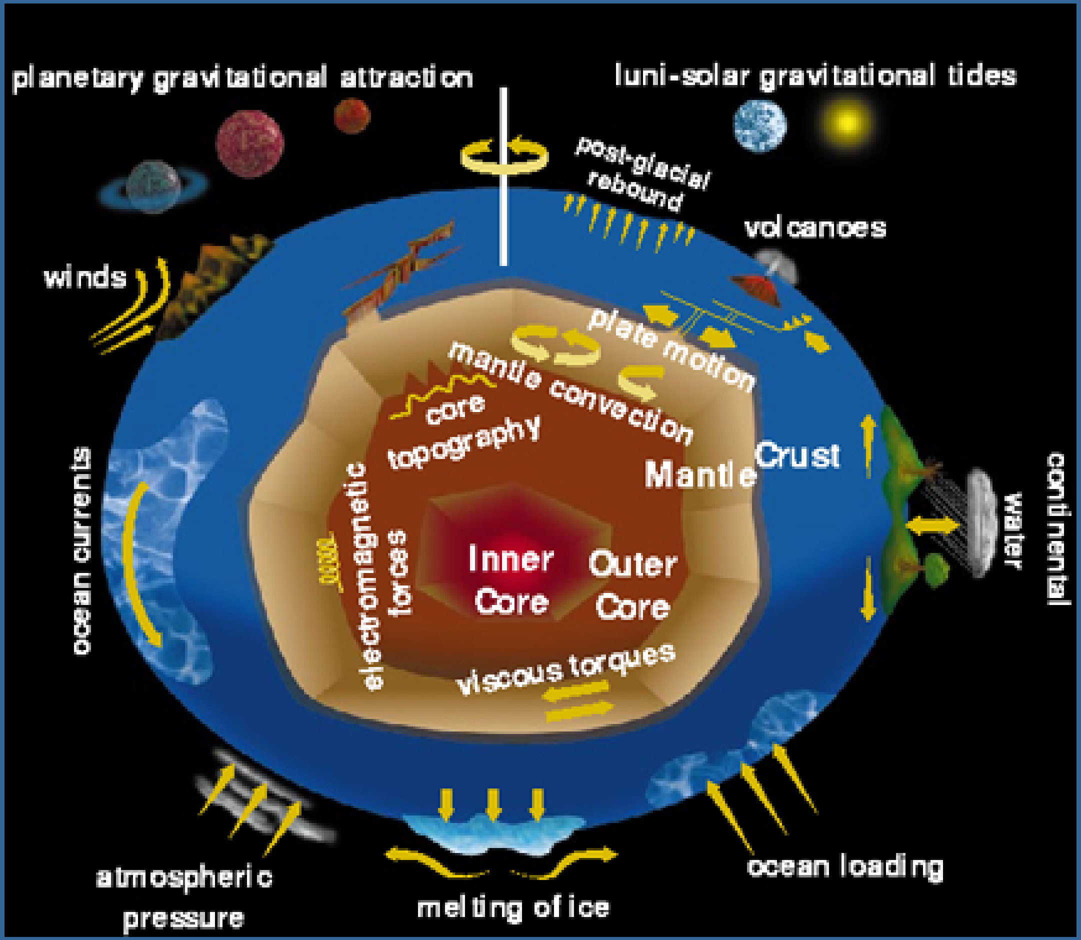
Tectonic Plate Motion



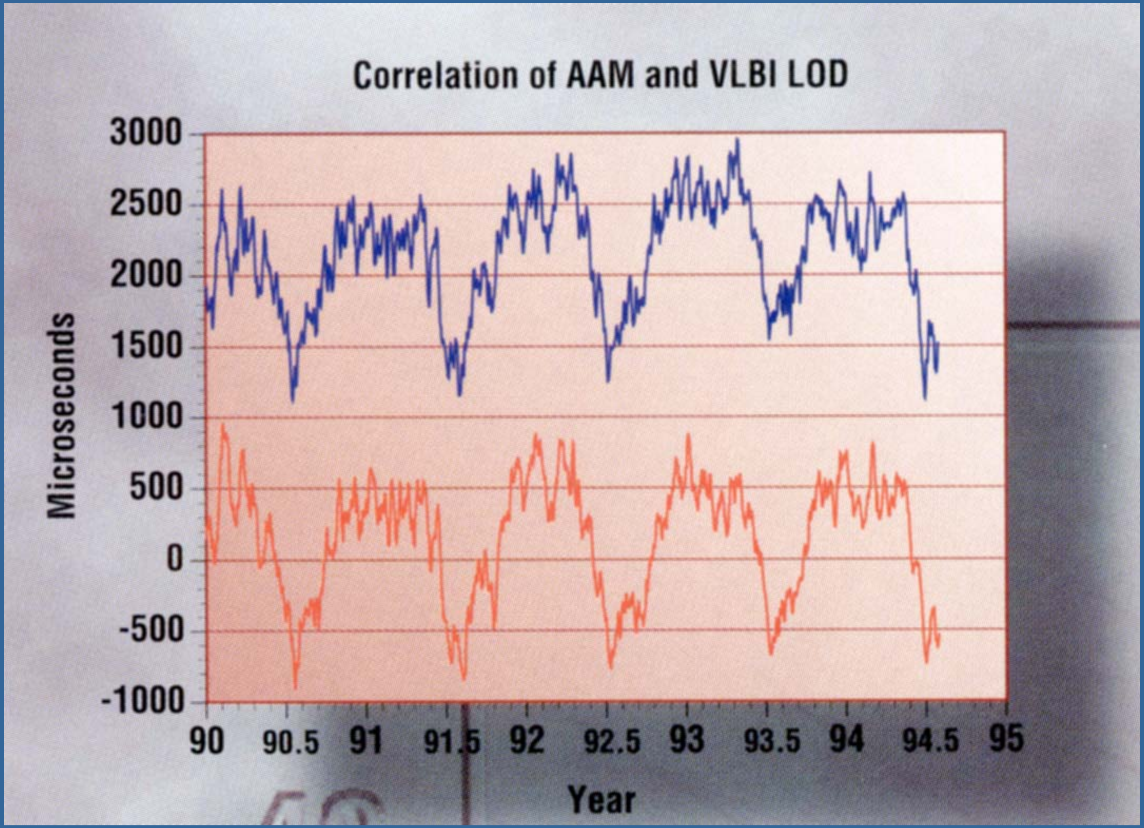
The wiggles and wobbles of the Earth in the reference frame of the distant quasars



The breathing, living Earth itself

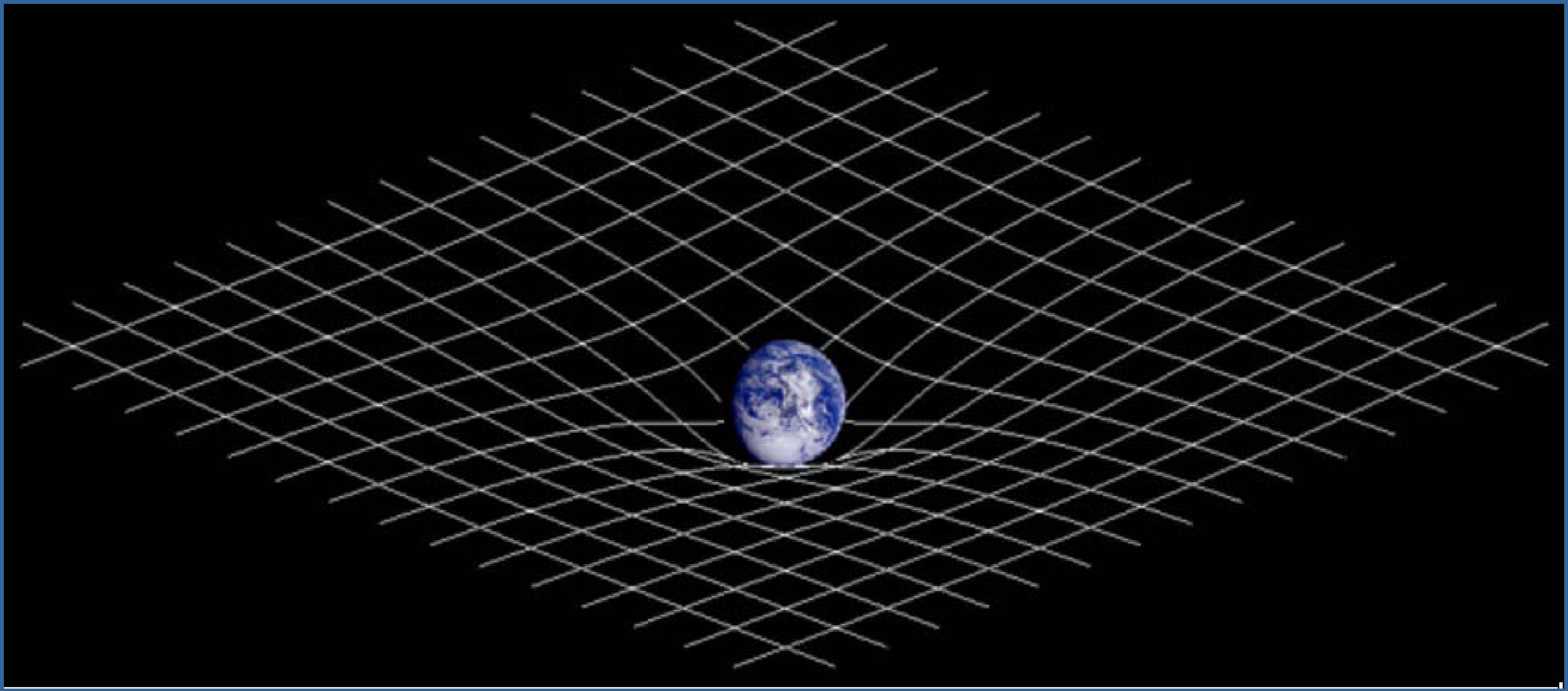


Atmospheric Angular Momentum & Length of Day



- 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 modelling 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:

Alessandra Bertarini
Roger Cappallo
Tom Clark
Dave Hall
Kerry Kingham
Arno Mueskins
Mike Titus

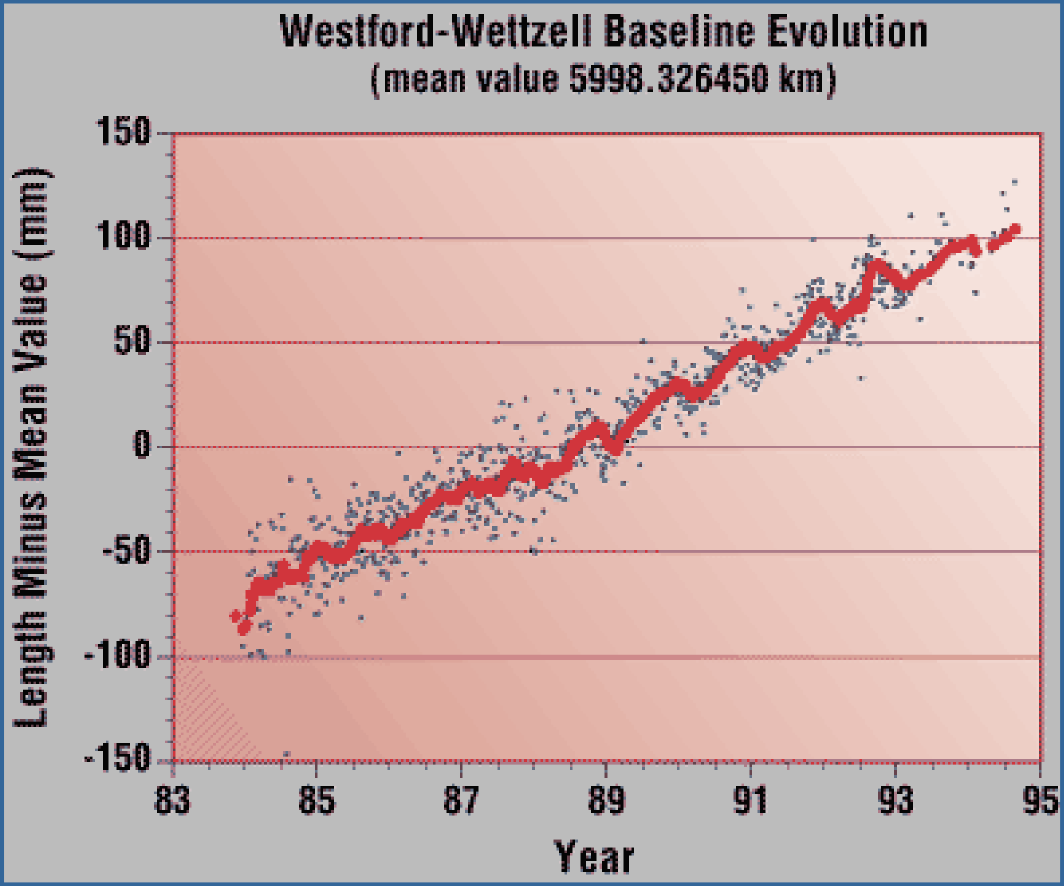
Thank you!

Extra Slides

Continental Drift from VLBI

Motions of the Earth's crust:

- Displacements due to earthquakes
- Plate tectonic motions

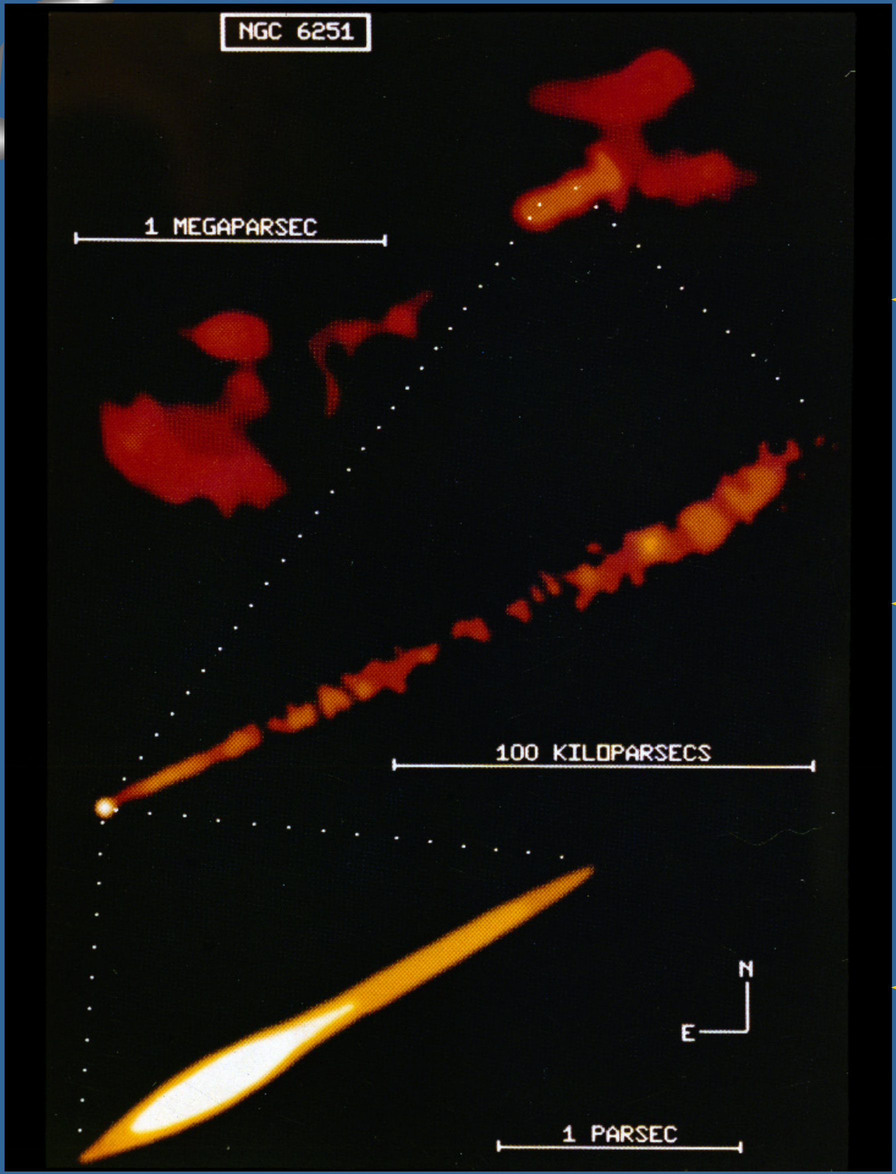


VLBI for Astronomy

- 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)

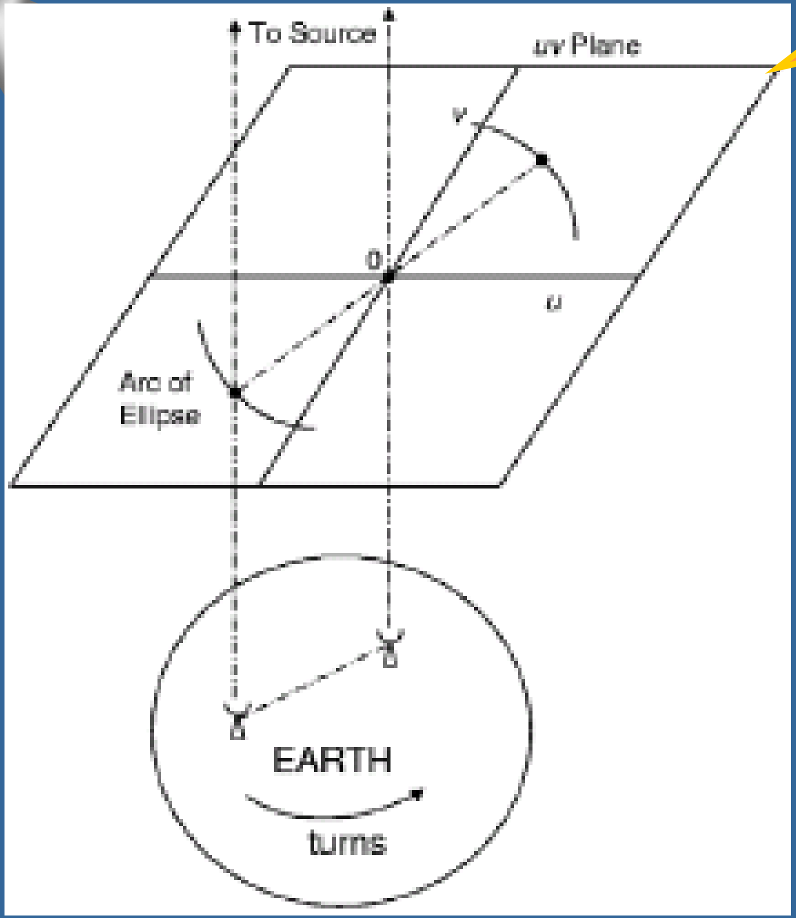
VLA image (100 kpc → 3 arcmin)

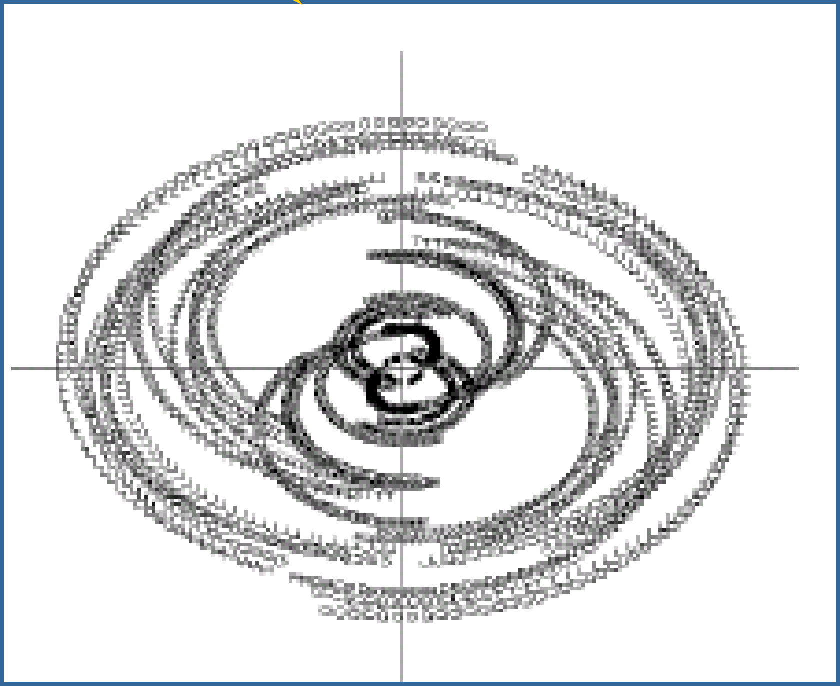
VLBI image (1 pc → 2 milli-arcsec)

Magnification ratio of 1,000,000!

Earth-Rotation Aperture synthesis

'Virtual antenna' aperture

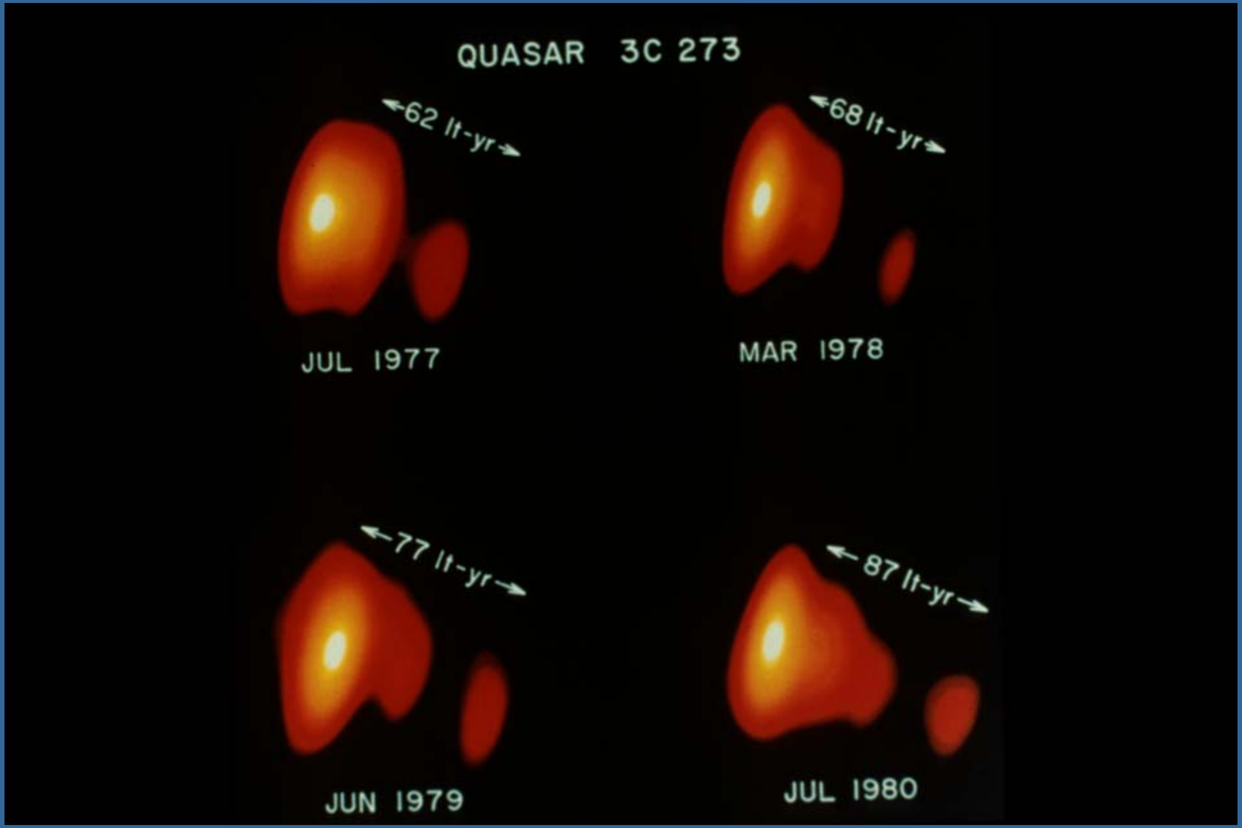




As the Earth turns, each antenna pair creates an ellipse in the aperture of the **Earth-size 'virtual antenna'**; many such ellipses from different antenna pairs help to 'fill' the virtual antenna aperture

“Superluminal motion“ in Quasar 3C273

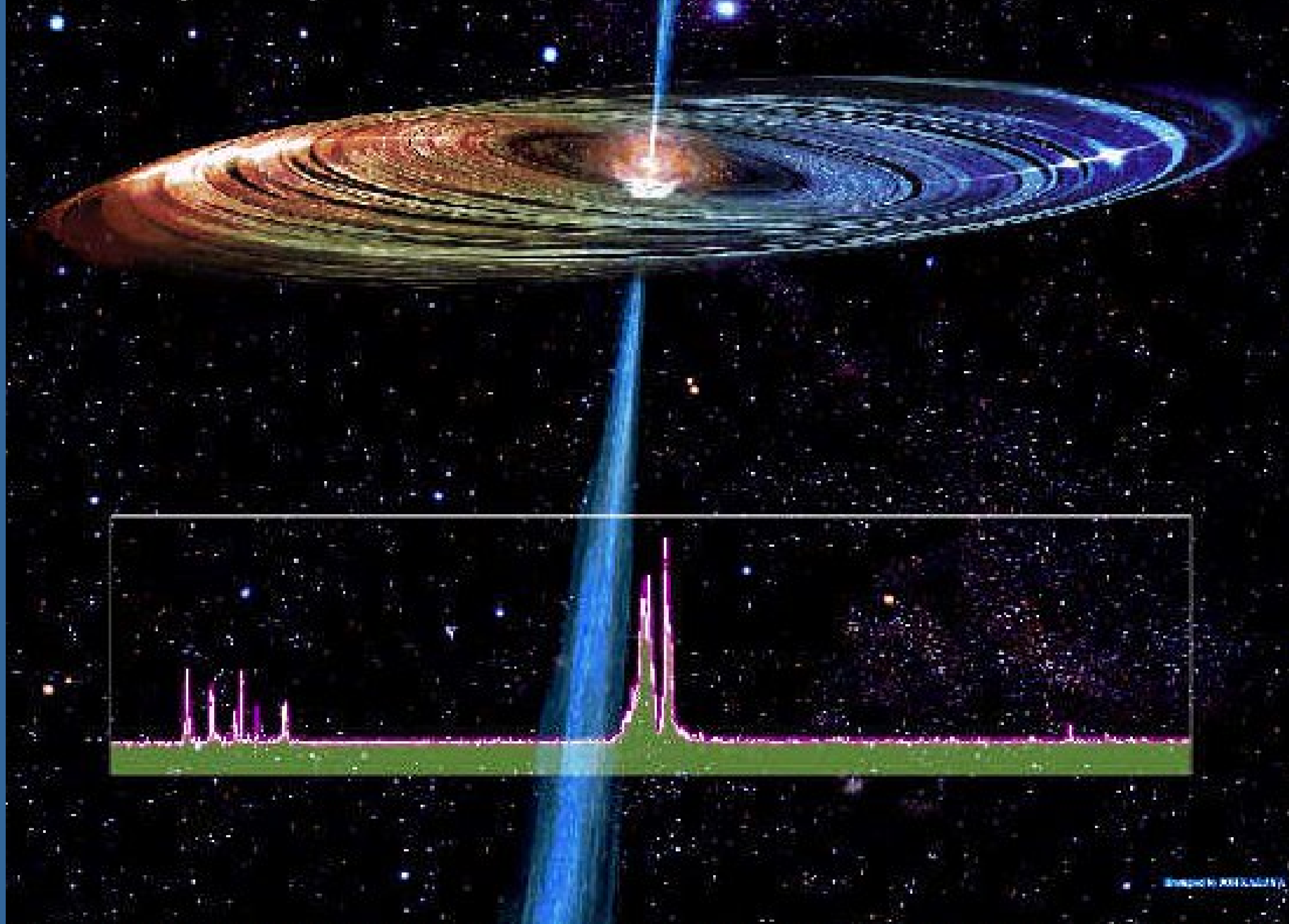
(Distance 2000 Mly = 600 Mpc)



Apparent motion faster than the speed of light!

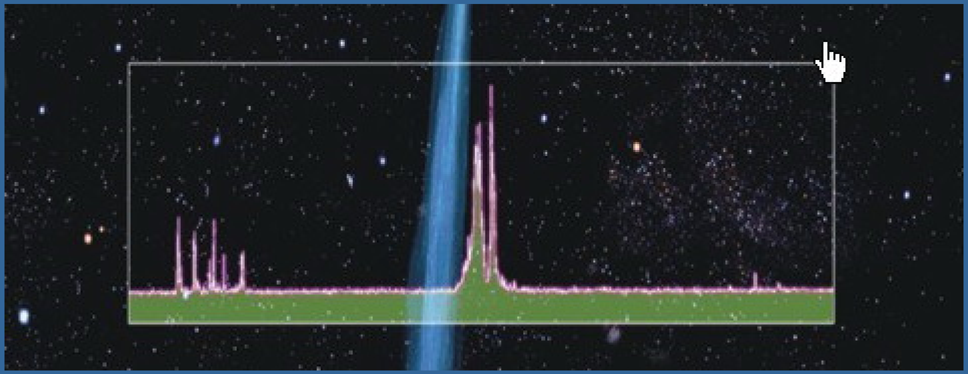
Galaxy NGC4258

- 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

-

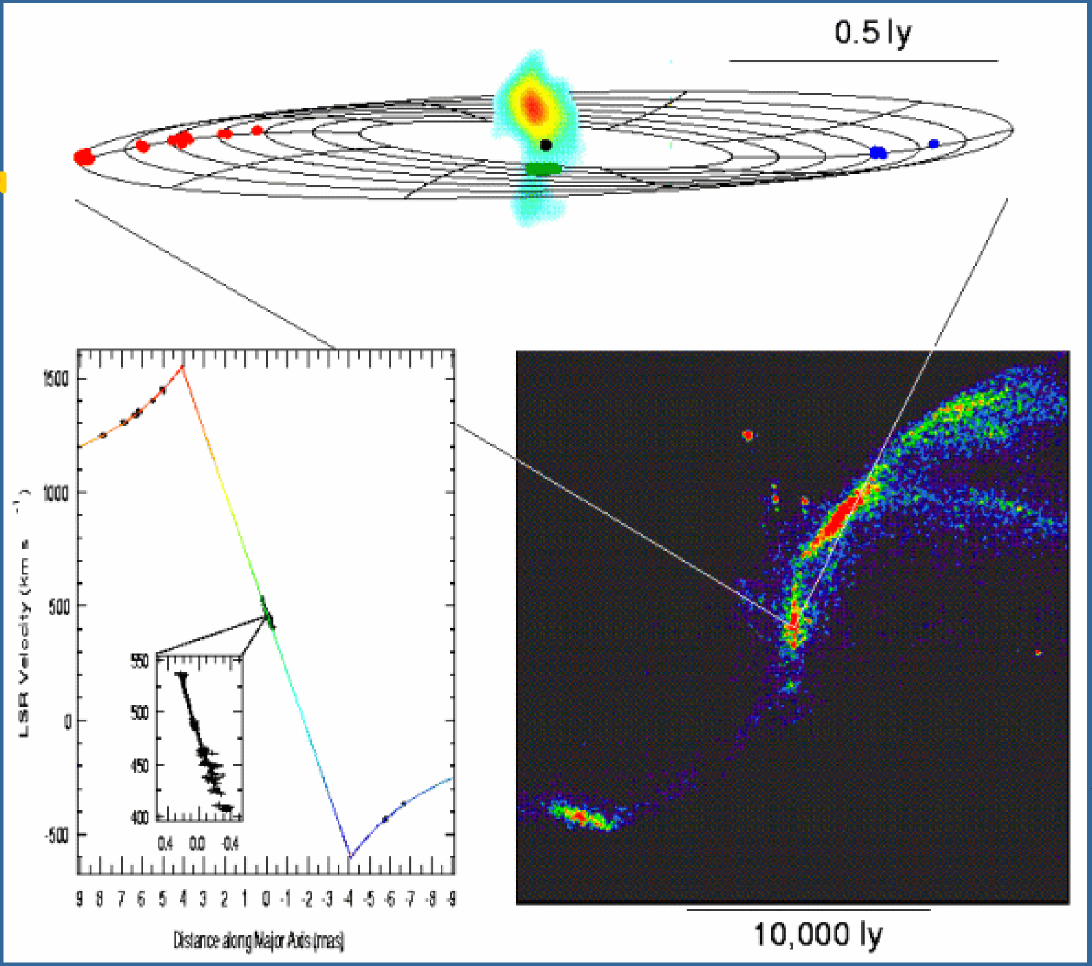


First hint was this spectra showing H2O maser lines:
- Red-shifted lines receding at 1300 km/sec
- Blue-shifted lines receding at -400 km/sec
- Center receding at 500 km/sec

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



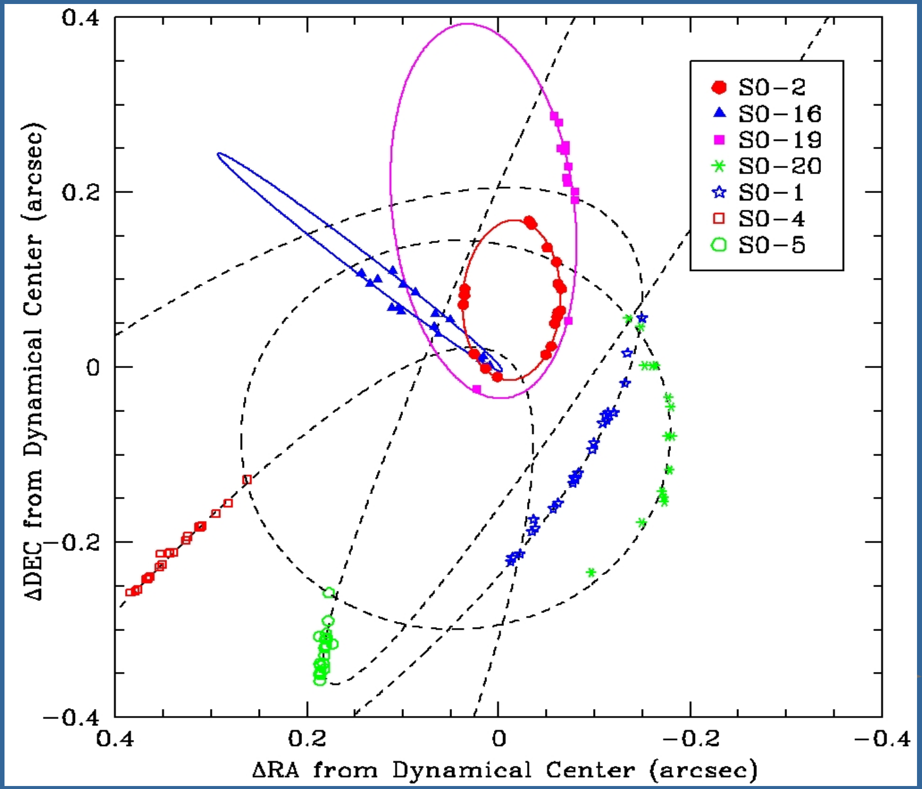
Getting to the Event Horizon: The Galactic Center

- **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

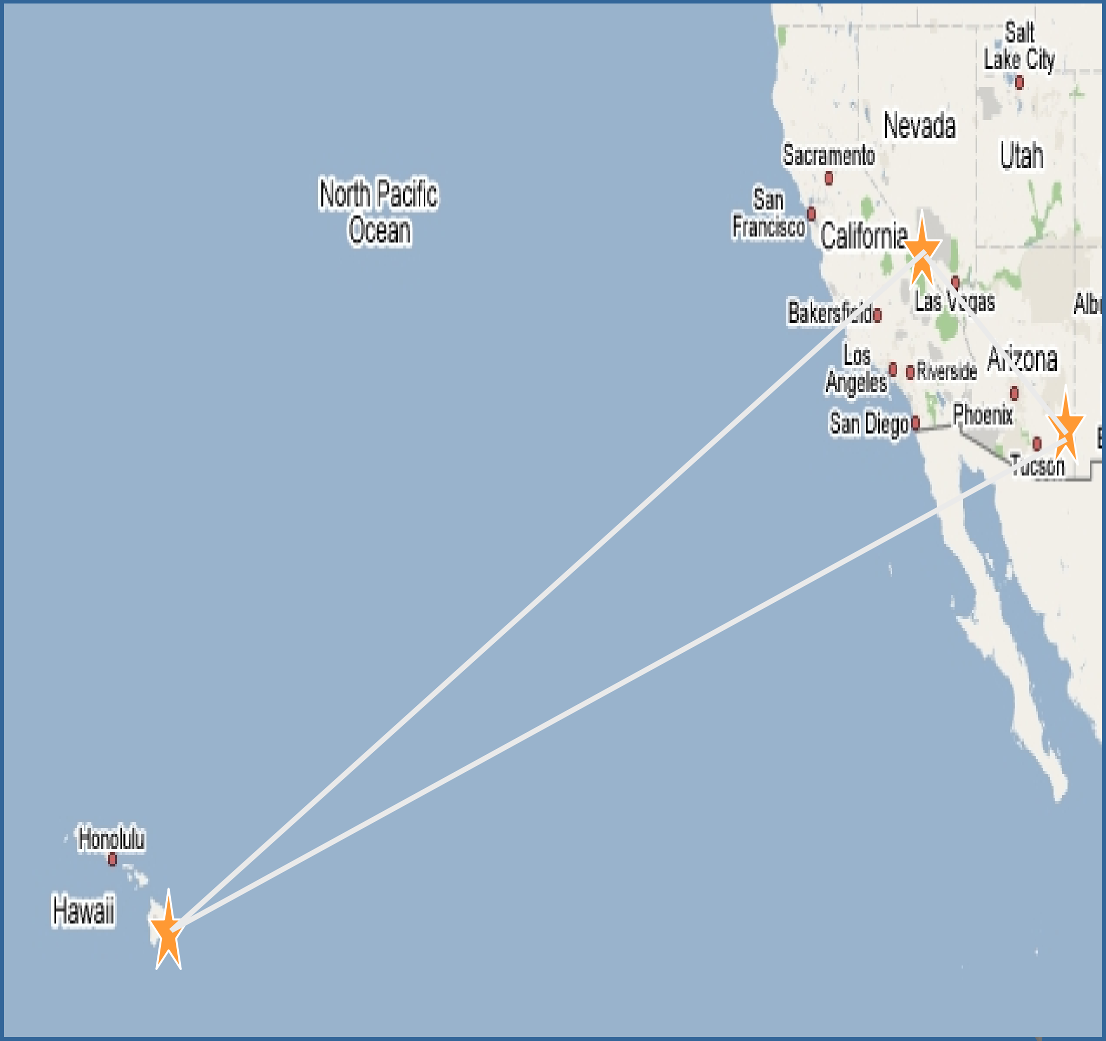
A big prize is understanding the black hole at the center of our galaxy!

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

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

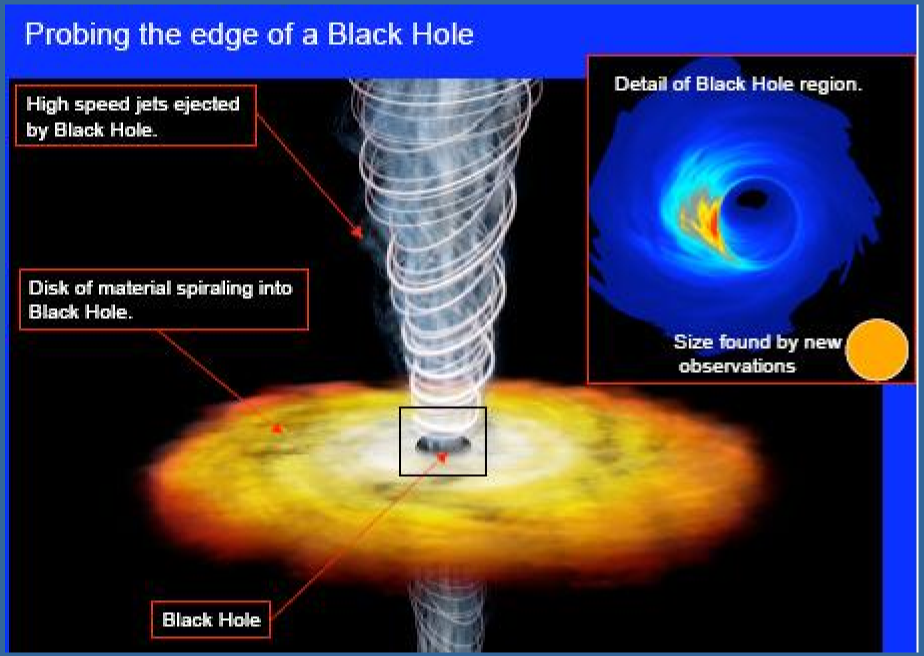
- Resolution on baselines to Hawaii is ~40 microarcsec; highest resolution ever achieved

- 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

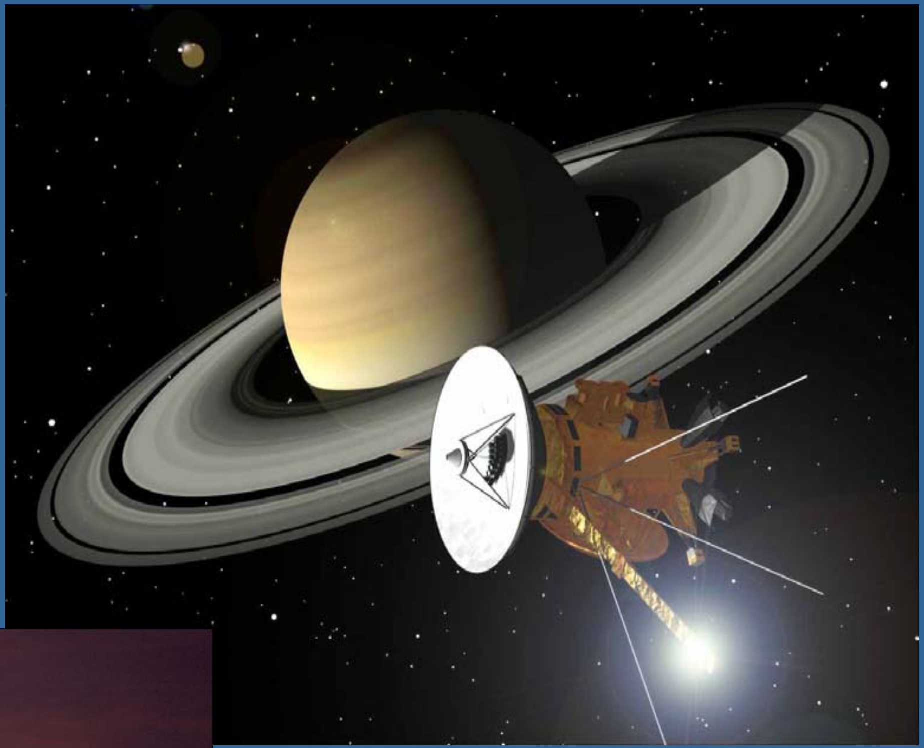


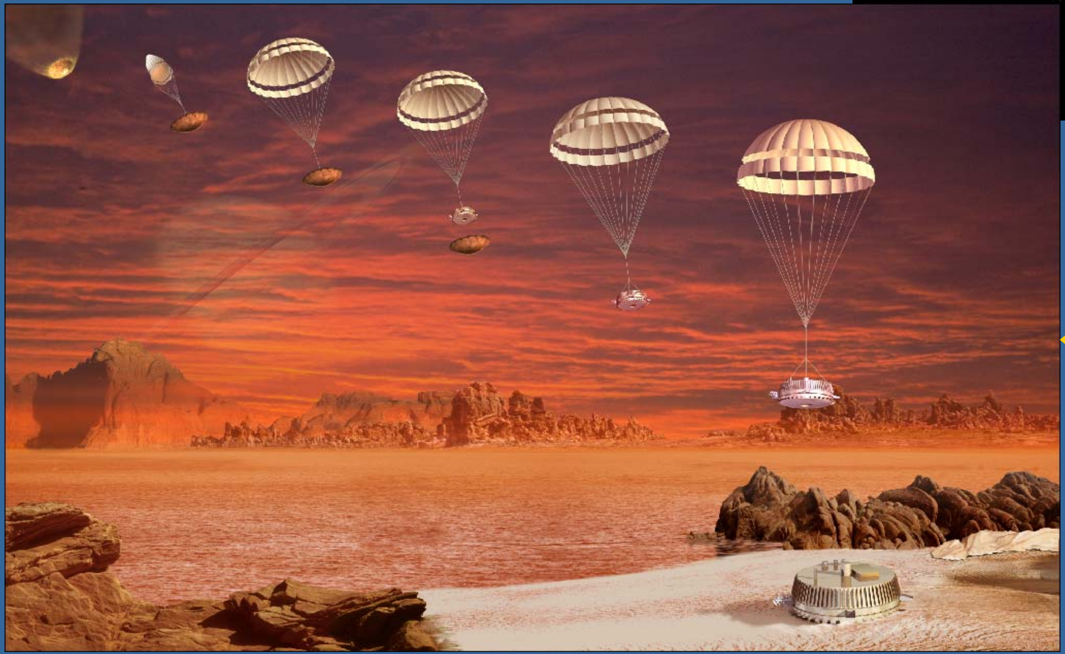
Differential VLBI for Deep Space Tracking

- 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

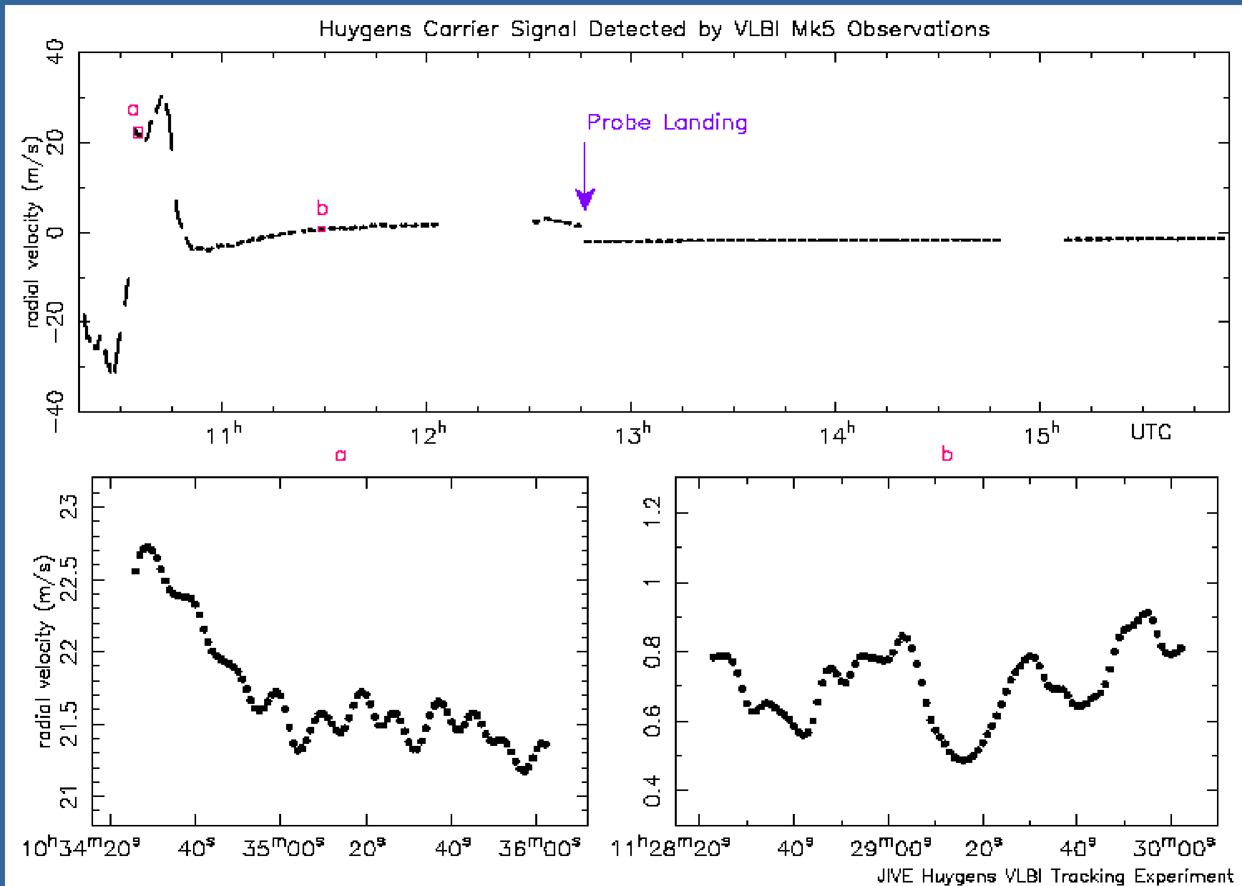
(14 January 2005)





⇐ 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