The University of Manchester
Jodrell Bank Observatory
MANCHESTER 1824

Calibration,
Editing and Averaging

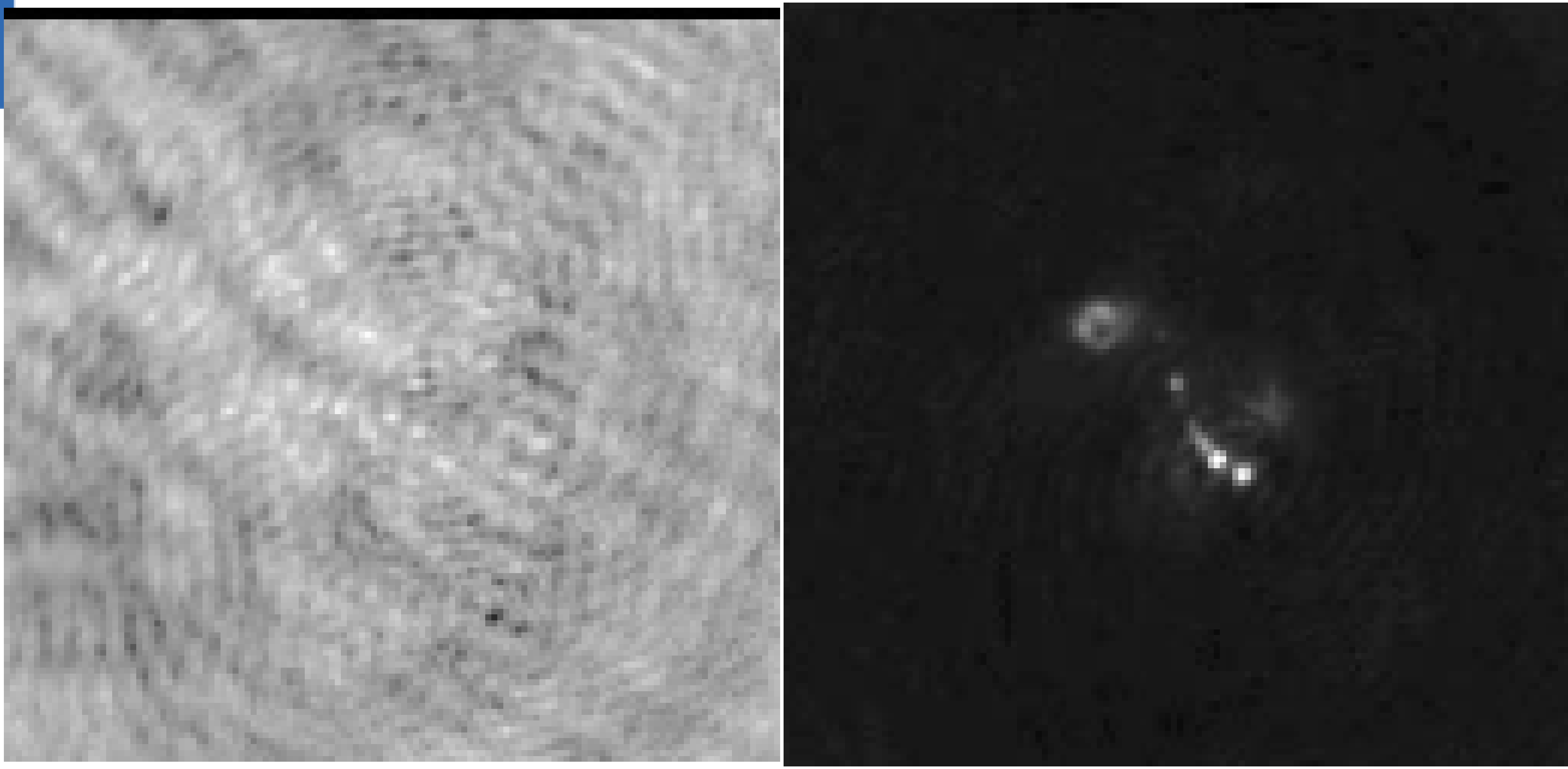
Simon Garrington

- Imaging talk considered idealised set of samples of visibility function
  - How to form an image (gridding, weighting and FFT)
  - How to deal with incomplete sampling of visibility function (deconvolution: CLEAN)
- This talk is about how we prepare the data for imaging
  - Editing to remove bad data
  - Averaging to reduce volume of data
  - Calibration
- As before, all steps essential

Importance of calibration

- For radio interferometers, calibration is much more than just setting an overall brightness scale
- Visibility samples come from different telescopes with different receivers: will differ by 10-100%
- Visibility phases are almost completely scrambled by the atmosphere and ionosphere
- FT of raw data usually unrecognisable
- Final image quality often limited by quality of calibration and presence of bad data rather than deconvolution

Importance of calibration



Automation?

- Should be a deterministic process … should use scripts (pipelines)
- Automatic editing?
  - For strong, simple sources, should be possible to recognise very discrepant amplitudes, especially for individual baselines in long track observation
  - Editing and Calibration often iterative
  - Weak sources: raw data looks like noise
- Automatic calibration
  - Often possible, with good quality control
  - Sometimes involves self-calibration to produce image of the calibrator source

Formalism
Simple Approach

- V(u,v) ⇔ I(l,m)
- Observed visibilities, single polarisation, single freq.

True visibility

$$\tilde{V}_{ij} = G_{ij}V_{ij} + \epsilon_{ij} + \eta_{ij}$$

Observed complex visibility on baseline from telescope i to telescope j.

Complex calibration factor for this baseline

Additive error (correlator offset)

noise

$$\mathbf{G}_{ij}(t) = \mathbf{g}_i(t)\mathbf{g}^*{}_j(t) = a_i(t)a_j(t)e^{(\phi_i(t)-\phi_j(t))}$$

- Estimate $a(t)$ and $\phi(t)$ for each telescope
- This is the approach used by AIPS, difmap, MIRIAD

Problems with simple approach

- Extend to cover frequency dependence
  - See Beswick lecture
- Extend for polarised receivers and sources, but not elegant or exact
  - See Cawthorne lecture
- Can include simple terms which cannot be factorised by telescope
- Does not show where calibration terms arise
- Not well suited for calibration terms which vary with position on the sky

Measurement equation

Polarisation: signal vector, corrupted by Jones matrix

$$\vec{V}_{ij}^{obs} = \left(\overleftrightarrow{J}_i^{vis} \otimes \overleftrightarrow{J}_j^{vis*}\right)\vec{V}_{ij}^{ideal}$$

$$= \left(\overleftrightarrow{J}_i^{vis} \otimes \overleftrightarrow{J}_j^{vis*}\right)\int_{sky}\left(\overleftrightarrow{J}_i^{sky} \otimes \overleftrightarrow{J}_j^{sky*}\right)\overleftrightarrow{S}\vec{I}(l,m)e^{-i2\pi\left(u_{ij}l+v_{ij}m\right)}dldm$$

- J_i contains many components:
    - F = ionospheric Faraday rotation
    - T = tropospheric effects
    - P = parallactic angle
    - E = antenna voltage pattern
    - D = polarization leakage
    - G = electronic gain
    - B = bandpass response
    - K = geometric compensation
- Order of terms follows signal path (right to left)

$$\overleftrightarrow{J}_i = \overleftrightarrow{K}_i\overleftrightarrow{B}_i\overleftrightarrow{G}_i\overleftrightarrow{D}_i\overleftrightarrow{E}_i\overleftrightarrow{P}_i\overleftrightarrow{T}_i\overleftrightarrow{F}_i$$

Measurement equation (2)

- Developed by Hamaker, Bregman Sault
  - Series of papers in A&A (1996->)
- Implemented in CASA (NRAO)
  - Matrix details hidden
  - Adopted by ALMA, (EVLA)
- MeqTrees (Noordam, Smirnov, ASTRON)
  - Important for WSRT,LOFAR, SKA
- See also NRAO Summer School lectures

Effects to be calibrated

- Telescope sensitivity: amplitude
  - Gain
    - Measure ‘single dish’ performance; gain depends on antenna size, geometry, surface accuracy
    - Antenna shape may deform with elevation
    - Surface properties may change with time
    - Pointing: direction dependent terms
  - System temperature
    - Receiver noise [Receiver gain does not matter]
    - Sky noise: object, surrounding emission, atmosphere
    - Scattering (rain); spillover (ground)
- Instrumental phase
  - System timing; synthesisers and LO
  - Major issue for VLBI
- Correlator delay,phase model
  - Geometry, static atmosphere
- Atmospheric fluctuations
  - Dry & wet components
  - Ionosphere
  - Atmospheric opacity
- Correlator effects

Calibration methods

- Direct calibration
  - Engineering knowledge of the system, requires frequent characterisation of equipment, stability with time, or model of variation with time
    - May be a useful starting point
    - May be essential for absolute measurements, eg CMB, establishing standards
- Monitoring calibration
  - Independent measurements of varying components, including receiver systems and atmospheric effects during the observation
    - Used in VLBI (see Reynolds lecture)
    - Used at mm wavelengths (see Gueth lecture)
    - Used for delay compensation in MERLIN, EVLA
- Astronomical calibration
  - Use of *calibrator sources* whose visibility can be accurately predicted and modeled. To calibrate varying components will require frequent observations of a close calibrator source: Phase Referencing
    - Main technique for MERLIN, VLA, WSRT, GMRT, VLBI
- Self calibration
  - Iterative approach using the target source itself
  - Only when target source is strong enough
    - See Lobanov lecture

Amplitude calibration

- Correlation coefficient for point source

$$\rho \simeq \eta[(\frac{S}{S_{E1}})(\frac{S}{S_{E2}})]^{1/2}$$

Where $S_{E1,2}$ = system equivalent flux density

= $2kT_{sys}/(A_{eff})$

$T_{sys} = T_{Rx} + T_{sky} + T_{spill} + T_{atm} + \ldots$

$A_{eff} = \varepsilon A_g$

ε includes telescope optics (0.4-0.7), loss due to surface accuracy, etc

η ~ 0.8 depends on ‘correlator efficiency’: digitisation effects due to sampling, fringe rotation etc.

All terms except η, A_g need to be determined and can vary with time.

Correlator phase model

- Correlator predicts delay for a given baseline using $\phi = \frac{2\pi}{\lambda}\mathbf{D}\cdot\mathbf{s}$
- Output phase should be zero for source at this position s.
- Need to include
  - Atmospheric delay (troposphere and ionosphere)
  - Relativistic and geometric effects
    - Moving baseline (SR)
    - Telescope geometry (phase centre = intersection of axes; many telescope have an offset)
  - Earth orientation effects (co-ordinate system for D)
    - Polar wobble (~0.3 arcseconds or 15m, mostly 12 – 14month seasonal components, hard to predict)
    - Variations in rotation speed (UT1-UTC) ~ 1ms
    - Correlators generally use predictions from IERS
  - Changes in telescope position
    - Tectonic motion (few cm/yr), tidal effects (~1 cm/day)
- Atmospheric delay is usually largest uncertainty.

Atmospheric delay model Troposphere

At the zenith…

- Dry air: L = 2.3(P/1000mb) m
  - Easy to estimate from surface pressure
- Water vapour: L = 6.3W where W is total liquid water column ~ 0.5 – 5cm
  - Very variable; hard to estimate from surface conditions
  - Fluctuates on small scales
  - Correlators generally used fixed or seasonal value
  - Can now use GPS or Water Vapour Radiometers

- Strong variation with elevation [zenith angle z]
  - Plane atmosphere: L(z) =L/cos(z)
  - Zenith angles different for separated telescopes observing same source: large effect at low elevation
  - Real troposphere is stratified, variable & curved
  - Range of ‘mapping functions’ L(z) developed
    - Best (Vienna) now use numerical weather forecasting grids

Atmospheric delay
Ionosphere

- Dispersive: $\tau \sim \nu^{-2}$ worse at low frequencies
- ~ 10[ν/GHz]$^{-2}$ m delay
  - Dominates tropospheric delay for $\nu < 4$ GHz
- Varies by x100 day-night
  - Large differential on long baselines
  - Local time, latitude & elevation
  - Strong diurnal signature
- Spatial fluctuations (travelling waves) on scales of ~100km, timescale 20 min, amplitude few % in electron density
- Not generally included in correlator model

Baseline-based calibration

- Observe point source, flux density S at tracking centre

  Model: |Vij|=S, phase = zero for all i,j,t

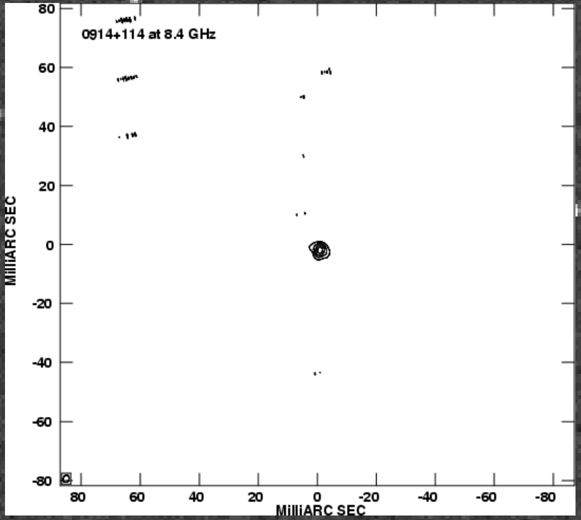
  Set all

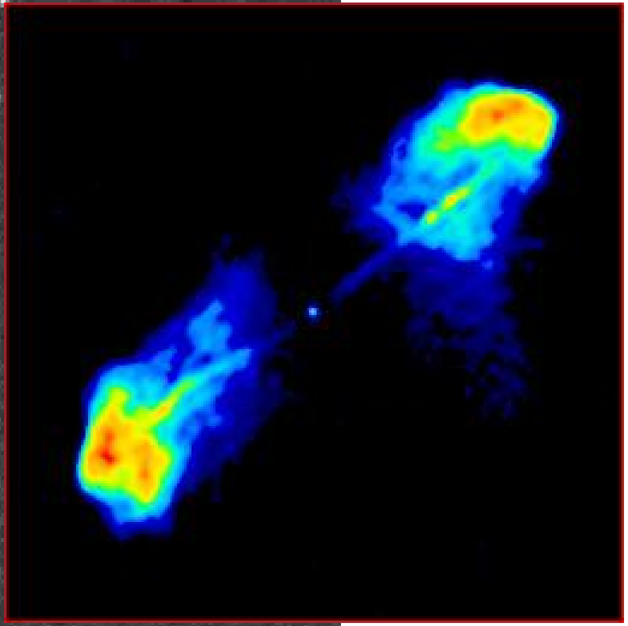
$$|G_{ij}(t)| = |\tilde{V}|_{ij}(t)/S$$
$$\arg(G_{ij}(t)) = \arg\left(\tilde{V}_{ij}(t)\right)$$

- Errors due to any real structure of calibrator source transfer to target sources
  - Need a very compact and stable source
- Assumes G constant between calibration and target
  - Ideally observations should be frequent and calibrator source should be close

Finding good calibrator sources

- Bright radio sources are associated with active galactic nuclei (AGN) is distant galaxies (typically z=0.7)
  - Compact core (AGN) << 1 arcsec
  - Extended jets and lobes >> 1 arcsec
- Core-dominated sources (Doppler boosted jets) are compact but variable
  - Often use a combination of sources (boostrapping)
  - Use well established, slightly extended sources (3C286, 3C48) to calculate flux density of unresolved source
- MERLIN (50 mas resolution) uses a few Gigahertz spectrum sources (OQ208, DA193, 2134+004): quite compact and stable
- VLBI (~1-20 mas resolution): no unresolved sources





Radio Galaxy 3C296
VLA 20cm image
Copyright (c) NRAO/AUI 1999

Antenna-based calibration

$$\mathbf{G}_{ij}(t) = \mathbf{g}_i(t)\mathbf{g}^*{}_j(t) = a_i(t)a_j(t)e^{(\phi_i(t)-\phi_j(t))}$$

- Use same point source calibrator approach
- But factorise G per antenna
- Instrumental phase is arbitrary, so fix *reference antenna* to have $\phi_i = 0$
- With 3 or more antennas, can solve for a and ϕ
- Becomes progressively more over-determined for larger number of antennas

Advantages of antenna-based calibration

- Antenna terms more accurately estimated (higher SNR)
- Physical association with antennas
- Fewer terms to store, plot, inspect
- Can restrict to range of baselines where FT of source is flat, and still obtain solutions for all antennas
  - Exclude longer baselines where source partly resolved
  - Exclude shortest baselines which see extended structure

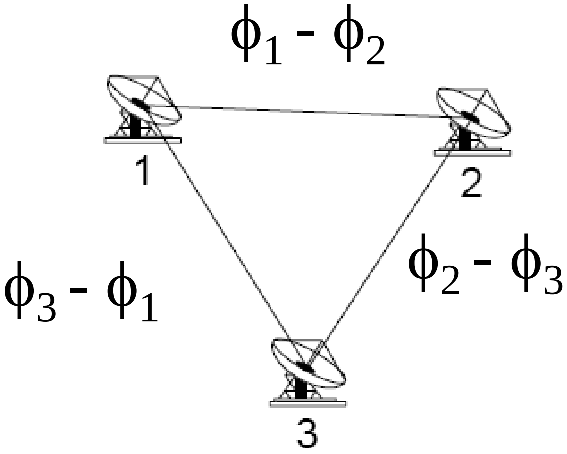
Closure relations (1)

- For point source, at phase centre
  model phase = 0
  observed phase on baseline ij = $\phi_i - \phi_j$
- Closure phase for this triangle defined as sum of baseline phases closing the loop
- Observed closure phase
  $= \phi_1-\phi_2 + \phi_2-\phi_3 + \phi_3-\phi_1$
  $= 0$
- Model closure phase = 0

➔ Closure phase unaffected by antenna-based errors (Jennison 1958)

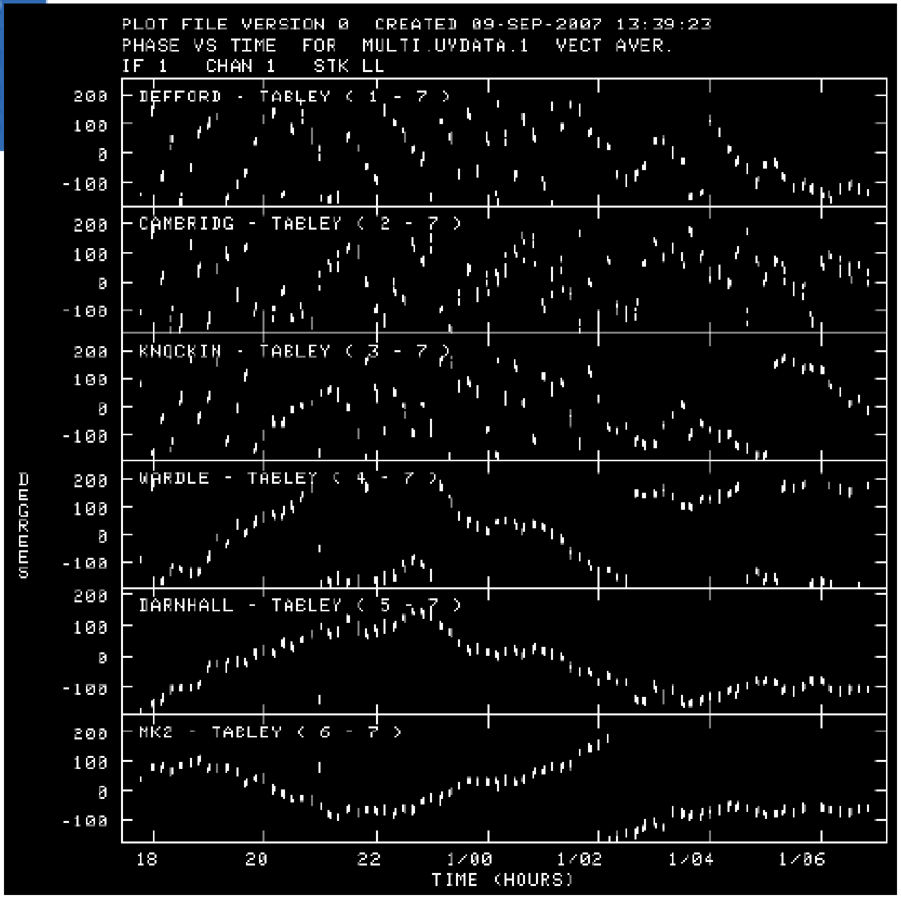
Similar approach for amplitudes in closure quadrilaterals

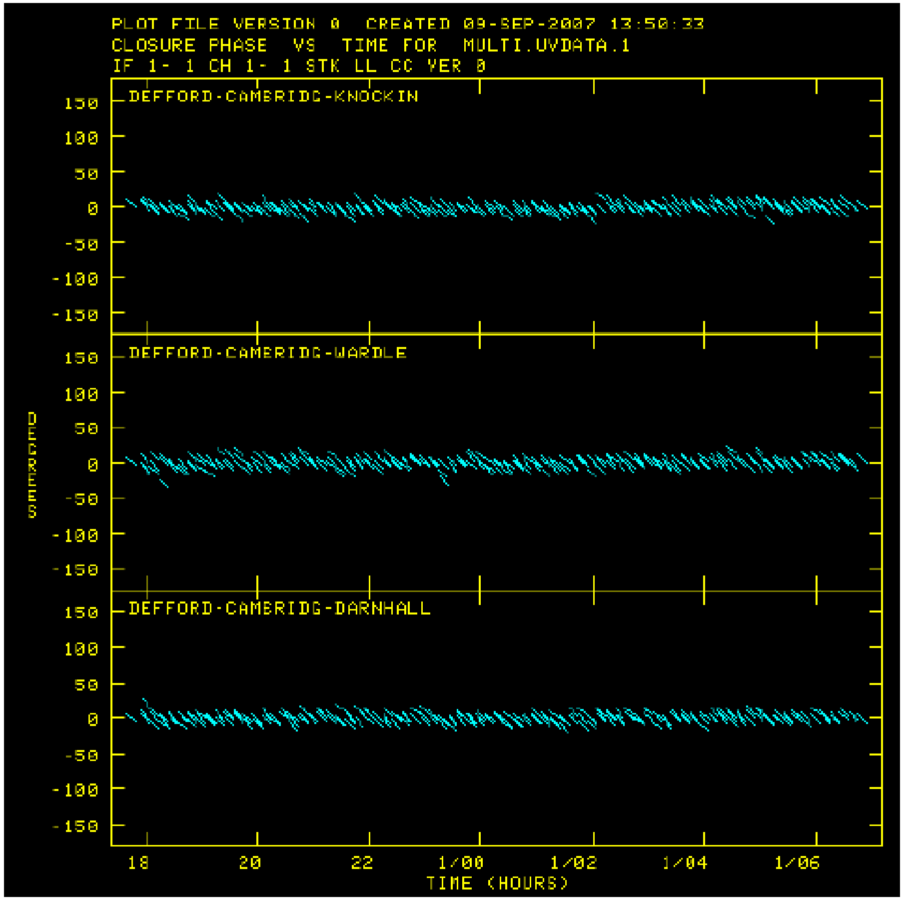
Model closure amplitude = 1 for point source



For n antennas,
½ (n-1)(n-2)
closure triangles
Ratio of baselines:triangles
is n/(n-2)

Closure phase plots

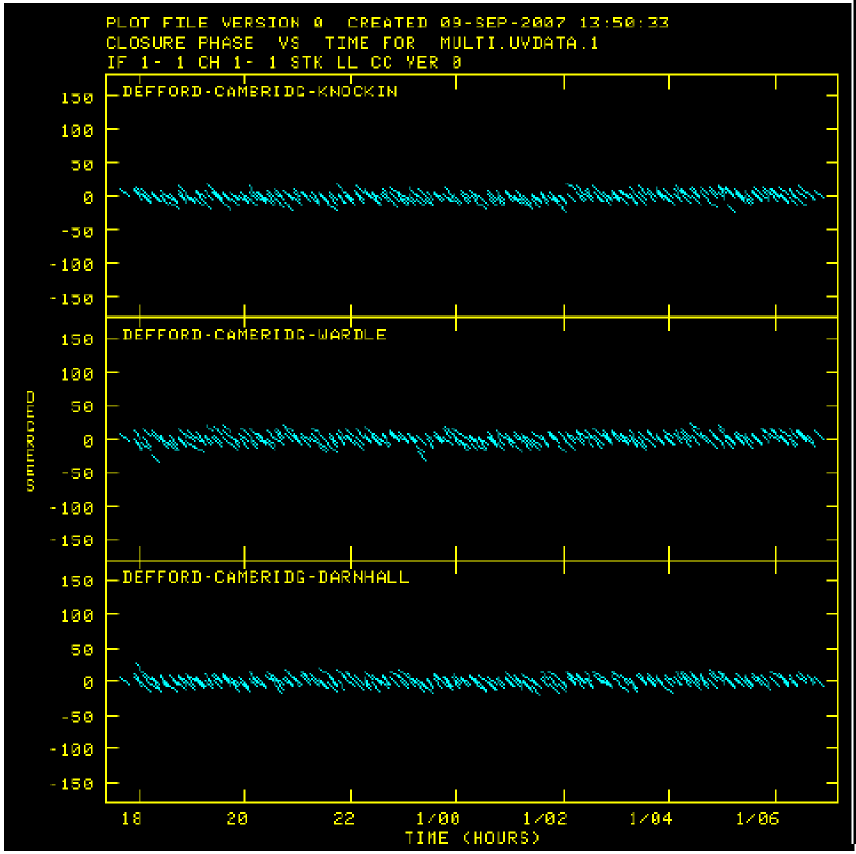




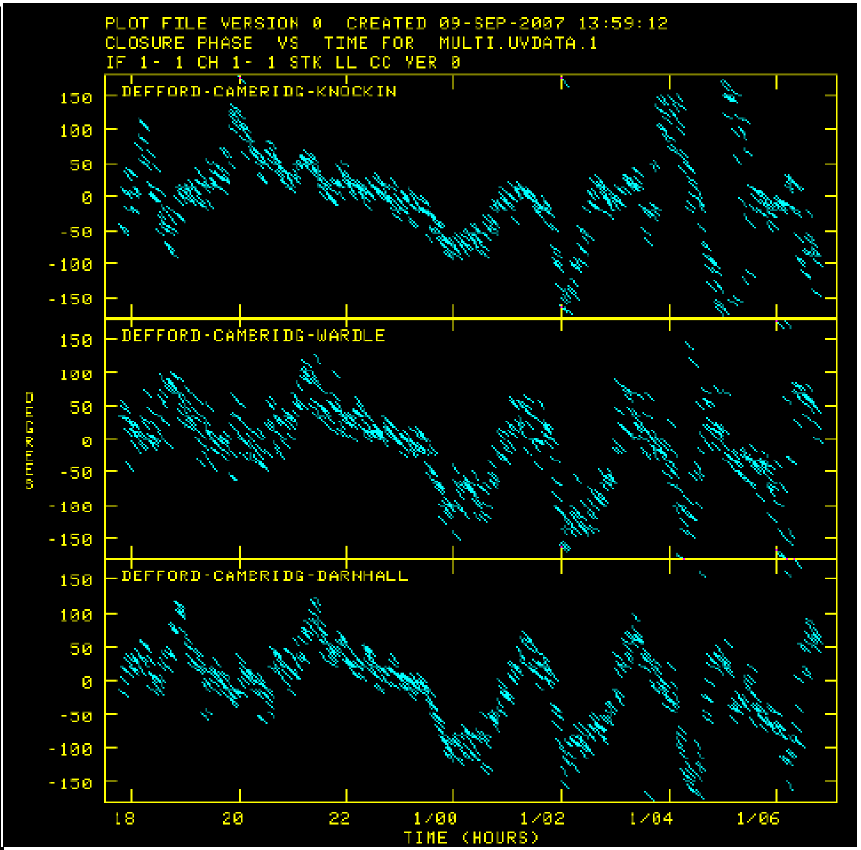
Closure quantities (2)

- Some early analysis techniques used closure quantities directly (Rogers 1974) or an explicit constrain in imaging process
- Now implicit in antenna based calibration
- Plotting closure quantities is a very useful diagnostic, independent of calibration errors
  - Check to see whether source has structure
  - Fit between model and data
- Point symmetric object has zero closure phase
- Closure phase contain no information about position
- Can be noisy

Closure Phase Plots



```
PLOT FILE VERSION 0  CREATED 09-SEP-2007 13:50:33
CLOSURE PHASE  VS  TIME FOR  MULTI.UVDATA.1
IF 1- 1 CH 1- 1 STK LL CC VER 0
```



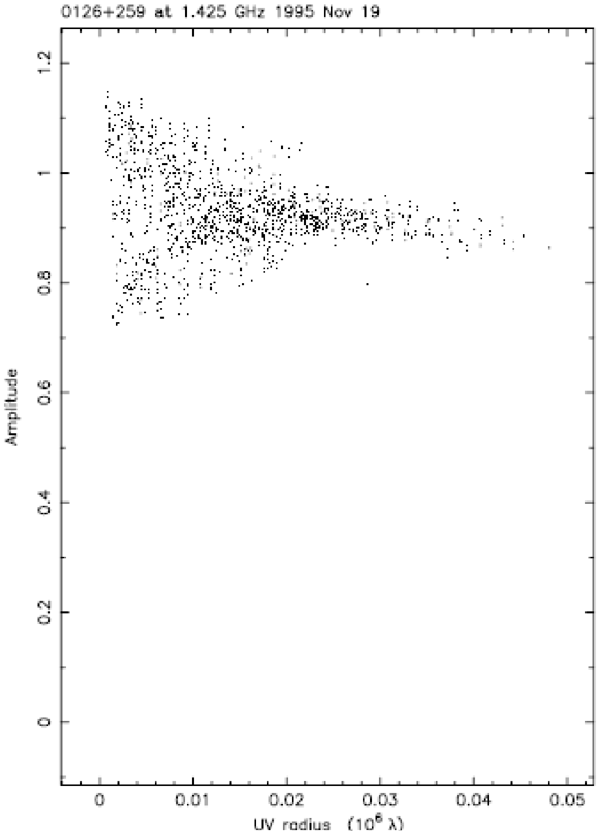
```
PLOT FILE VERSION 0  CREATED 09-SEP-2007 13:59:12
CLOSURE PHASE  VS  TIME FOR  MULTI.UVDATA.1
IF 1- 1 CH 1- 1 STK LL CC VER 0
```

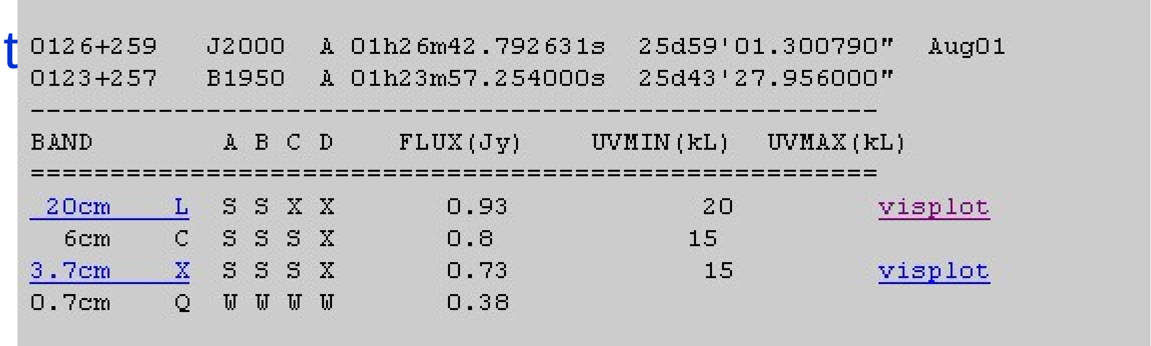
Choice of reference antenna

- For point source, antenna phase $\phi_i \sim \phi_{ir}$
- Sometimes used as initial value for solution, especially in fringe fitting
  - For VLBI often pick big antenna for reference
- Plots of antenna phase vs time will all show variation of ref antenna
  - Good to pick antenna with slow expected phase rates
- Ensure that reference antenna takes part in range of baseline lengths (near centre of array)
- Important for R-L delay calibration (see Cawthorne lecture)

Resolved calibrator sources (1)

- Use restricted range of baseline lengths (`uvrange in CALIB`) for which point source assumption is valid
- Not very critical for phase calibration
- VLA calibration procedure
  - See VLA Calibrat
    Manual





```
0126+259    J2000   A 01h26m42.792631s   25d59'01.300790"   Aug01
0123+257    B1950   A 01h23m57.254000s   25d43'27.956000"
-----------------------------------------------------
BAND          A  B  C  D     FLUX(Jy)     UVMIN(kL)   UVMAX(kL)
=====================================================
 20cm      L  S  S  X  X        0.93            20          visplot
   6cm     C  S  S  S  X     0.8             15
3.7cm      X  S  S  S  X     0.73             15          visplot
0.7cm      Q  W  W  W  W     0.38
```

Resolved calibrator sources(2)

- Start with point source assumption
  - Could use restricted uvrange
- Apply calibration
- Make image using IMAGR
- Use this as the MODEL for CALIB
  - See demo next
- This is ‘self calibration’
  - See Lobanov lecture, next

Using a model in calibration

- Divide observed visibilities by model
- Work with

$$\frac{\tilde{V}_{ij}}{V_{ij}^{M}}$$

- Where $V^M = FT(I^M)$ at $u_{ij}(t)\ v_{ij}\ (t)$

- Then equivalent to unit point source at origin
- Usually use DFT of clean components from a CLEAN map of object
  - Often restricted to brighter, positive CC
- Can use gridded FFT interpolated to $u_{ij}(t)\ v_{ij}\ (t)$

Solution interval for calibration

- Observed visibilities divided by model point-by-point
- Can then average all points to a single complex number per baseline and solve for antenna terms
  - Maximum signal:noise
  - Averages over real variations in antenna terms:
    - Variations in telescope sensitivity with time or elevation
    - Phase fluctuations due to atmosphere
  - Often want to track these variations

Phase referencing

- This is the standard observing mode with VLA, MERLIN, EVN,...
- Observe a nearby calibrator source for 1-5 minutes every 3-30 minutes
- Derive antenna gains (amplitudes and phases) for each scan, interpolate in time to target source
- Often use a resolved source
- Want a source as close as possible, within ~3 dg
  - Minimize variation of phase with position in sky (isoplanatic patch)
  - Minimize change in elevation (sky noise, static troposphere)

Choosing phase reference source

- Proximity:
  - Ideally <4dg MERLIN <2dg VLBI
  - Reduces errors due to phase fluctuations, elevation differences, geometric errors (astrometry)
- Strength
  - Need SNR > 5 within 0.5-1 min in each pol. For each baseline: 60 mJy for 16 MHz bandwidth, 1 min. solution with 25-m antennas and 35K Tsys
- Structure
  - Simpler the better. Distant, isolated antennas (Cambridge in MERLIN, Shanghai in EVN) will be hard to calibrate if source is strongly resolved
  - Ensure SNR criterion still holds for these long baselines

Lists of potential phase. ref sources

- VLA Calibrator manual

  http://www.vla.nrao.edu/astro/calib/manual/
- VLBA calibrator lists

  http://www.vlba.nrao.edu/astro/calib/

  Includes JVAS
- USNO database

  http://rorf.usno.navy.mil/rrfid.shtml

Recap

- Aim to find and apply complex calibration factors (gains) for each telescope, so that if we observe point source S Jy, |V|= S and phases are all zero.
- Assume no direction-dependent effects, so that same cal factors apply across the field of view
- Use *a priori* information where available
  - Done by VLA on-line
  - VLBI Tsys measurements
- Use a ‘point source calibrator’ to refine this
  - MERLIN, VLA, WSRT

  Solve for gains using measured visibilities
- Use a ‘phase reference source’ to follow variations with time
  - MERLIN, VLA,VLBI

  Closer,weaker, often resolved, observed every few minutes

Calibration in practice

- CALIB
  - Derives antenna-based solutions from observations of calibrator source(s)
  - Works on (multi-source) uv data file
  - Can assume point source, or use map as a model
  - Generates SN table
- SETJY
  - Set point source flux densities; formula for 3C286
- GETJY
  - Compare solutions (SN tables) for 3C286 and other calibrators, hence drive their flux densities
- SNPLT
  - Plots output SN table
- CLCAL
  - Transfers, interpolates SN values to CL table
  - Allows incremental calibration
- SPLIT
  - Applies CL values to visibilities
- Most major tasks (IMAGR etc) will apply CL calibration as required

Controlling CALIB

- Specify uv file (GETN, INNAME etc)
- Choose calibrator sources (CALSOUR)
  - Can use multiple (point) sources
- Specify flux density (SMODEL or use GETJY/SETJY) OR
- Specify model image for CALSOUR
  - GET2N, IN2N etc
  - NCOMP specifies how many CCs to use in model
- Specify UVRANGE
  - Only important for resolved calibrators or where model does not fit extended structure on short baselines
- Specify REFANT
- Choose what to solve for
  - SOLMODE ‘A&P’ … amplitude and phase
- Specify solution criteria
  - APARM(1) = 4 … min number of antennas
  - APARM(7) = 5 … min SNR (try 3, if CALIB does not find enough solutions

Editing

- Hard to give general guidance
- Use QUACK to trim start and end of scans for phase referencing observations
- Use UVPLT, VPLOT to examine data
- Use CLPLT to plot closure phases
- Use IBLED for interactive editing MERLIN, VLBI
- Not worth chasing single discrepant 4σ points
- For weak sources hard to tell even if antenna is on source – use phase ref source and flag weak target source too.

Averaging

- Averaging only useful to reduce volume of data, to speed processing and make plots easier to inspect
- Calibration and Imaging perform their own sums and averages: do not gain SNR.
- Averaging in time or across frequency channels causes smearing of sources away from centre of map and reduces field of view.

Averaging

- Frequency averaging:
  - u,v measured in wavelengths. Changing frequency correponds to radial motion in u,v plane. Image at distance θ is smeared by an amount $\beta \sim (\Delta\nu/\nu)(\theta/\theta_b)$ in radial direction. Loss in amplitude

    $R \sim 1/\sqrt{(1+0.9\beta^2)}$.
- Time averaging
  - For point at distance θ from centre of map; phase changes within $1/\theta$ in uv plane, Baseline length D covers $\tau\omega D/\lambda$ in time τ. Require $\tau < 0.1/(\omega\ \theta/\theta_b)$
- Eg 4k x 4k map: $(\theta/\theta_b) \sim 1000$ at edge

  $t < 0.1*86400/(2\pi\ 1000) < 1.5s$