Principles of Interferometry

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acknowledgement

- Mike Garrett lectures
- James Di Francesco crash course lectures NAASC
Lecture 5

- calibration
- image reconstruction
- self-calibration
- measurement equation
structure traced by baseline

resolve both sources

can not disentangle both sources
A multi-element interferometer (say with $N$ antennas) produces $N(N-1)/2$ unique responses.

For $N=4$, 6 baselines responses are measured: $r_{12}, r_{13}, r_{14}, r_{23}, r_{24}, r_{34}$.

<table>
<thead>
<tr>
<th>Array</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLA</td>
<td>$\frac{(27\times26)}{2} = 351$</td>
</tr>
<tr>
<td>WSRT</td>
<td>91</td>
</tr>
<tr>
<td>GMRT</td>
<td>435</td>
</tr>
</tbody>
</table>
uv - coverage

GMRT

- geometric quantity
- there is nothing to be done if the model is correct
- unless you do Geodesy
what needs calibration

UV coverage amplitude (colour coded)  UV coverage phase (colour coded)

\[ V_{ij}^{\text{true}}(t) = A_{ij}(t) e^{i \varphi_{ij}(t)} \]
closure relation - phase

antenna based errors introduce phase and amplitude error

The measured visibility phase on baseline “12” is then: $\Phi_{12} = \varphi_{12} + \phi_1 - \phi_2 \quad [1]$ where $\varphi_{12}$ is the true source visibility on baselines 1-2. $\Phi$ are phase offsets introduced by the clouds above each telescope.
closure relation - phase

So:

\[ \Phi_{12} = \varphi_{12} + \phi_1 - \phi_2 \]
\[ \Phi_{23} = \varphi_{23} + \phi_2 - \phi_3 \]
\[ \Phi_{31} = \varphi_{31} + \phi_3 - \phi_1 \]

Clearly if we add these relations together:

\[ \Phi_{12} + \Phi_{23} + \Phi_{31} = \varphi_{12} + \varphi_{23} + \varphi_{31} + (\phi_1 - \phi_1) + (\phi_2 - \phi_2) + (\phi_3 - \phi_3) \]

\[ = \varphi_{12} + \varphi_{23} + \varphi_{31} \]

This formulation of adding together the observed visibility phases together of any 3 telescopes is known as forming a “closure triangle”. [2b] is known as the closure phase for these 3 telescopes.

N.B. the important thing to note is that the closure phase contains information only on the true visibility of the source itself, i.e. its brightness distribution - ALL other telescope based errors cancel out (e.g. atmosphere, cable lengths, electronics etc.).
closure relation - phase

For a given array of $N$ telescopes, there are:

$\frac{(N-1)(N-2)}{2}$ independent closure phases \[3\]

e.g. for $N=4$ there are 3 independent closure relations.
# known are needed to solve the equations

So from the closure relations we have \((N-1)(N-2)/N\) good observables (measurements).

However, there are \(N\) telescope unknowns. We can reduce this to \((N-1)\) unknowns if we make one of the telescopes the “reference antenna” (i.e. set the phase error to zero for this telescope).

Note that the ratio of good observables/unknowns (see eqn[3]) is then just:

\[
\frac{N-2}{N} \quad [4]
\]

So for \(N=3\) we have only 33% of the information we need.

But for \(N=27\) (the case of the VLA) we have 93% of the information we need.

\[\Rightarrow \text{in general the reliability of Interferometric images favours large-N telescope arrays (e.g. see SKA, ALMA and SKA pathfinders) - calibration is more robust and uv-coverage more complete.} \]
Telescope errors do not only effect the phase of the visibility. The amplitude can also be degraded. However, phase errors usually dominate (at least at cm wavelengths where attenuation by the atmosphere is a relatively small effect).

In order to consider how self-calibration can be used to correct for amplitude errors, we must use a complex formalism:

\[ V_{ij}^{\text{obs}}(t) = g_i(t) g^*_{i}(t) V_{ij}^{\text{true}}(t) \]  \[7\]

where \( V_{ij} \) are the measured and true visibilities, and \( g_i(t) g^*_{i}(t) \) are known as the complex gains of the telescopes \( i,j \).

The gains contain corrections to both the amplitude and phase of the visibility:

\[ e.g. \quad g_i(t) = a_i(t) e^{i\phi_i(t)} \]

In this formalism the observed and true Visibility can be written as:

\[ V_{ij}^{\text{obs}}(t) = a_i(t) a_j(t) e^{i(\phi_i - \phi_j)} A_{ij}(t) e^{i\varphi_{ij}(t)} \]  \[8\]  

\[ V_{ij}^{\text{true}}(t) = A_{ij}(t) e^{i\varphi_{ij}(t)} \]  \[9\]
Note that by taking the ratios of eqns such as [7] we arrive at the “closure quantities”. e.g.

\[ V_{12}^{\text{obs}}(t) = g_1(t) g_2(t) V_{12}^{\text{true}}(t) = a_1(t)e^{i\phi_1(t)} a_2(t)e^{-i\phi_2(t)} A_{12}(t) e^{i\phi_{12}(t)} \]
\[ V_{23}^{\text{obs}}(t) = g_2(t) g_3(t) V_{23}^{\text{true}}(t) = a_2(t)e^{i\phi_2(t)} a_3(t)e^{-i\phi_3(t)} A_{23}(t) e^{i\phi_{23}(t)} \]
\[ V_{13}^{\text{obs}}(t) = g_1(t) g_3(t) V_{13}^{\text{true}}(t) = a_1(t)e^{i\phi_1(t)} a_3(t)e^{-i\phi_3(t)} A_{13}(t) e^{i\phi_{13}(t)} \]

If we consider the phase terms only and implicitly accept time dependance:

\[ V_{12}^{\text{obs}} V_{23}^{\text{obs}} / V_{13}^{\text{obs}} = e^{i(\phi_1 + \phi_{12} + \phi_2) - i(\phi_1 + \phi_{13})} \]

\[ = e^{i(\phi_{12} + \phi_{23} - \phi_{13})} \quad [10] \]

Note that [10] is just the equivalent of our original closure phase presented in eqn[2b]
If we consider only the amplitude terms, we can see that for some combination of observed visibilities, the amplitude gains will cancel:

$$\frac{V_{12}^{\text{obs}}V_{34}^{\text{obs}}}{(V_{13}^{\text{obs}}V_{24}^{\text{obs}})} = \frac{A_{12}A_{34}a_1a_2a_3a_4}{A_{13}A_{24}a_1a_2a_3a_4} = \frac{A_{12}A_{34}}{A_{13}A_{24}} \quad [11]$$

Such ratios are known as “closure amplitudes” and require at least 4 telescopes to be formed.

Like closure phases, closure amplitude is a "good observable", since it is not sensitive to measurement error. The closure amplitude and closure phase relations can be exploited in the hybrid mapping algorithm (see earlier slides).

In the early days of hybrid mapping the closure phases and amplitudes were explicitly used to constrain the hybrid mapping process. In the era of the VLA it was no longer computationally efficient to calculate all the closure quantities. More sophisticated algorithms were constructed but they are all roughly equivalent to the original method. Modern algorithms seek to minimise the difference between the observed data and the predicted data:

$$S = \sum_{ij, i<j} w_{ij} |V_{ij}^{\text{obs}} - g_i g_j^* V_{ij}^{\text{true}}| \quad [12]$$

The $w_{ij}$ reflect the fact that some data are higher weighted than other data (e.g. especially for VLBI arrays where all the telescopes have different sensitivities).
If we consider only the amplitude terms, we can see that for some combination of observed visibilities, the amplitude gains will cancel:

\[
\frac{V_{12}^{\text{obs}} V_{34}^{\text{obs}}}{V_{13}^{\text{obs}} V_{24}^{\text{obs}}} = A_{12} A_{34} a_1 a_2 a_3 a_4 = A_{12} A_{34}
\]

Such ratios are known as "closure amplitudes" and require at least 4 telescopes to be formed.

Like closure phases, closure amplitude is a "good observable", since it is not sensitive to measurement error. The closure amplitude and closure phase relations can be exploited in the hybrid mapping algorithm (see earlier slides).

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\[
S = \sum_{i,j, i<j} w_{ij} |V_{ij}^{\text{obs}} - g_i g_j^* V_{ij}^{\text{model}}|
\]

The \(w_{ij}\) reflect the fact that some data are higher weighted than other data (e.g. especially for VLBI arrays where all the telescopes have different sensitivities).
calibrate data – single source

actually a off diagonal complex matrix per integration time

\[ V_{ij}^{\text{model}}(t) = A_{ij}(t) \ e^{i \phi_{ij}(t)} \]

can only be solved with a trick

assume a calibration source of 5 Jy at phase centre: \( A_{ij} = 5 \) & \( \phi_{ij}(t) = 0 \)

divide all the off diagonal terms of the matrix

add ones on the diagonal term

solve the matrix with the Gaussian elimination method to get diagonal matrix

the complex values on the diagonal are the complex gains for the antennas
information on calibrators

calibrators
4 absolute amplitude calibrator know
3C147, 3C48, 3C286 (~few percent polarized), 1934-638

There are initiatives to increase the number of absolute amplitude calibrators

phase-calibrator should be a point source!

calibrator data bases

VLA - http://www.aoc.nrao.edu/~gtaylor/csource.html

NVSS - http://www.cv.nrao.edu/nvss/


fring finder - http://www.aoc.nrao.edu/~analysts/vlba/ffs.html
Imaging

\[ V_\nu(u, v, w) = \int \int \frac{A_\nu(l, m) \cdot I^D_\nu(l, m)}{\sqrt{1 - l^2 - m^2}} e^{-2\pi i [ul + vm + w\sqrt{1 - l^2 - m^2}]} dldm \]

\[ I^D_\nu(l, m) = FT(\Pi(u, v)) \otimes I_\nu(l, m) \]

A_\nu(l,m) primary beam

UV coverage defines when

\[ V_\nu(u, v, w) = 0 \]

\[ V_\nu(u, v, w) = 1 \]
UV coverage sampling function of the sky

UV coverage

synthesized beam (dirty beam)

Fourier Transformation
data weighting

using FFT and gridding the data can use different weighting

natural weighting use numbers of visibility points per bin
uniform weighting use only 1 points per bin
weighting

natural weighting

uniform weighting

example with the synthesized beam (dirty beam)
analyse interferometer data

UV plane analysis
good for simple sources, point sources, doubles sources, disks

image plane analysis
difficult to do science on the dirty image
deconvolve $I^D_\nu(l,m)$ with dirty beam to determine model of $I_\nu(l,m)$

$$I^D_\nu(l, m) = \text{FT}(\Pi(u, v)) \otimes I_\nu(l, m)$$

visibilities       dirty image       sky brightness

Fourier transform  \rightarrow  deconvolve
Deconvolution

- Deconvolution:
  - uses non-linear techniques effectively interpolate/extrapolate samples of \( V(u,v) \) into unsampled regions of the \( (u,v) \) plane
  - aims to find a sensible model of \( I(x,y) \) compatible with data
  - requires a priori assumptions about \( I(x,y) \)

- CLEAN (Högbom 1974) is most common algorithm in radio astronomy
  - a priori assumption: \( I(x,y) \) is a collection of point sources
  - variants for computational efficiency, extended structure

- deconvolution requires knowledge of beam shape and image noise properties (usually OK for aperture synthesis)
  - atmospheric seeing can modify effective beam shape
  - deconvolution process can modify image noise properties
basic clean algorithm

cleaning is chipping the dirty brightness distribution

1. Initialize
   • a residual map to the dirty map
   • a CLEAN component list
2. Identify strongest feature in residual map as a point source
3. Add a fraction $g$ (the loop gain) of this point source to the clean component list ($g \sim 0.05-0.3$)
4. Subtract the fraction $g$ times $b(x,y)$ from residual map
5. If stopping criteria* not reached, go back to step 2 (an iteration), or...
6. Convolve CLEAN component (cc) list with an estimate of the main dirty beam lobe (i.e., the “CLEAN beam”) and add residual map to make the final “restored” image

* Stopping criteria = $N \times$ rms (if noise limited), or $I_{\text{max}}/N$ (if dynamic range limited), where $N$ is some arbitrarily chosen value
deconvolution

CLEAN model

residual map
sensitivity image / baseline

System Equivalent Flux Density

\[ SEFD = \frac{T_{sys}}{K} \quad K = (\eta_a A) / (2 k_B) \]
equ. (9-5)

Baseline sensitivity for one polarization

\[ \Delta S_{ij} = \frac{1}{\eta_s} \sqrt{\frac{T_{syi} T_{sysj}}{2 \Delta \nu \tau_{acc} K_i K_j}} \]

or in terms of the SEFDs defined in Equation 9-5:

\[ \Delta S_{ij} = \frac{1}{\eta_s} \sqrt{\frac{SEFD_i SEFD_j}{2 \Delta \nu \tau_{acc}}} \]

Image sensitivity for one polarization

\[ \Delta I_m = \frac{1}{\eta_s} \sqrt{N (N-1) \Delta \nu t_{int}} \]

Divide by square root 2 for 2 polarization!

A = Area
\( K_b \) = Boltzmann
\( \eta_a \) = efficiency
\( \eta_s \) = losses in electronics
\( \tau_{acc} \) = integration time [s]
\( \Delta \nu \) = bandwidth [Hz]
image quality measures

• “dynamic range”
  – ratio of peak brightness to rms noise in a region void of emission (common in astronomy)
  – an easy to calculate lower limit to the error in brightness in a non-empty region

• “fidelity”
  – difference between any produced image and the correct image
  – a convenient measure of how accurately it is possible to make an image that reproduces the brightness distribution on the sky
  – need a priori knowledge of correct image to calculate

  – fidelity image = input model / difference
  – fidelity is the inverse of the relative error
model

easy brightness distribution modelled by point sources or Gaussian

complicated brightness distribution modelled by number of Gaussian or use wavelet components

large fields of view one need the local sky model

   In case you use catalogued source from e.g. the NVSS you need to decrease the flux densities with respect to the phase centre or in other word careful the interferometer sees the local sky convolved with the primary beam

to detect a model component on a single baseline assume 6-8 sigma with respect to the rms of the baseline
self-calibration

self-calibration is an iterative procedure to determine the complex gains to calibrate the visibilities by iteratively improving the brightness distribution model on the sky.

- the model is based on the cleaned image
- number of clean components
- averaged time interval to determine gain solutions
  - phase: use minimum 3 antennas
  - amplitude: use minimum 4 antennas
- use dynamic range or rms as criteria to stop the self-calibration process

Caution: lose absolute phase from calibrators and therefore the position.
100 clean components
calibrate phase
60 minutes
integration time

80 clean components
calibrate phase
1 minutes
integration time

30 clean components
calibrate amplitude
1 minutes
integration time
calibration generations

closure phases and amplitudes

calibration assume antenna based errors

directional dependent calibration

peeling – subtract all sources except the most strongest one, self-cal on source, use final model of this source to subtract out of the database

measurement equation – MeqTree or CASA
Need of a good model of the sources brightness distribution within the LSM and of the directional dependent parameter of the interferometer and the single antennas all can be written as a matrix

\[
V_{pq} = G_p \left( \sum_{k=1}^{N} E_{pk} X_k E_{qk}^\dagger \right) G_{q}^\dagger
\]

where \( V_{pq} \) is the \( 2 \times 2 \) visibility (also called coherency, or uv-data) matrix measured by the interferometer formed by stations \( p \) and \( q \). The sum is taken over the contributions \( X_k \) from \( N \) discrete sources in the field, at positions \( l_k, m_k \).

Hamaker et al. 1996
In the $2 \times 2$ signal domain, the electric field vector $\vec{E}$ of the incident plane wave can be represented either in a linear polarisation coordinate frame $(x,y)$ or a circular polarisation coordinate frame $(r,l)$. Jones matrices are linear operators in the chosen frame:

$$\vec{V}_i^+ = \begin{pmatrix} v_{ip} \\ v_{iq} \end{pmatrix} = J_i^+ \begin{pmatrix} e_x \\ e_y \end{pmatrix} \quad \text{or} \quad \vec{V}_i^\ominus = J_i^\ominus \begin{pmatrix} e_r \\ e_l \end{pmatrix}$$ (13)

For linear polarisation coordinates, equation 1 becomes:

$$\vec{V}_{ij}^+ = (J_i^+ \otimes J_j^{+*}) (\vec{E} \otimes \vec{E}^*) = (J_i^+ \otimes J_j^{+*}) \begin{pmatrix} e_x e_x^* \\ e_x e_y^* \\ e_y e_x^* \\ e_y e_y^* \end{pmatrix} = (J_i^+ \otimes J_j^{+*}) S^+ \vec{I}(l,m)$$ (14)

and there is a similar expression for circular polarisation coordinates. Thus, as emphasised in [2], the Stokes vector $\vec{I}(l,m)$ and the coherency vector $\vec{V}_{ij}$ represent the same physical quantity, but in different abstract coordinate frames. A ‘Stokes matrix’ $S$ is a coordinate transformation matrix in the $4 \times 4$ coherence domain: $S^+$ transforms the representation from Stokes coordinates $(I,Q,U,V)$ to linear polarisation coordinates $(x,x,y,y)$. Similarly, $S^\ominus$ transforms to circular polarisation coordinates $(r,r,l,l)$. Following the convention of [4], we write:

$$S^+ = \frac{1}{2} \begin{pmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & i \\ 0 & 0 & 1 & -i \\ 1 & -i & 0 & 0 \end{pmatrix} \quad S^\ominus = \frac{1}{2} \begin{pmatrix} 1 & 0 & 0 & 1 \\ 0 & 1 & i & 0 \\ 0 & 1 & -i & 0 \\ 1 & 0 & 0 & -1 \end{pmatrix}$$ (15)
measurement equation

\[ J_i = G_i \begin{bmatrix} H_i \end{bmatrix} \begin{bmatrix} Y_i \end{bmatrix} B_i K_i T_i F_i = G_i \begin{bmatrix} H_i \end{bmatrix} \begin{bmatrix} Y_i \end{bmatrix} (D_i E_i P_i) K_i T_i F_i \]

in which

- \( F_i(\vec{\rho}, \vec{r}_i) \) ionosospheric Faraday rotation
- \( T_i(\vec{\rho}, \vec{r}_i) \) atmospheric complex gain
- \( K_i(\vec{\rho}, \vec{r}_i) \) factored Fourier Transform kernel
- \( P_i \) projected receptor orientation(s) w.r.t. the sky
- \( E_i(\vec{\rho}) \) voltage primary beam
- \( D_i \) position-independent receptor cross-leakage
- \( [Y_i] \) commutation of IF-channels
- \( [H_i] \) hybrid (conversion to circular polarisation coordinates)
- \( G_i \) electronic complex gain (feed-based contributions only)

CAUTION matrices do NOT commute
the order of each matrix has a physical reason
measurement equation matrices

The following matrices and vectors play a role in the Measurement\textsuperscript{Equation}:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\vec{I}$</td>
<td>Stokes vector of the source $(I,Q,U,V)$.</td>
</tr>
<tr>
<td>$\vec{V}, \nu$</td>
<td>Coherency vector, and one of its elements.</td>
</tr>
<tr>
<td>$S$</td>
<td>Stokes matrix, conversion between polarisation representations.</td>
</tr>
<tr>
<td>$S^+$</td>
<td>Conversion to linear representation.</td>
</tr>
<tr>
<td>$S^{\circ}$</td>
<td>Conversion to circular representation.</td>
</tr>
<tr>
<td>$\mathcal{M}$</td>
<td>Mueller matrix: Stokes to Stokes through optical ‘element’</td>
</tr>
<tr>
<td>$\vec{X}, \chi$</td>
<td>Correlator matrix ($4 \times 4$).</td>
</tr>
<tr>
<td>$\vec{M}, m$</td>
<td>Multiplicative interferometer-based gain matrix ($4 \times 4$).</td>
</tr>
<tr>
<td>$\vec{A}, a$</td>
<td>Additive interferometer-based gain vector.</td>
</tr>
</tbody>
</table>
The following *feed*-based Jones matrices (2 × 2) have a well-defined meaning:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(J_j)</td>
<td>(\text{m}_j\text{Jones}, \text{m}_j\text{JonesEl}) Jones matrix, and one of its elements.</td>
</tr>
<tr>
<td>(F,f)</td>
<td>(\text{m}_j\text{Prot}, \text{m}_j\text{ProtEl}) Faraday rotation (of the plane of linear pol.)</td>
</tr>
<tr>
<td>(T,t)</td>
<td>(\text{m}_j\text{Trop}, \text{m}_j\text{TropEl}) Atmospheric gain (refraction, extinction).</td>
</tr>
<tr>
<td>(P,p)</td>
<td>(\text{m}_j\text{Proj}, \text{m}_j\text{ProjEl}) Projected receptor angle(s) w.r.t. (x,y) frame</td>
</tr>
<tr>
<td>(B,b)</td>
<td>(\text{m}_j\text{Btot}, \text{m}_j\text{BtotEl}) Total <em>feed</em> voltage pattern (i.e. (B = D E P)).</td>
</tr>
<tr>
<td>(E,e)</td>
<td>(\text{m}_j\text{Beam}, \text{m}_j\text{BeamEl}) Traditional <em>feed</em> voltage beam.</td>
</tr>
<tr>
<td>(C,c)</td>
<td>(\text{m}_j\text{Conf}, \text{m}_j\text{ConfEl}) Feed configuration matrix (...).</td>
</tr>
<tr>
<td>(D,d)</td>
<td>(\text{m}_j\text{DrCP}, \text{m}_j\text{DrCPEl}) Leakage between receptors (a) and (b).</td>
</tr>
<tr>
<td>(H,h)</td>
<td>(\text{m}_j\text{Hybr}, \text{m}_j\text{HybrEl}) Hybrid network, to convert to circular pol.</td>
</tr>
<tr>
<td>(G,g)</td>
<td>(\text{m}_j\text{Grec}, \text{m}_j\text{GrecEl}) <em>feed</em>-based electronic gain.</td>
</tr>
<tr>
<td>(K,k)</td>
<td>(\text{m}_j\text{Kern}, \text{m}_j\text{KernEl}) Fourier Transform Kernel (baseline phase weight)</td>
</tr>
<tr>
<td>(K^0,k^0)</td>
<td>(\text{m}_j\text{Kref}, \text{m}_j\text{KrefEl}) FT kernel for the fringe-stopping centre.</td>
</tr>
<tr>
<td>(K',k')</td>
<td>(\text{m}_j\text{Koff}, \text{m}_j\text{KoffEl}) FT kernel relative to the fringe-stopping centre.</td>
</tr>
<tr>
<td>(Q,q)</td>
<td>(\text{m}_j\text{Qsum}, \text{m}_j\text{QsumEl}) Electronic gain of tied-array <em>feed</em> after summing.</td>
</tr>
</tbody>
</table>

Some special matrices and vectors:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{mmZero})</td>
<td>Zero matrix</td>
</tr>
<tr>
<td>(\text{vvZero})</td>
<td>Zero vector</td>
</tr>
<tr>
<td>(\text{mmUnit})</td>
<td>Unit matrix</td>
</tr>
<tr>
<td>(\text{m}_j\text{Diag})</td>
<td>Diagonal matrix with elements (a, b)</td>
</tr>
<tr>
<td>(\text{m}_j\text{Mult})</td>
<td>Multiplication with factor (a)</td>
</tr>
<tr>
<td>(\text{m}_j\text{Rot})</td>
<td>[pseudo] Rotation over an angle (\alpha, \beta)</td>
</tr>
<tr>
<td>(\text{m}_j\text{Ell})</td>
<td>Ellipticity angle[s] (\alpha, \beta)</td>
</tr>
</tbody>
</table>
so why do we need that again

going deeper in sensitivity implies that effects need to be modelled which have been ignored so far

strong sources far from the phase centre
so why do we need that again

model of the interferometer needs to be more realistic

primary beam

note that the primary beam is frequency dependent

old software packages are not able to model this

The effect will change e.g. source flux densities adding a systematic error if you do surveying