

Figure 1: Casseopeia A (Cambridge 1-mile)





Fig. 2. Contour map of Cygnus A. The contour interval is 26,000° K. The beam to half power is shown in the corner of the map. The limits of the optical source are shown by the dotted ellipse

Figure 3: Cygnus A (Cambridge 1-mile)



Figure 4: Cygnus A (Cambridge 1-mile)



Figure 5: The Very Large Array (VLA)



Figure 6: Casseopeia A (VLA)



Figure 7: Cygnus A (VLA)



Figure 8: Cygnus A (VLA)



Figure 9: Cygnus A (VLA)



Figure 10: The Very Long Baseline Array (VLBA)



Figure 11: How a radio telescope functions

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2 Introduction

- Very Long Baseline Interferometry: VLBI
- Use longest possible baselines on the Earth
- \bullet Use arrays of ${\sim}10$ antennas: EVN and VLBA
- Use baseline from Earth to a radio telescope on an orbiting satellite: VSOP mission.
- Higher angular resolution imaging for finer structural detail
- Higher precision astrometry

- Traditionally realized without real-time signal links between antennas
- Local autonomous telescope control, executing a pre-distributed observing schedule to synchronise telescopes in the array
- Independent local oscillator signals
- Local sampling of voltage signals and recording on tapes (and disks)
- Later off-line replay of sampled voltage signals for multiplication at a correlator; JIVE, Bonn, VLBA-Socorro
- Modern realization of real-time VLBI

- 3 Principles and Practice of VLBI
 - Basic principles are exactly the same as for any other radio interferometry.
 - Realization of long baselines involves practical differences It is instructive to group the reasons why these arise under a number of headings:
 - High angular resolution of long baselines
 - The "geophysics" of long baselines
 - Interferometer connection over long distances
 - Recorded signals and off-line correlation
 - The "geopolitics" of long baselines !

- 4 High angular resolution of long baselines
 - Longer baselines magnify the effect of small angular quantities

- Increased phase difference between 2 points in the sky produces better angular resolution of target source ! Need small pixels ! AIPS IMAGR, CELLSIZE=0.0004
- But also on amplitude calibrators they may be heavily resolved

Generally cannot rely on point source amplitude calibrators

- Calibration by radiometry (SEFD) of individual antennas We calibrate the "noise" level and hence the correlation in Jy AIPS tasks ANTAB APCAL CLCAL
- May need to correct for bias in the digital representation of the voltage if the sampler levels are not correct. This correction is done at the EVN correlator at JIVE, but not at the VLBA correlator.

AIPS tasks FITLD (option DIGICOR=) and ACCOR

- Larger holes in the u,v plane "Missing flux" if interferometer array does not have sufficiently short baselines
- Characteristic brightness temperature lower limit for detection given by shortest baseline in the array. Source must be sufficiently compact (i.e. have sufficiently high brightness temperature) to be detectable
- This limit is much higher for VLBI because the shortest baselines are usually longer !

 $T_b > 10^8$ - 10^{12} ; synchrotron emission, maser emission

- Increased path difference produced by small angular errors Need more accurate angular geometry to ensure path difference is less than 1/b
- More accurate source positions

1 arcsec with 5 km baseline; 2.4 cm (144° at 5 GHz)
1 arcsec with 5000 km baseline; 24 m (80 nanoseconds; 12 MHz)
Smaller delay beam; decreased field of view

- Earth Orientation Parameters (UT1-UTC, position of the pole) GR deflection due to the Sun is important over whole sky
- Need finer frequency sampling at the correlator (0.5 MHz) Can be achieved with multi-lag correlation

- Increase rate-of-change of phase errors Residual fringe rate, f Cannot average data longer than a time 1/f
- Smaller fringe-rate beam; decreased field of view
- Need finer time sampling at the correlator (1 s) May need shorter time intervals in AIPS CL table
- Finer time and frequency sampling of the visibility function increases the volume of data !

- As with other interferometers we must calibrate phase errors.
- Phase self-calibration leads to a detection threshold i.e. must have sufficient signal-to-noise ratio in the solution interval
- Need to average data in frequency and time to achieve this
- Need to determine the unknown residual delay and residual fringe-rate to permit this averaging
- Fringe Fitting procedure is used to determine the residual fringe rate and delay
- Forms averages of the data in time and frequency with a range of trial fringe rates and delays, and determines which values maximise the signal.
- Requires enough signal-to-noise to recognise the signal so sets a minimum correlated flux density threshold for detection

- AIPS task FRING does a "global" search for all baselines simultaneously, making use of the fact that the residual delay and fringe rate on a baseline may be expressed as the difference between antenna-based delay and rate residuals
- **FRING** also incorporates a **phase self-calibration** solution with a default point-source model
- For an N-antenna array, **FRING** determines (N-1) antennabased phase, fringe-rate and delay solutions with respect to a reference antenna whose residuals are assigned to zero.
- Note that the act of averaging the visibility function, using the residual delays and fringe rates determined by FRING, decreases the field of view of the averaged data.

- 5 The "geophysics" of long baselines
 - The Earth is round
 - It is surrounded with a layer of neutral and ionized gas
 - It is not entirely solid
 - Source has different elevations at different antennas Short time of mutual visibility for low declination sources Galactic Centre source not visible on transatlantic baselines
 - Program **SCHED** for planning observing sequence
 - For a VLBI array there may be much more data for short baselines than for long baselines

- Parallactic angles are different for azimuth/elevation mounted antennas at different sites.
- Need to use feeds which respond to a circular polarization mode to get correlation
- The parallactic angle difference for the 2 antennas of a baseline introduces an additional phase term which is not corrected by the correlator, and is of opposite sign for RHC and LHC
- It may be necessary to correct for this when making polarization VLBI observations, or when averaging LHC and RHC correlations together, or when doing phase-reference observations if the target and reference source have different parallactic angles.

AIPS task CLCOR, option PANG

- Non-equal tropospheric paths
- For very short baselines (< 5 km) we assume that the tropospheric paths of the signals to the 2 antennas have the same physical length and that the temporal fluctuations along them are the same. The increased path lengths, and temporal phase fluctuations, cancel.
- For longer baselines (> 10 km) we assume the tropospheric paths have the same physical length but that temporal phase fluctuations are independent along the 2 paths. The increased path lengths cancel but the phase fluctuations do not, and appear in the measured visibility function.

They must by removed (be phase-referencing or phase selfcalibration)

- For VLBI the physical paths through the troposphere have very different lengths because of the different elevations of the antennas.
- The increased path lengths do not cancel but produce a relative delay, τ , which is a function of the zenith delays, z and the elevations e for the 2 antennas (A,B):

 $\tau = z_A / \cos(e_A) - z_B / \cos(e_B)$

In order to equalize the paths for correlation, a model of the tropospheric delay is needed.

• Phase-reference observations

Target and phase-reference source observations are alternated, and the phase measured on the reference is used to calibrate the tropospheric phase fluctuations on the target.

• Note that τ_{target} and $\tau_{reference}$ are not equal and it is therefore essential to have a model for the tropospheric delay path.

• Non-equal ionospheric paths

More significant at low frequencies Varies with time of day, latitude, Solar cycle..... "Zenith delay" increase can be very different for different antennas

- It is unpredictable so no correction is made for this by VLBI correlators.
- For phase-referenced observations it may be necessary to correct for the ionospheric path increases *after* correlation, using an ionospheric model derived from GPS data. AIPS task TECOR
- Telescopes may be on different tectonic plates Telescope baselines can change by \sim cm per year
- Telescopes at different longitudes experience different displacements due to solid Earth tides (~ 10 cm).

- 6 Interferometer connection over long distances
 - Could control telescopes centrally in real time over telephone/internet lines (but we don't..)
 - Cannot easily use cables, waveguides or microwave links to bring the wideband (e.g. 128 MHz) signals together.
 - Cannot easily distribute common LO signal (but may use satellite link for SKA)

• Use independent LOs derived from Hydrogen maser frequency standard

Phase stability of 1 part in 10^{14}

- Sampling of signal voltages controlled by accurate local clock.
- Encode time signals to identify each sampled bit
- \bullet Accurate monitoring of observatory clocks using GPS (${\sim}100$ nanoseconds)

- eVLBI: Bring bit-streams together via internet, or satellite, or dedicated optical fibres
- Real-time correlation, with suitably large buffer to accommodate large astronomical and terrestrial delay between bit-streams.

Corresponding bits must be matched and multiplied

- Need to take account of local clock and clock-rate differences using fringe fitting
- eVLBI is being developed at present

- 7 Recorded signals and off-line correlation
 - VLBI traditionally performed by recording the bit-streams and the encoded clock information on magnetic tape (and now computer disks)
 - Replace cables, optical fibres, internet with airplanes, ships and trucks
 - Assemble all the recorded bit-streams at the correlator, some weeks later
 - Synchronised replay of the recorded bit-streams under computer control
 - The correlator need not know they are not in real time !
 - Tape recorded radio interferometry was the only possibility in the late 1960's when VLBI was first performed

- The main difficulty is to write, record and replay a sufficiently high bit-rate
- Bit-rate = twice the bandwidth
- Initially done using computer tape ($\sim 100 \text{ kHz}$ bandwidth)
- 1974: NRAO Mk2 system; 2 MHz (4 Mbps) Using professional TV video recorders (later VCRs)
- Further translation of IF signal to baseband (0 2 MHz) using baseband converter (also video-converter) before sampling the voltages.
- 1979: Haystack Mk3 system; 28 Mk2s in parallel

28 separate 2 MHz channels (112 Mbps)

14 baseband converters (upper and lower sidebands)

longitudinal recording on 1" magnetic tape at 3m/s with 28 parallel tracks !

• 1980's VLBA and Mk4 recording systems

8 separate 8 MHz channels (128 Mb/s for 1 bit per sample)
4 separate 8 MHz channels (128 Mb/s for 2 bits per sample)
8 separate 8 MHz channels (256 Mb/s for 2 bits per sample)
etc....

- Can have 4 channels RHC and 4 channels LHC for polarization VLBI
- \bullet Can have 4 channels 2.3 GHz and 4 channels 8.4 GHz
- 2004: Mk5 disk-based recording Increases possible bit-rate to 1024 Mbps

- The main effect from using recorded interferometry comes from the (traditional) use of multiple channels of relatively narrow bandwidth (in AIPS "multiple IFs")
- Different basebands have different instrumental phase errors
- The instrumental phase differences between basebands are generally fairly constant with time during an experiment
- Need to calibrate these phase offsets in order to average the "IFs" to get better signal-to-noise ratio (e.g. for FRING or CALIB)
- VLBA has phase-cal system; a series of standard tones is inserted in the RF signal band and the phases are measured in each baseband.
- AIPS tasks **PCLOD** and **PCCOR** are used to apply these phase corrections

• In the absence of a phase-cal signal, a strong source can be used to determine the relative phase between basebands.

Known as manual phase-cal

Use FRING to determine instrumental phase in each "IF" separately

- The use of "off-line" correlation instead of realtime correlation has little effect for most observations.
- Correlation can be repeated if replay is poor or if mistakes are made !
- Multiple-pass correlation can be performed in certain special cases:

If the number of telescopes exceeds the number of playback units (> 16 for JIVE; > 20 for VLBA)

If 2 separate field-centres in the primary telescope beams are to be correlated

• The data on the tape delivered from the correlator may not be in strict time-baseline, tb order

Use AIPS task **MSORT** to order it if desired

- 8 The "geopolitics" of long baselines
 - Long baselines tend to cross international borders !
 - Leads naturally to international collaboration for performing VLBI observations.

Example: the European VLBI Network (EVN)

- Use of recorded VLBI makes it easy to use a variety of different radio telescopes, built for other purposes.
 Telescopes in such an array can have a large range of sizes, sensitivities, beamwidths, etc
- Different baselines in the array can have very different sensitivities

Need to consider carefully how to weight the data from different baselines when performing mapping and self-calibration In AIPS, consider "calibrate the weights" (DOCALIB=2) • Organization and operation of an international array such as the EVN has to involve many different national funding agencies (unlike the US VLBA).

Telescopes available for the EVN depends on observing frequency.

- Some observing options:
- EVN (9+ telescopes at 1.7 GHz and 5 GHz, 8+ at 6 GHz)
- VLBA (10 telescopes at a range of frequencies)
- Global array of VLBA + EVN (16+ telescopes)
- Global 3mm VLBI array (13 telescopes)
- The High Sensitivity Array (HSA): VLBA + GBT + VLA + ARECIBO + EFFELSBERG

- 9 Some useful AIPS tasks for VLBI analysis
 - **FITLD** to read in data (**DIGICOR** option for VLBA correlator)
 - **MSORT** if data not in TB order
 - **FXPOL** is sometimes needed to fix wrongly-labelled polarization channels from the VLBA correlator !
 - ACCOR determines amplitude corrections from sampling level errors for each antenna and writes an SN table (for VLBA correlator)
 - CLCOR with option PANG to make parallactic angle correction in a CL table if necessary

- ANTAB reads external file of amplitude calibration radiometry and produces **TY** (system temperature) and **GC** (gain curve) tables.
- APCAL extracts amplitude calibration data from TY and GC tables and writes an SN table.
- **PCLOD** reads external file of phase-cal data and writes a **PC** table
- **PCCOR** extracts phase-cal information from PC table and writes an SN table

- **CLCAL** interpolates SN table values into a **CL** (calibration) table
- FRING determines (antenna-based) residual phase, delay and fringe-rate by self-calibration and writes an SN table. Can be used to determine "IF" instrumental phase offsets.
- CALIB for self-calibration of antenna phases and amplitudes
- **SPLIT** to apply accumulated calibration (maybe calibrate the weights) and to average frequencies (and possibly "IFs")