# Creating a Global Radio Telescope the Diameter of the Earth

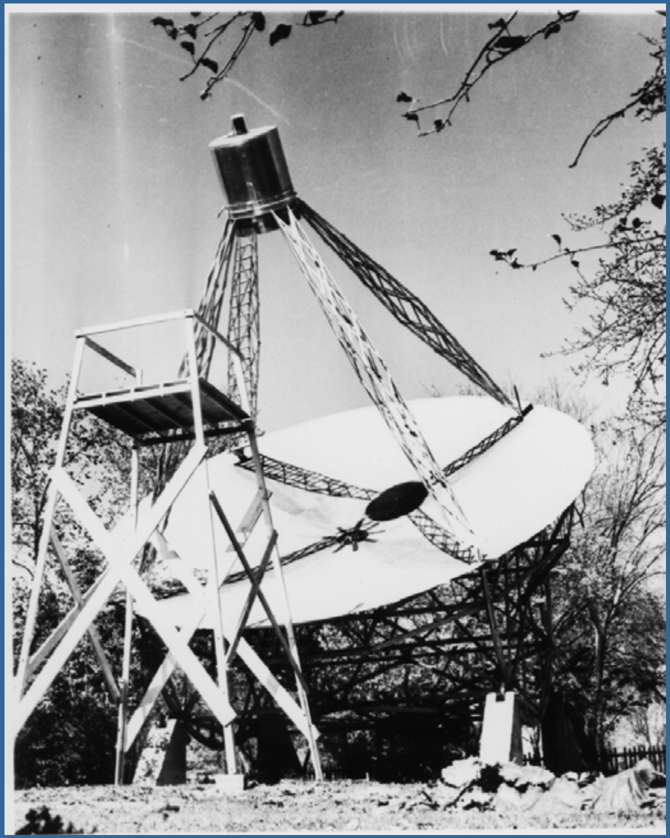
Alan R. Whitney
MIT Haystack Observatory

**Australian Institute of Physics**
**University of Tasmania**
**Hobart, Tasmania**
**11 Feb 2010**

# Karl Jansky’s radio antenna - 1931

(Replica at Green Bank, WV)

# 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)

# Mt. Pleasant Observatory

12m diameter (9 Feb 2010)

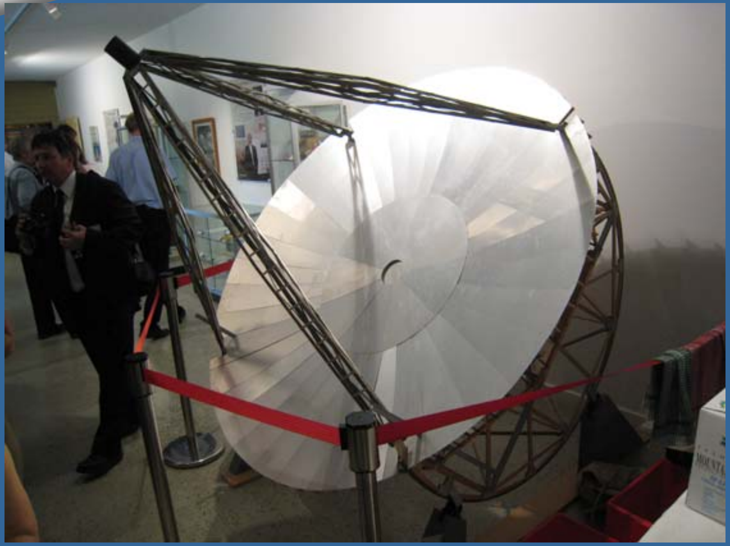
The AuScope VLBI Array
Hobart 12m Antenna
Opened by
His Excellency The Honourable
Peter Underwood AC
Governor of Tasmania
9 February 2010

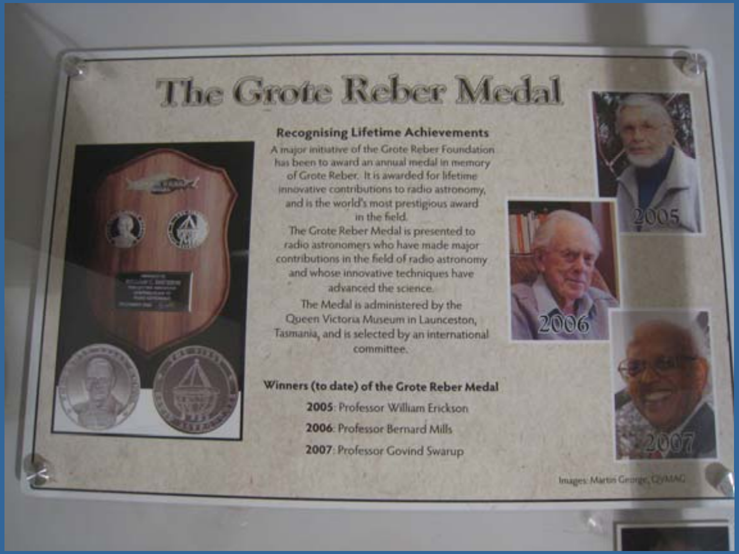
UTAS

AuScope

AuScope is supported by the Australian Government
through the National Collaborative Research Infrastucture Strategy

# Grote Reber Museum at Mt. Pleasant Observatory





The Grote Reber Medal

**Recognising Lifetime Achievements**

A major initiative of the Grote Reber Foundation has been to award an annual medal in memory of Grote Reber. It is awarded for lifetime innovative contributions to radio astronomy, and is the world's most prestigious award in the field.

The Grote Reber Medal is presented to radio astronomers who have made major contributions in the field of radio astronomy and whose innovative techniques have advanced the science.

The Medal is administered by the Queen Victoria Museum in Launceston, Tasmania, and is selected by an international committee.

**Winners (to date) of the Grote Reber Medal**

**2005**: Professor William Erickson

**2006**: Professor Bernard Mills

**2007**: Professor Govind Swarup

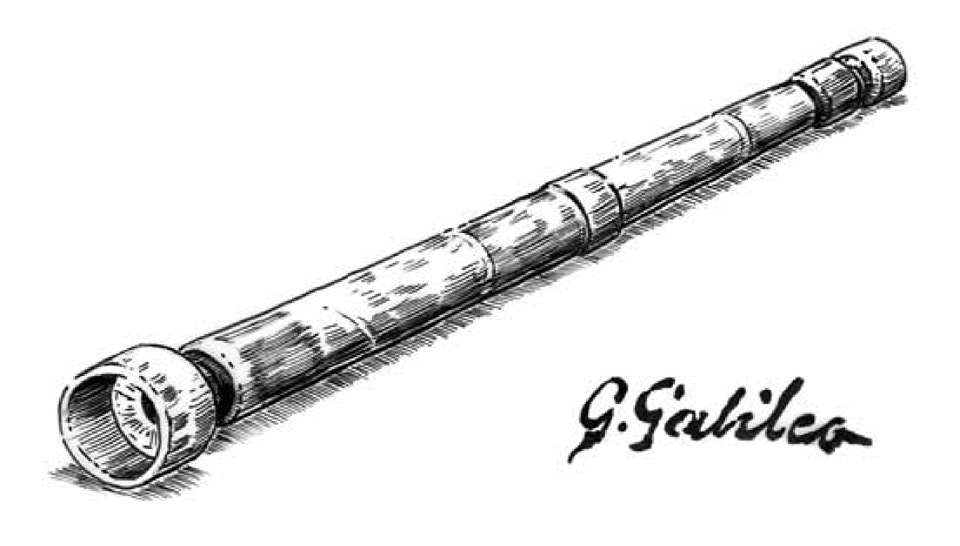
Images: Martin George, QVMAG

2005 Prof. William Erickson
2006 Prof. Bernard Mills
2007 Prof. Govind Swarup
2008 Dr. Sander Weinreb

# 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*

$$\frac{\lambda}{D} \quad \textbf{(radians)}$$

where

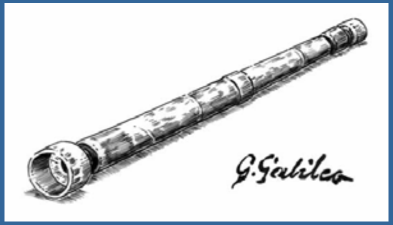
$\lambda$ = wavelength

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)

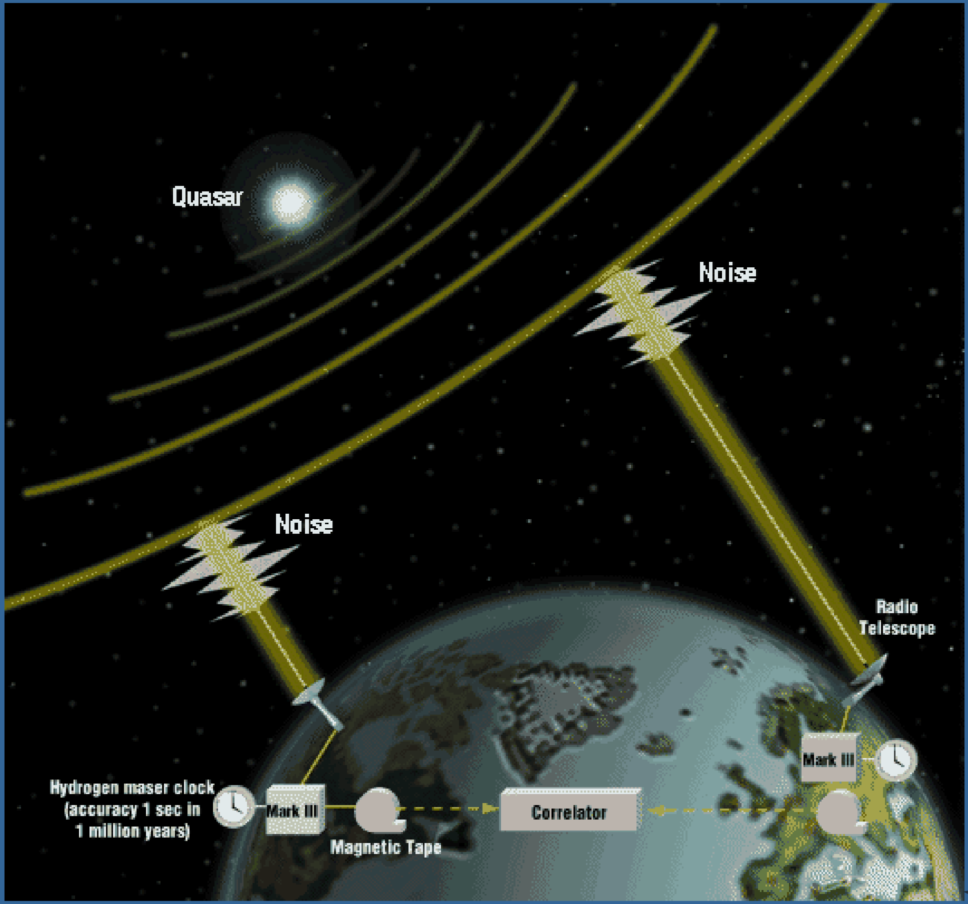
10,000 km telescope at λ=1cm→ $\frac{\lambda}{D}$ ~200 micro-arcsec
(~40 cm on moon;
~5 mm at 5000 km)

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 radio telescope 10,000 km in diameter?

- Very Long Baseline Interferometry (VLBI)
- How (in a nutshell)?
    - Place telescopes in many places over the Earth
    - Provide each with an atomic clock
    - Observe the same radio source, at the same time, at the same radio frequency, with the same polarization
    - Send data to a central processing facility (traditionally recorded and shipped)
    - Synthesize an Earth-sized telescope in a computer

# Very Long Baseline Interferometry (VLBI)



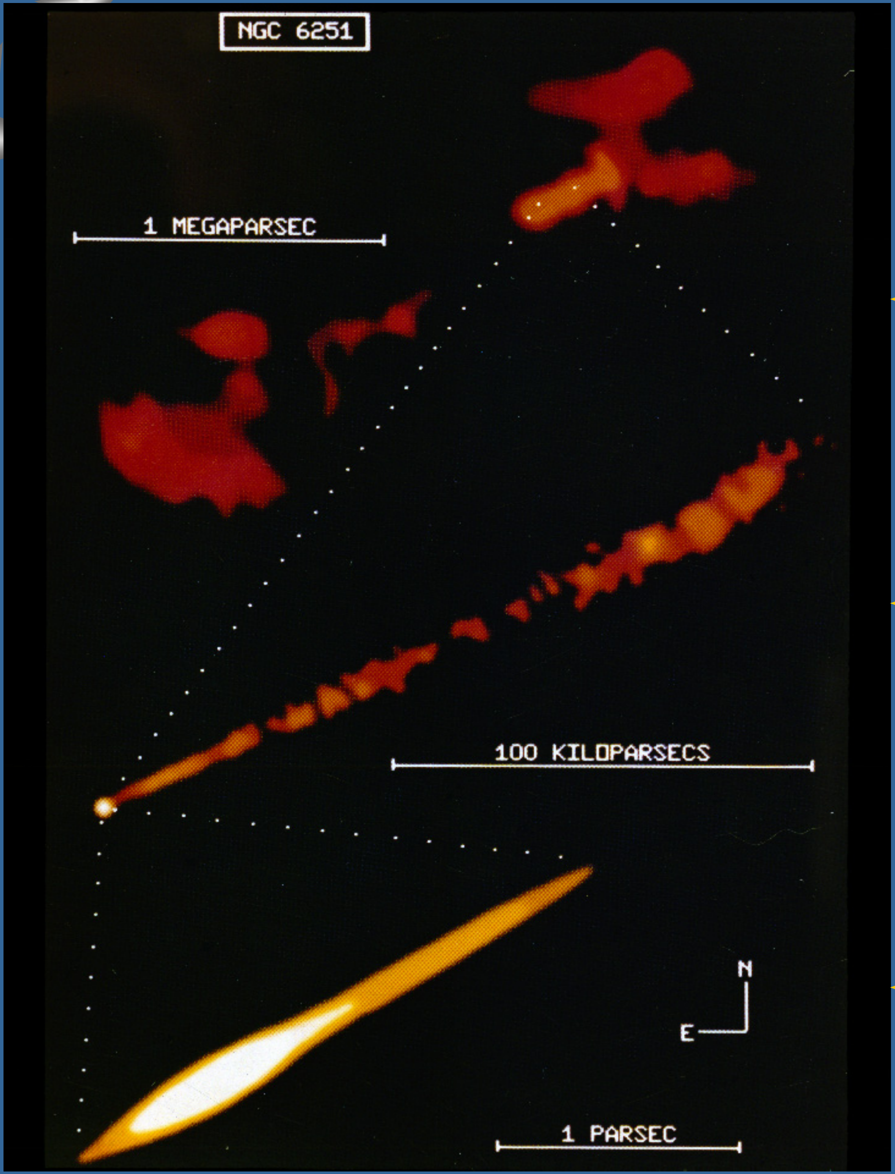
# Some of the world’s VLBI antennas

# VLBI for Astronomy

- Highest-resolution technique available to astronomers (or anyone else!) – tens of microarcseconds
- 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)

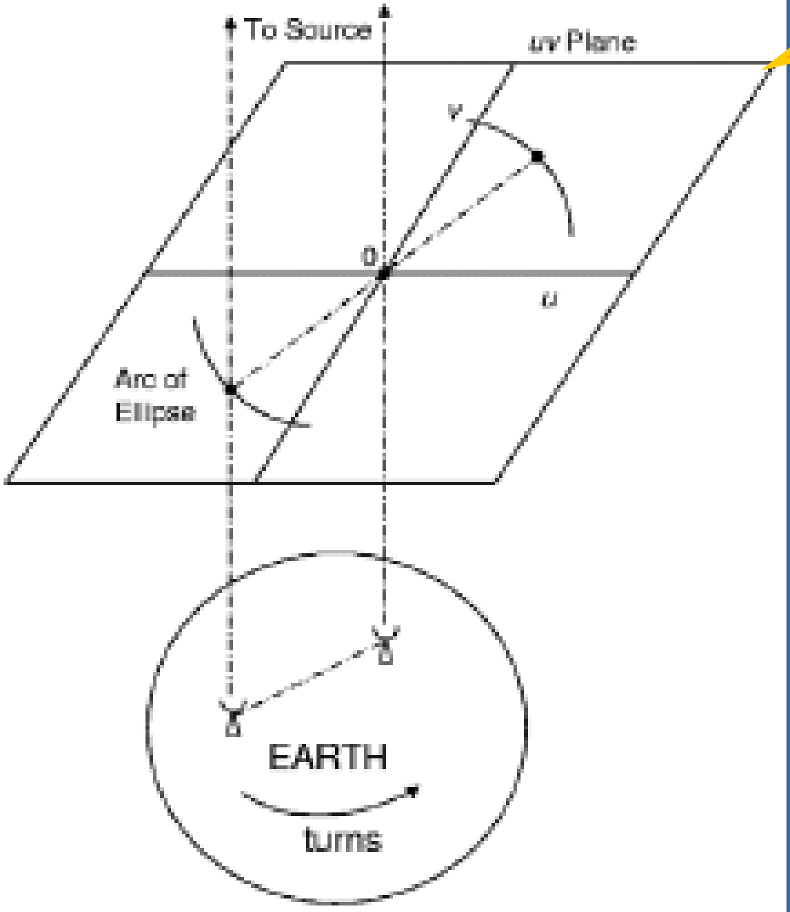
VLA image
(100 kpc → 3 arcmin)

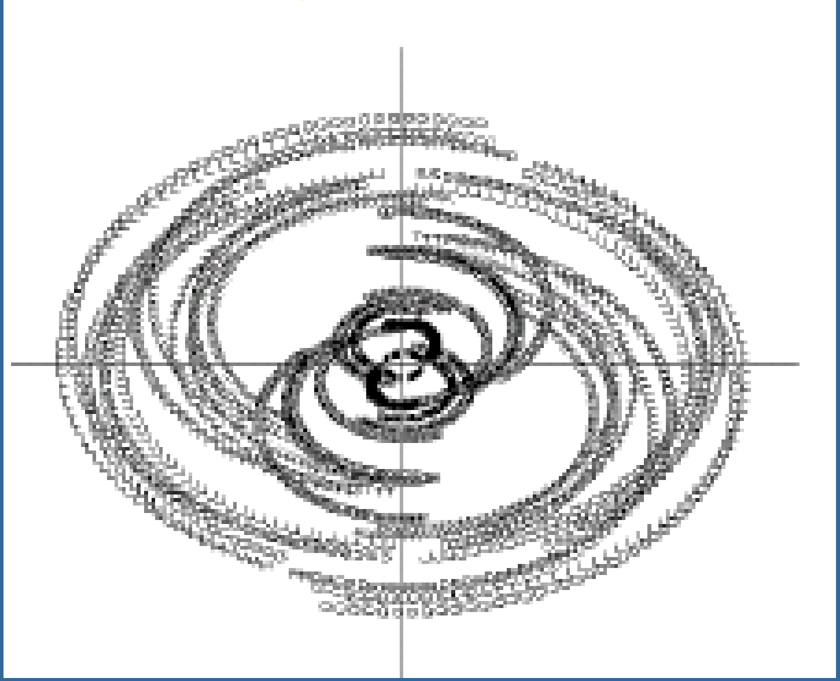
VLBI image
(1 pc → 2 milli-arcsec)

**Magnification ratio of 1,000,000!**

# Earth-Rotation Aperture synthesis

‘Virtual antenna’ aperture

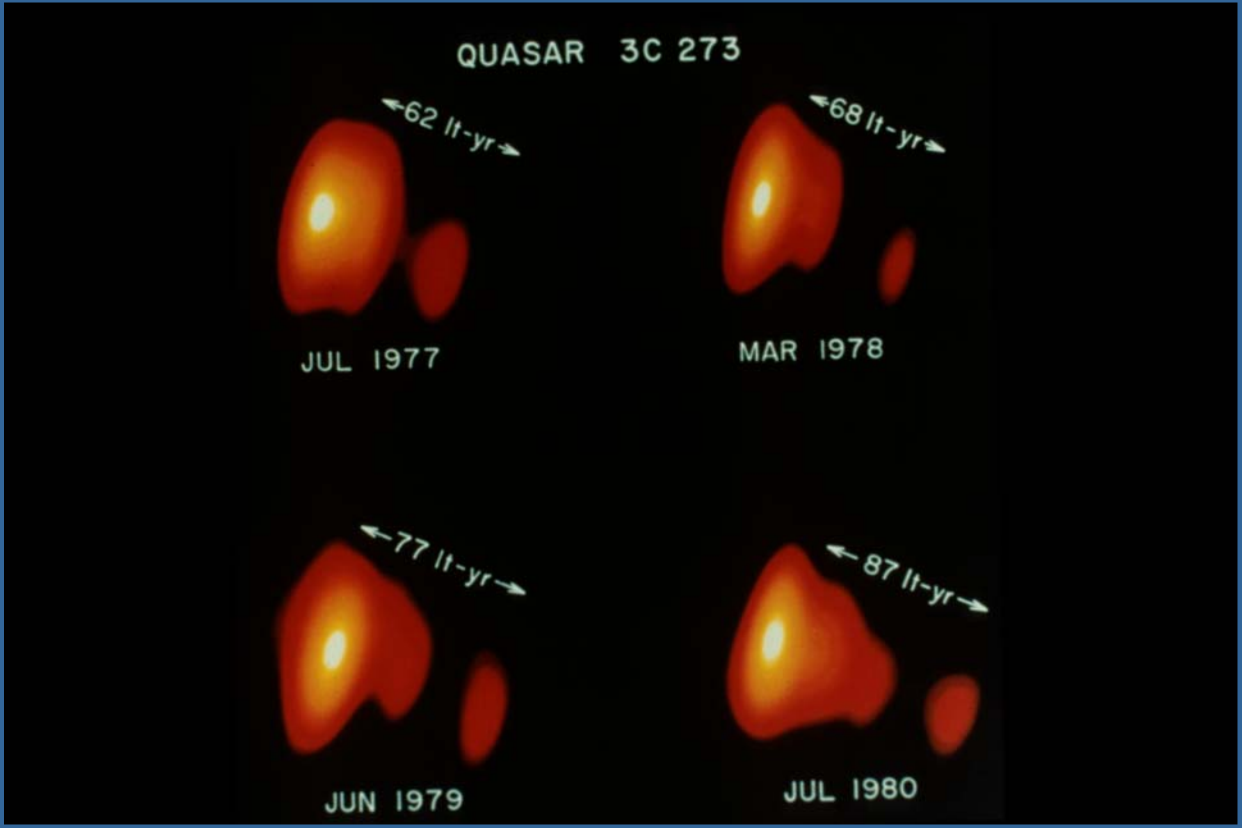




As the Earth turns, each antenna pair creates an ellipse in the aperture of the **Earth-size ‘virtual antenna’**; many such ellipses from different antenna pairs help to ‘fill’ the virtual antenna aperture

# “Superluminal motion“ in Quasar 3C273

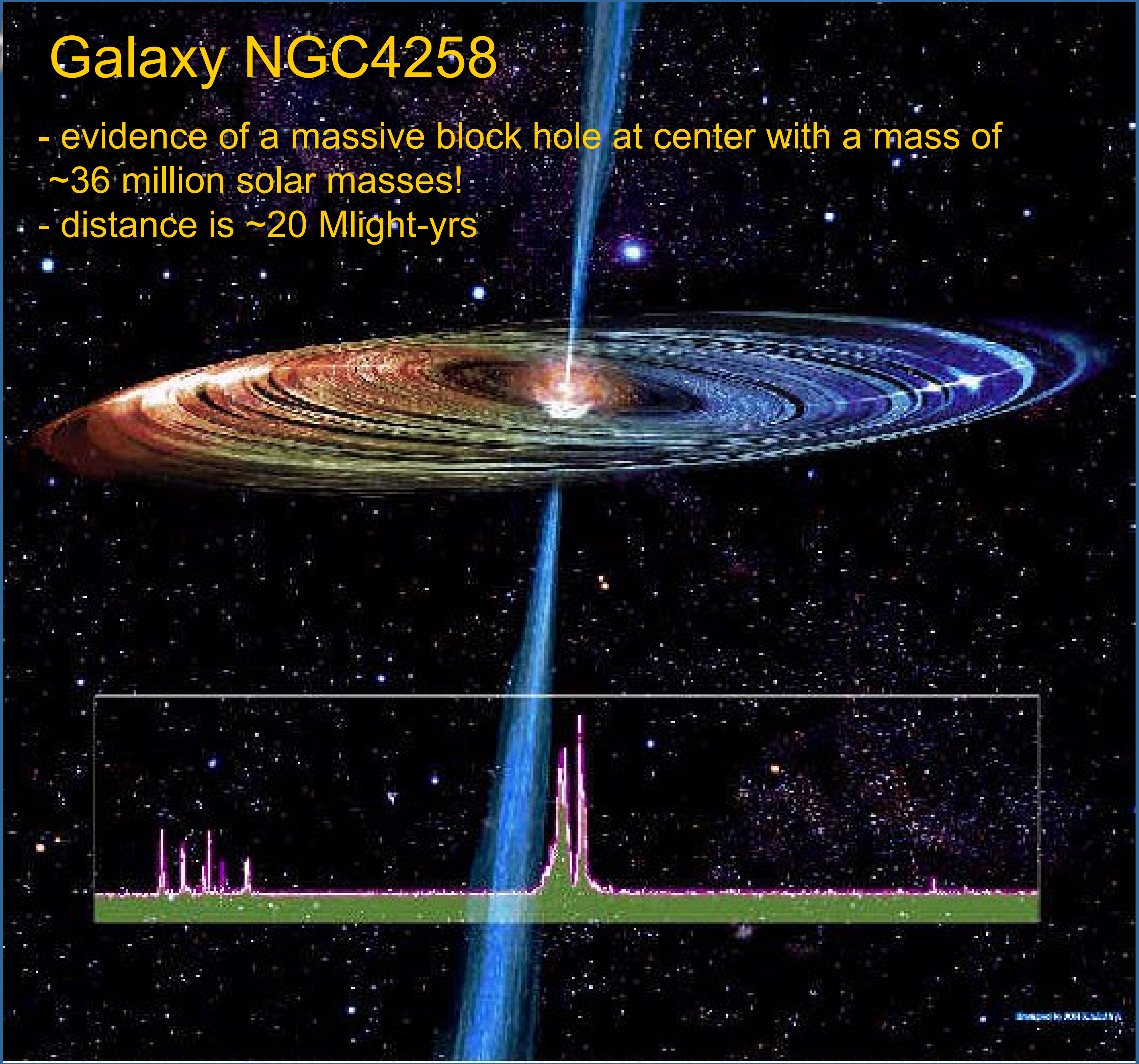
(Distance  2000 Mly = 600 Mpc)



**Apparent motion faster than the speed of light!**

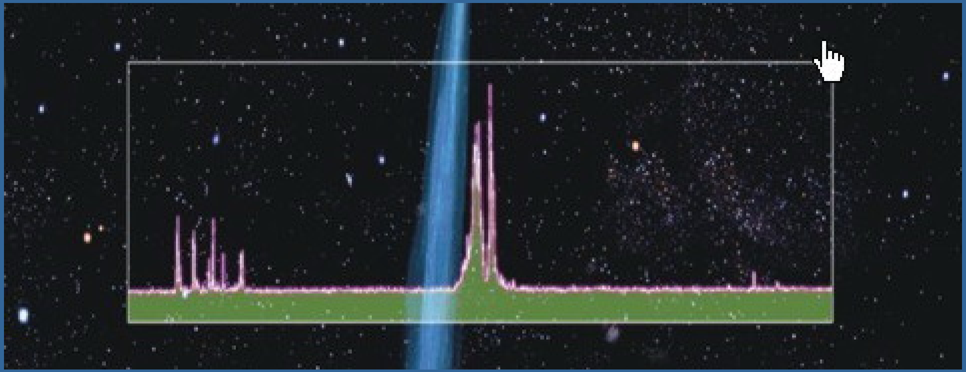
# Galaxy NGC4258

- 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

-



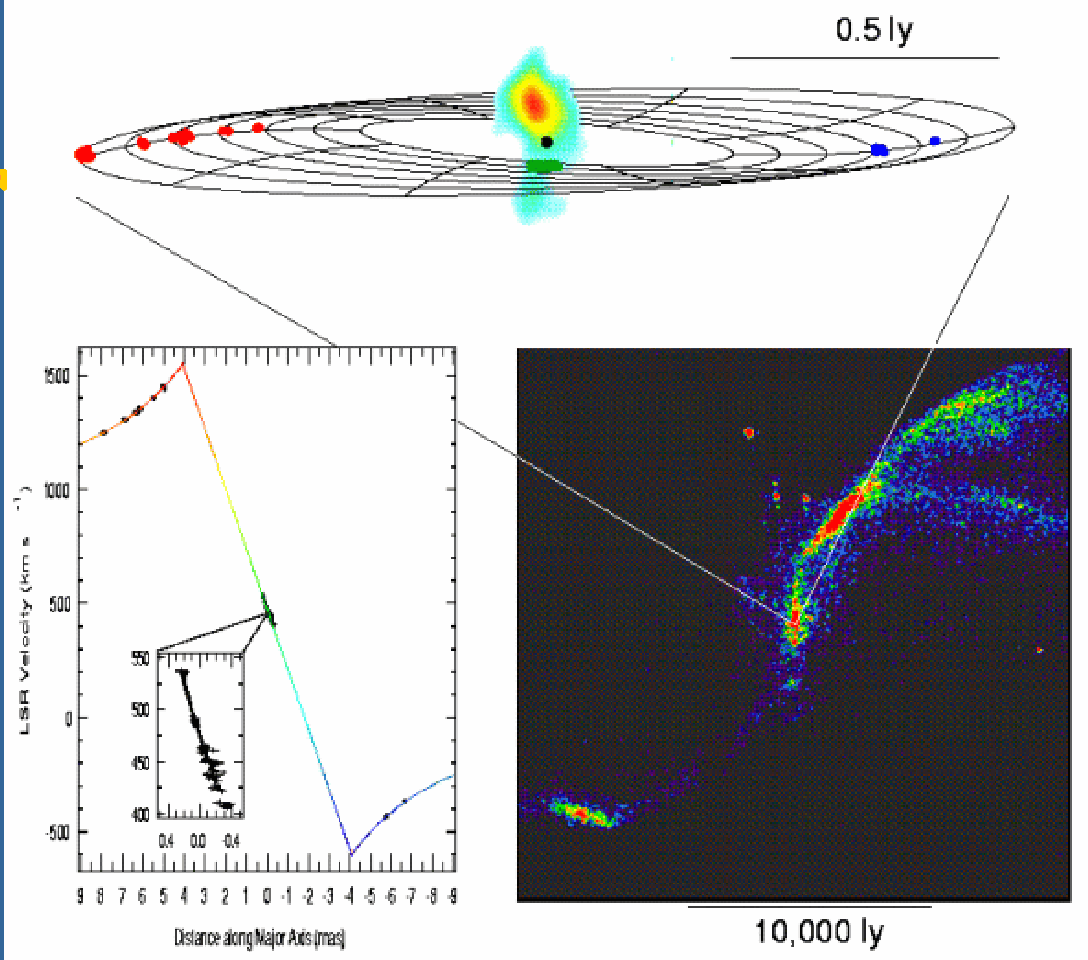
First hint was this spectra showing H2O maser lines:

- 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



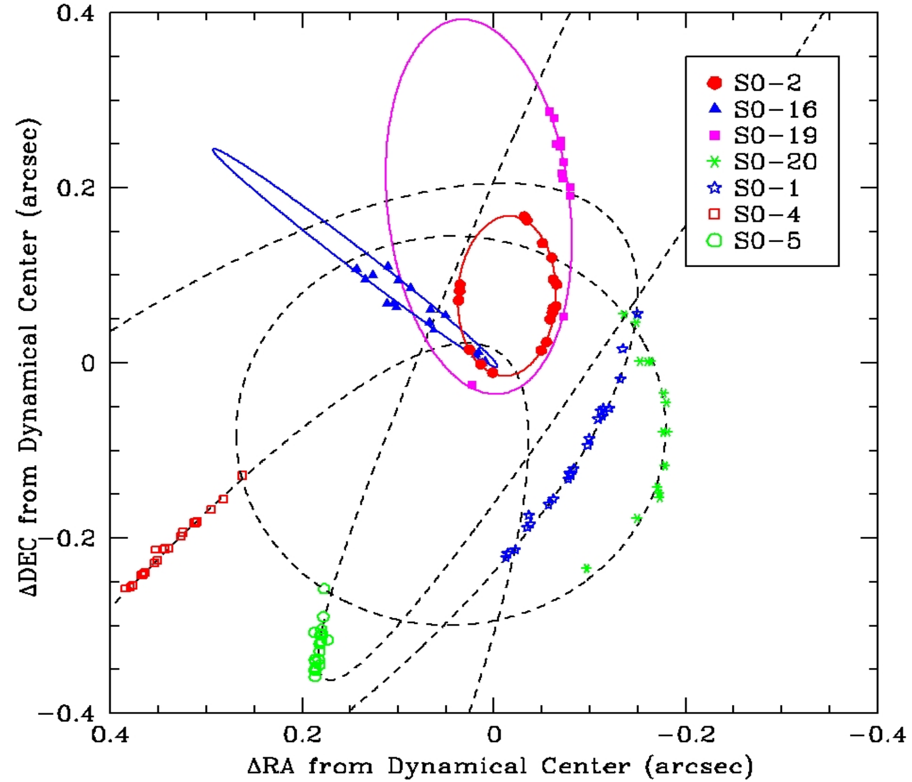
# Getting to the Event Horizon: The Galactic Center

- **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.

- 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

Ghez et al 2005



# 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

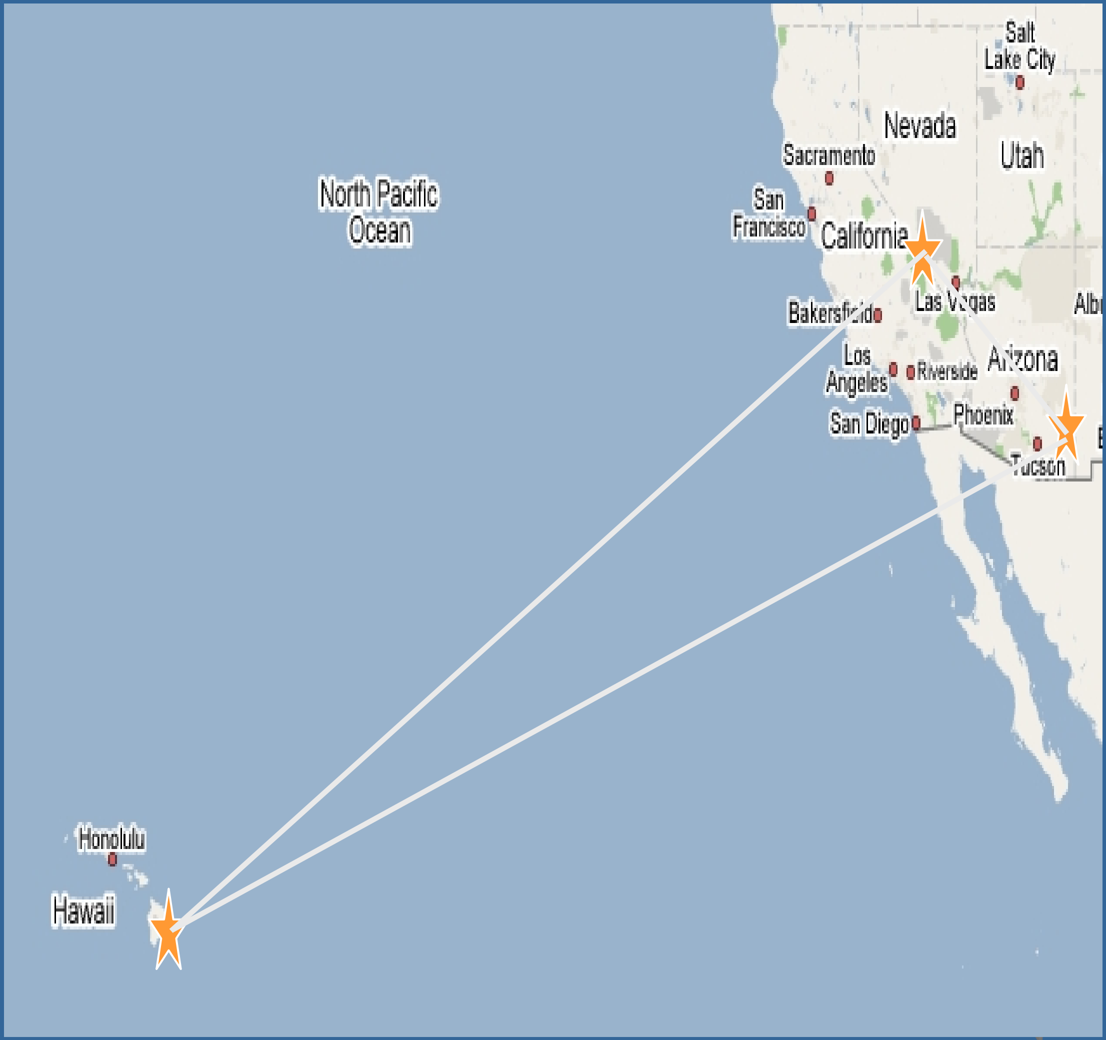
A big prize is understanding the black hole
at the center of our galaxy!

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

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

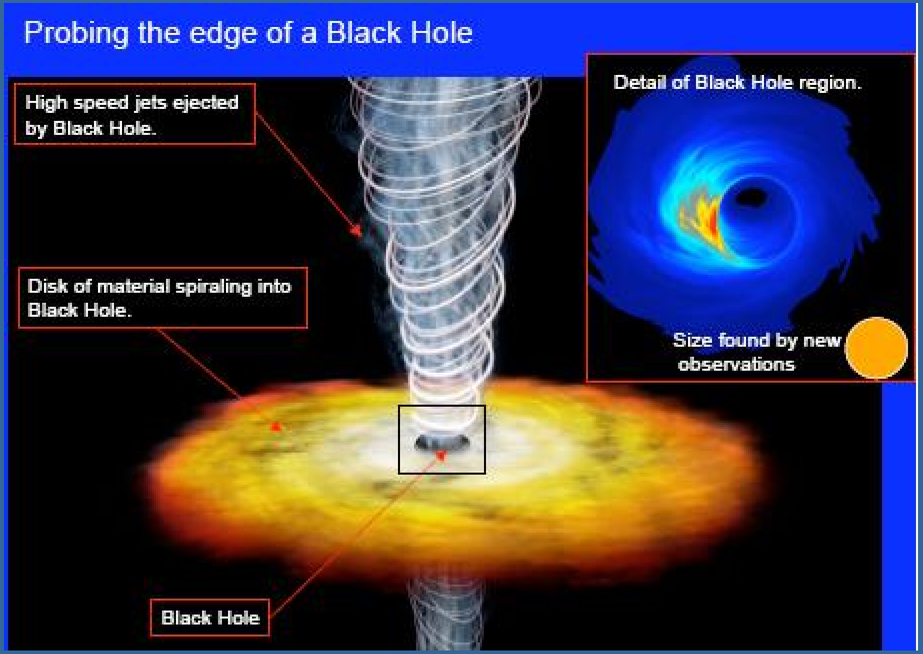
- Resolution on baselines to Hawaii is ~40 microarcsec; highest resolution ever achieved

- 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

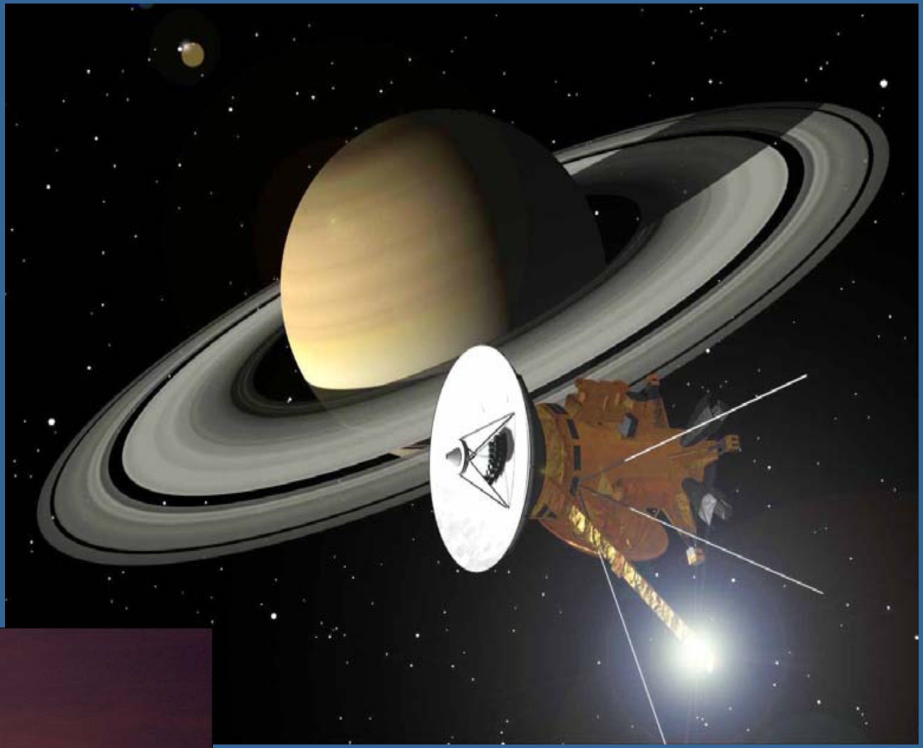


# Differential VLBI for Deep Space Tracking

- 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

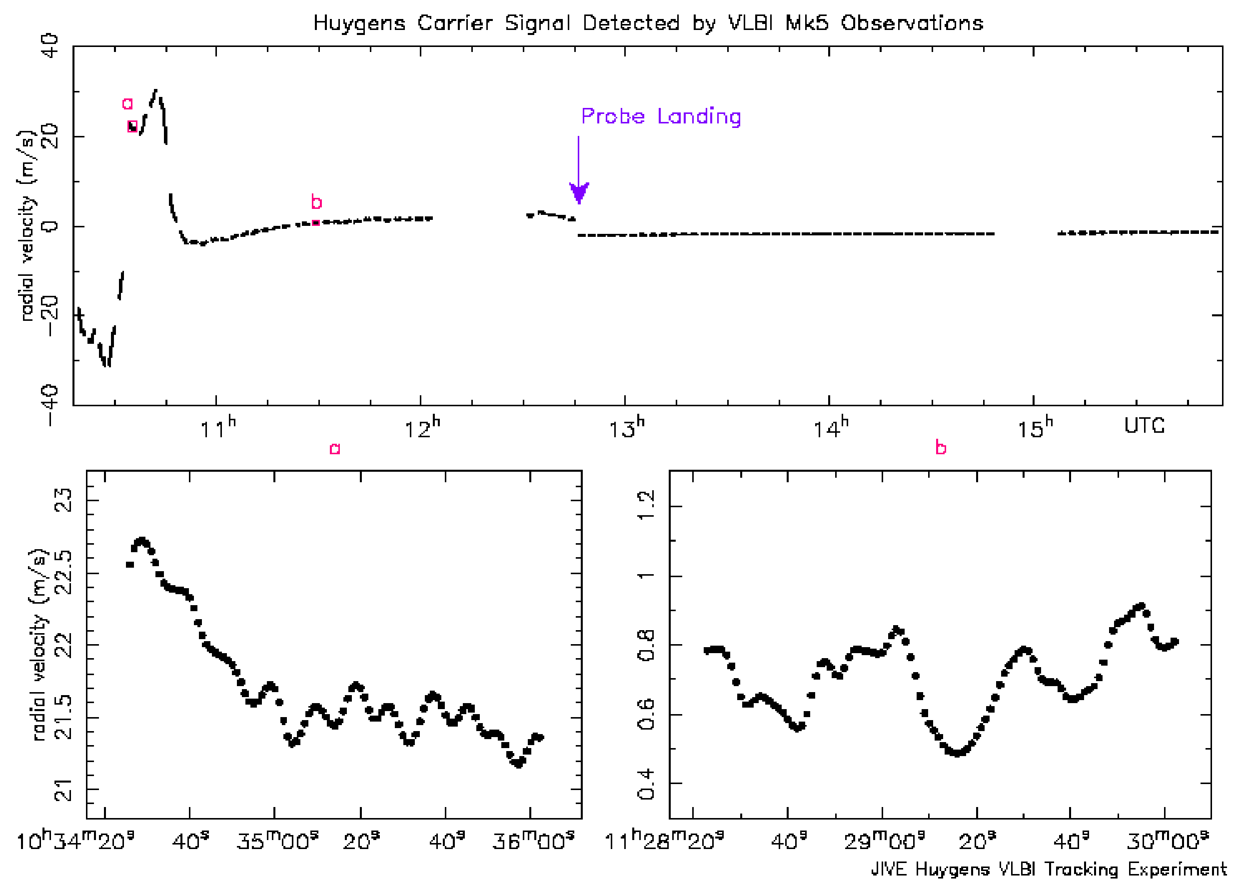
# Cassini-Huygens probe to Saturn

## (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

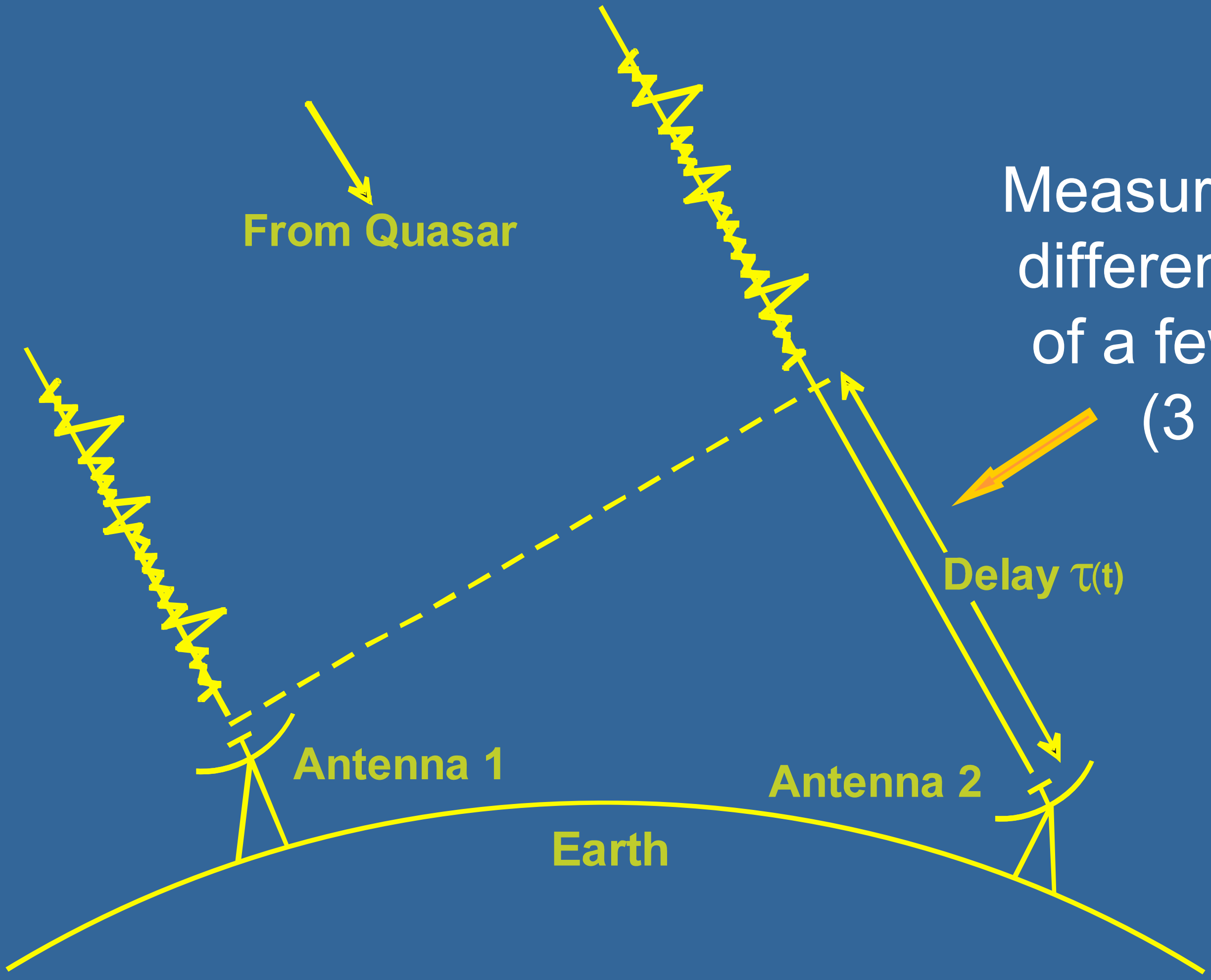
**Proposal**: Float a long-lived balloon in the atmosphere of Titan, the largest moon of Saturn

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

# VLBI for Geodesy

- Highest precision (few mm) 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

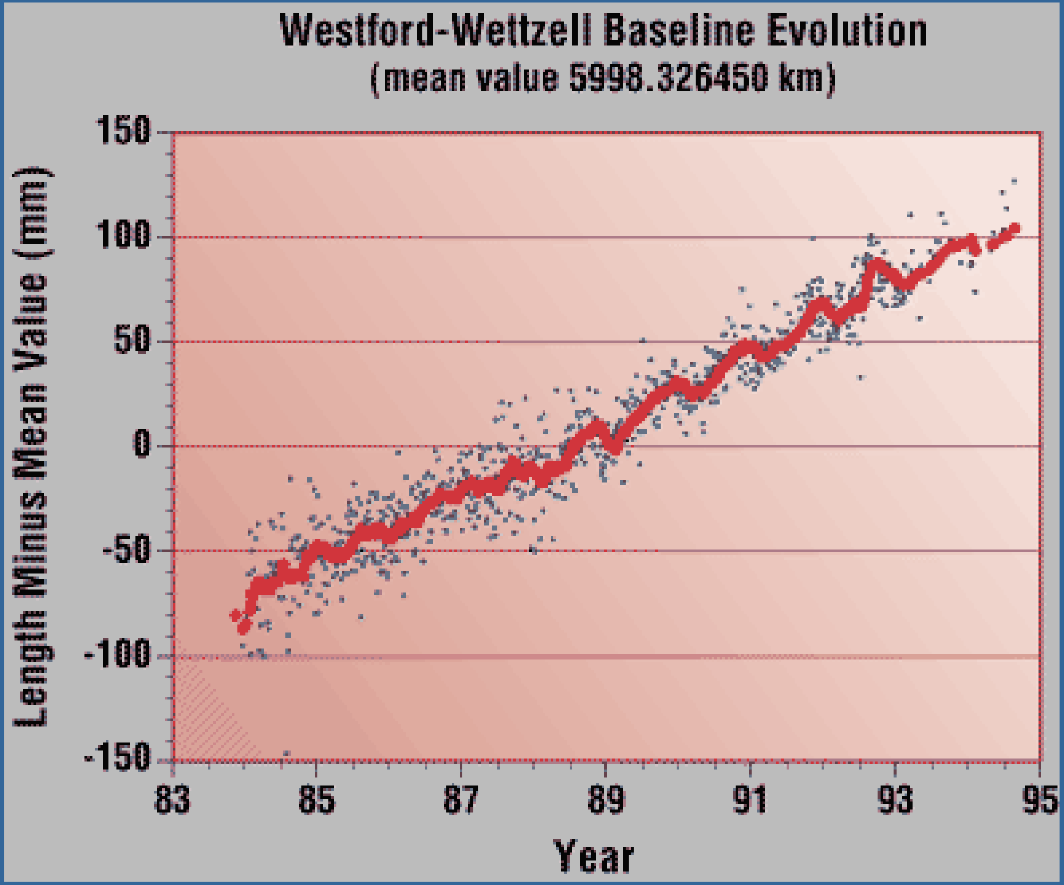


Measure time-of-arrival difference to accuracy of a few picoseconds (3 ps =1 mm)

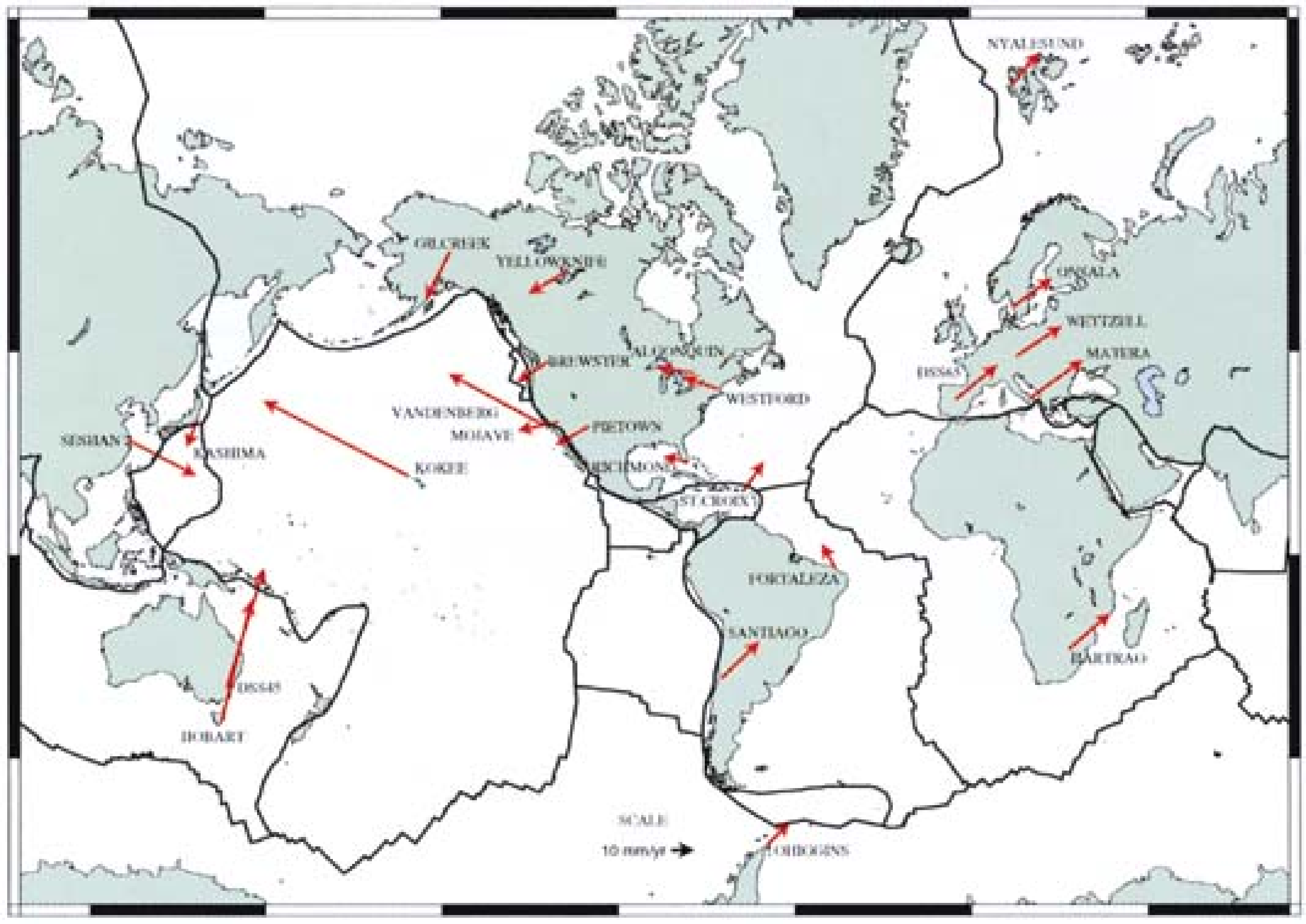
# Continental Drift from VLBI

**Motions of the Earth's crust:**

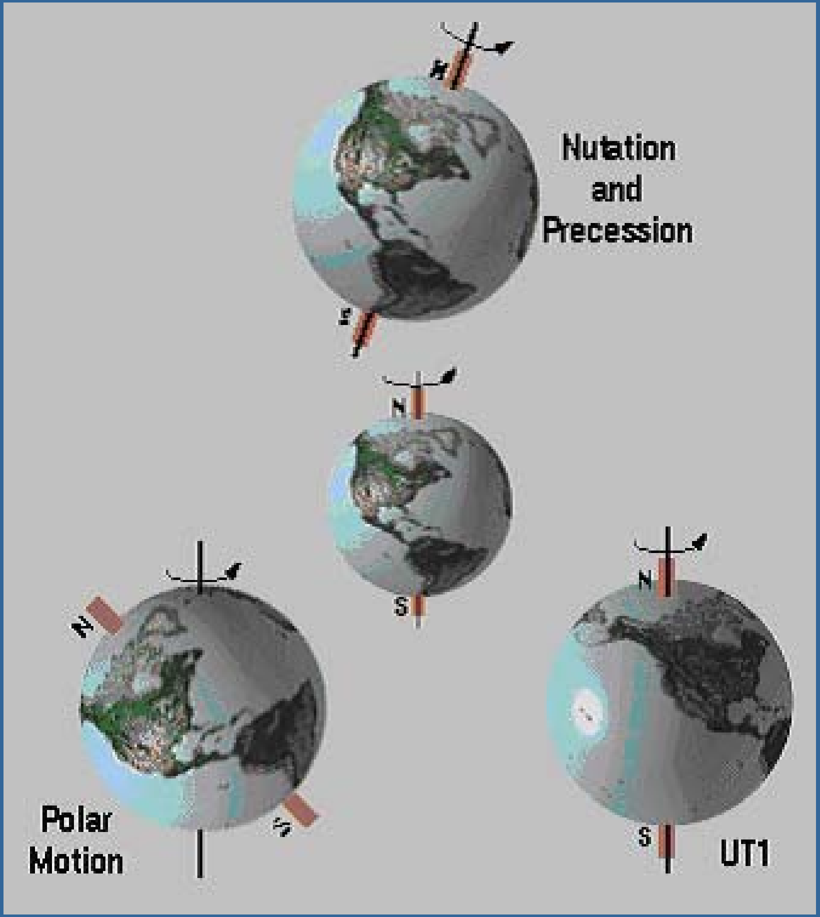
- Displacements due to earthquakes
- Plate tectonic motions



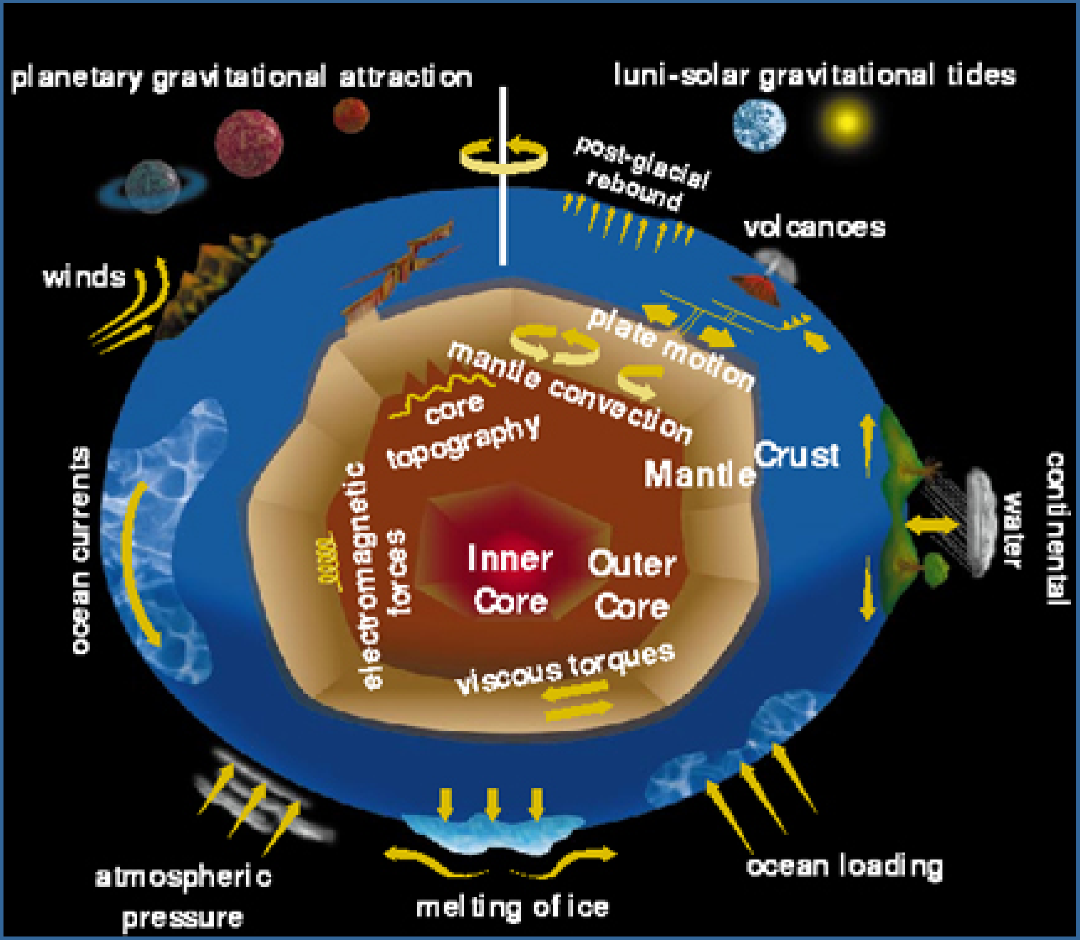
# Direct VLBI Measurement of Tectonic Plate Motion



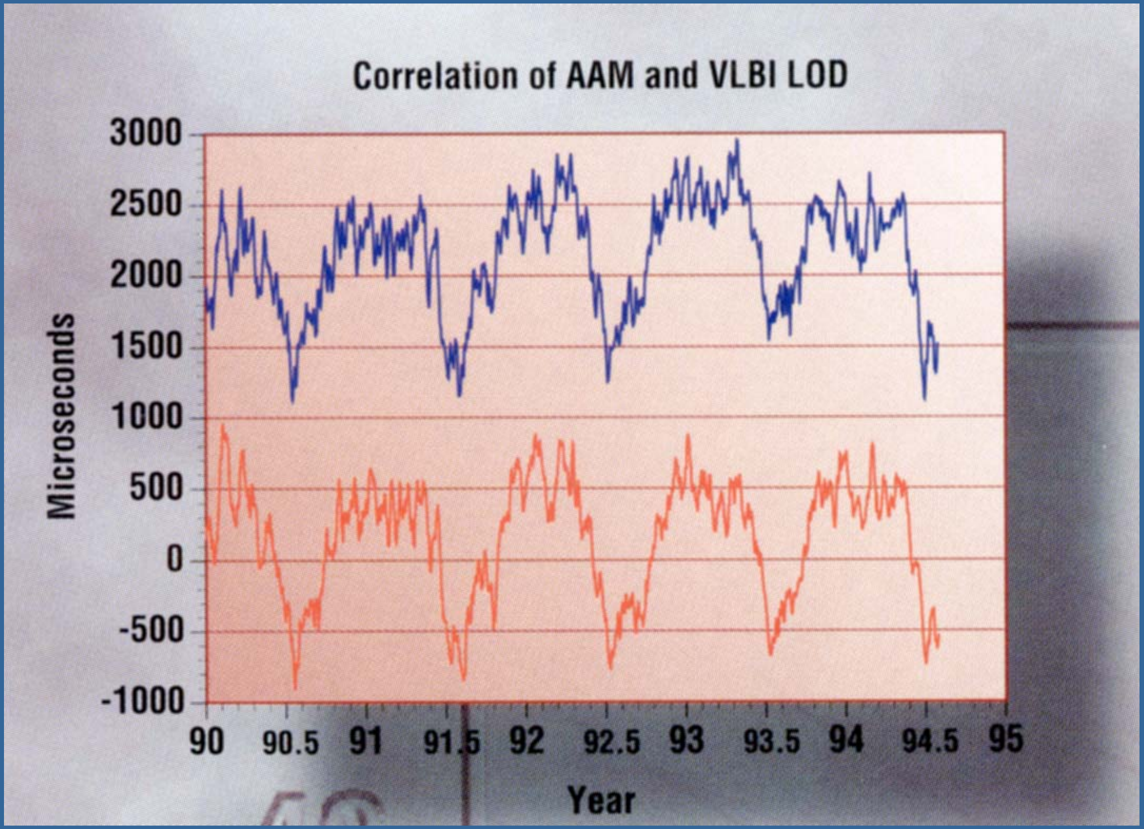
# The wiggles and wobbles of the Earth



# The breathing, living Earth

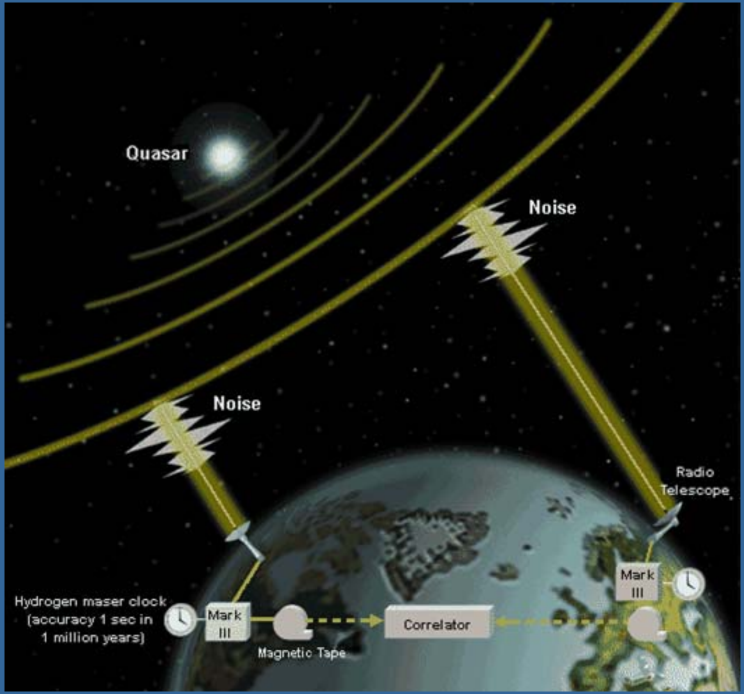


# Atmospheric Angular Momentum & Length of Day



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

# Complications!



The Earth and the universe are messy places:

- atmosphere
- ionosphere
- 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

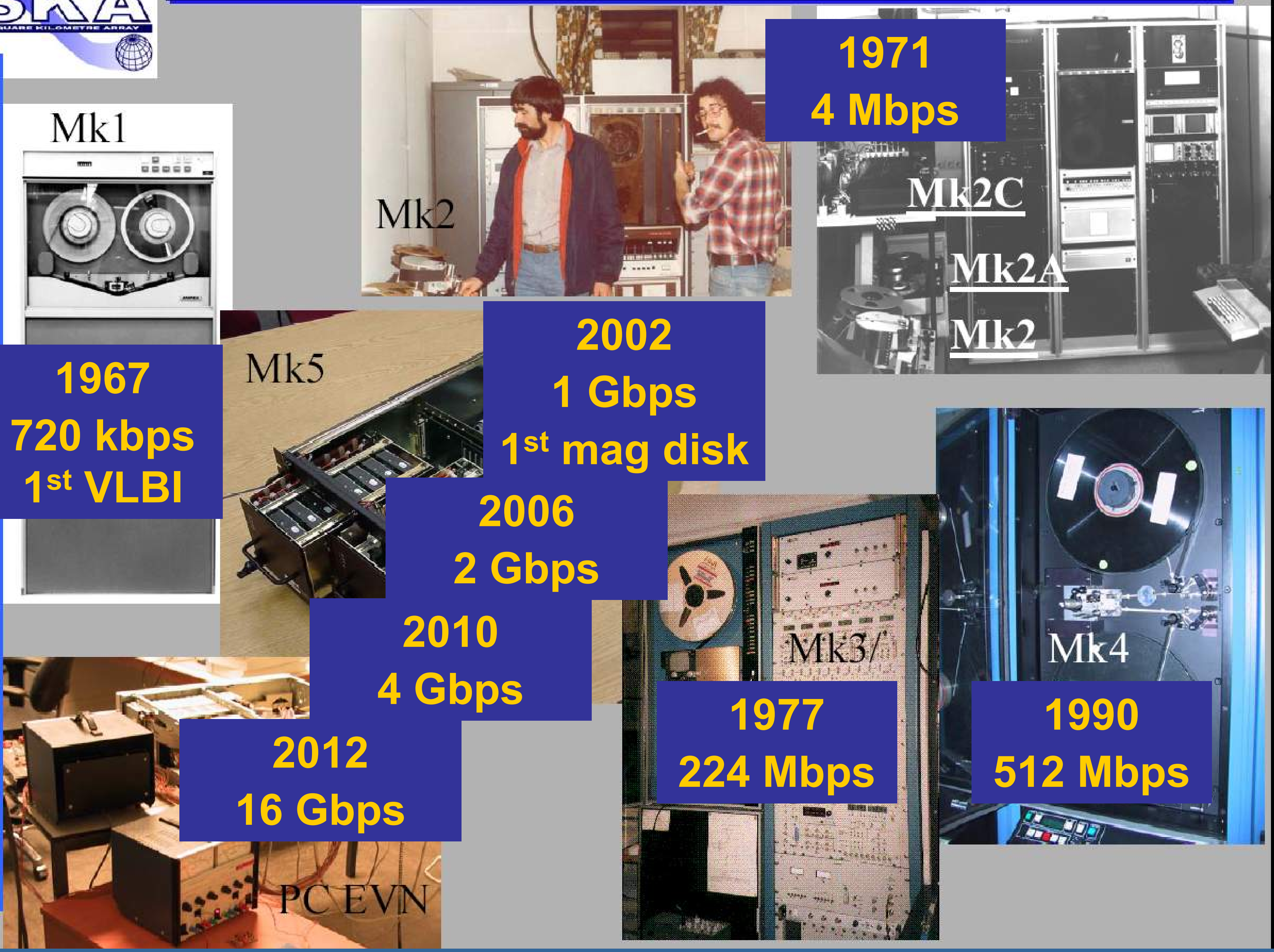
- **Astronomy**
  - Number of accessible sources increases exponentially as detection limits improve; can look further back in time
  - Increased sensitivity → lower noise → better images
- **Geodesy and geophysics**
  - Better distribution of available point-like sources over the sky improves quality 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

# Only options to improve VLBI sensitivity are . . .

- Bigger antennas, but cost tends to go as $D^{2.7}$
- Quieter receivers, but many receivers are already approaching quantum noise limits or are dominated by atmospheric noise
- Wider observing bandwidth
  - For most VLBI observations, sensitivity increases as square root of observed bandwidth
  - Increasing BW is usually the most cost-effective way to increase sensitivity
  - As a result, VLBI has always pushed data recording technology to its limits!



**1967**
**720 kbps**
**1st VLBI**

**1971**
**4 Mbps**

**1977**
**224 Mbps**

**1990**
**512 Mbps**

**2002**
**1 Gbps**
**1st mag disk**

**2006**
**2 Gbps**

**2010**
**4 Gbps**

**2012**
**16 Gbps**

# What data are actually recorded?

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

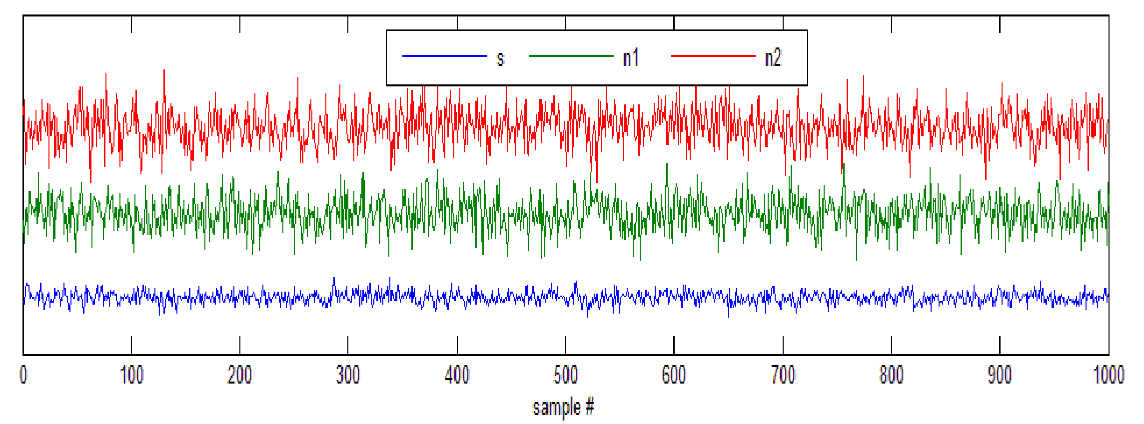
Interesting fact: Normally, the voltage signal is sampled with only 1 or 2 bits/sample

Big consequence: It is 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)

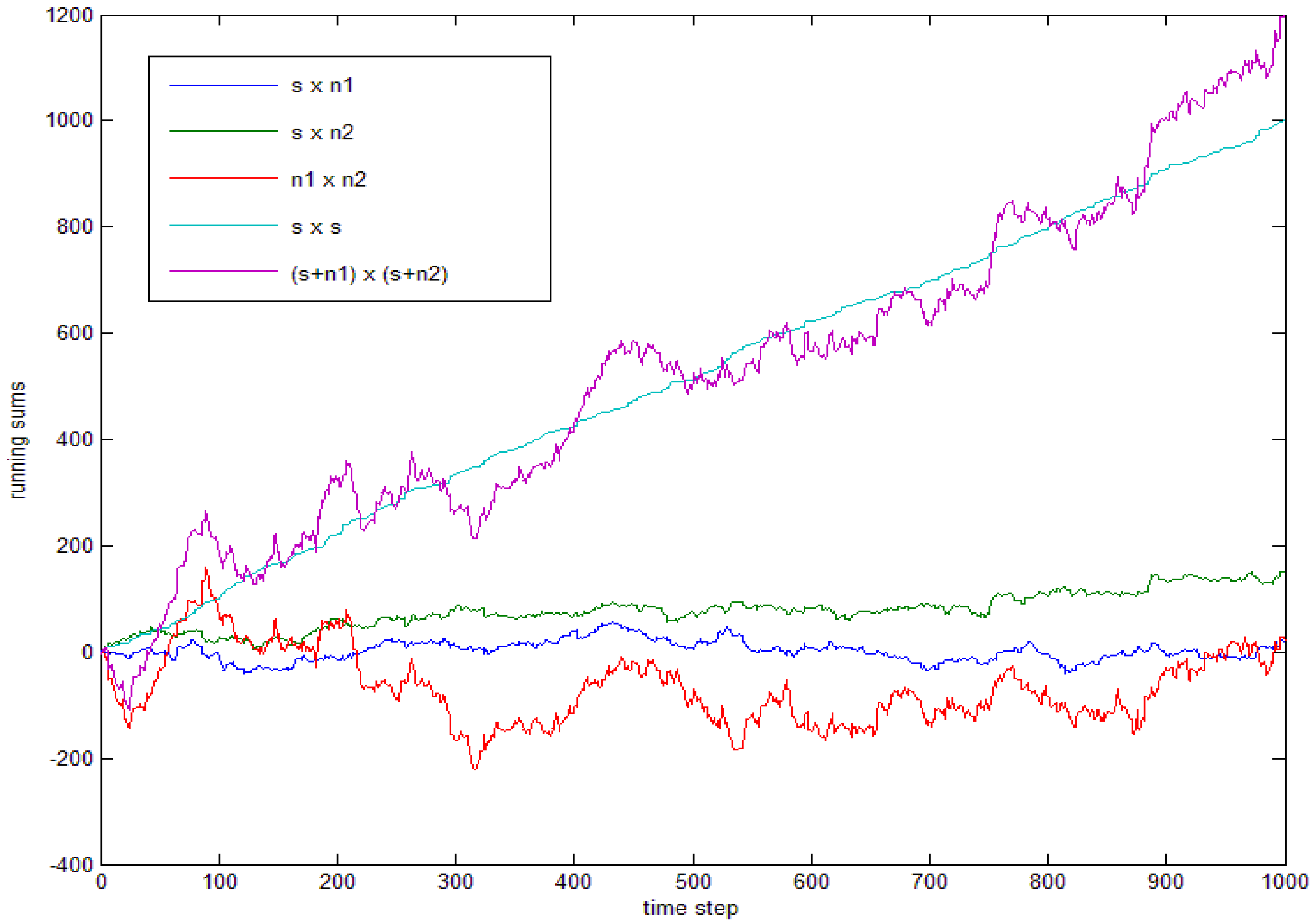
# Cross-correlation of weak signals (cont'd)

- 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

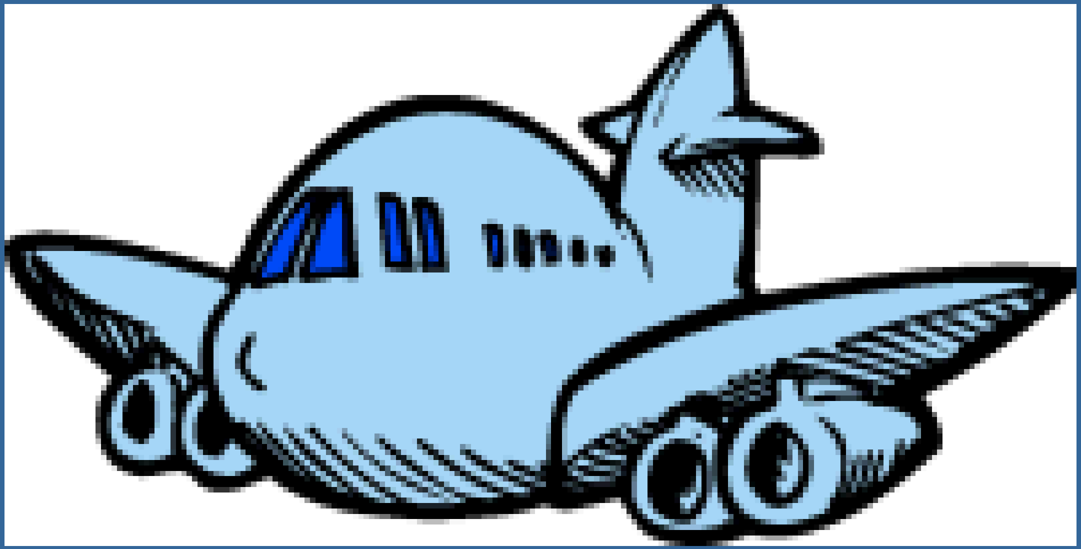
# Correlation components



# 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



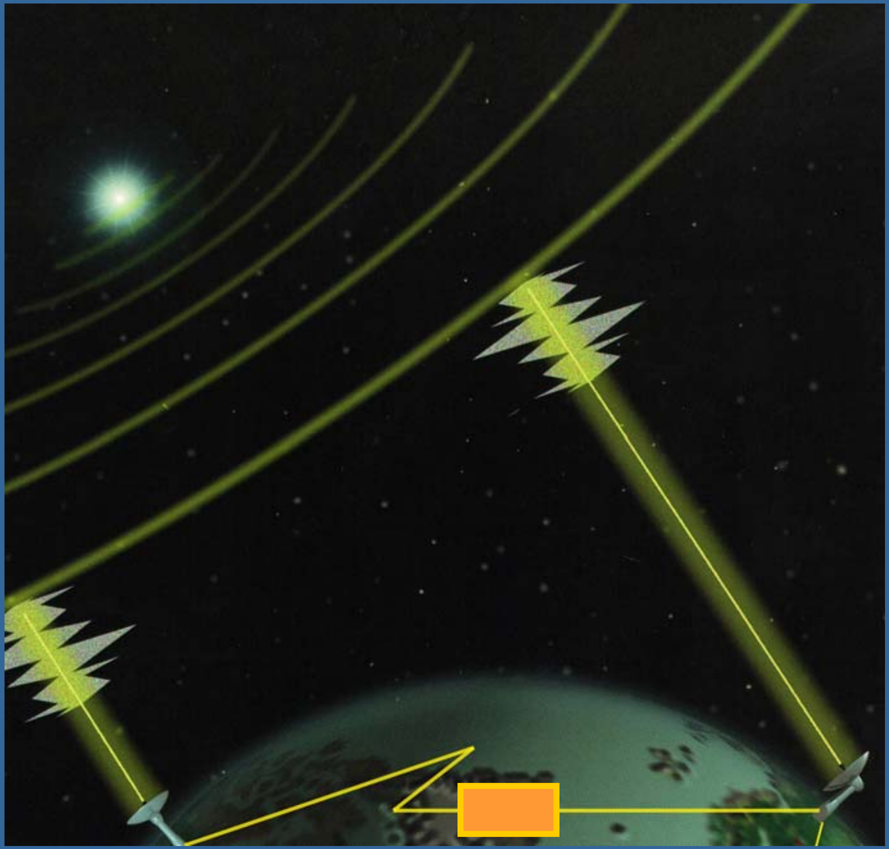
….but that takes time and ties up large amounts of expensive media

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

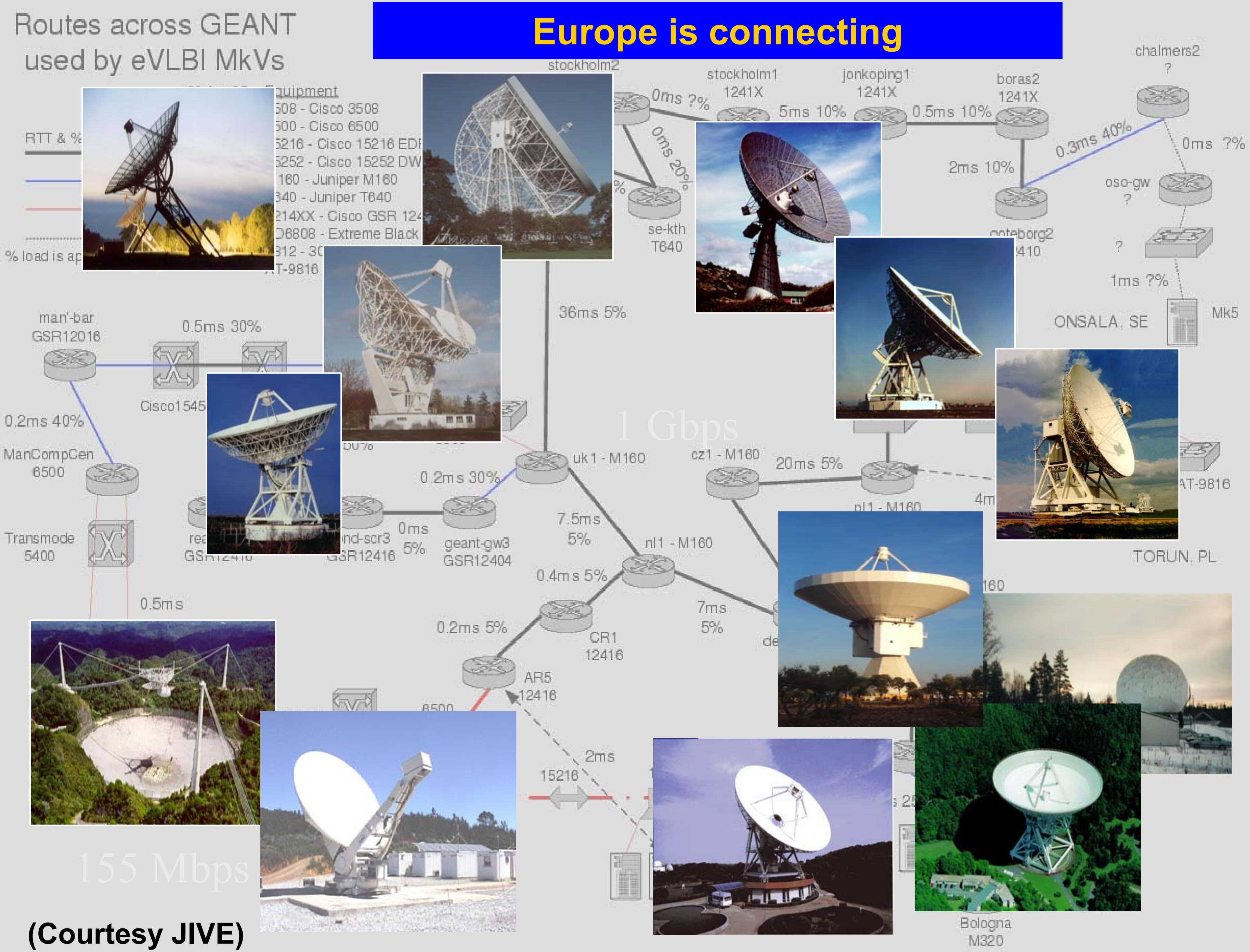
Of course, not a new idea, but only recently becoming somewhat practical and economical

- **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!

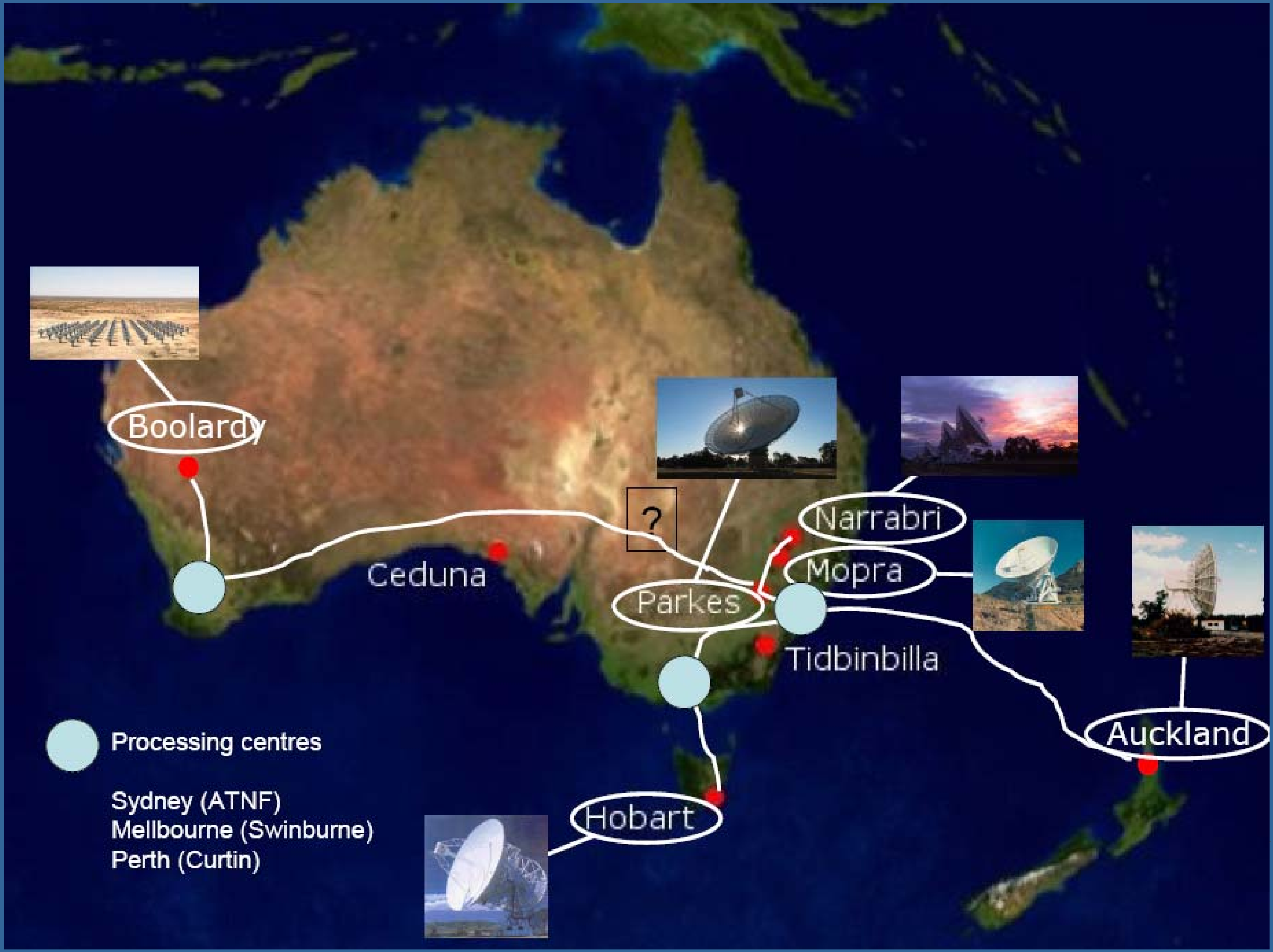


# Europe is connecting



**(Courtesy JIVE)**

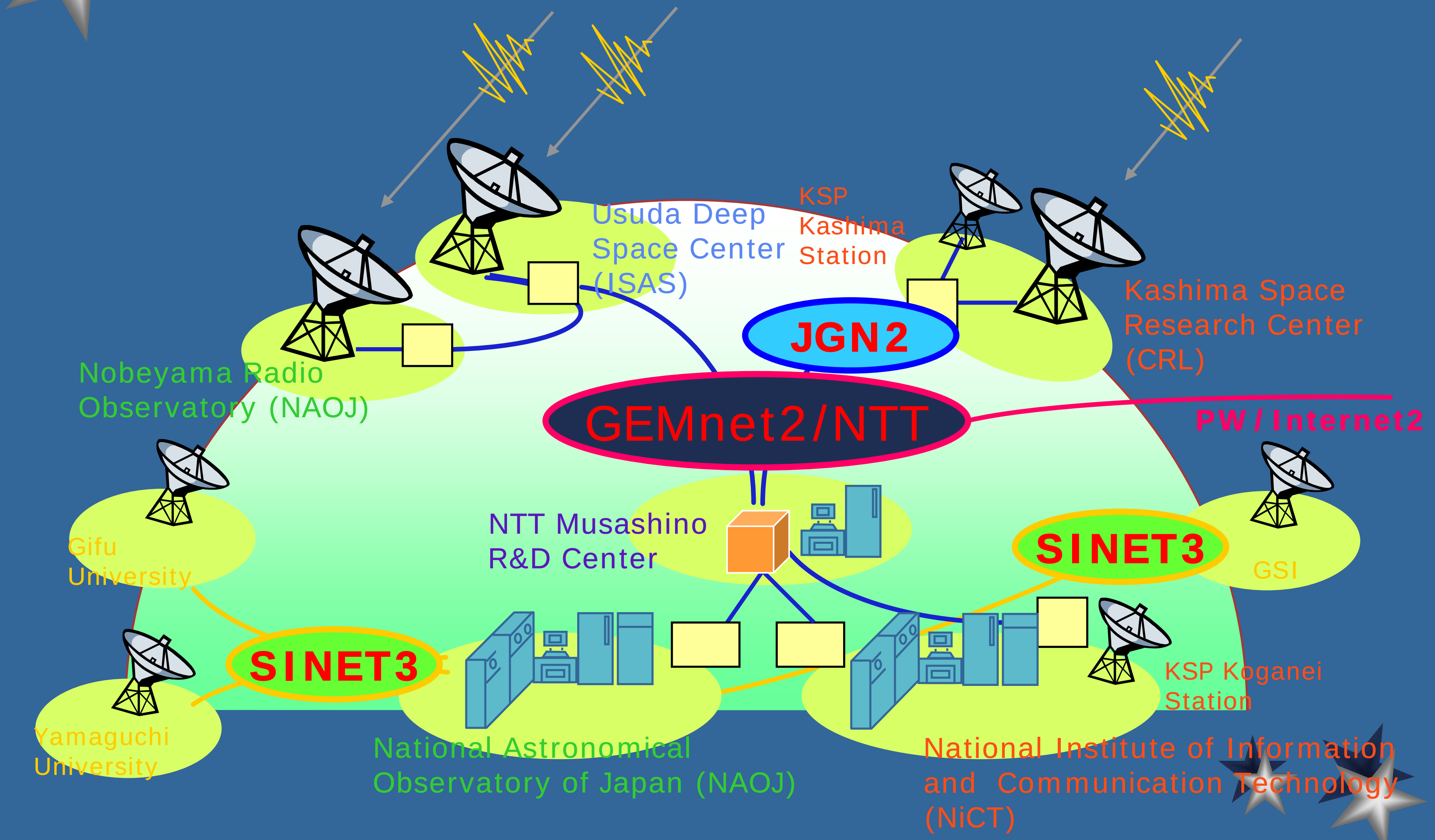
# Australia is in process of connecting stations at 10 Gbps



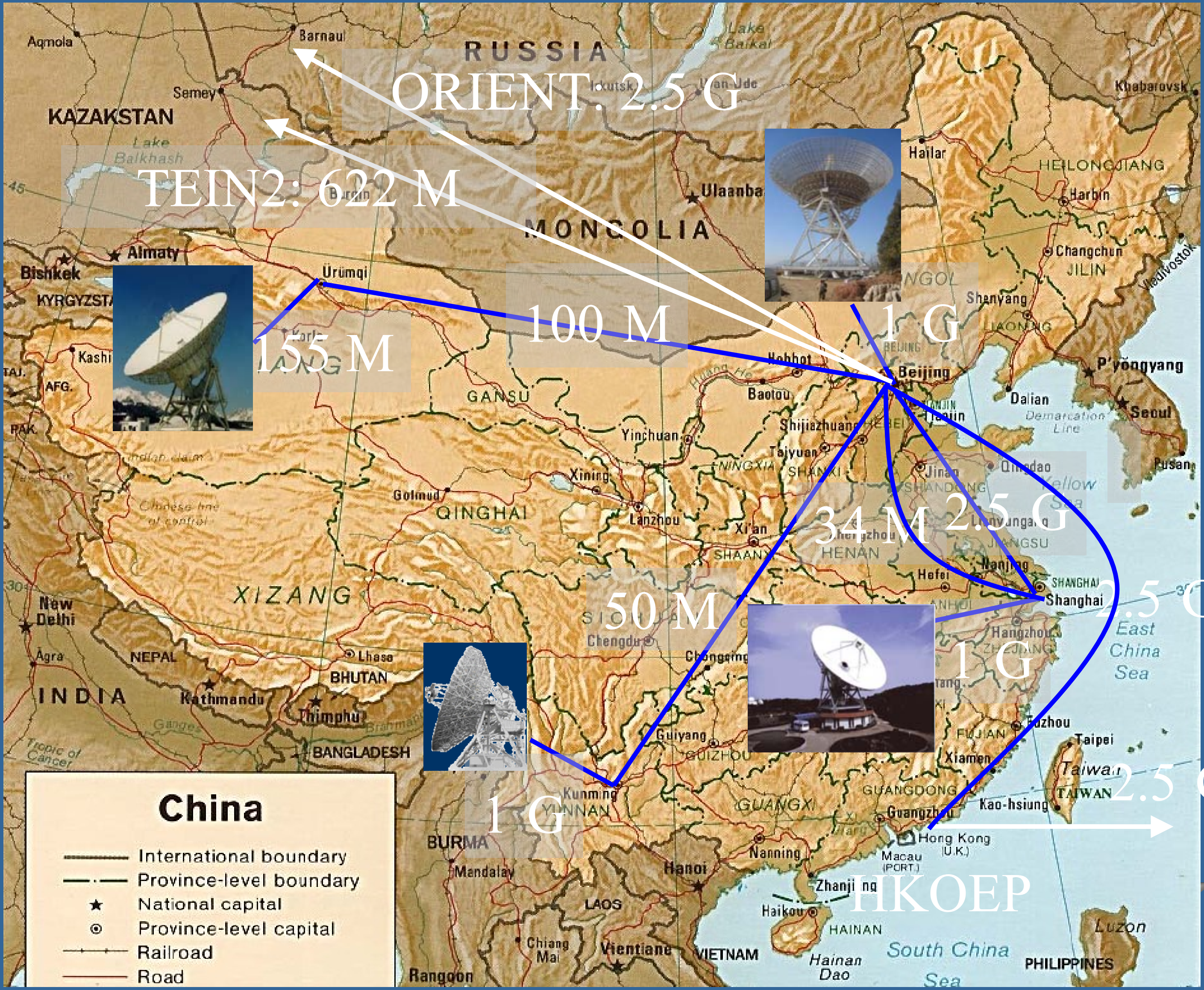
● Processing centres

Sydney (ATNF)
Mellbourne (Swinburne)
Perth (Curtin)

# Japan already has many of its telescopes connected at high speeds

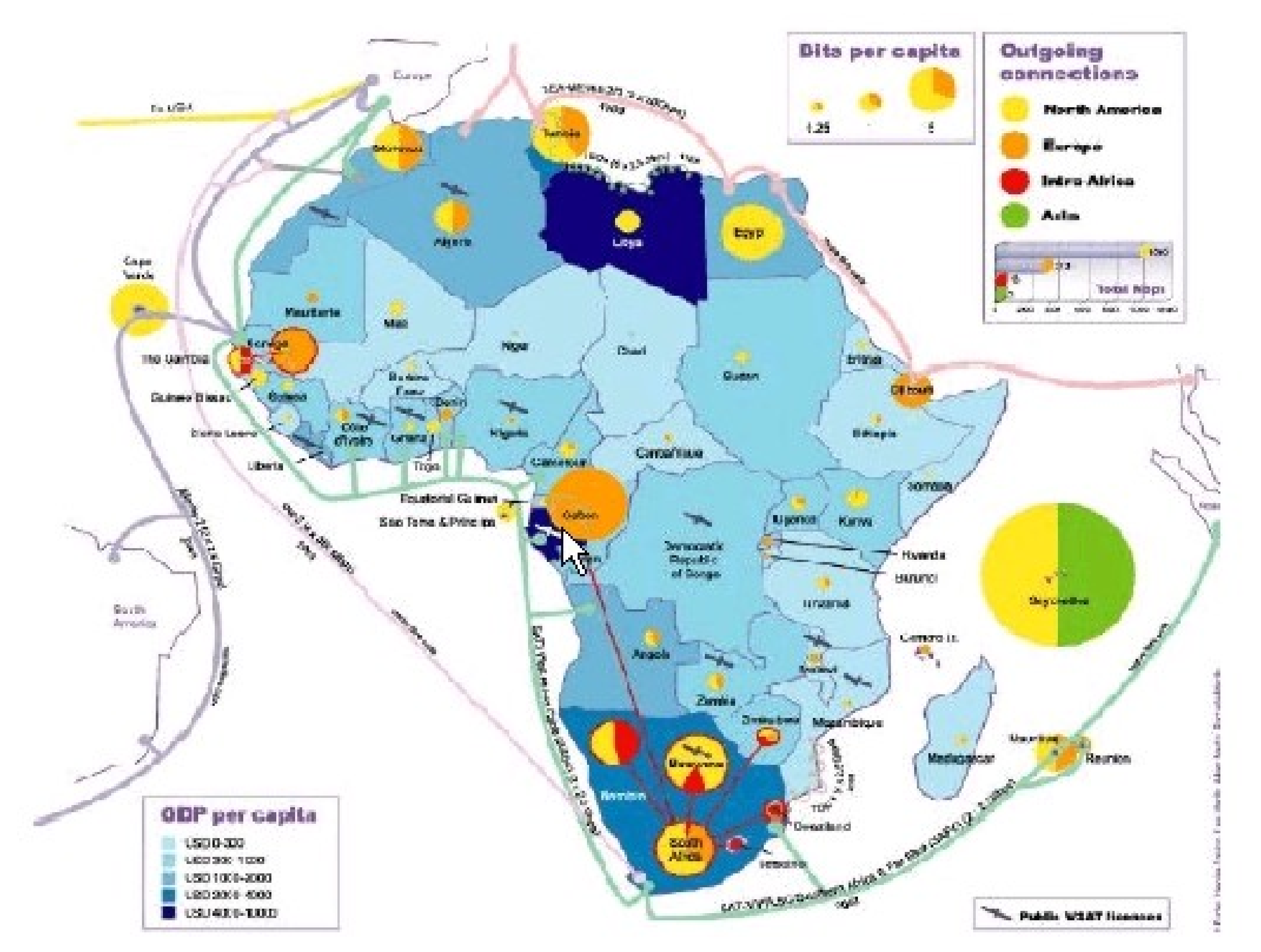


# China connections are increasing

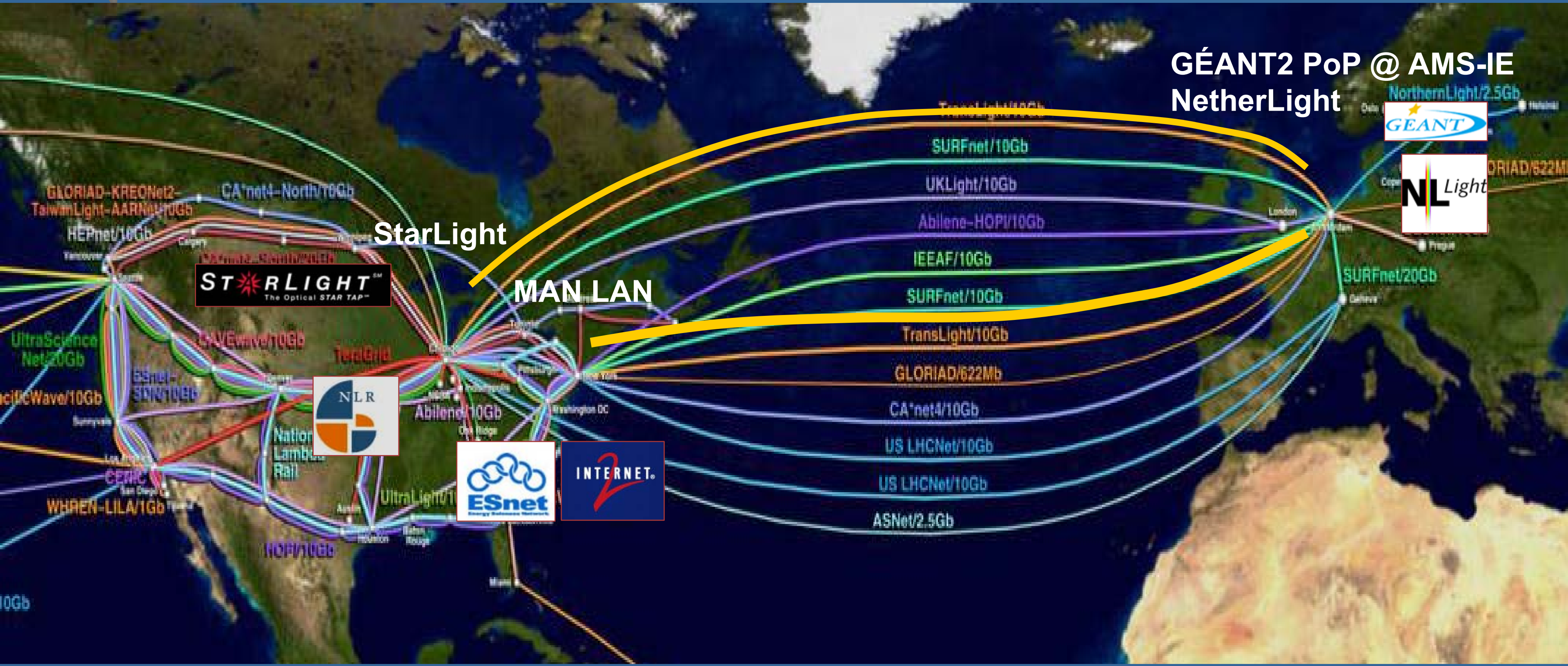


# Some links available to South America and improving

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



# Lots of links across the Atlantic



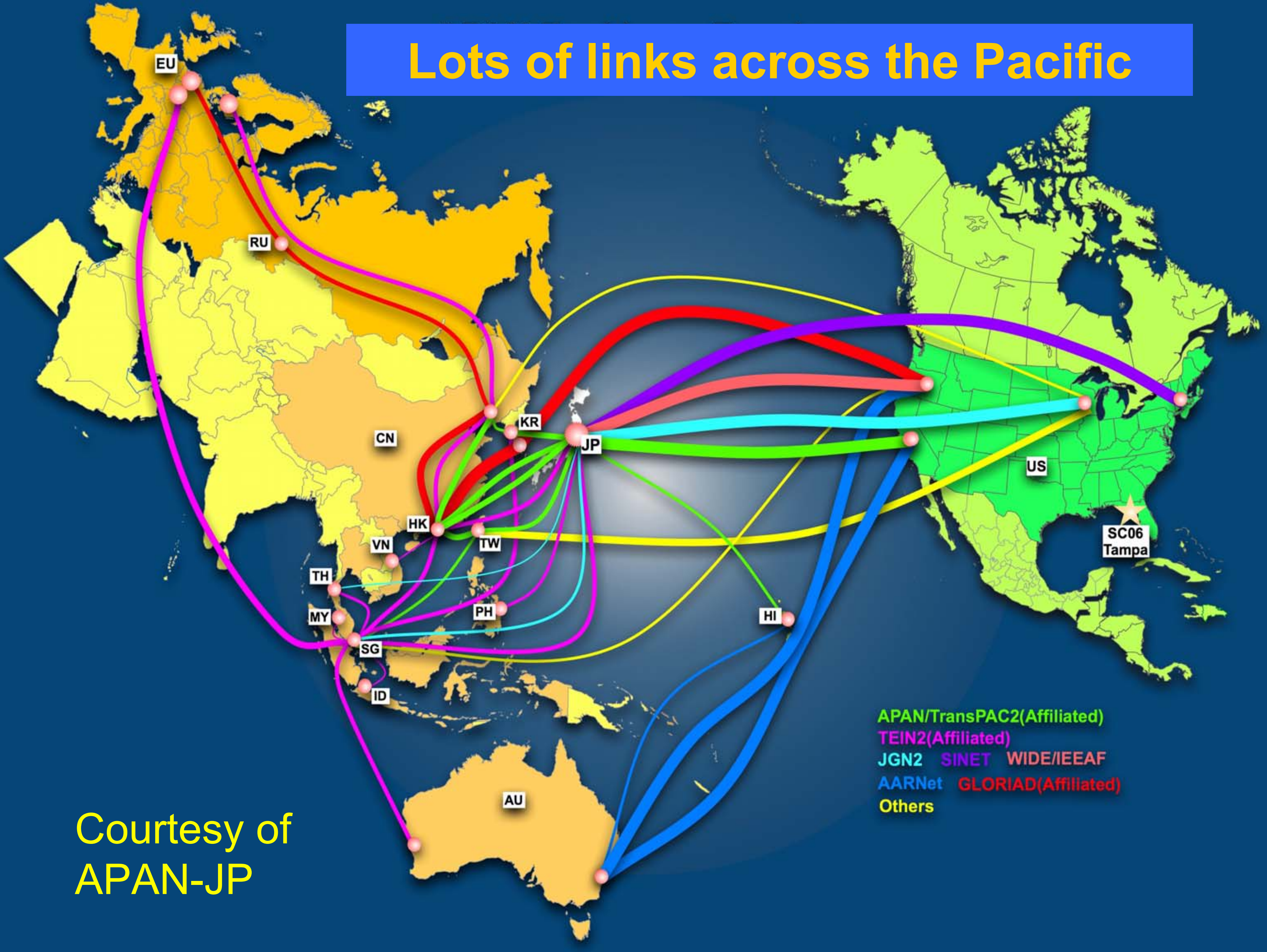
StarLight

MAN LAN

GÉANT2 PoP @ AMS-IE
NetherLight

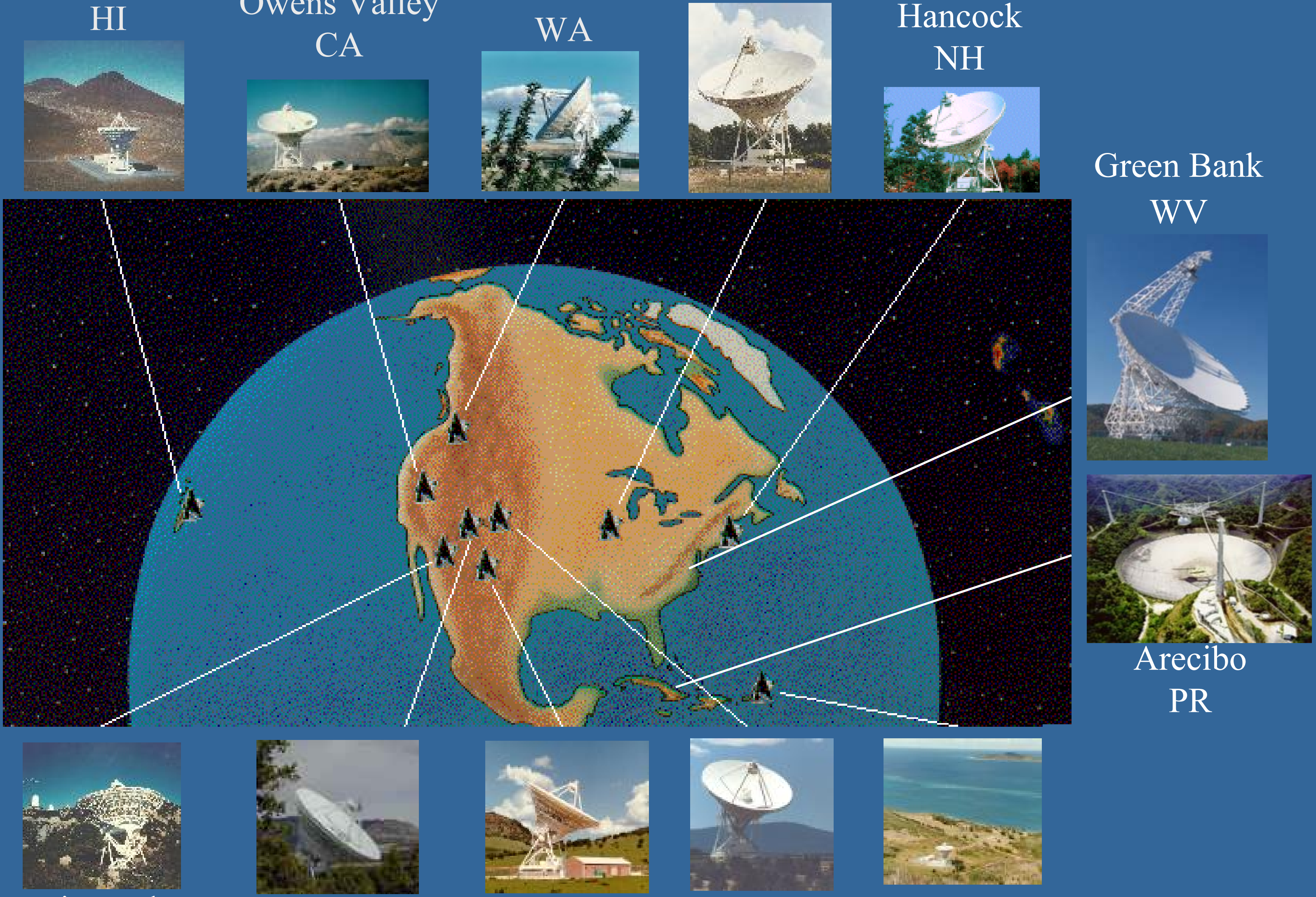
www.startap.net/translight

# Lots of links across the Pacific



Courtesy of APAN-JP

# VLBA – The World's Only Full-Time VLBI Array



Mauna Kea
HI

Owens Valley
CA

Brewster
WA

N. Liberty
IA

Hancock
NH

Green Bank
WV

Arecibo
PR

Kitt Peak
AZ

Pie Town
NM

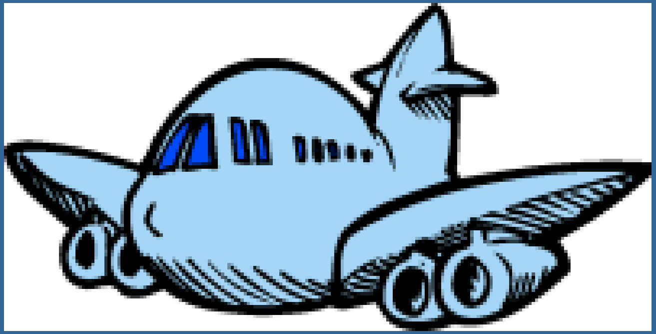
Fort Davis
TX

Los Alamos
NM

St. Croix
Virgin Is.

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.

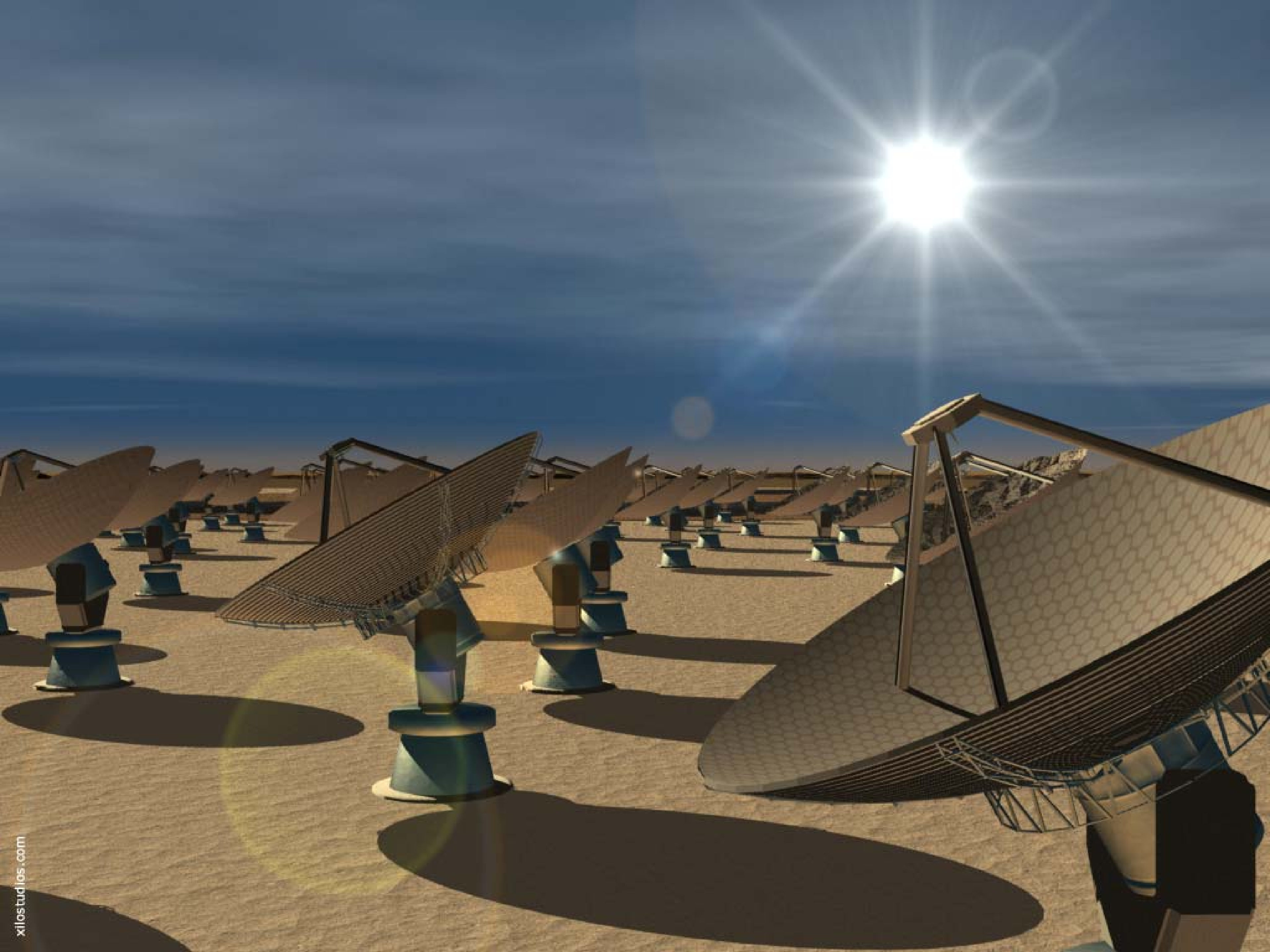
The Big Challenge:
When will e-VLBI catch up to a B747?!

# 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

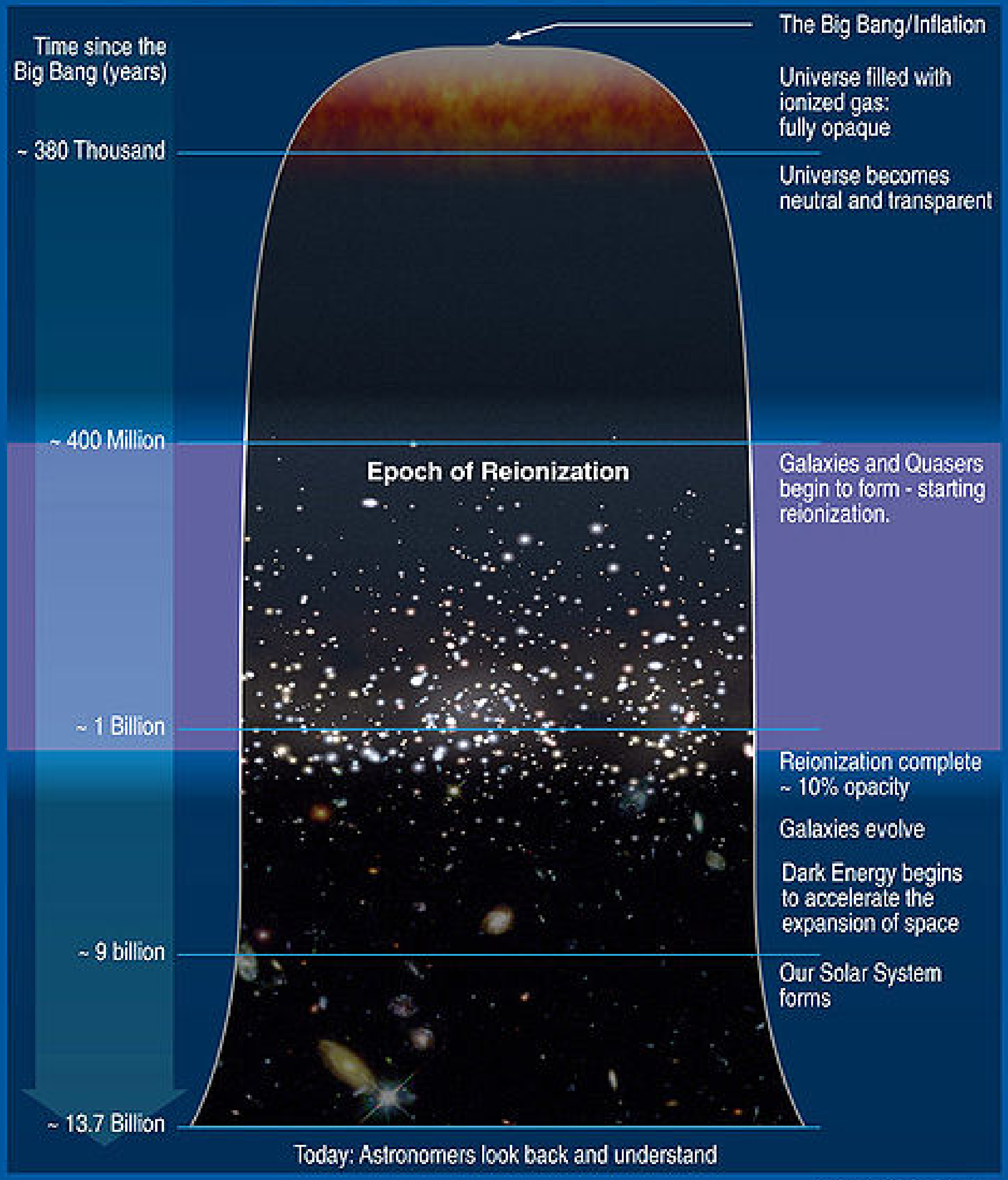
- Collecting area of order 1 million square meters, array of ~5000 dishes each ~12m in diameter
- Antennas are highly concentrated in the central 5km, and further distributed in stations at distances up to at least 3000km
- Individual antennas are connected via wide-band fibre links (100 Gbit/s) to a 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



NASA/WMAP Science Team

# The End

Thanks for your attention!