

Very Long Baseline Interferometry

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*ATNF Synthesis Imaging School, Narrabri
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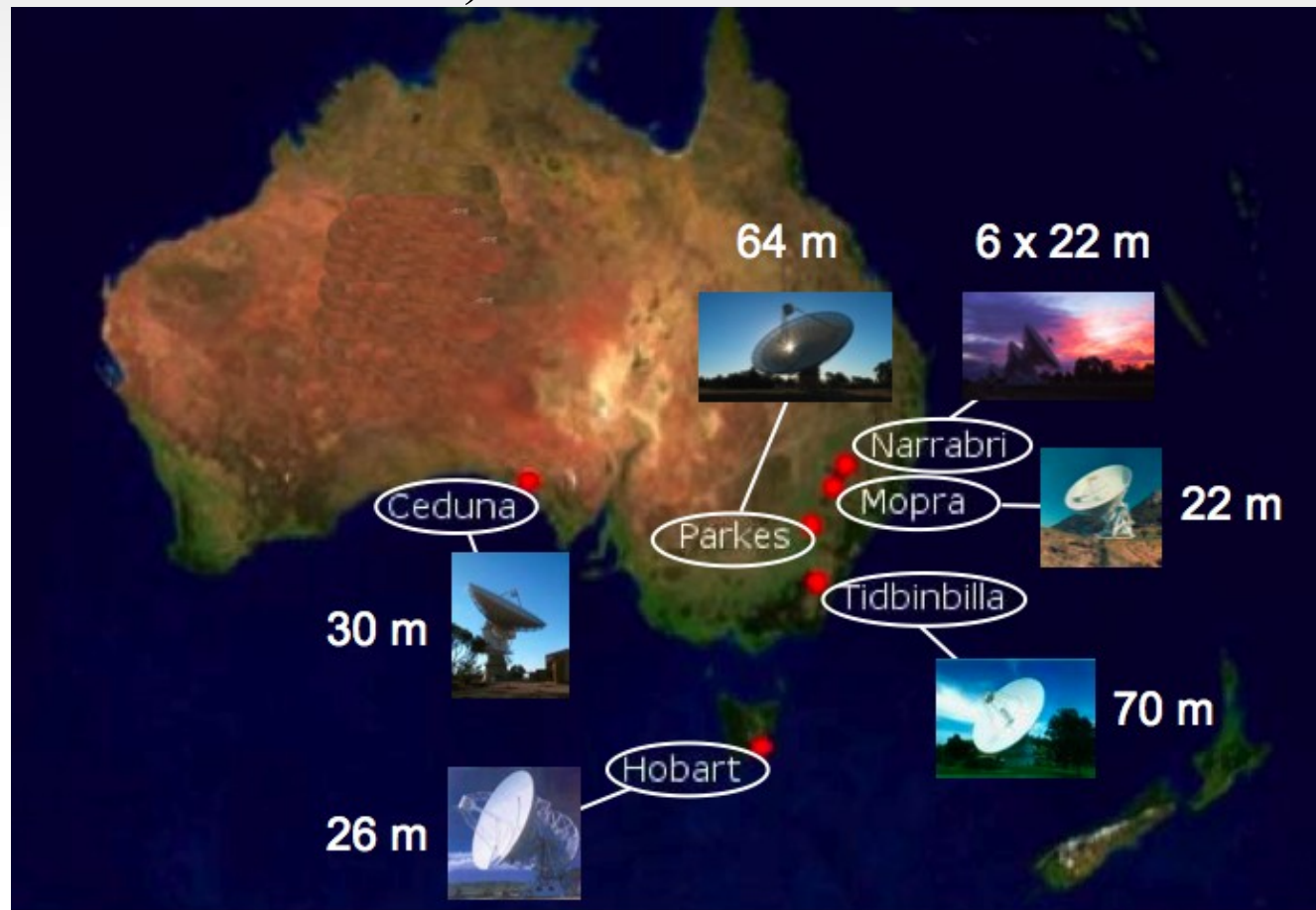
Outline

- Very brief history
- Data acquisition
- Calibration
- Applications

Acknowledgements: C. Walker, S. Tingay

What Is VLBI?

- VLBI: Very Long Baseline Interferometry
- Very Long Baseline: baselines long enough to make life difficult, (e.g. no distributed LO...)



Very Brief History of VLBI

- First interferometers all used a distributed clock and real time correlation – limited to 10's of km.
- 1950s – first long baseline 'intensity' interferometers (no phase)
- Early 1960's – Jodrell Bank microwave linked 127 km baseline
- Mid 60's – first rubidium standards and affordable tape recorders
 - 1967 – first VLBI fringes
- 1997 – Space VLBI
- 2001 – Disk recording systems

Alef 2004



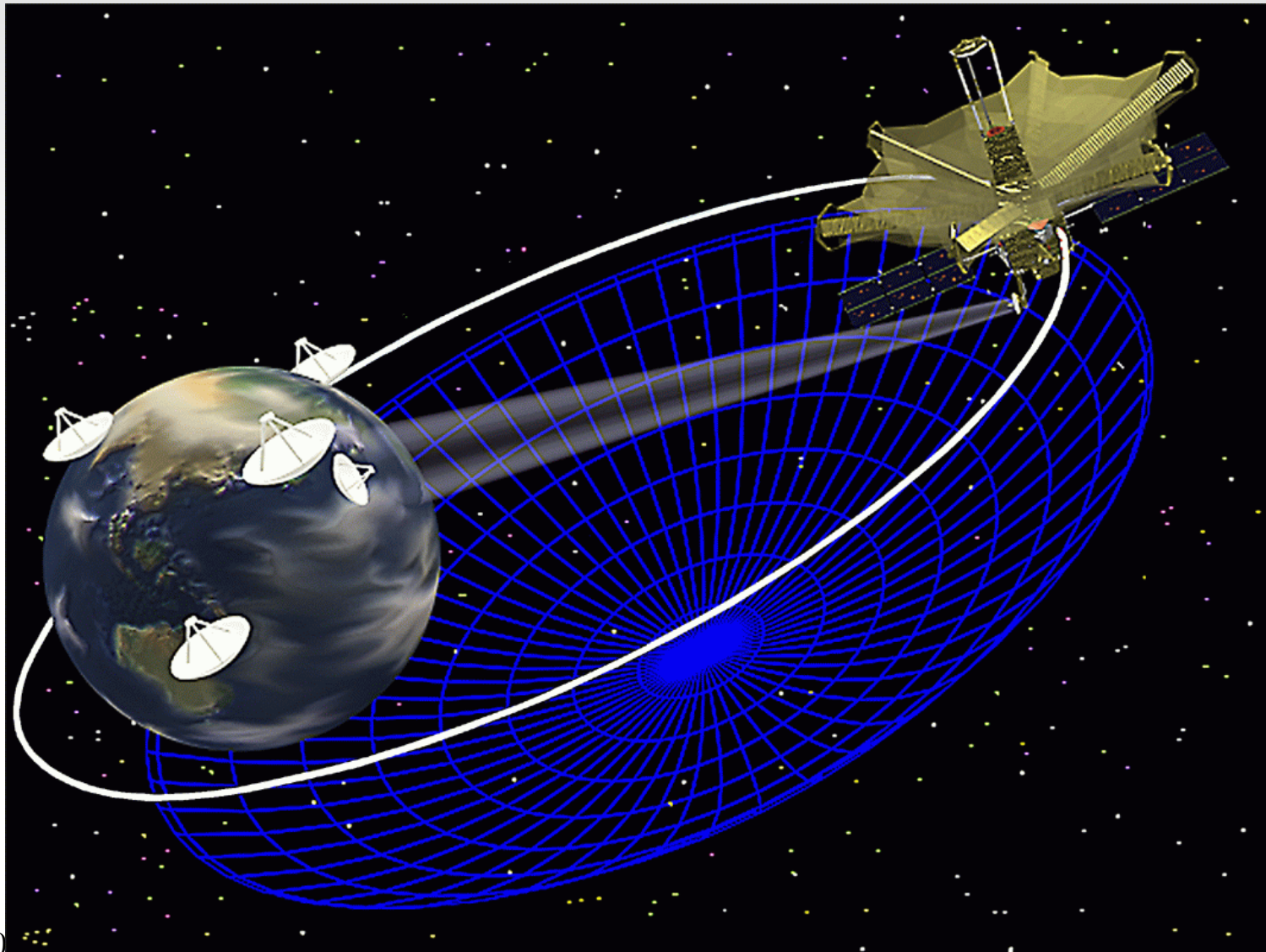
VLBI Arrays

- LBA (Australia)
- EVN (Europe, China, South Africa, Arecibo)
- VLBA (USA)
 - EVN + VLBA coordinate joint observing => Global VLBI
 - VLBA + VLA + GBT + Arecibo + Efflesberg => High Sensitivity Array (HSA)
- VERA (Japan)
- Geodetic network (Global)
 - AUSCOPE (Australia 2009)

Can form a global network of radio telescopes

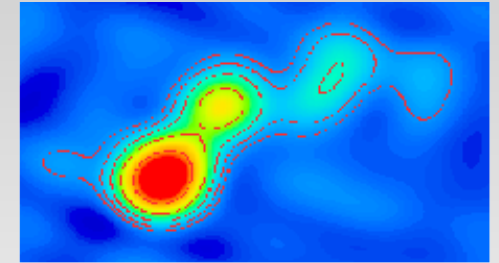


Highest resolution: space VLBI

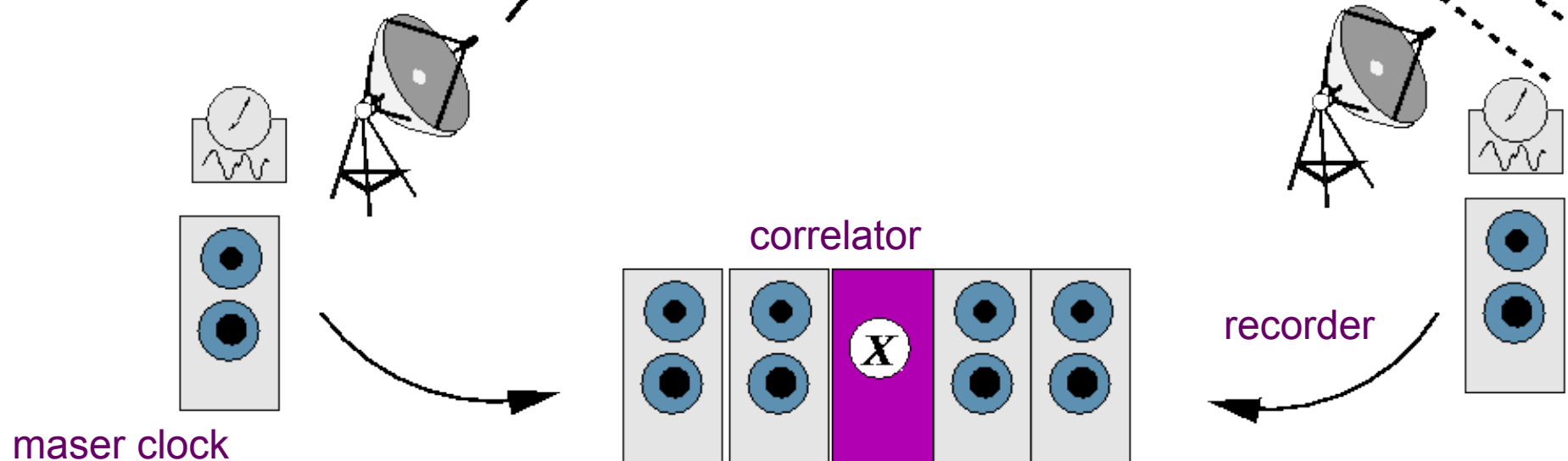


Principle of VLBI

- Record same frequency band simultaneously at N telescopes
- Use earth rotation to sample various spatial scales
- Obtain high spatial resolution measuring Fourier components of sky brightness



weak radio source

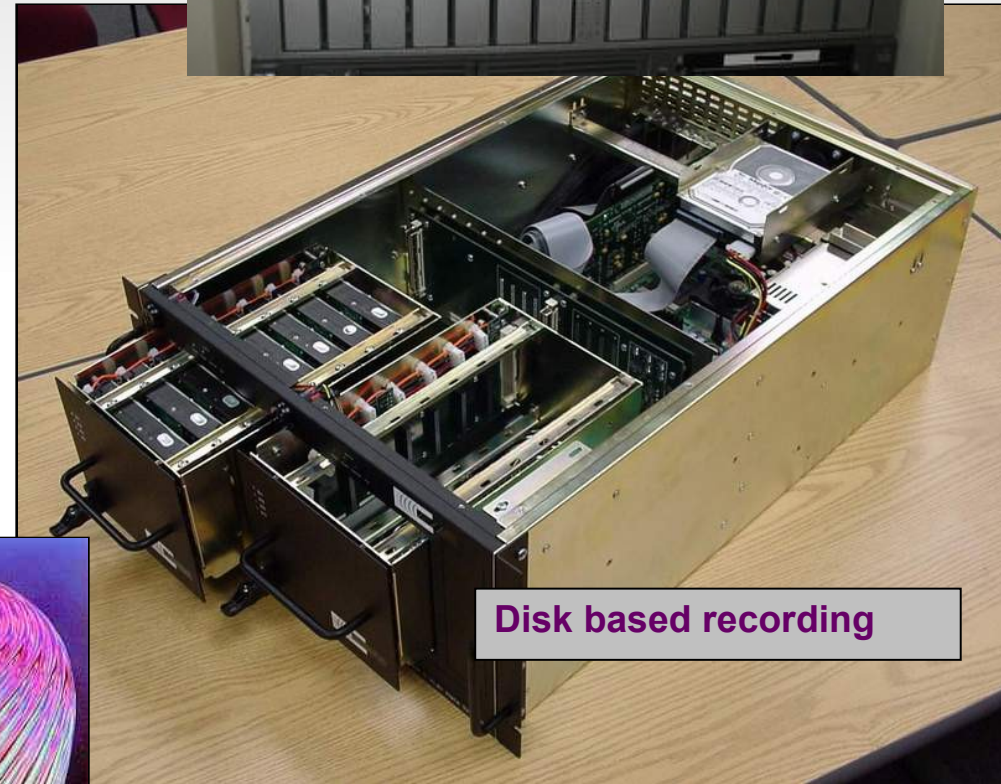


VLBI in a Nutshell

- Just interferometry
- Baseband data usually recorded on disks – limited bandwidth, data transport by truck (except *e*VLBI)
- Independent clocks at each station – phase/delay errors
- Telescopes moving at different speeds w.r.t source
 - Requires sophisticated earth orientation model (for correlator)
- No flux calibrators or point sources
- Heterogeneous arrays (except VLBA)
 - different primary beams
 - different a priori calibration possibilities
- Longer baselines => increased time and BW smearing
 - less correlator averaging, hence bigger datasets for given FOV

Data Acquisition

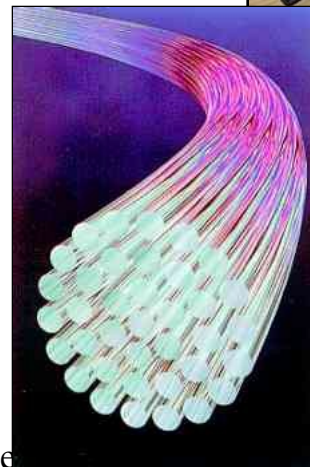
- Standard is disk recording
- eVLBI will be the future
 - No consumables
 - Higher bandwidth
 - Fast turn-around



Disk based recording



disk VLBI using light aircraft



eVLBI using fiber

VLBI Signal Path

- 2-4 cables bring IF signals from antenna to IF distributor
- Baseband Converters are fed by the IF distributor
 - BBCs have up to 16 x 16 MHz outputs
- BBCs output baseband signal to formatter
- Accessible spectrum often constrained by fixed first LO (to IF) and BBCs tunable over a range of 400-500 MHz
- BBC output digitally sampled at 1-8 x Nyquist rate (usu. 1) with 1 or 2 bits
- Data recorded on disk (Mk5A => Mk5B soon, LBA DAR)

VLBA Signal Path

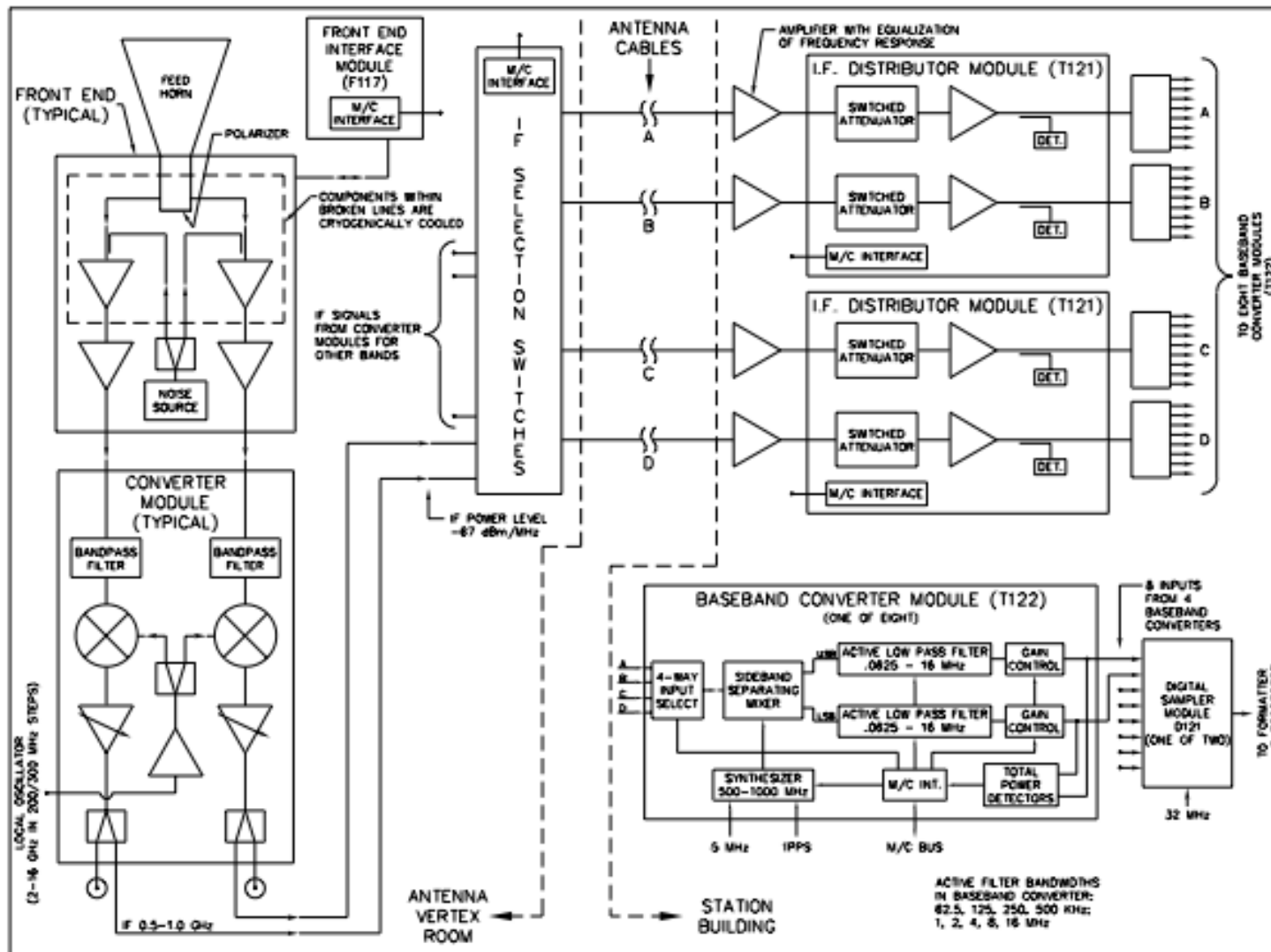
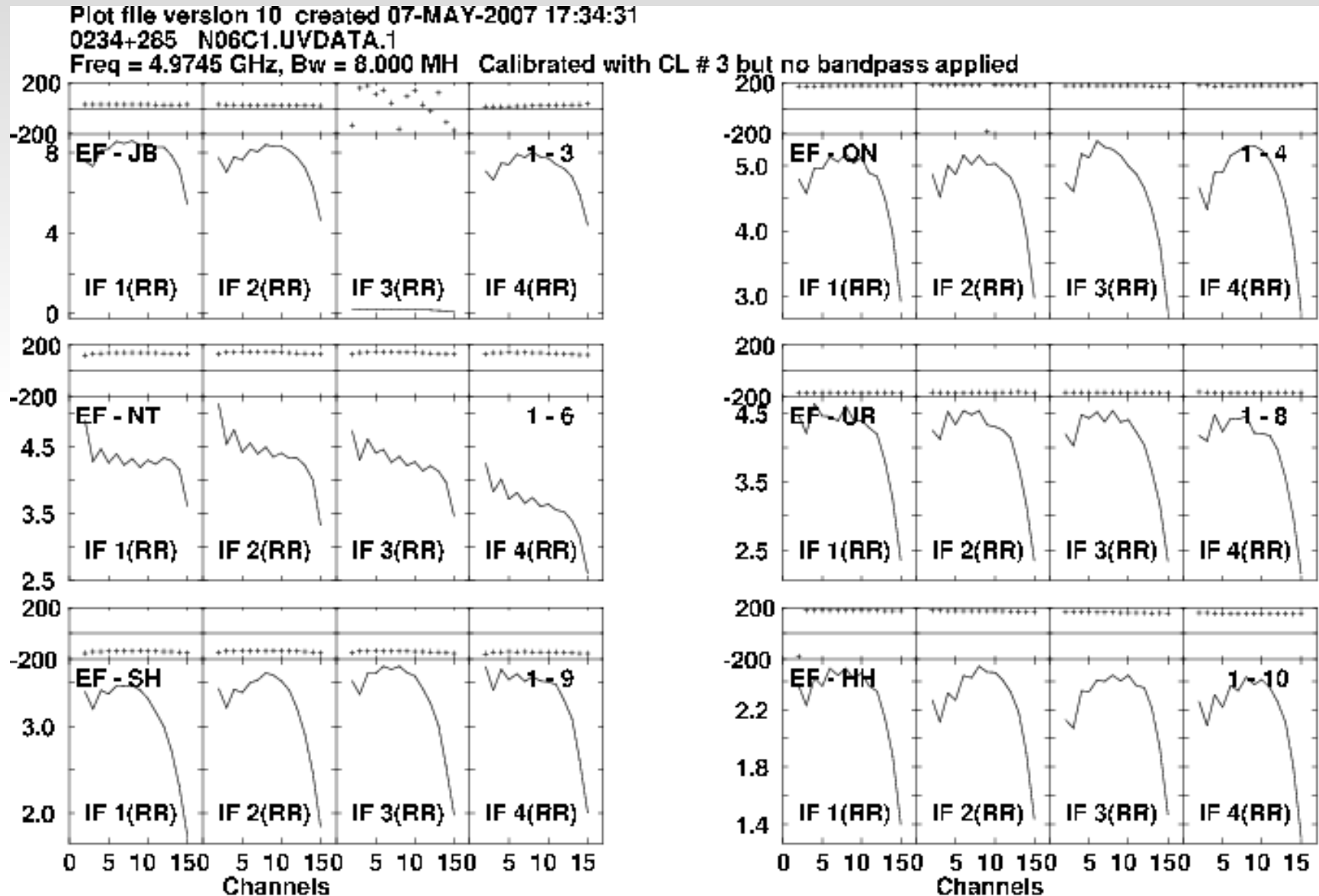


Figure 5.3: Simplified block diagram of the analog signal path at RF, IF, and baseband frequencies.

VLBI Frequency setup

- Constrained by (often fixed) first LO and limited tuning range of BBCs (approx 500 MHz with current systems)
- BBCs produce up to 16 independently tunable subbands (0.5 – 16 MHz)
 - useful for wide bandwidth coverage (RM or Spectral index mapping, improved u,v coverage)
- Any frequency (usually) within the 500 MHz range is simultaneously available, though maximum recordable bandwidth is 128 MHz for dual-pol, 2-bit (= 1Gbps)
 - fast frequency switching possible on VLBA
- Data within subbands channelised by correlator (gives spectral resolution, prevents de-correlation and bandwidth smearing)

VLBI Subbands (AIPS IFs)

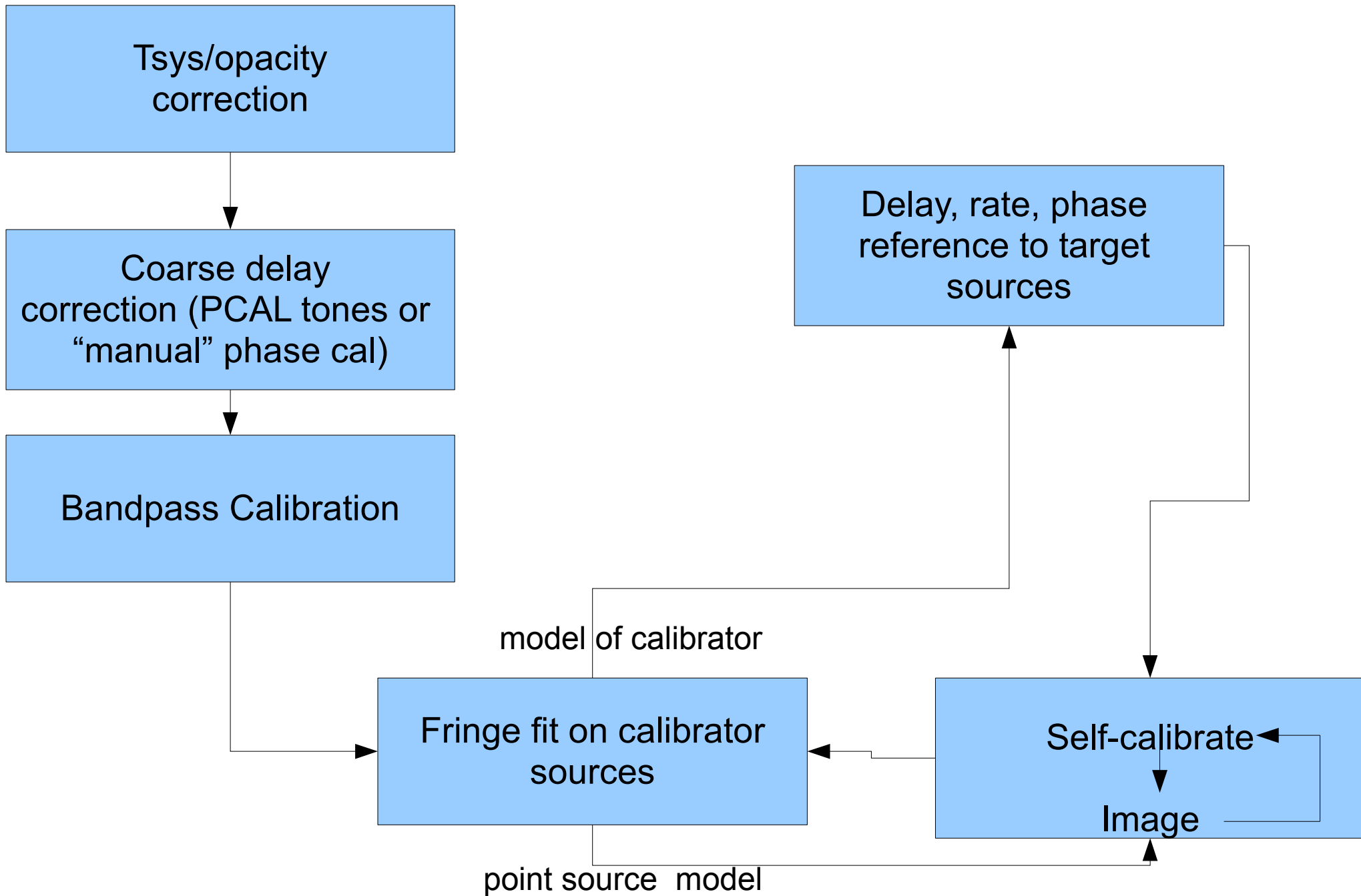


Lower frame: Ampl Jy Top frame: Phas deg
 Scalar averaged cross-power spectrum Several baselines displayed
 Timerange: 00/13:56:02 to 00/14:05:58

How Many Bits?

- VLBI observations limited by available recording rate
- 2-bit increases sensitivity by factor 1.38 over 1 bit
- Doubling bandwidth improves sensitivity by $\sqrt{2} = 1.41$ (assuming a continuum source)
 - practicalities tend to favour 2-bit with half the bandwidth
- 4-bit only increases the sensitivity by factor 1.1 over 2-bit (TMS)
 - inefficient use of limited recording rate
 - not available on current VLBI systems
- Digitization losses may be compensated for at the correlator, or in post processing.

VLBI Data Analysis



Delay Calibration

- Interferometer phase is frequency times delay
- The delay offset gives a phase slope as a function of frequency
- The change of this delay with time is the fringe rate
- The data are correlated with a range of delays and rates which encompass the actual values
- The delay can then be solved for in the analysis
 - => Fringe fitting

Fringe Fitting

- Correlator model errors (delay)
 - atmospheric fluctuations, clock errors
- Interferometer Phase: $\phi_{t,\nu} = 2\pi \nu \tau_t$
 - τ = interferometer delay
 - phase error depends on delay error
- Linear phase model for a baseline
$$\Delta \phi_{(\tau,\nu)} = \phi_0 + \frac{\delta \phi}{\delta \nu} \Delta \nu + \frac{\delta \phi}{\delta t} \Delta t$$
 - phase error at reference time and freq; delay; delay rate
- Determined by process of fringe-fitting

Fringe-Fitting

- Baseline fringe-fit
 - FT to delay-rate domain
 - Fit each baseline independently for delay and rate
 - Must detect source on all baselines and does not preserve closure

- Can factor delay model by antenna

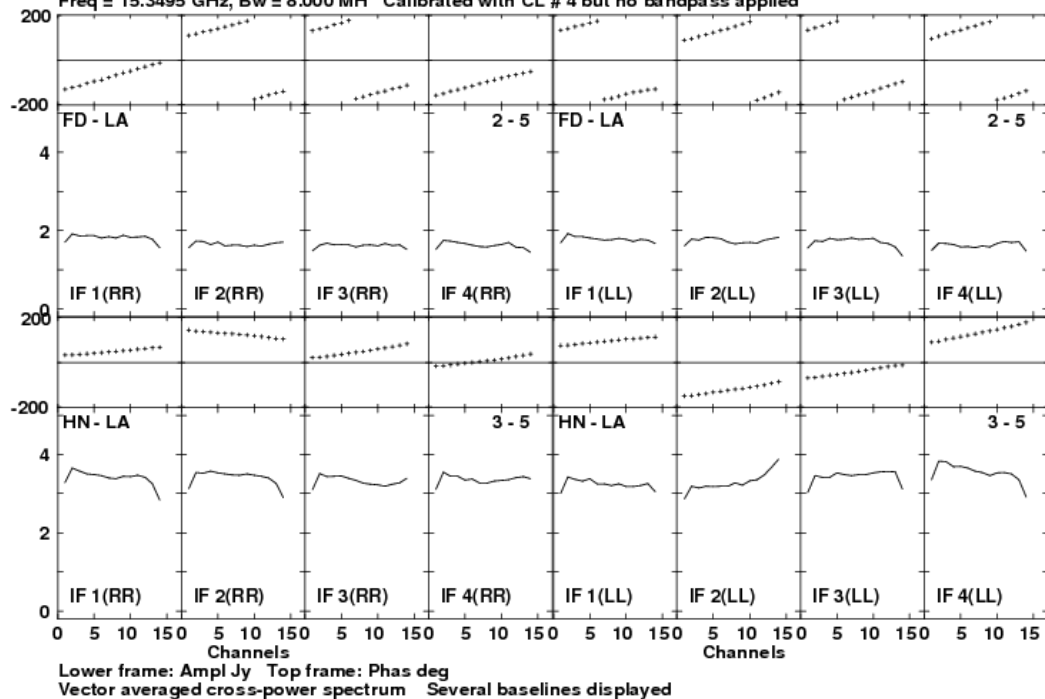
$$\Delta \phi_{ij} = [\phi_{i0} - \phi_{j0}] + \left[\frac{\delta \phi_i}{\delta \nu} - \frac{\delta \phi_j}{\delta \nu} \right] \delta \nu + \left[\frac{\delta \phi_i}{\delta t} - \frac{\delta \phi_j}{\delta t} \right] \Delta t$$

- Global fringe-fit (equation above)
 - Use all baselines to jointly estimate *antenna* phase, delay, rate relative to a reference antenna
 - Choice of solution time important – must have good SNR, but not exceed coherence time
 - Good a-priori source model can help...

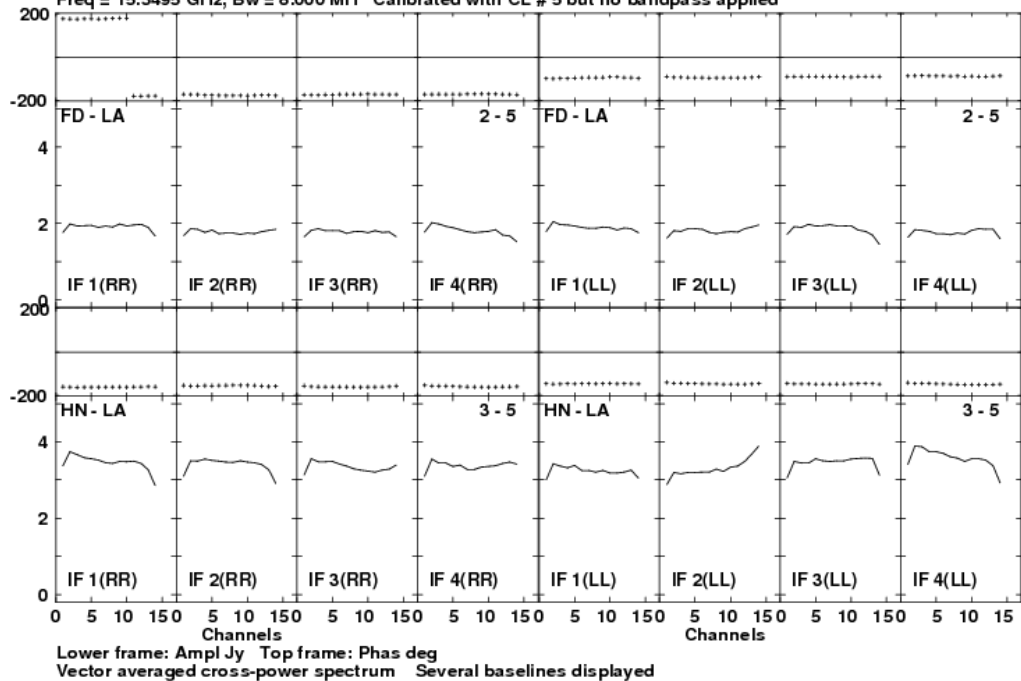
Phase cal signals

- VLBI data usually has multiple subbands
 - partially independent phases and delays, some calibration required before averaging.
- Stable calibration tones injected near feed
 - measure the instrumental phases and delays
- Used to improve initial alignment of phases
- “Manual” phase-cal also useful
 - fringe-fit short interval on strong calibrator
 - apply delay solutions to full experiment
 - assumes instrumental delays slowly varying (usu. true)

Plot file version 1 created 01-OCT-2008 08:09:51
J0927+39 BP124A KU.UVCOP.1
Freq = 15.3495 GHz, Bw = 8.000 MH Calibrated with CL # 4 but no bandpass applied



Plot file version 2 created 01-OCT-2008 08:09:55
J0927+39 BP124A KU.UVCOP.1
Freq = 15.3495 GHz, Bw = 8.000 MH Calibrated with CL # 5 but no bandpass applied



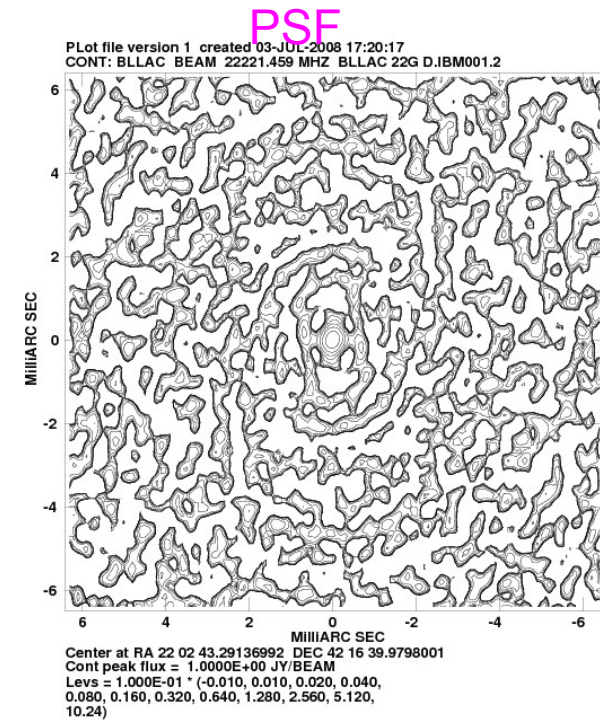
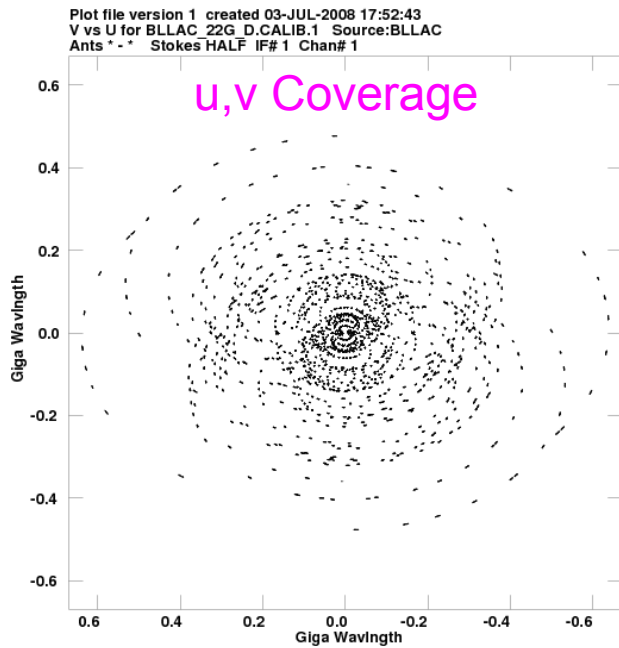
Phase Referencing

- Transfer self-cal and/or fringe fit solutions from calibrator source to nearby target
- Must have excellent earth orientation model (e.g. antenna positions better than a few cm)
- Sources must be close - described by a single atmosphere and errors resulting from earth model increase with distance
- Switching times must be shorter than the atmospheric fluctuations ($< \sim 10$ mins at 5 GHz)
- Should remove calibrator source structure phases before applying corrections

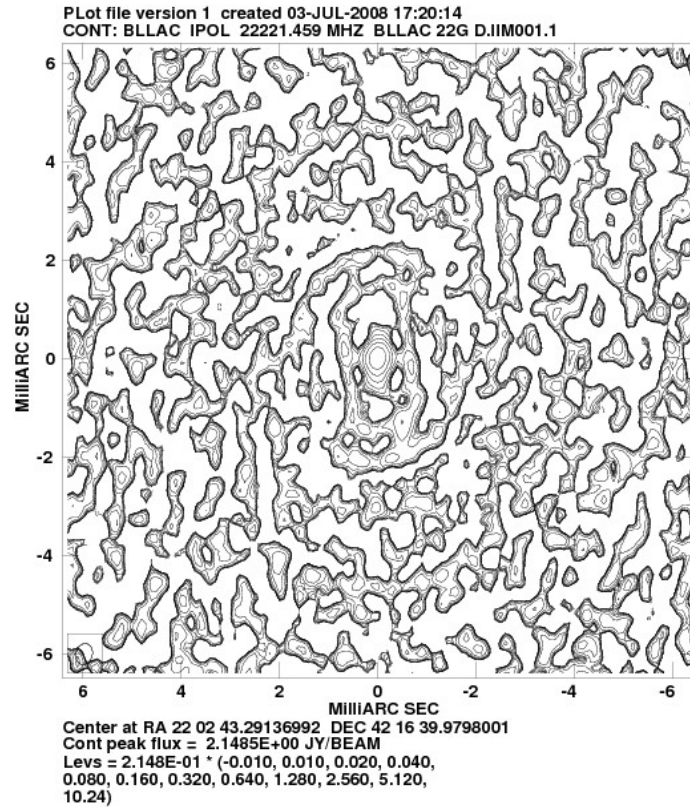
Self-calibration and mapping

- Similar to any other interferometer (see Tingay and Wieringa lectures)
 - sparse u,v coverage and poor a priori calibration can make deconvolution tricky and convergence slow

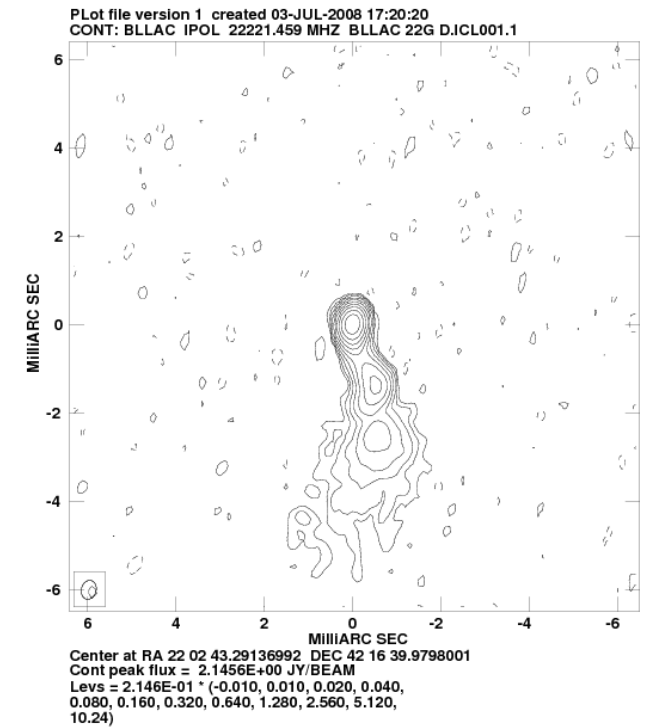
Deconvolution - Example



'Dirty' Image



'Clean' Image



A Priori Amplitude Calibration

- There are no standard flux calibrators on VLBI scales
 - sources that compact are variable
- Must measure sensitivity of the individual stations
- Tsys and Gain curves distributed as additional tables with your visibility data
- Tables can be loaded with ANTAB (if not already attached) and applied with APCAL.
 - currently only available in AIPS

System Noise & Source Equivalent Flux Density (SEFD)

- In the usual case where system noise power dominates over noise power from the source, then the net amplitude of the complex correlation coefficient is

$$C_{ij} = B \frac{V_{ij}}{\sqrt{N_i N_j}}$$

Where V_{ij} is the visibility amplitude in Jy, B is the dimensionless factor taking into account the effects of digitisation and N_i and N_j represent the system noise of the two antennas expressed as a Source Equivalent Flux Density (SEFD) in Jy

- The SEFD is defined as the source flux density that would contribute an antenna output equal to that due to the system noise, i.e. which would double the total antenna power

SEFD

- The SEFD of an antenna can be divided into two parts such that

$$N = \frac{T_i}{G_i}$$

where T_i is the system temperature in K and G_i is the antenna gain in K/Jy

- T_i is defined as the physical temperature of a load in the antenna beam that contributes the same output power as the system noise
- G_i is defined as the increase in system temperature that occurs when looking at a 1Jy source. G_i changes mainly due to elevation dependent distortions of the dish due to gravity

System Temperature

- System defined as the increase in system temperature that occurs when looking at a 1Jy source. G_i changes mainly due to elevation dependent distortions of the dish due to gravity

$$T_{sys} = T_{receiver} + T_{ground} + T_{sky}$$

- System temperatures can vary unpredictably during a VLBI experiment due to changes in the receiver temperature, the spillover, RFI etc. and so must be monitored continuously
- A calibration source (usually a broad-band ‘noise cal’ signal) of constant noise temperature T_{cal} is periodically injected the system temperature T_{sys} can be derived via;

$$T_{sys} = \frac{T_{cal} P_{cal-off}}{P_{cal-on} - P_{cal-off}}$$

Gain Calibration

- For the purposes of calibration, G must be found experimentally by measuring the change in system temperature going on and off sources of known flux density (usually done beforehand)
- The antenna gain can be parameterised in terms of an absolute gain or DPFU (Degrees Per Flux Unit) and an accompanying gain curve g , usually expressed as a polynomial function of elevation or zenith angle z such that the DPFU multiplied by the polynomial gives the correct antenna gain at each elevation, thus

$$G(z) = DPFU \times g(z)$$

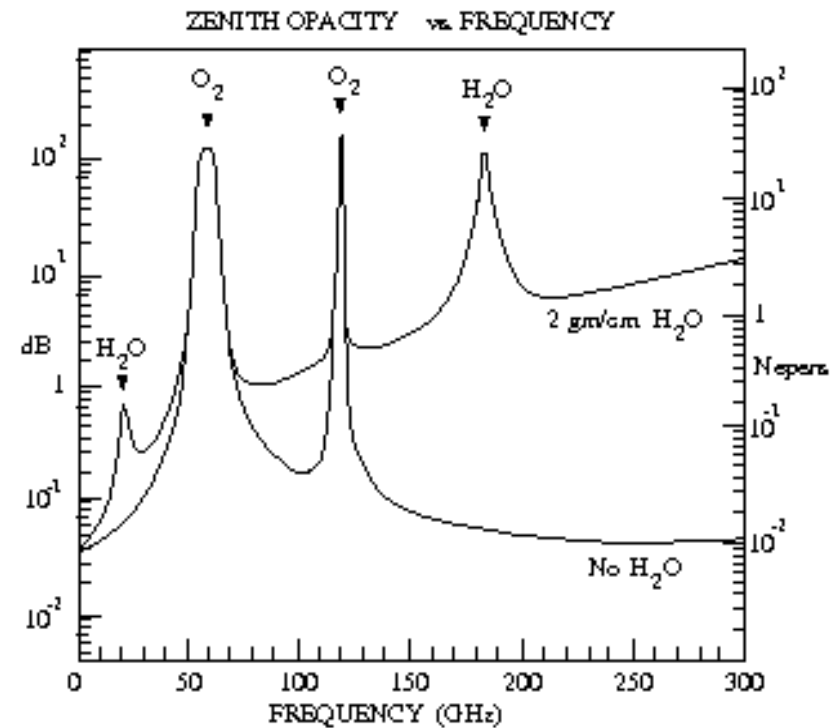
where the polynomial $g(z)$ is

$$g(z) = a_0 + a_1 z + a_2 z^2 + a_3 z^3 \dots$$

This “gain curve” should be distributed with your data.

Opacity Effects

- Radio waves are also absorbed by the atmosphere
- Mostly due to spectral lines of water vapor and oxygen, hence most severe at 20 GHz and above
- Can estimate change in T_{sys} if T_{rec} and T_{atm} are known independently (APCAL)
- New techniques will use a Water Vapour Radiometer (can also estimate the atmospheric delay for phase calibration)



Atmospheric Opacity Vs freq (TMS)

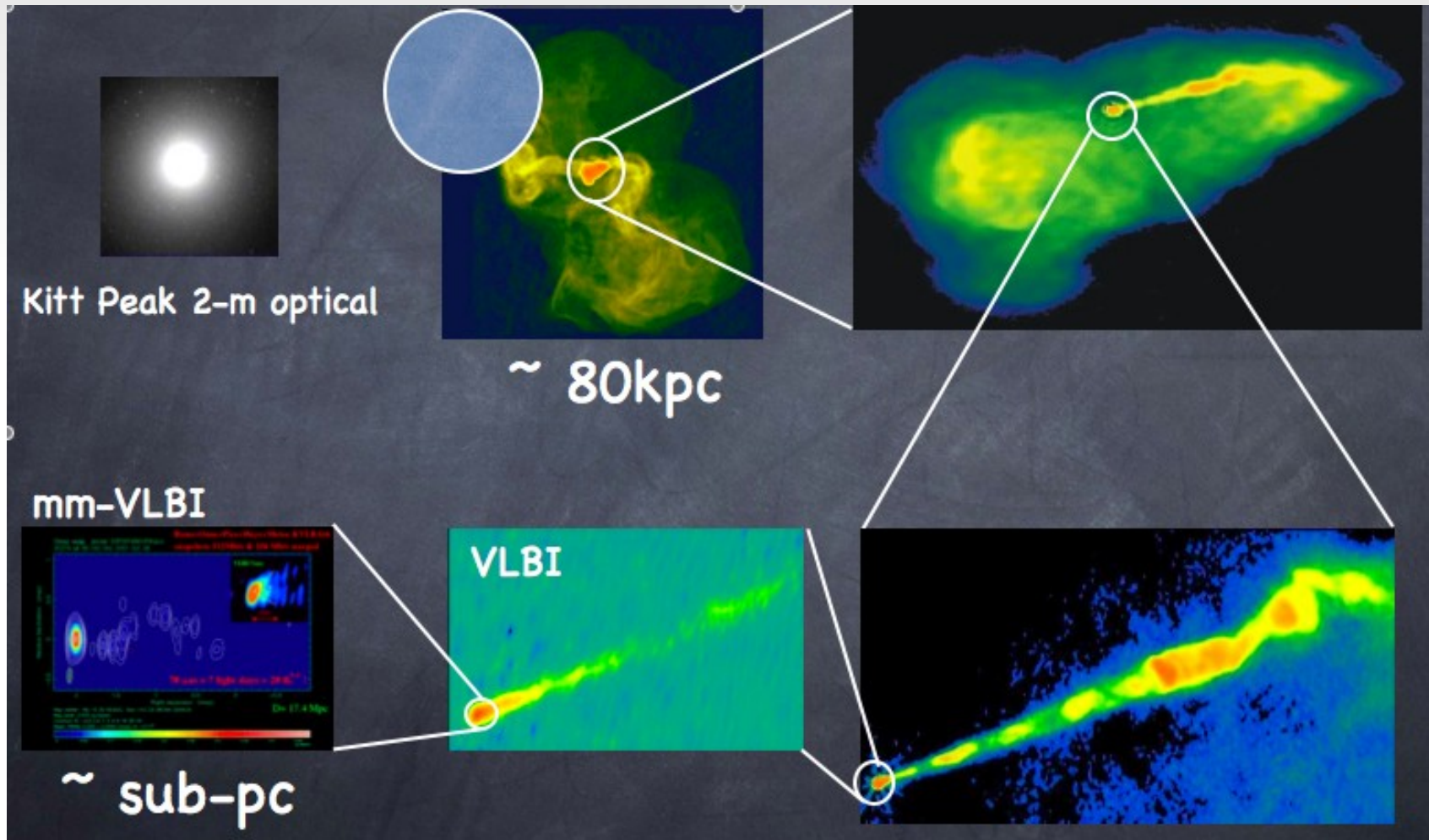
A Priori Amplitude Calibration Summary

- Essentially, the combination of DPFU, gain curve and calibration signal temperature T_{cal} are all that are required to provide accurate calibration information for a given antenna
- The absolute values of these parameters are not important, only that their combination reflects the actual performance of the antenna

VLBI – The Motivation

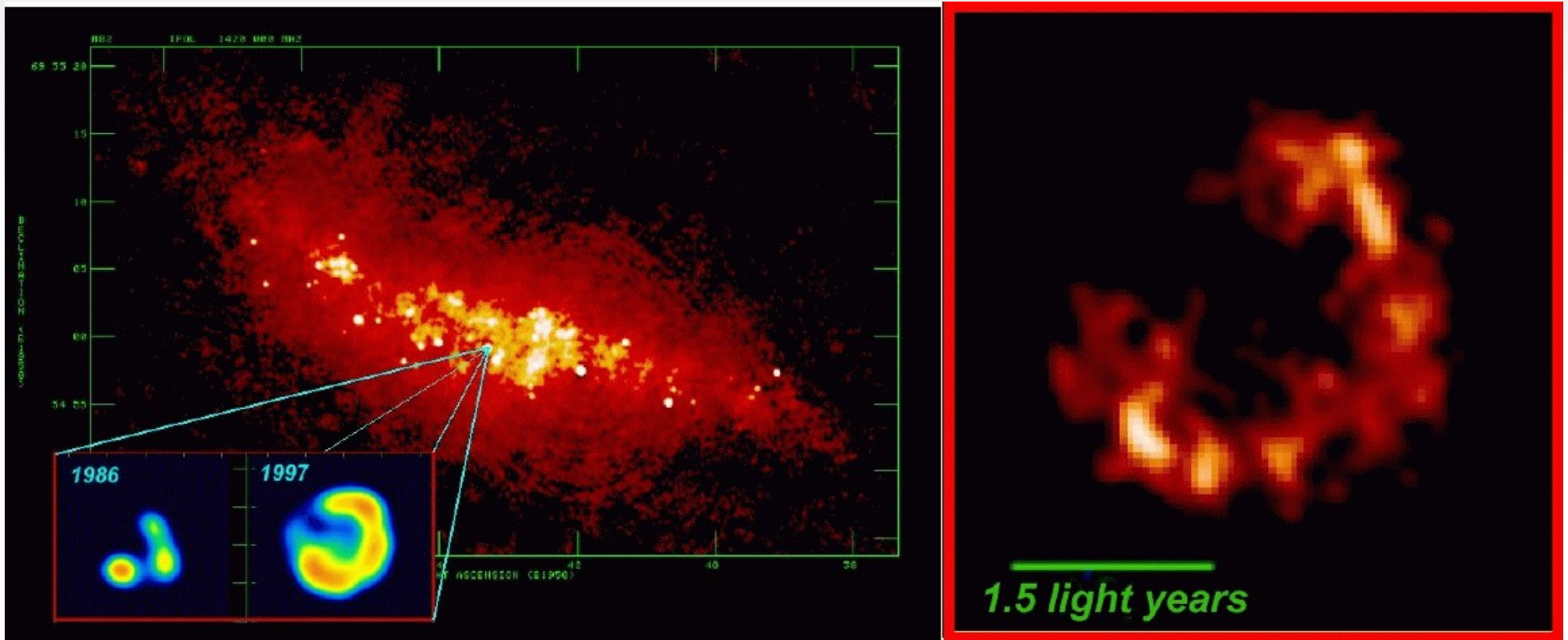
- VLBI enables imaging with (sub-) milliarcsecond resolution
 - AU scale for galactic objects
 - pc scale for extragalactic objects
 - These are scales on which changes can occur on human timescales
 - Unrivalled astrometric precision
- Geodetic applications
 - Ties terrestrial reference frame to inertial celestial reference frame
 - Measure polar motion and continental drift
- Spacecraft Tracking

M87 On All Scales



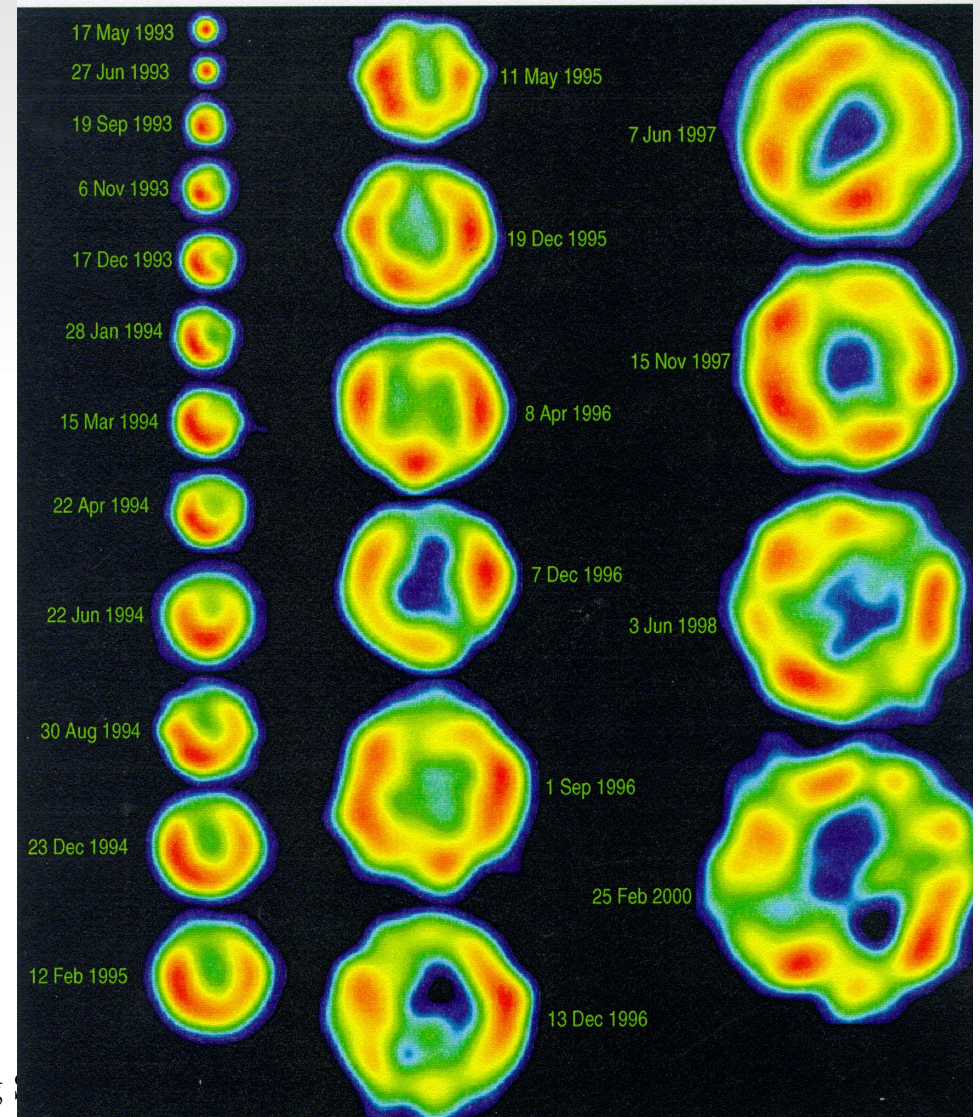
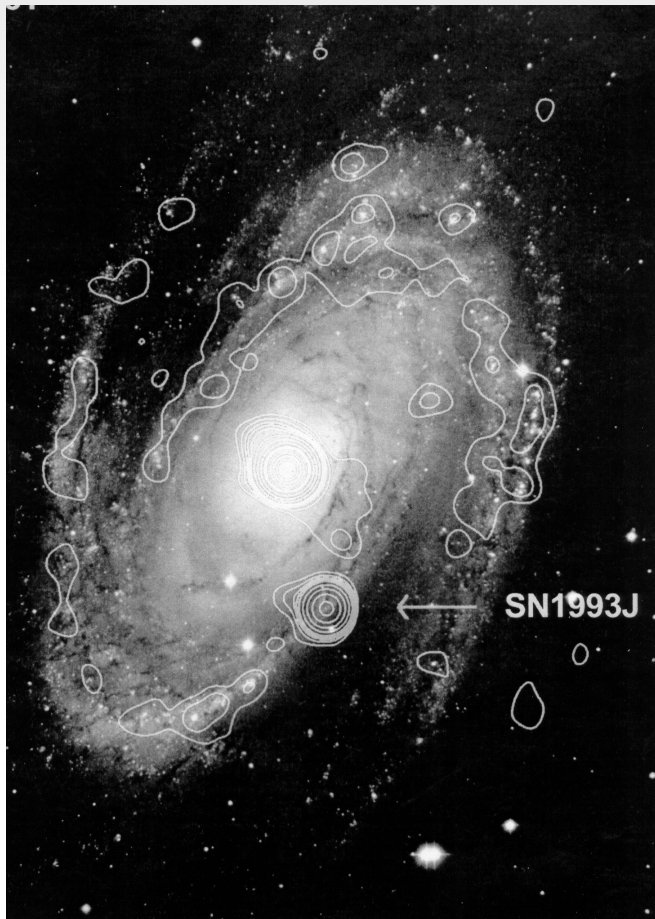
Results in extremely high resolution

- Supernova remnants in M82 (low-res MERLIN, high-res VLBI)



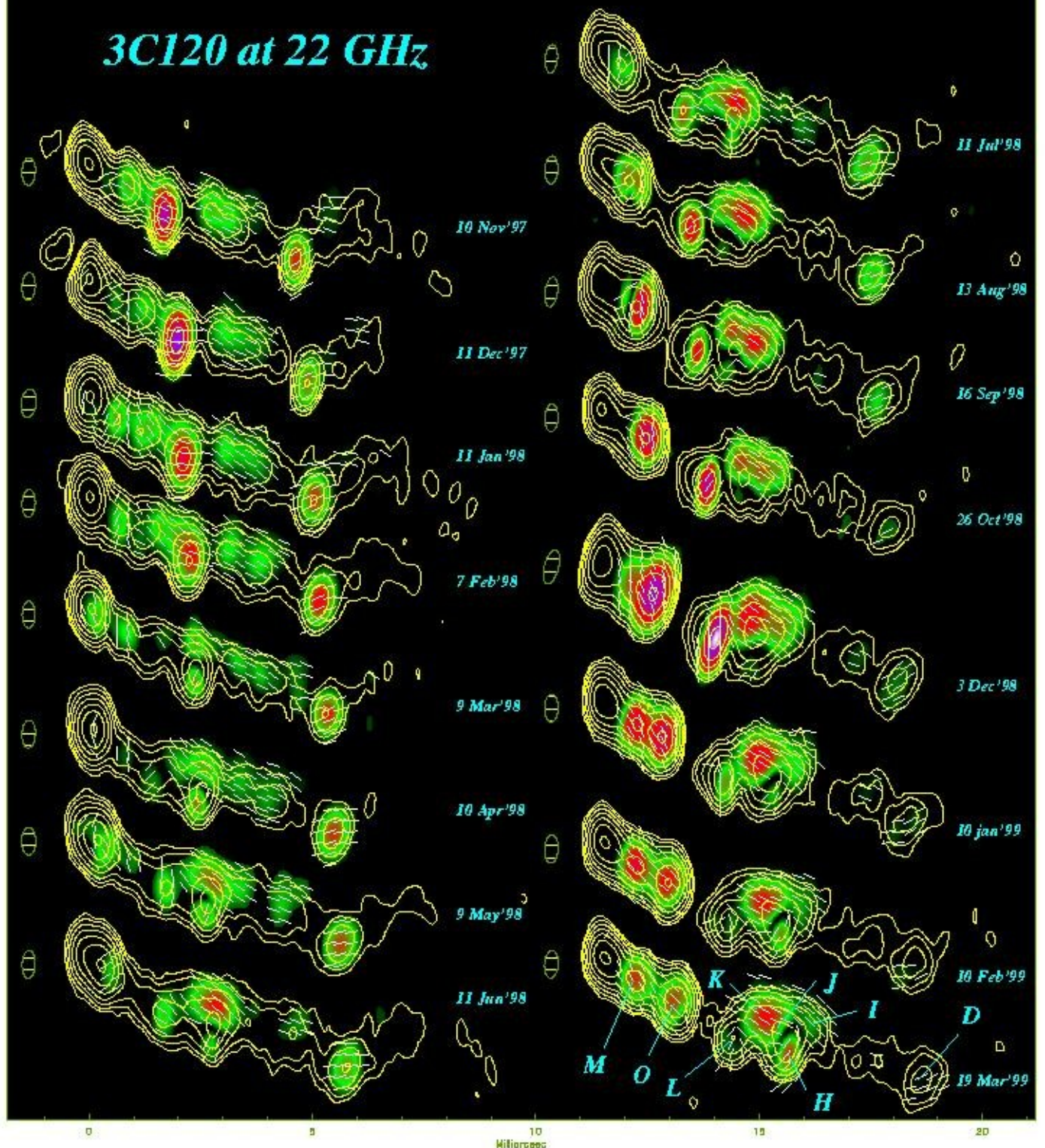
Exploding stars in other galaxies

supernova in M81 (1993)

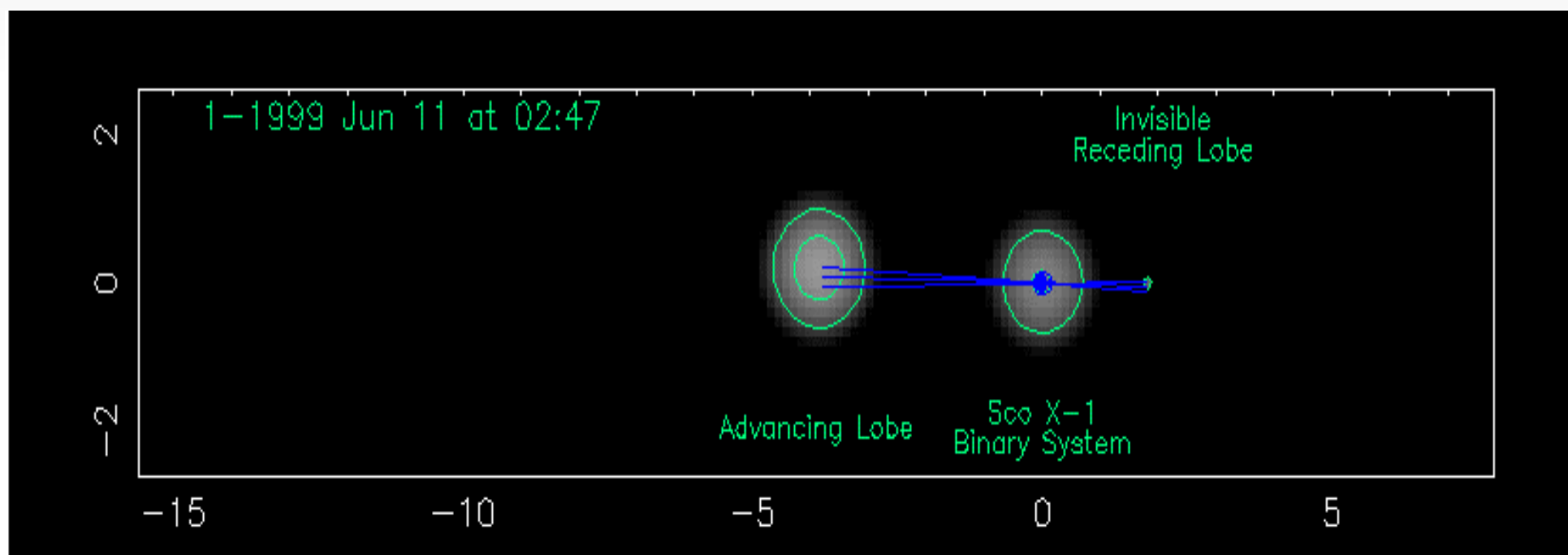


3C120

3C120 at 22 GHz



- Sco-X1 (low mass X-ray binary) evolving over 2 days



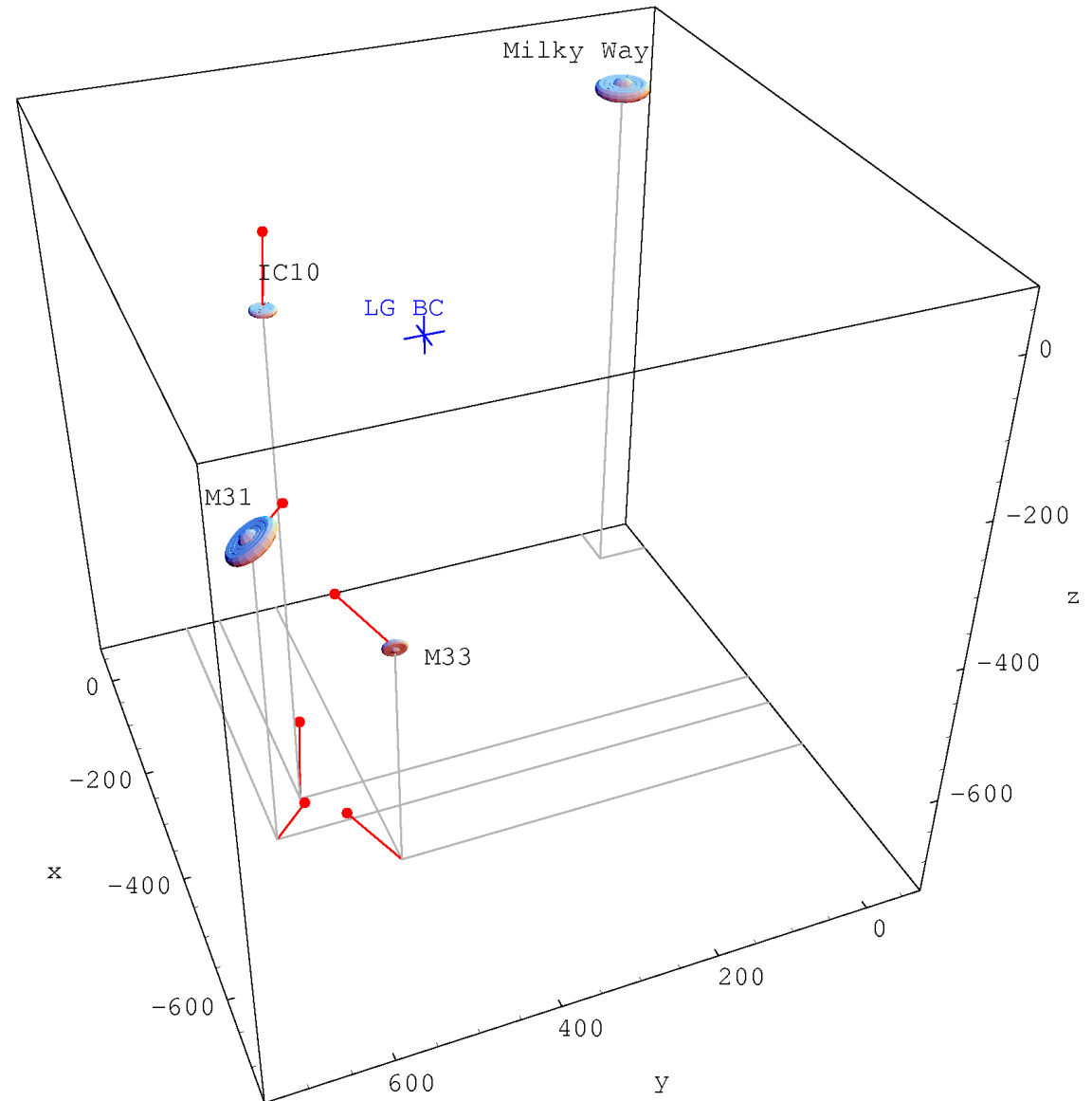
Space Motion of Local Group Galaxies

RA:

$$V_{\text{prop}} = -29.3 \pm 7.6 \mu\text{as/yr}$$
$$= -101 \pm 35 \text{ km/s}$$

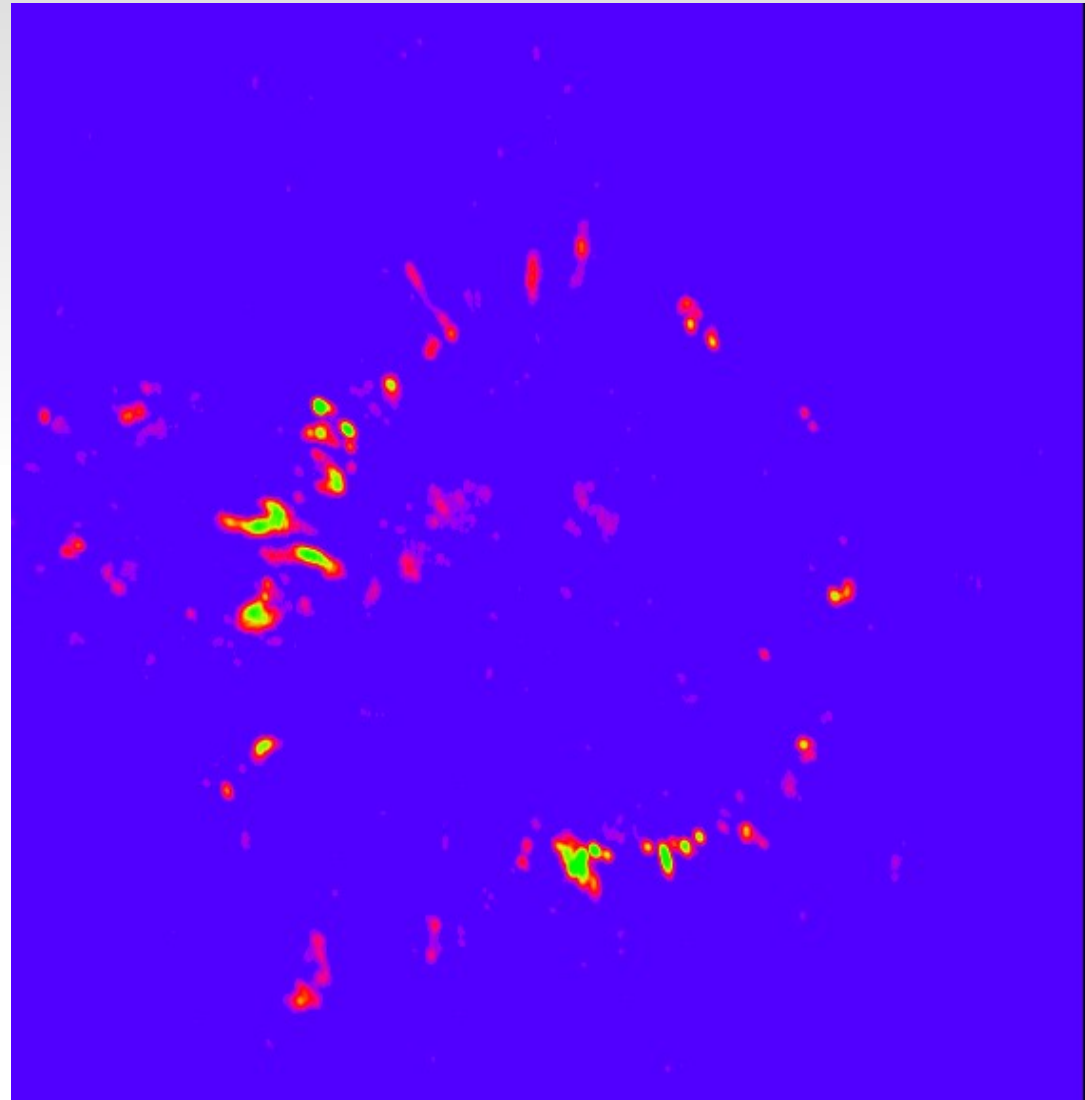
DEC:

$$V_{\text{prop}} = 45.2 \pm 9.1 \mu\text{as/yr}$$
$$= 159 \pm 47 \text{ km/s}$$



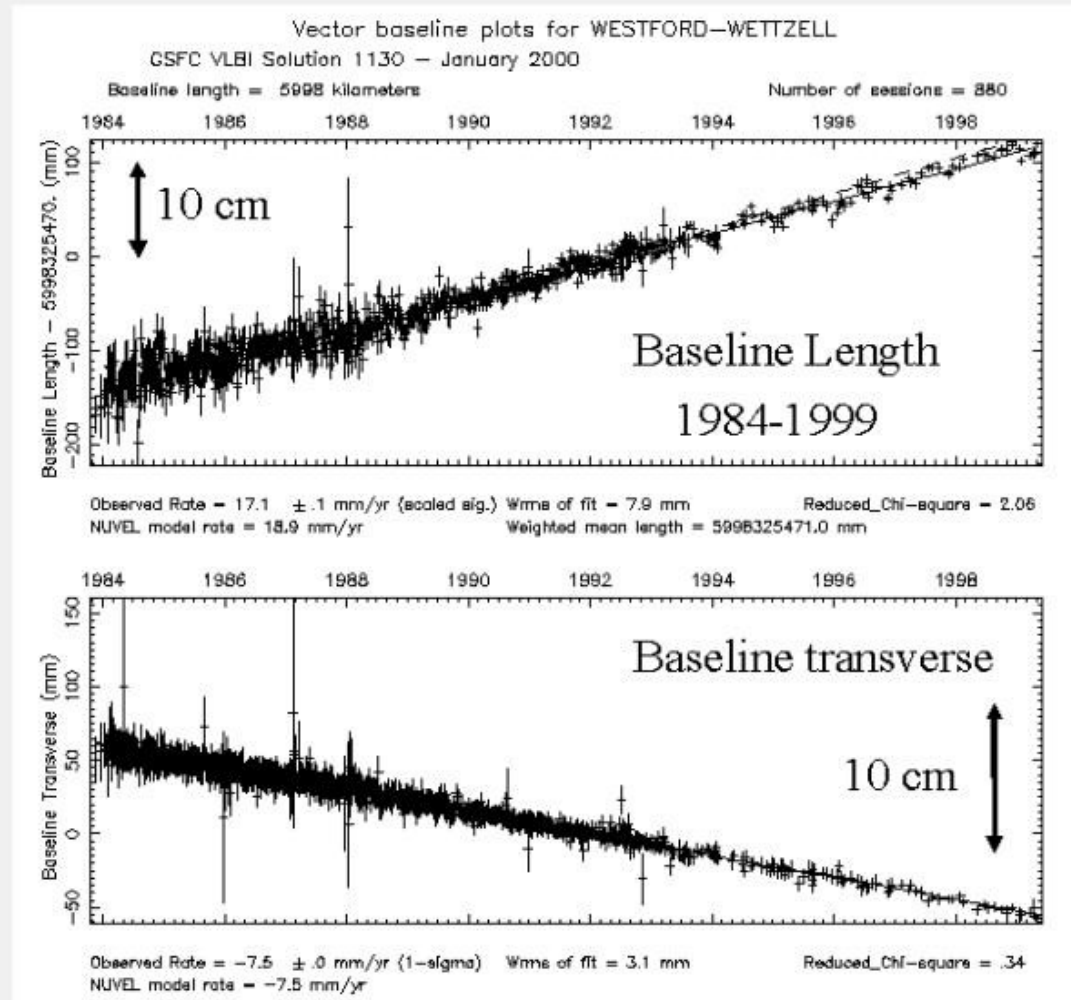
Mass loss around an old star

- SiO masers in TX Cam



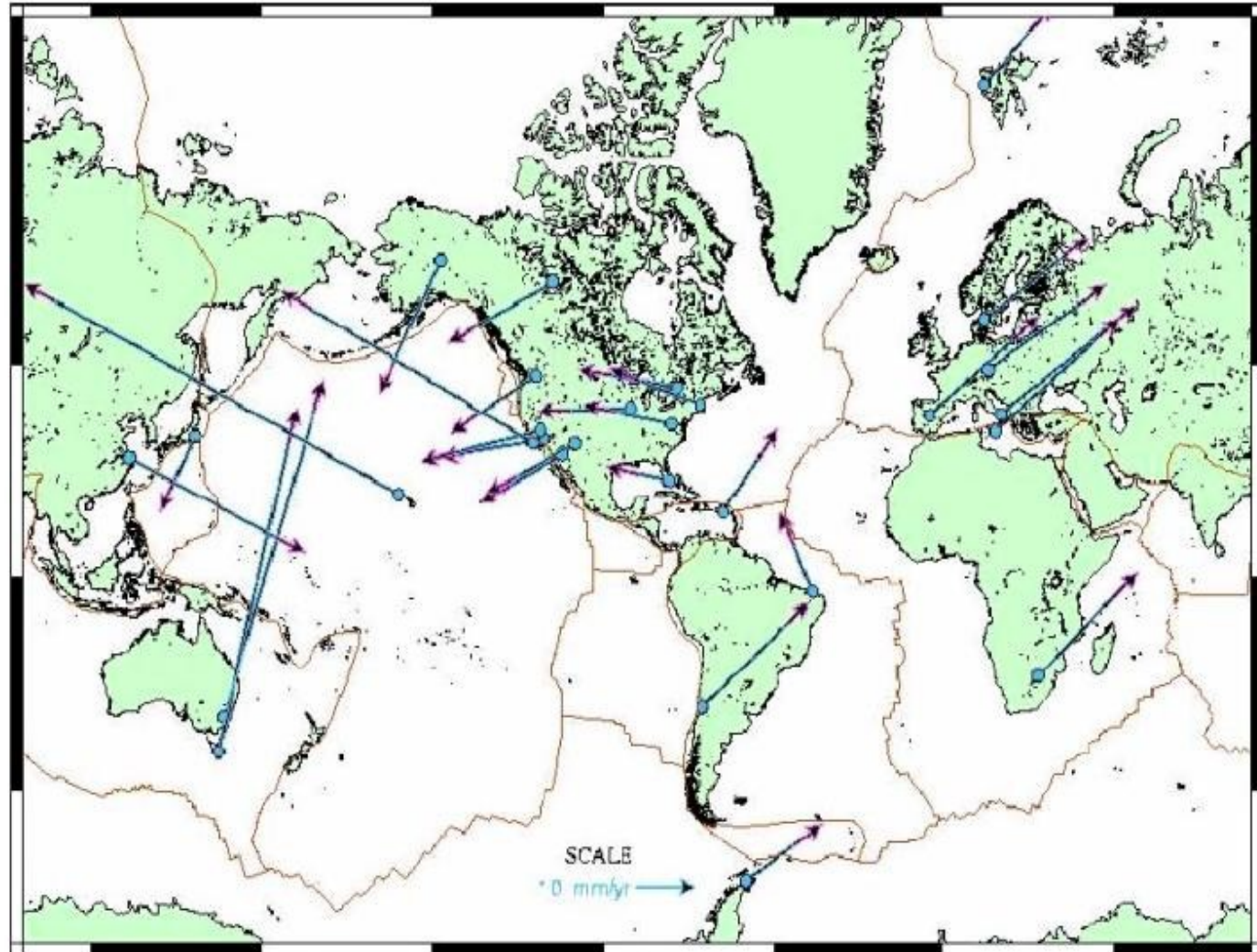
Geodesy

GERMANY to MASSACHUSETTS



Geodesy

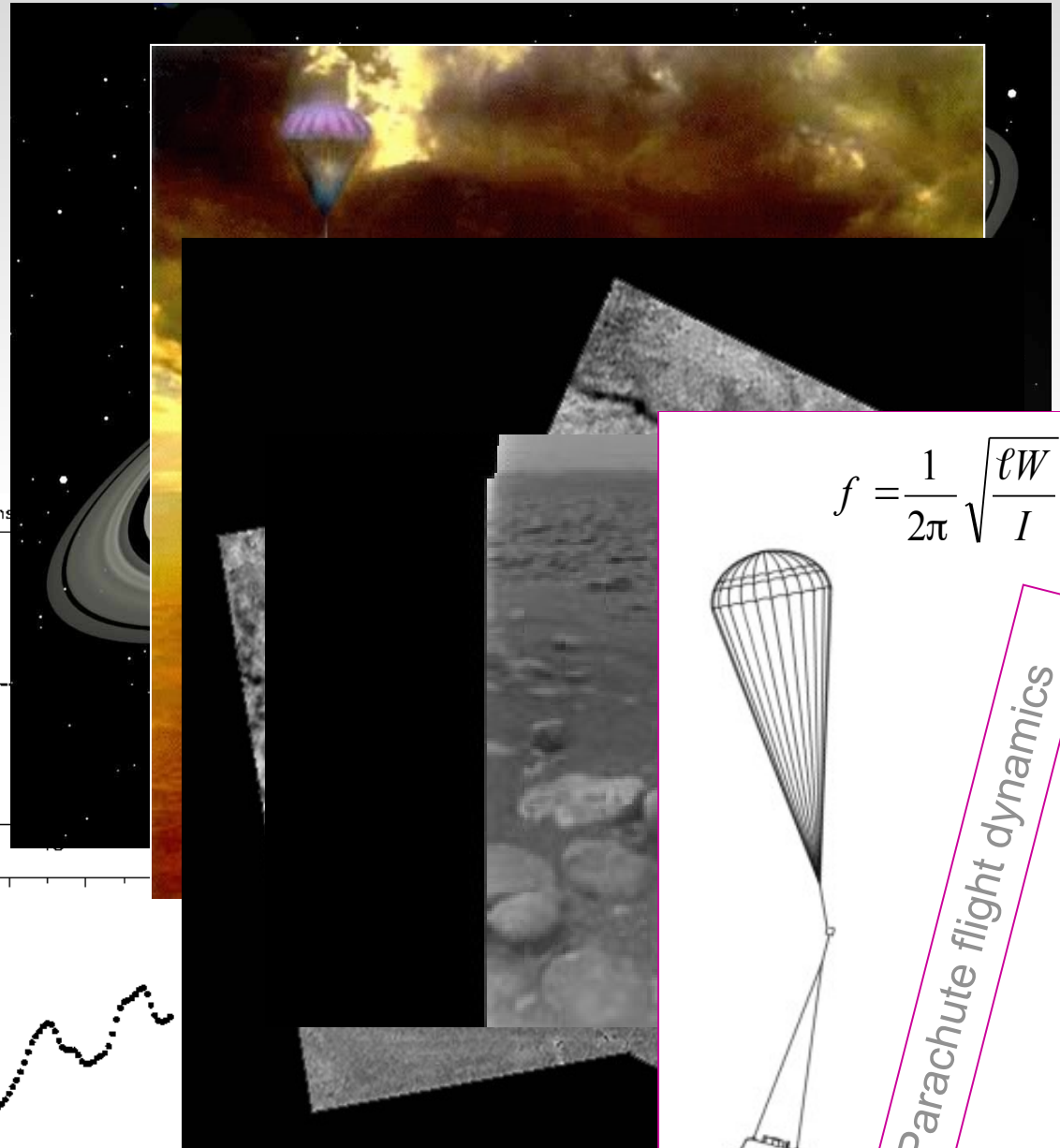
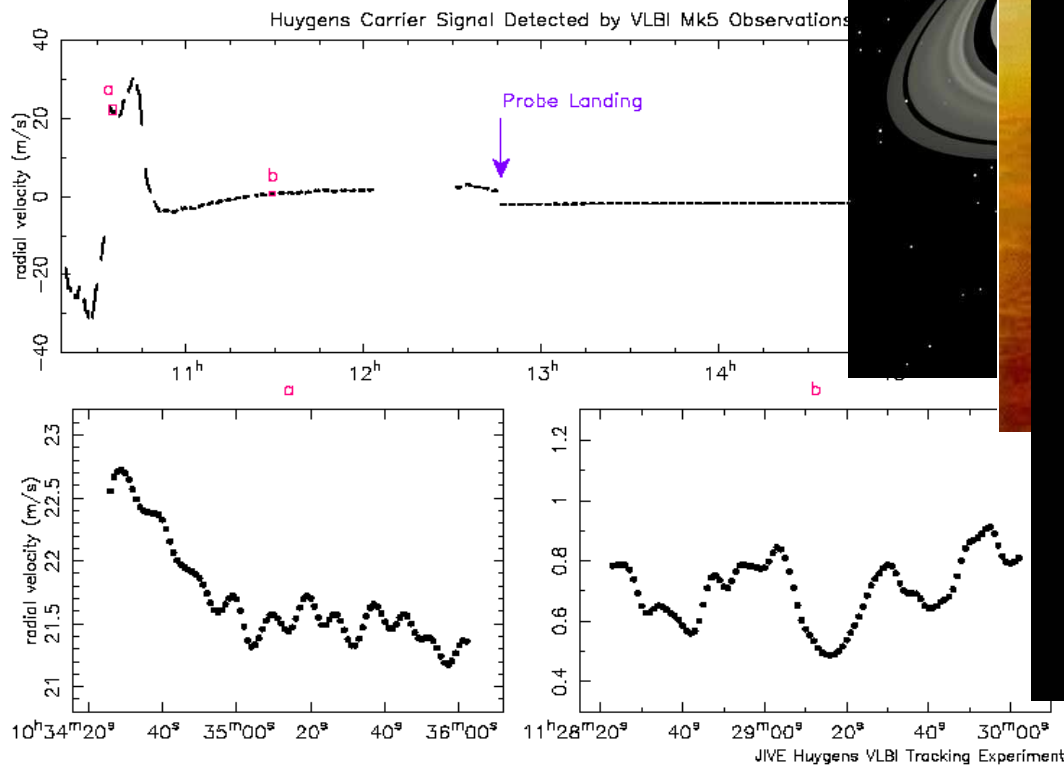
Selected VLBI Velocities



Goddard Space Flight Center VLBI solution CM 1122 version 02
NUVEL1A-NNR reference frame.

Huygens Descent Tracking

- LBA + Pacific telescopes
- Detection during descent
- Salvage of Doppler experiment
 - Special purpose, narrow band software correlator



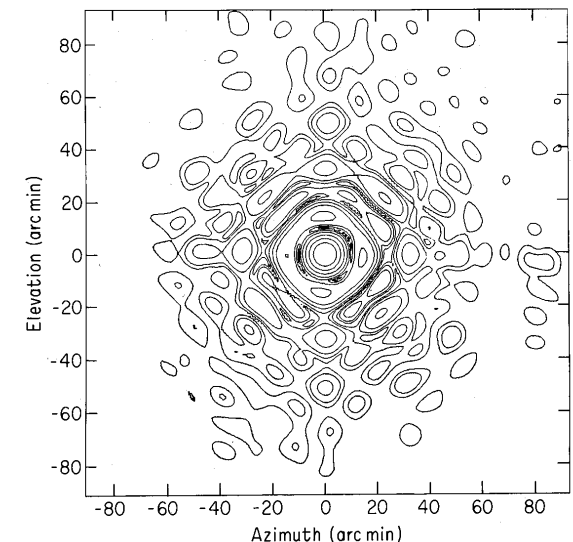
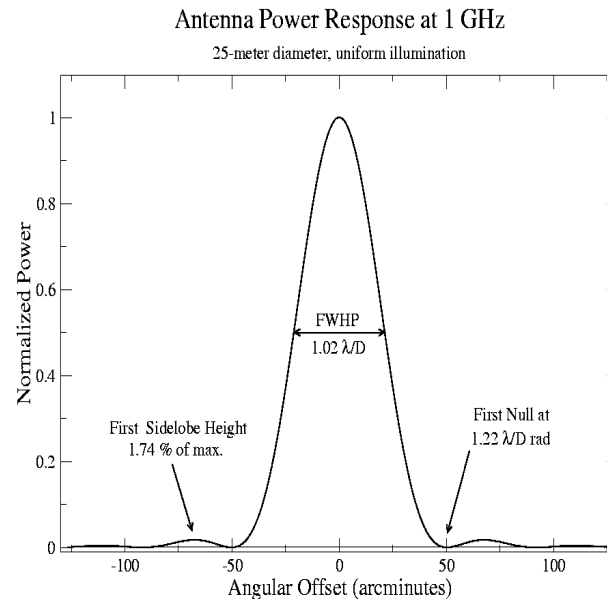
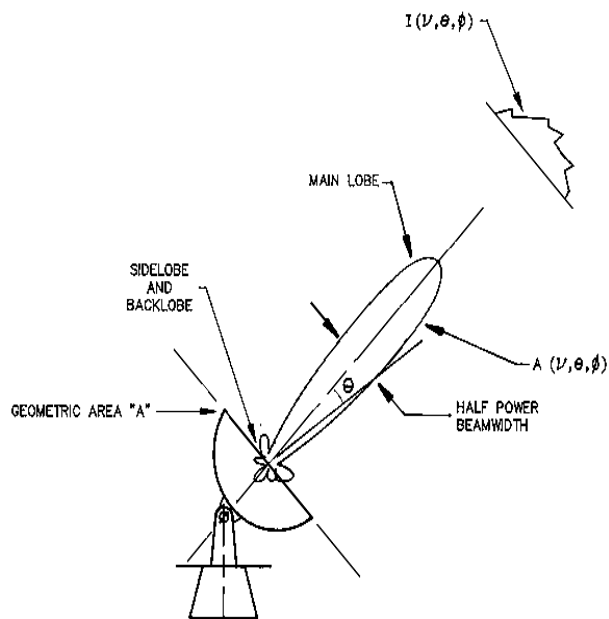
$$f = \frac{1}{2\pi} \sqrt{\frac{\ell W}{I}}$$

Parachute flight dynamics

END

Antenna Beamwidth, Pointing & Focus

- The beamwidth of an antenna with characteristic size D is approximately λ/D
- Most sensitivity is concentrated in a smaller solid angle that is often characterised by the half-power beamwidth (HPBW)



Pointing

- Ideally, a radio source should be centred in the antenna main beam to prevent loss of signal
- A pointing error of 0.1 times the HPBW causes a 3% loss in signal; for an error of 0.2 HPBW, it rises to 10% and for 0.3 HPBW it becomes 22%