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Very Long Baseline Interferometry

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Outline

- What is VLBI?
 - And why is it such a bad name?
- Examples of VLBI arrays
- Why do VLBI?
 - Is it really so difficult?
- An example of VLBI data reduction
 - Simple step-by-step guide
- Examples of VLBI
 - Pulsars, masers, AGN, geodesy
- Summary

History

- VLBI became possible in the late 1960s as
 - Atomic clocks provided stable time signals
 - Tape recorders allowed wide bandwidth signals to be recorded
 - Computers were becoming more powerful and more available
- Before VLBI, the tightest constraints on angular sizes were placed by scintillation measurements, and accurate positions were determined by lunar occultations

Quiz 1

- But for the quirks of history, VLBI might have been called
 - 1) ICBM
Inter-Continental Baseline Measurements
 - 2) ILOI
Independent Local Oscillator Interferometry
 - 3) RIOTS
Radio Interferometry at One Thousandth of a Second-of-arc
 - 4) FAR
Fantastic Angular Resolution Telescope

The Long Baseline Array (LBA)

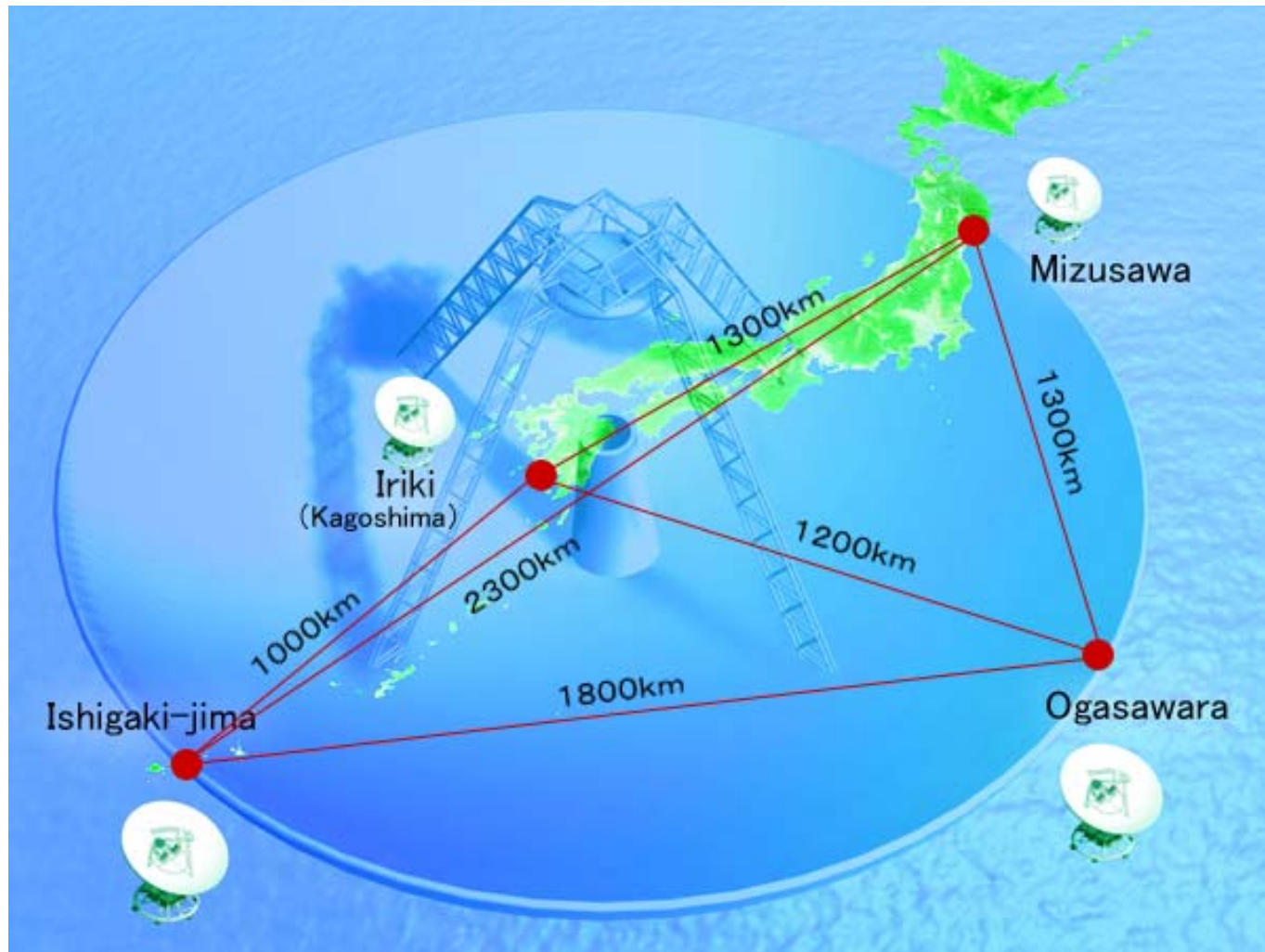


VLBA



A dedicated homogeneous array of ten 25m telescopes

VERA



VERA



Why do VLBI?

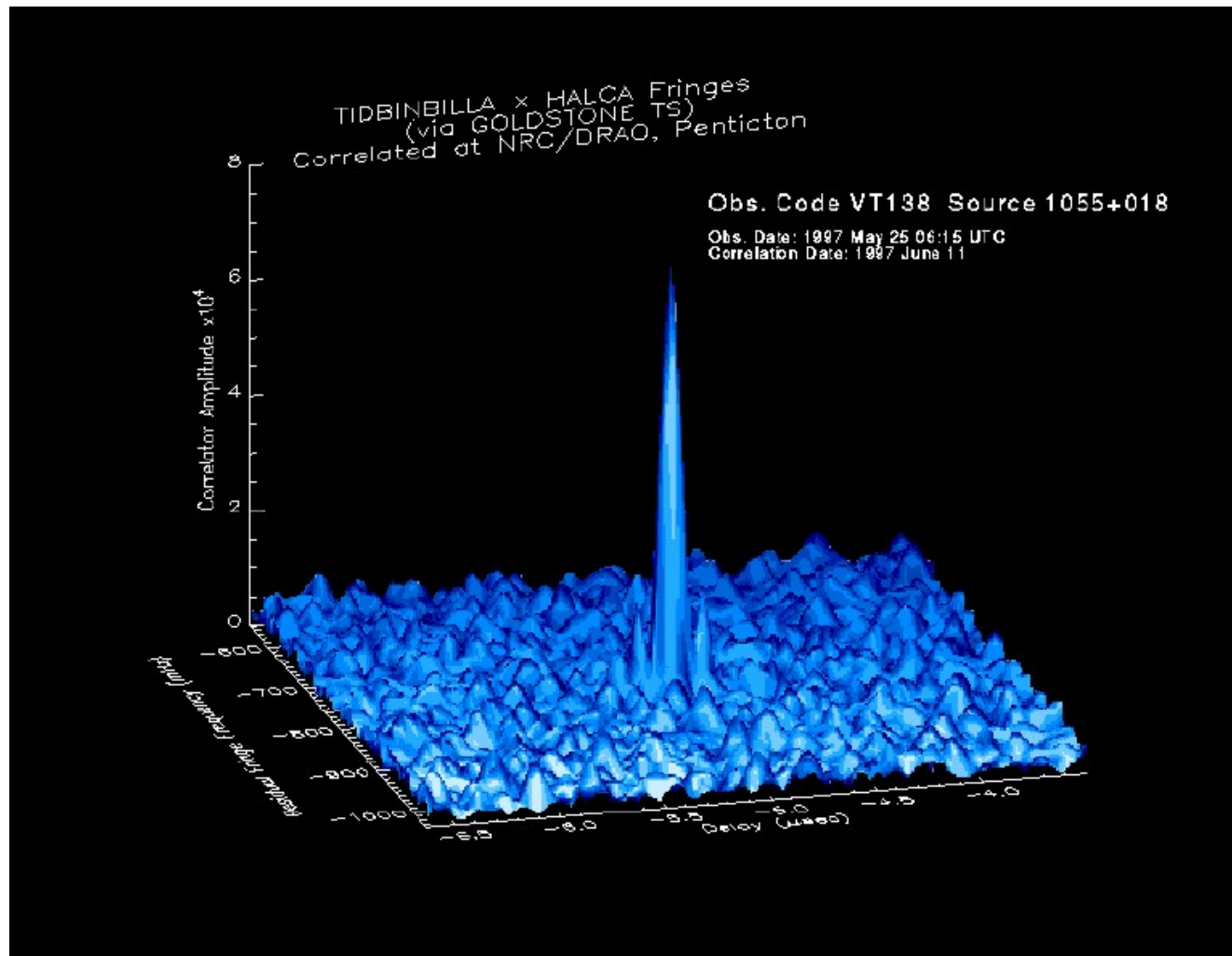
- VLBI enables imaging with milli-arcsecond angular resolution
 - AU scale for galactic objects
 - Parsec-scale for extragalactic objects
- These are scales on which structural changes can occur on human timescales
- VLBI thus enables movies to be made of structural evolution of astronomical objects
- The only complications are unstable phases, and $T_B > 10^6$ K, i.e. bright, compact objects

- The raw phases in VLBI data are not stable:
 - atmospheric conditions can vary significantly between sites
 - each telescope has its own clock
 - telescopes are moving at different speeds toward the source
 - subtle geophysical and geodetic effects become important
- The correlator attempts to correct for these with a sophisticated model.
- Telescope positions are known with cm-level accuracy.

- With connected element interferometers, observations start by calibrating the delays.
- Interferometer phase (ignoring instrumental effects) is frequency times delay.
- The delay offset appears as a phase slope as a function of frequency.
- The change of this delay with time is the fringe rate.
- VLBI data are correlated using a range of delays and rates which are expected to encompass the actual values.



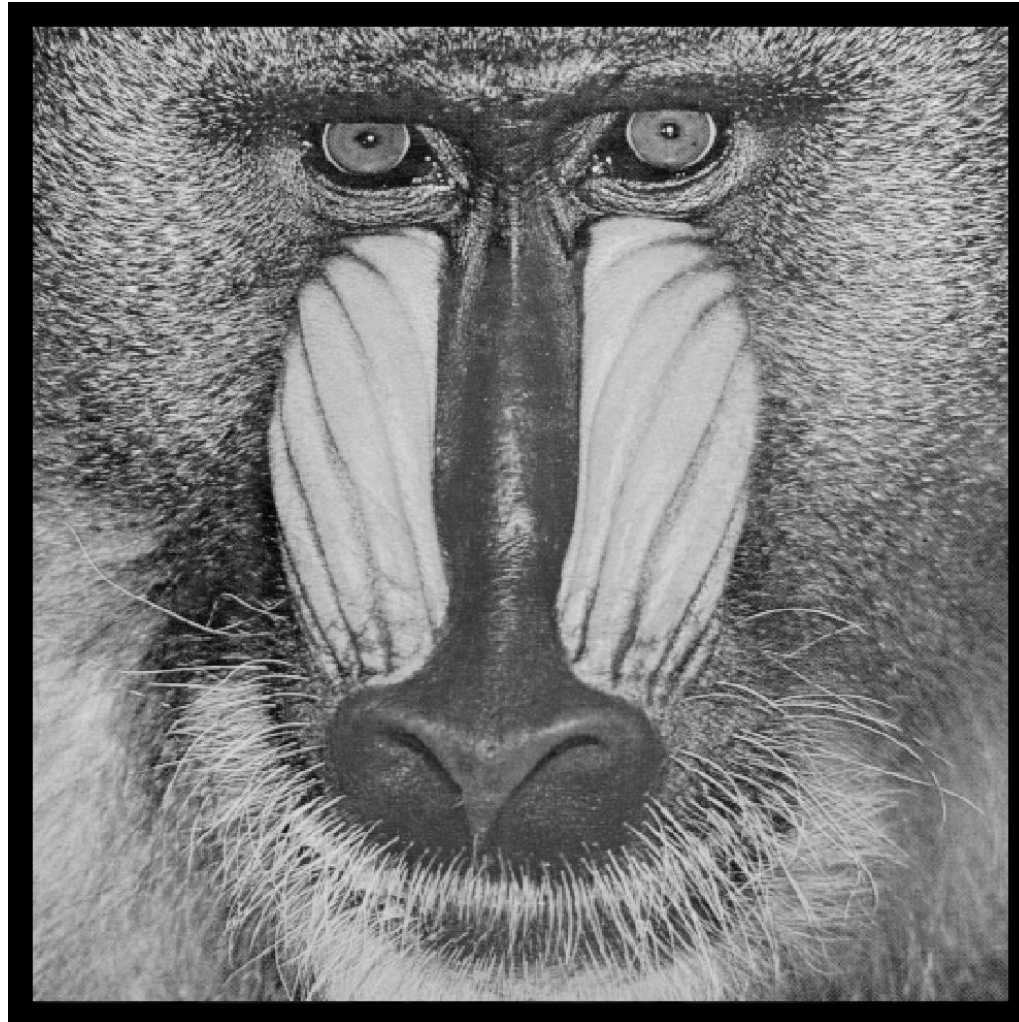
Fringes!



- The main difference from connected element interferometry is the need for a software package to determine the delays and rates as a function of time.
- The good news is that such a package exists: the *Astronomical Image Processing System*



AIPS



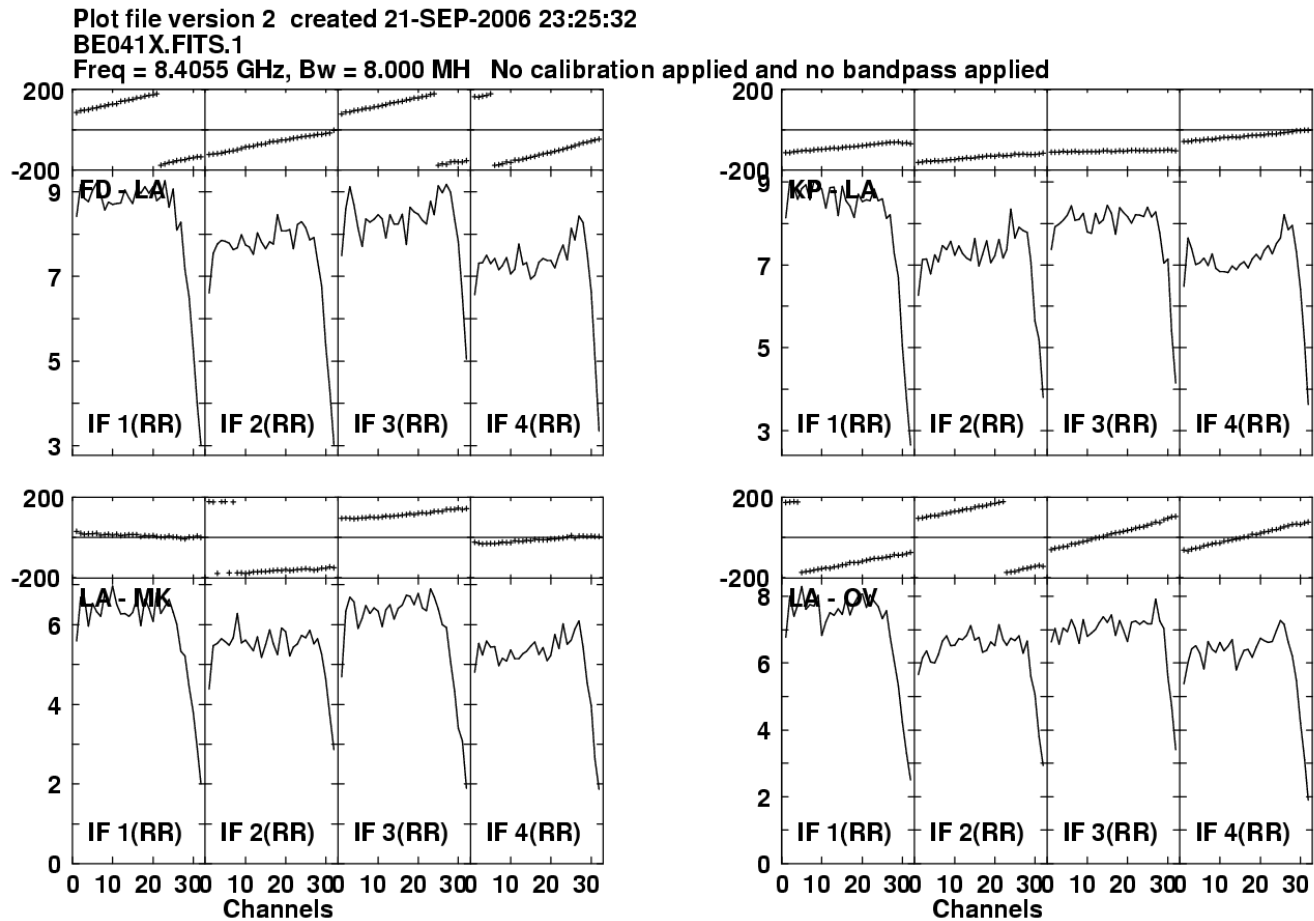
Quiz 2

- The AIPS user guide is unusual in that it contains
 - 1) warning messages in seven languages
 - 2) recipes which involve bananas
 - 3) advice encapsulated in iambic pentameter
 - 4) suggestions for tripling the processing power of your PC

Data reduction in AIPS

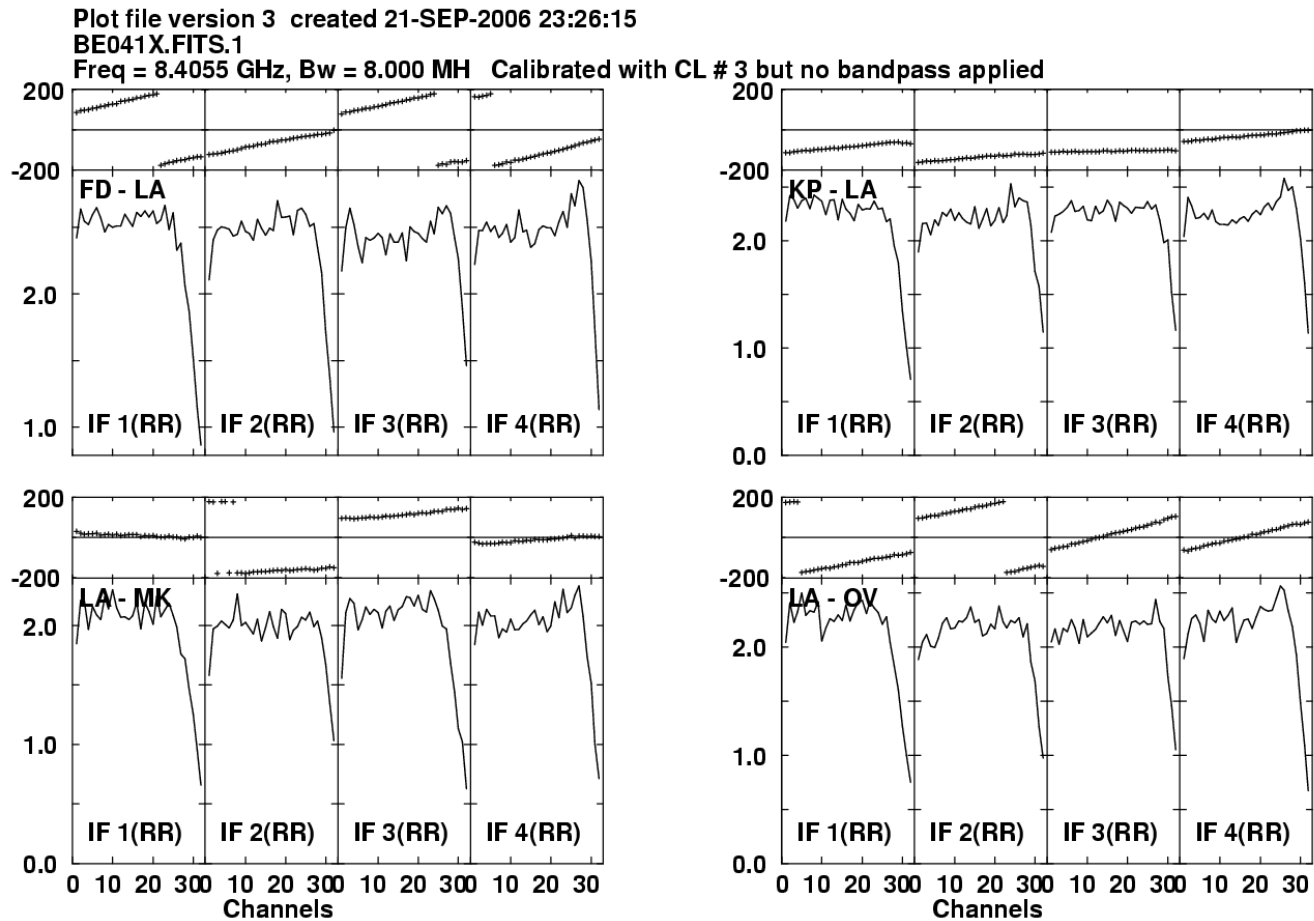
- open the AIPS cookbook to chapter 9...
- read in the data with `fit1d (cl1)`
- preview the data with `prtan, listr, ...`
- correct for sampler biases with `accor (sn1) & clcal (cl2)`
- check raw phases on short timerange with `possm`
- apply a priori calibration with `apcal (sn2) & clcal (cl3)`
- manual phase cal with `fring (sn3)`, apply with `clcal (cl4)`
- check calibrated phases on short timerange with `possm`
- fringe fit with `fring`
- split with `split`
- image!

Amplitude and phase: No calibration



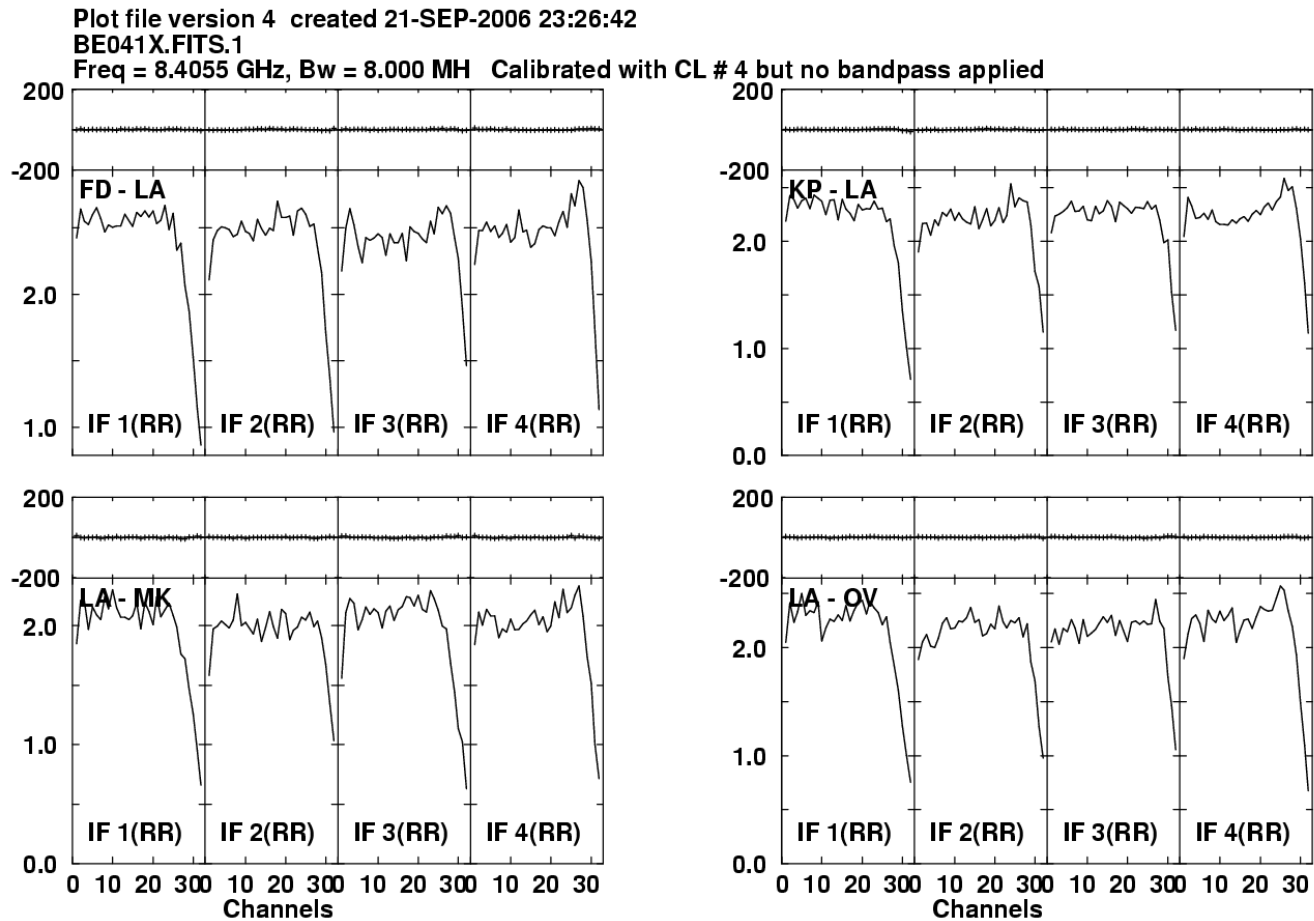
Lower frame: Milli Ampl Jy Top frame: Phas deg
Vector averaged cross-power spectrum Several baselines displayed
Timerange: 00/06:45:00 to 00/06:46:00

After amplitude calibration



Lower frame: Ampl Jy Top frame: Phas deg
Vector averaged cross-power spectrum Several baselines displayed
Timerange: 00/06:45:00 to 00/06:46:00

After removing the delays



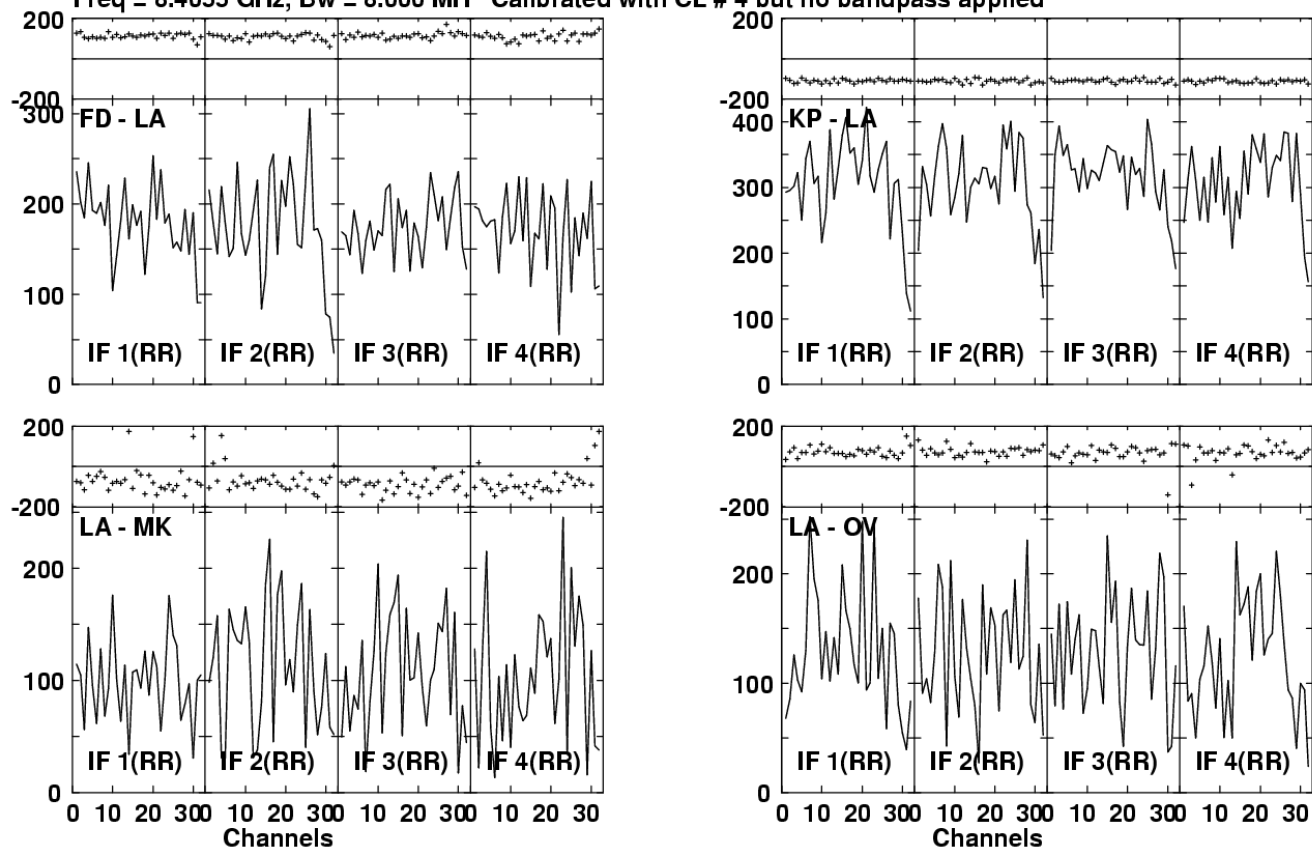
Lower frame: Ampl Jy Top frame: Phas deg
Vector averaged cross-power spectrum Several baselines displayed
Timerange: 00/06:45:00 to 00/06:46:00

Applying solutions to target source

Plot file version 5 created 21-SEP-2006 23:26:54

BE041X.FITS.1

Freq = 8.4055 GHz, Bw = 8.000 MH Calibrated with CL # 4 but no bandpass applied



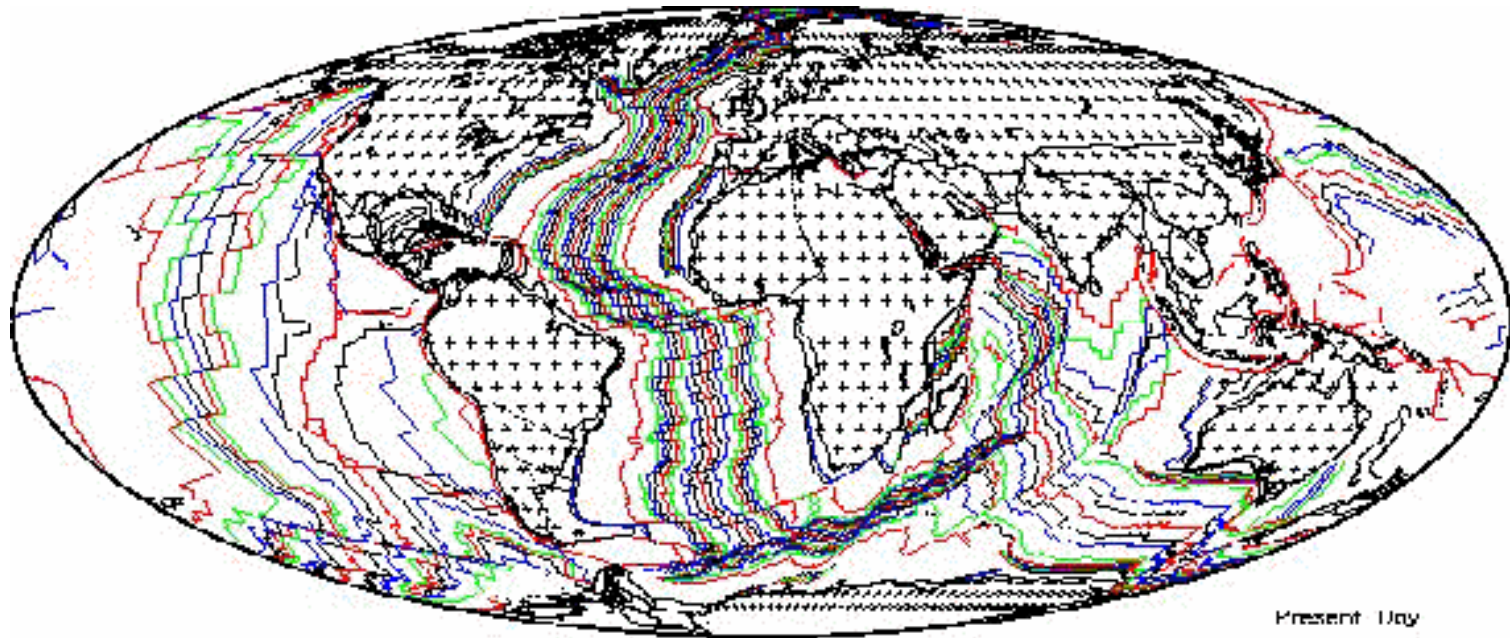
Lower frame: Milli Ampl Jy Top frame: Phas deg
Vector averaged cross-power spectrum Several baselines displayed
Timerange: 00/06:50:00 to 00/06:52:00

Types of VLBI observing

- **Dual polarization – record LCP and RCP**
 - Need good parallactic angle coverage to solve for D-terms
- **Spectral line**
 - Careful bandpass calibration required
- **Phase referencing**
 - Regular scans on nearby calibrator, yields absolute position, improves sensitivity
- **Spacecraft tracking**
 - Phase referencing for absolute position

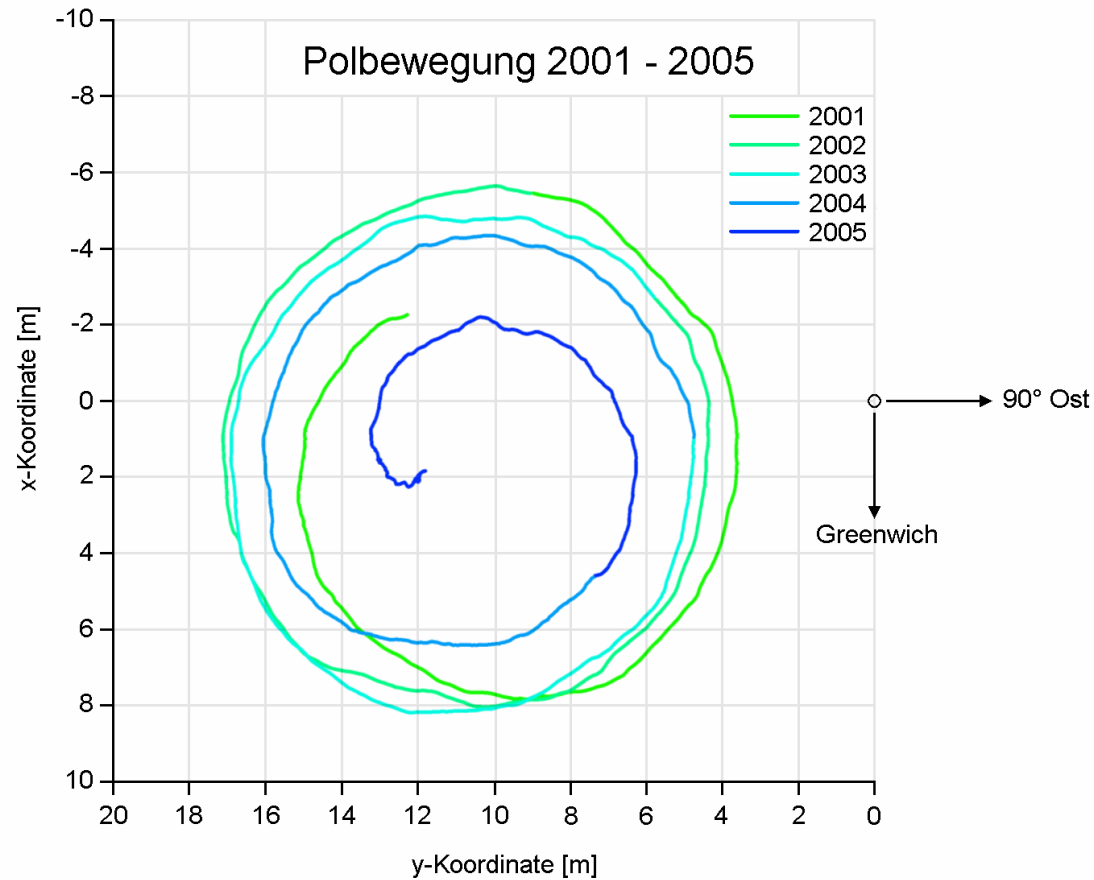
Types of VLBI observing

- **Wide field imaging**
 - Need to avoid time and bandwidth smearing effects
- **eVLBI**
 - Disks replacing tape, fibre replacing trucks, software correlation
- **Geodetic**
 - Dual S (2 GHz) and X (8 GHz) observations to calibrate out atmospheric effects
 - Many short scans of bright AGN across the sky
 - Use widely spaced IFs so that delays can be measured accurately



Australia is moving north at about 7cm per year

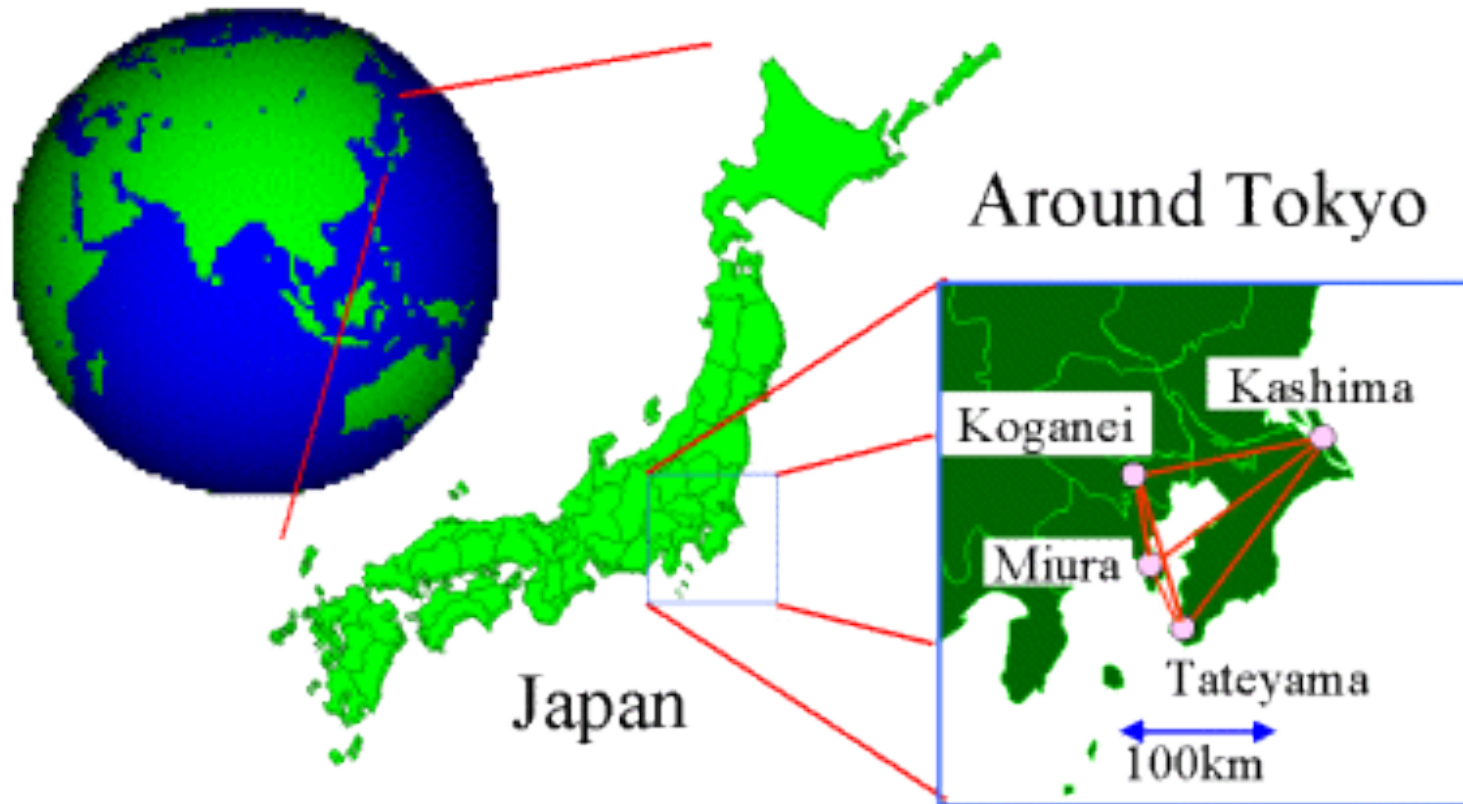
Polar motion

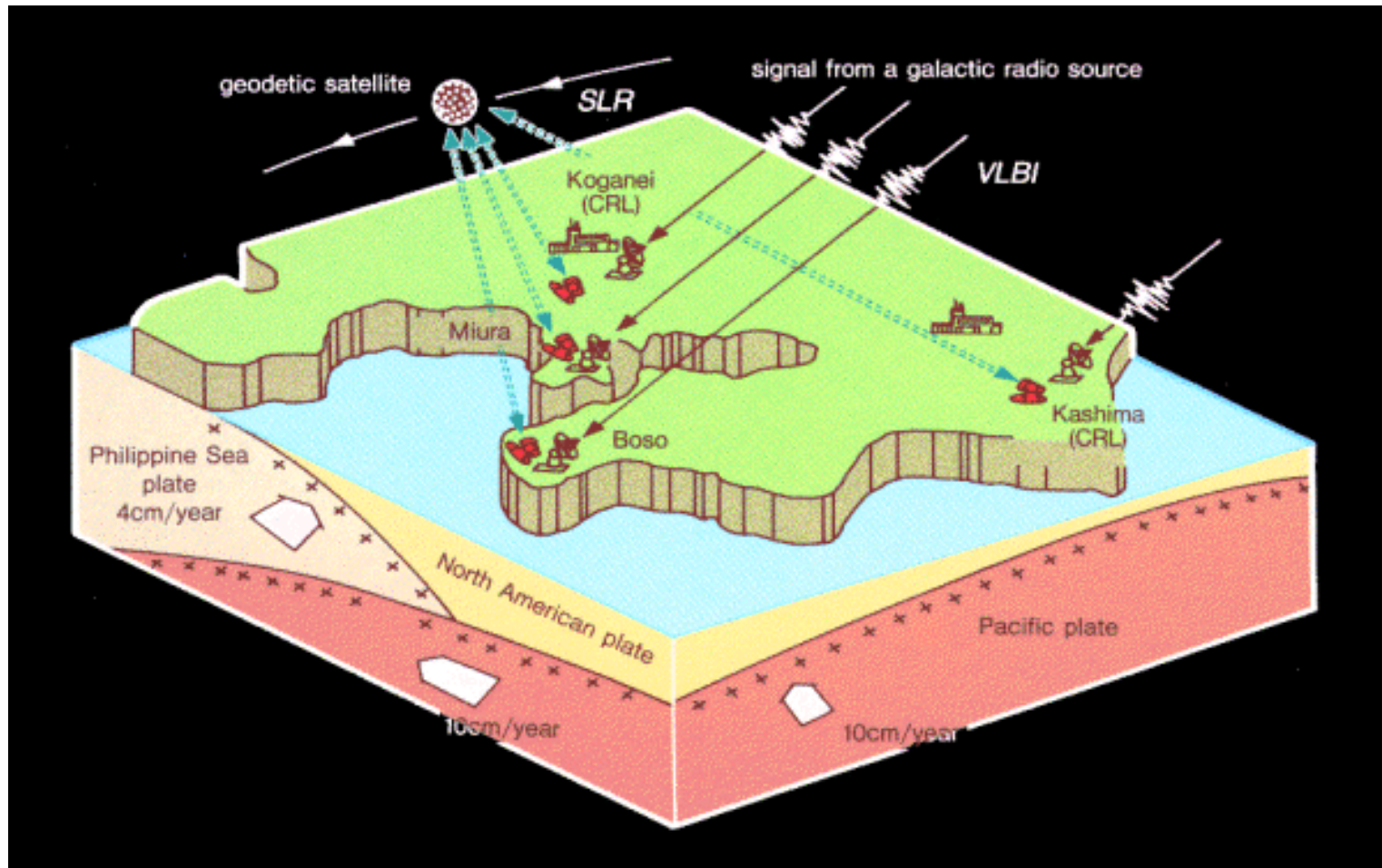


Precession changes declination but not latitude,
Wobble change latitude but not declination

Japan's Key Stone Project

Where is the KSP network?

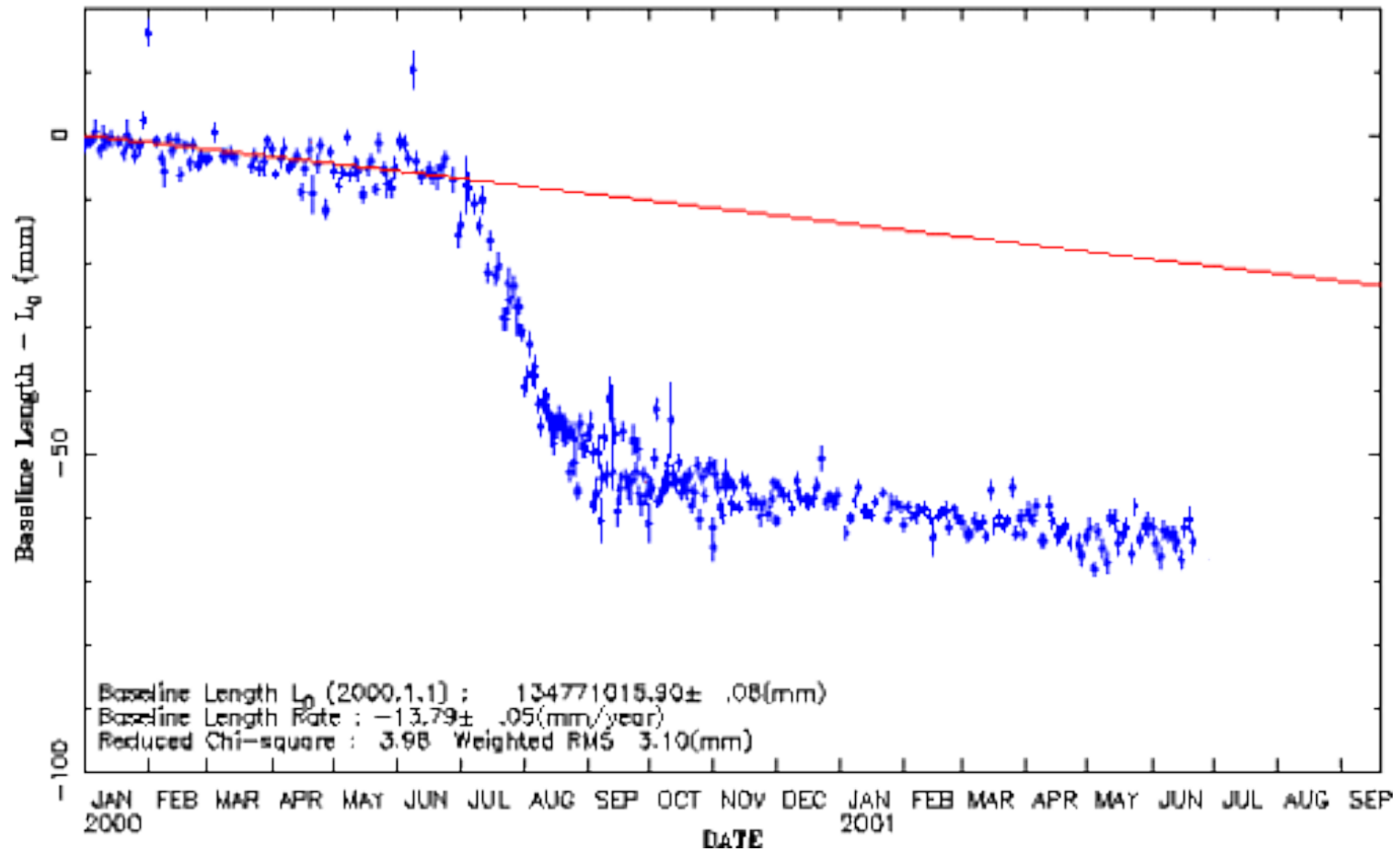


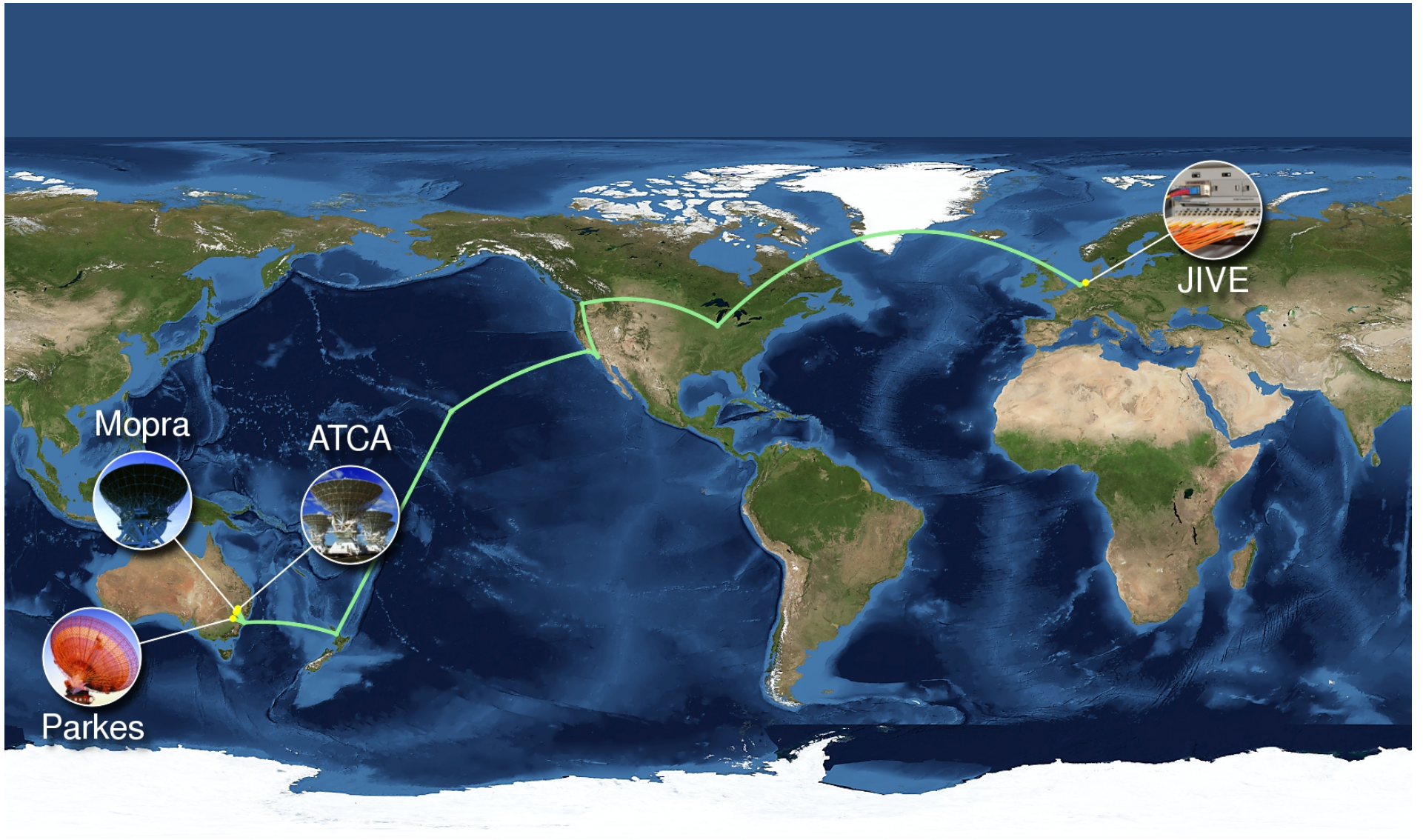


The eruption of Mt Oyama on Miyake-jima

KASHIM11-TATEYAMA

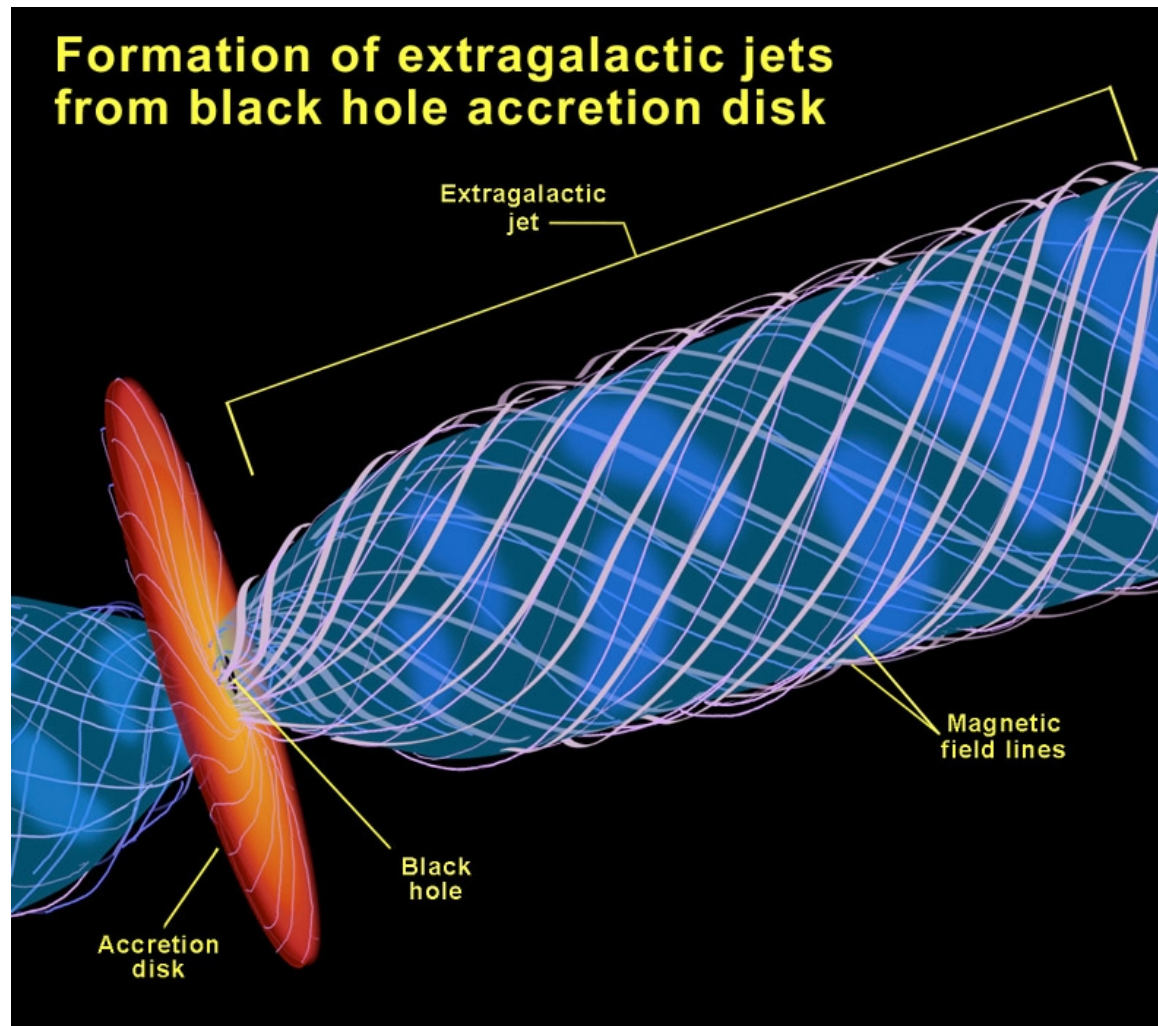
11-Sep-01 10:05:50 (JST)



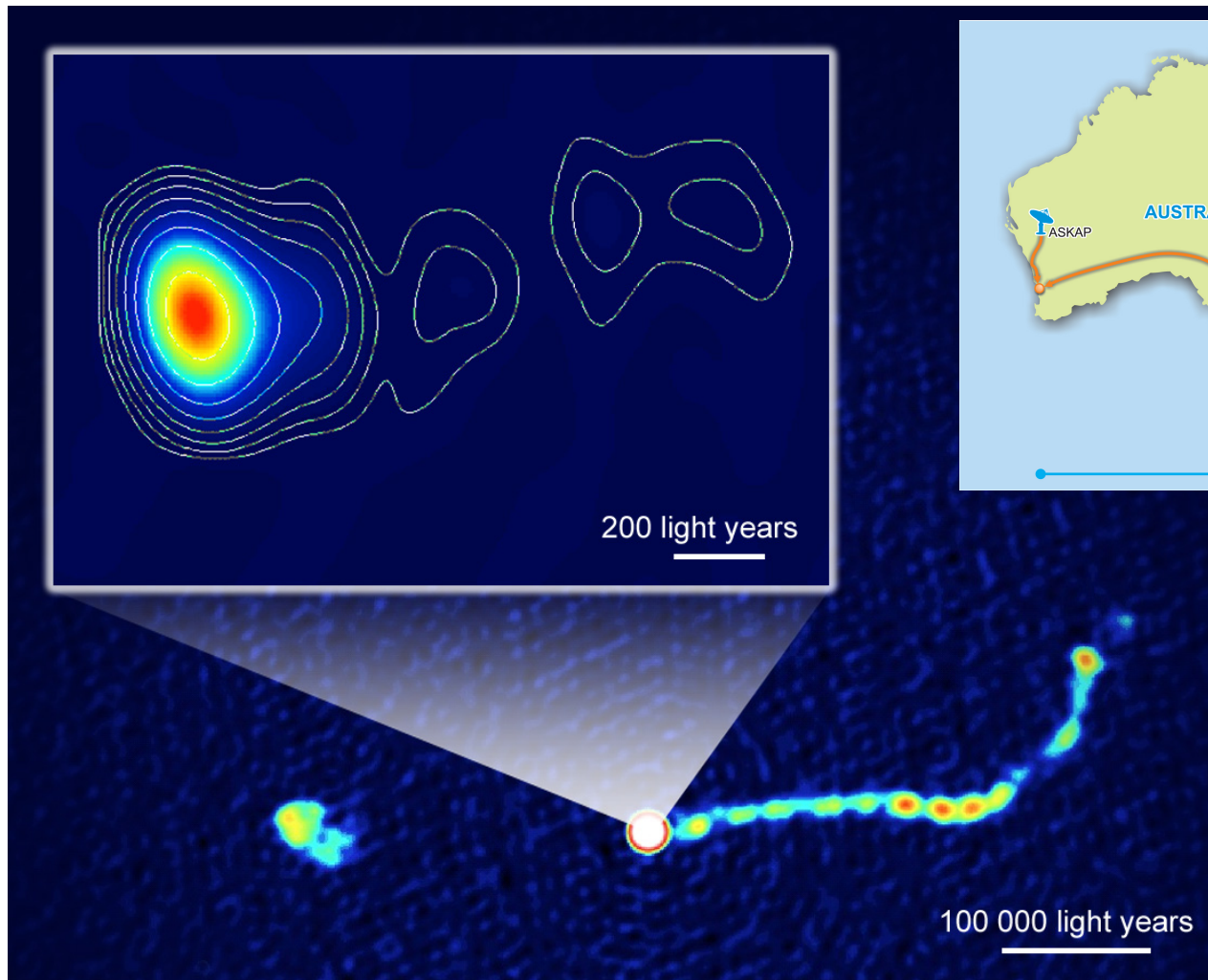


eVLBI

Formation of extragalactic jets from black hole accretion disk



PKS 0637-752



TANAMI – Cen A

See the TANAMI project press release video at
www.youtube.com/watch?v=bOjCrVQusYI

TANAMI Cen A results are presented in
Mueller et al. 2011, A&A, 530, L11



VLBA observations of 3C120 – the movie

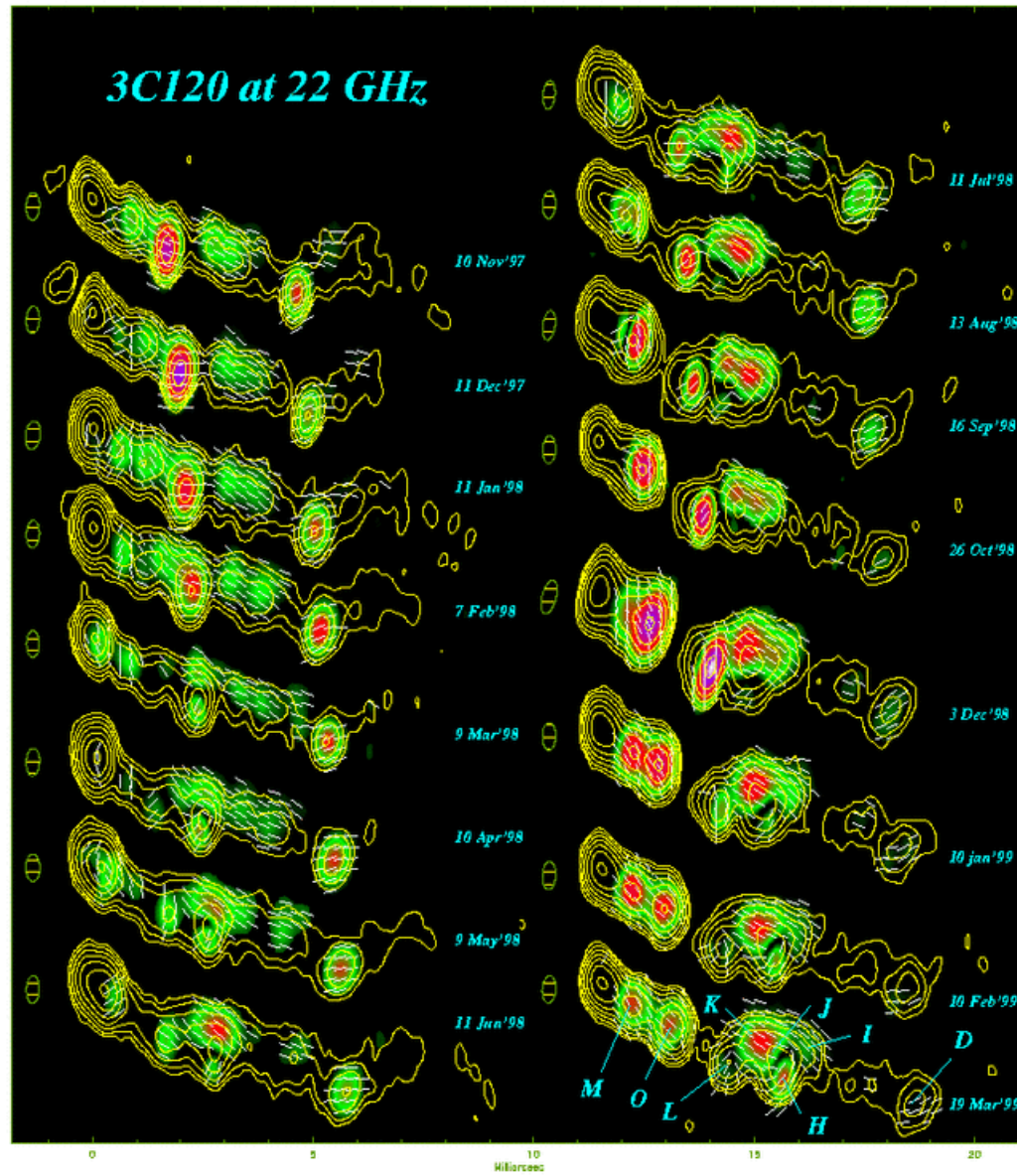
See the movie made from multi-epoch VLBA observations of 3C120 at

<http://www.bu.edu/blazars/3c120.html>

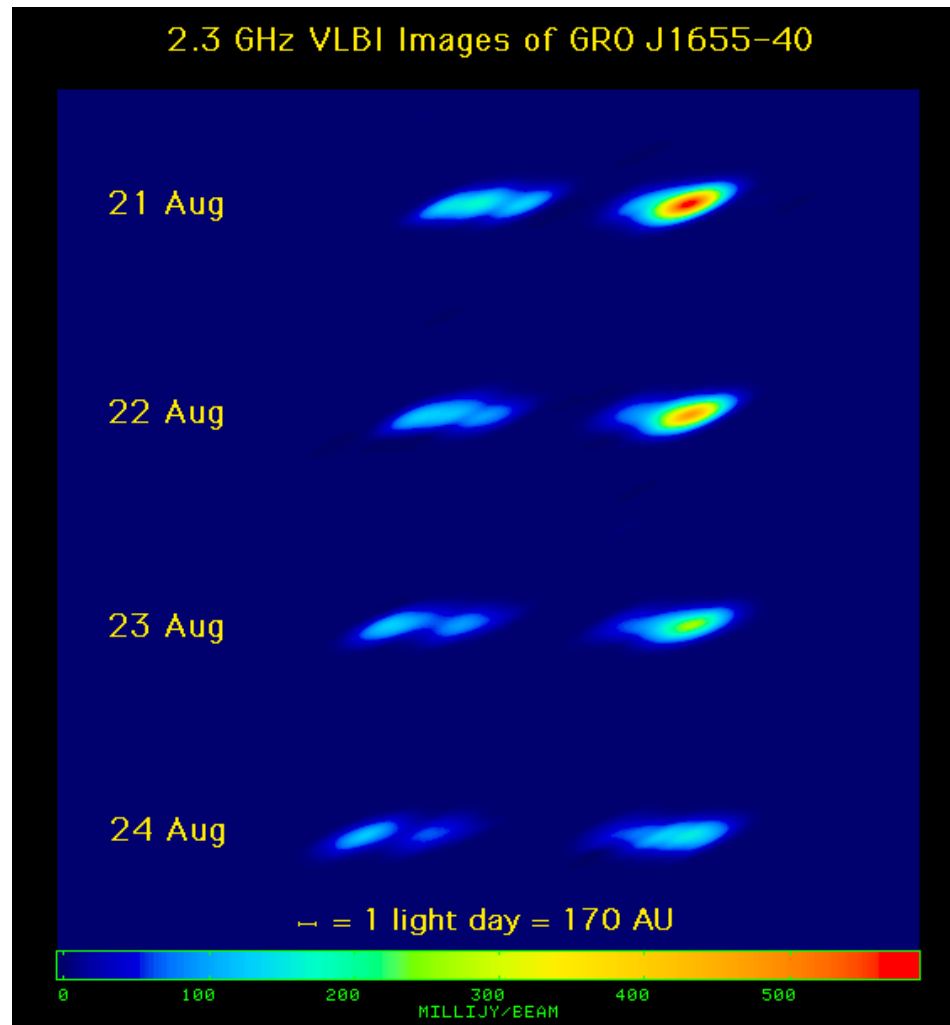
The results are presented in
Gomez et al 2000 Science, 289, 2317



3C120 at 22 GHz

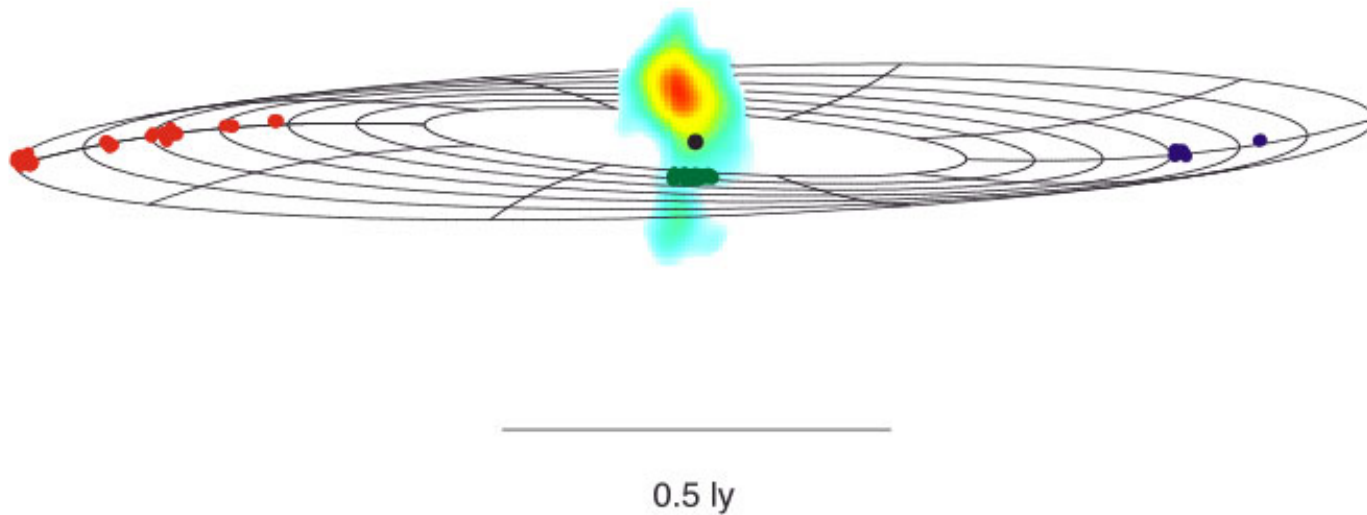


A micro-quasar in our galaxy



Tingay et al. 1995

The water megamasers in NGC 4258



Miyoshi et al. 1995; Herrnstein et al. 1999 ($D=7.4\pm 0.3$ Mpc)

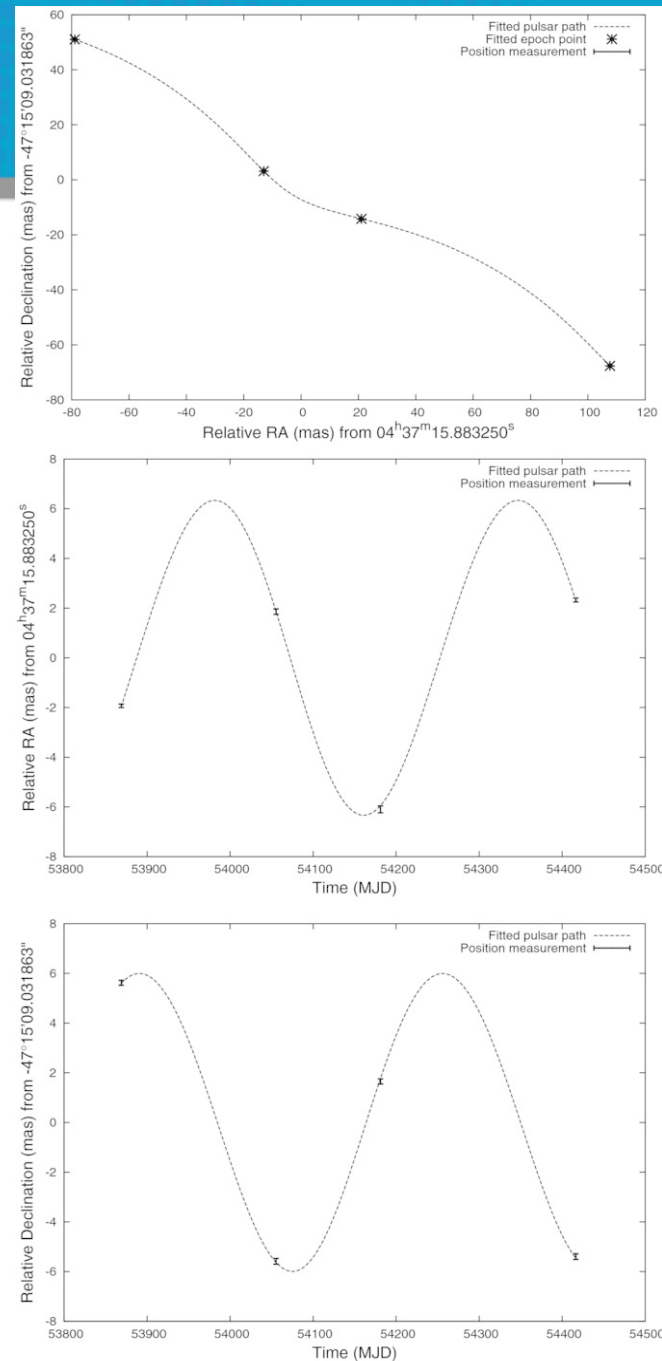
Pulsar astrometry

Four epoch LBA
observations over two
years at 8.4 GHz

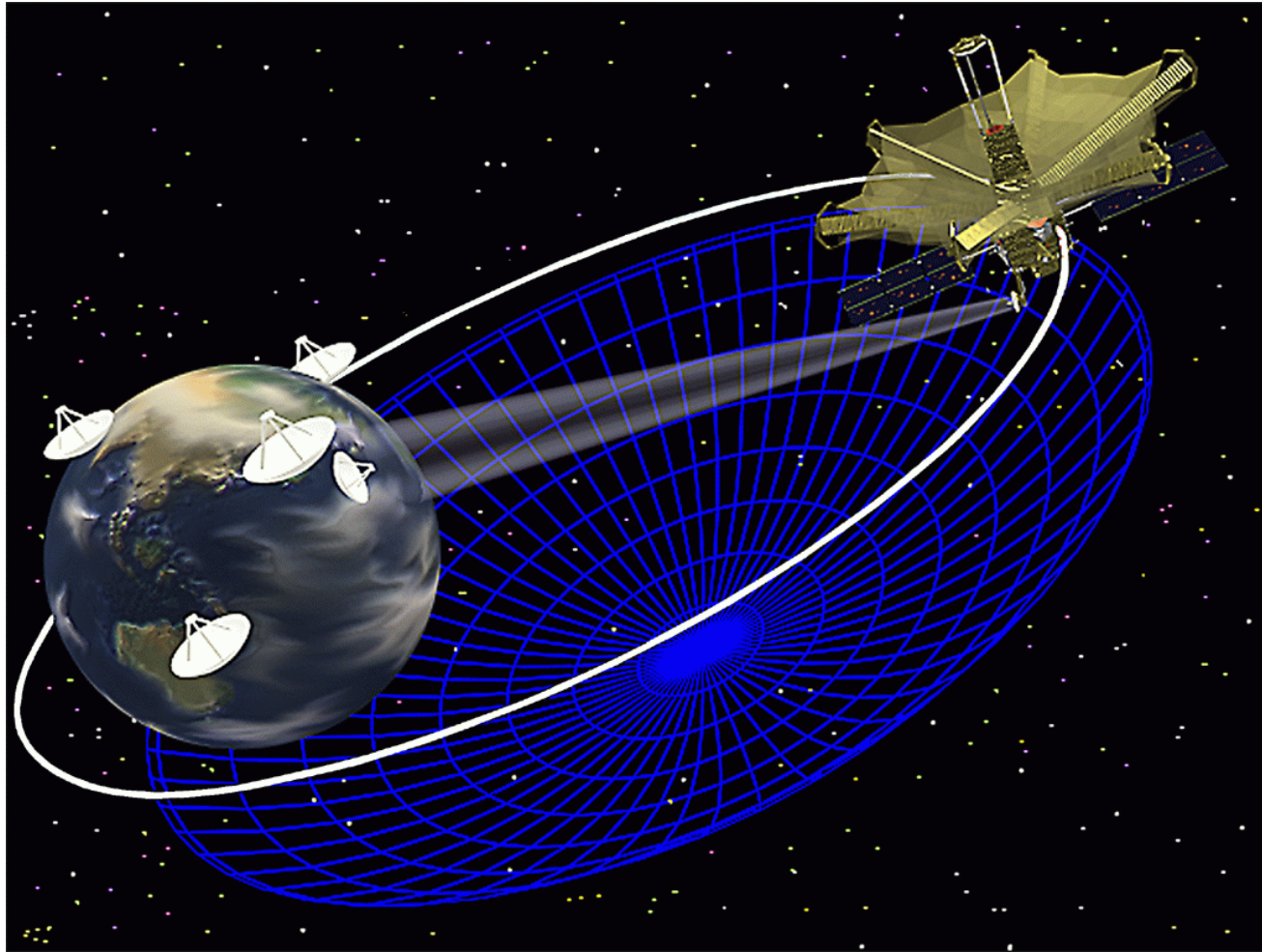
Distance 156.3 ± 1.3 pc

Transverse velocity
 104.7 ± 1.0 km/s

Figure 4 from **Precision Southern Hemisphere VLBI Pulsar Astrometry. II. Measurement of Seven Parallaxes**
A. T. Deller et al. 2009 ApJ 701 1243

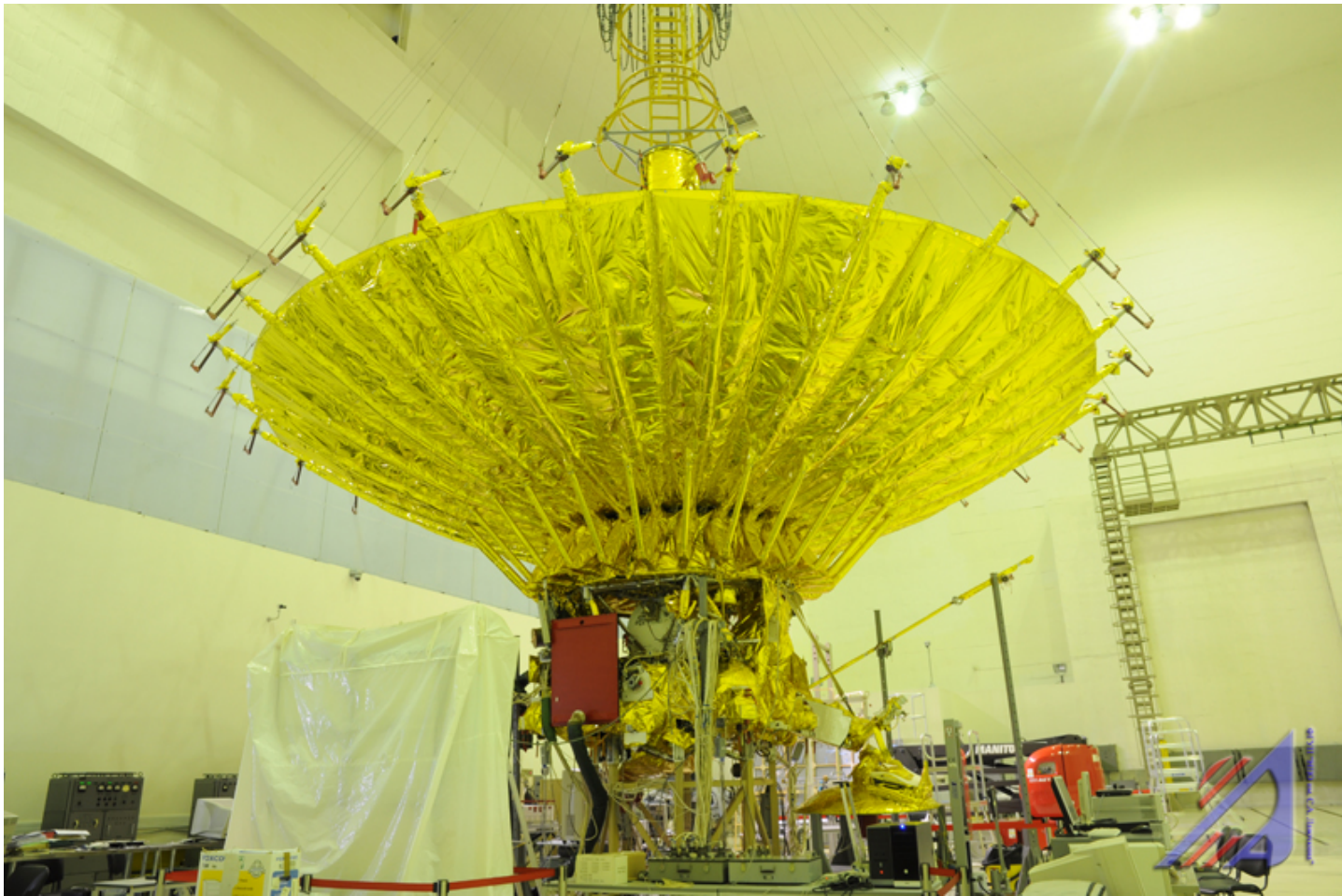


The sky's the limit!



The HALCA satellite and the VLBI Space Observatory Programme

RadioAstron



Launched 18 July 2011, with an ATNF receiver on board

Russia's RadioAstron space observatory

The RadioAstron observatory with an unprecedented high resolution capability will make it possible to observe remote objects in space

- Parabolic antenna**
- Diameter: 10 meters
 - Comprises 27 carbon-plastic "petals"

This is the first Russian orbital radio telescope

It will study:

- Galaxy nuclei
- Black holes
- Neutron stars
- Interstellar plasma clouds
- The Earth's gravitational field
- And many other objects and phenomena in the Universe

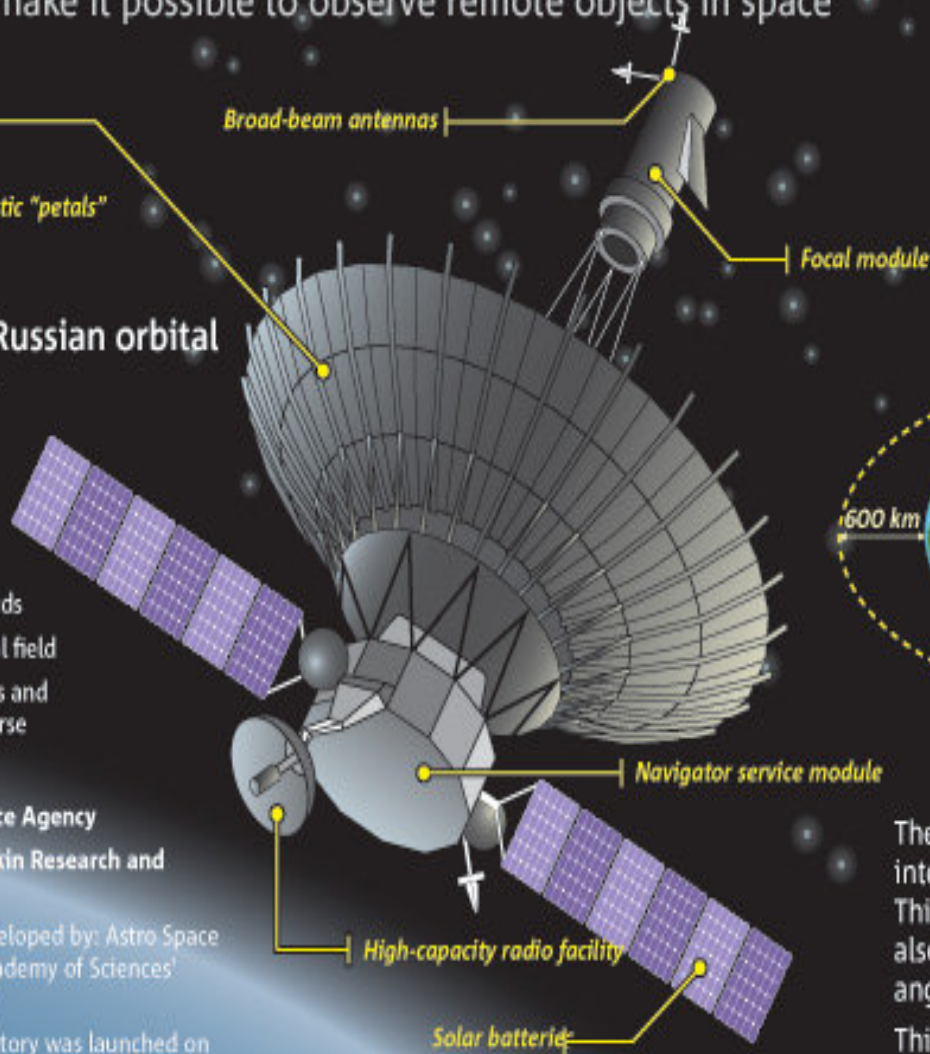
Ordered by: **Federal Space Agency**

Chief contractor: **Lavochkin Research and Production Association**

Scientific equipment developed by: **Astro Space Center of the Russian Academy of Sciences' Lebedev Physics Institute**

The RadioAstron observatory was launched on July 18, 2011.

Active service life: At least five years



- Highly elliptical orbit**
- Apogee: 330,000 kilometers
 - Perigee: 600 km
 - Orbital period: 8.2 days



The RadioAstron observatory will operate with an international network of ground-based radio telescopes. This huge ground- and space-based telescope system, also called an interferometer, will provide the finest angular resolution.

This will make it possible to obtain images of remote objects with a resolution exceeding that of NASA's Hubble orbital telescope a thousand times over

Summary

- VLBI is not really that different from connected element interferometry
- The phases are less well behaved
- Improvement in angular resolution of 1000x
- Increased reliability and enhanced capabilities now available
- Next LBA deadline Dec 15th
 - www.atnf.csiro.au/vlbi



CSIRO/ATNF

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Thank you

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