Calibration and Editing

George Moellenbrock

- Why calibration and editing?
- Formalism: Visibilities, signals, matrices
- Laundry List of Calibration Components
- Practical Calibration Planning
- Editing and RFI
- Calibration Sequence Examples
- Evaluating Calibration Performance
- Summary

Why Calibration and Editing?

- Synthesis radio telescopes, though well-designed, are not perfect (e.g., surface accuracy, receiver noise)
- Need to accommodate engineering (e.g., frequency conversion, digital electronics, etc.)
- Hardware or control software occasionally fails or behaves unpredictably
- Scheduling/observation errors sometimes occur (e.g., wrong source positions)
- Atmospheric conditions not ideal (not just bad weather)
- RFI

Determining instrumental properties (calibration)
is as important as
determining radio source properties

From Idealistic to Realistic

- Formally, we wish to obtain the visibility function, which we intend to invert to obtain an image of the sky:

$$V(u,v) = \int I_n(l,m)\, e^{-i2p\,(ul+vm)}\, dl\, dm$$

- In practice, we correlate the electric field (voltage) samples taken at pairs of telescopes (baselines i -j):

$$V_{ij}(t) = \left\langle x_i(t) e^{i f_i^{comp}} \cdot x_j^*(t) e^{-i f_j^{comp}} \right\rangle_t$$

- Single radio telescopes are devices for collecting the signal $x_i(t)$ and providing it to the correlator.

What signal is really collected?

- The net signal delivered by antenna i, $x_i(t)$, is a combination of the desired signal, $s_i(t,l,m)$, corrupted by a factor $J_i(t,l,m)$ and integrated over the sky, and noise, $n_i(t)$:

$$x_i(t) = \int J_i(t,l,m) s_i(t,l,m)\, dldm + n_i(t)$$
$$= s_i'(t) + n_i(t)$$

- $J_i(t,l,m)$ is the product of a host of effects which we must *calibrate*
- In some cases, effects contained in the $J_i(t,l,m)$ term corrupt the signal irreversibly and the resulting data must be *edited*
- $J_i(t,l,m)$ is a complex number
- $J_i(t,l,m)$ is *antenna-based*

Aside: Correlation of signals

- The correlation of two realistic signals from different antennas:

$$\langle x_i \cdot x_j^* \rangle = \langle (s_i' + n_i)\cdot(s_j' + n_j)^* \rangle$$
$$= \langle s_i' \cdot s_j'^* \rangle + \langle s_i' \cdot n_j^* \rangle + \langle n_i \cdot s_j'^* \rangle + \langle n_i \cdot n_j^* \rangle$$
$$= \langle s_i' \cdot s_j'^* \rangle$$
$$= \left\langle \int J_i(t) s_i(t)\, dldm \cdot \int J_j^*(t) s_j^*(t)\, dldm \right\rangle$$
$$= \left\langle \int J_i(t) J_j^*(t) s_i(t) s_j^*(t)\, dldm \right\rangle$$

  - Noise doesn't correlate—even if $n_i >> s_i$, correlation isolates desired signals
  - In integral, only $s_i(t,l,m)$, from the same directions correlate, so order of integration and signal product can be exchanged and terms re-ordered
- …and the auto-correlation of a signal from a single antenna:

$$\langle x_i \cdot x_i^* \rangle = \langle s_i' \cdot s_i'^* \rangle + \langle n_i \cdot n_i^* \rangle$$

  - Desired signal not isolated from noise (less useful!)

Formalism: Describe both polarizations via matrices

- Need two polarizations (p,q) to fully describe sampled EM wave front, where $p,q = R,L$ (circulars) or $p,q = X,Y$ (linears)
- Some components of J_i involve mixing of polarizations, so dual-polarization description desirable or even required
  - So substitute:

$$s_i \rightarrow \vec{s}_i = \begin{pmatrix} s^p \\ s^q \end{pmatrix}_i, \quad J_i \rightarrow \overleftrightarrow{J}_i = \begin{pmatrix} J^{p\rightarrow p} & J^{q\rightarrow p} \\ J^{p\rightarrow q} & J^{q\rightarrow q} \end{pmatrix}$$

  - The *Jones matrix* thus corrupts a signal as follows:

$$\vec{s}_i' = \overleftrightarrow{J}_i \vec{s}_i \qquad (l = m = 0,\ \text{integral omitted})$$

$$\begin{pmatrix} s'^p \\ s'^q \end{pmatrix}_i = \begin{pmatrix} J^{p\rightarrow p} & J^{q\rightarrow p} \\ J^{p\rightarrow q} & J^{q\rightarrow q} \end{pmatrix}_i \begin{pmatrix} s^p \\ s^q \end{pmatrix}_i$$
$$= \begin{pmatrix} J^{p\rightarrow p} s^p + J^{q\rightarrow p} s^q \\ J^{p\rightarrow q} s^p + J^{q\rightarrow q} s^q \end{pmatrix}_i$$

Signal Correlation and Matrices

- Four correlations are possible from two polarizations. The *outer product* (a 'bookkeeping' product) forms them:

$$\left\langle \vec{s}_i' \otimes \vec{s}_j'^{*} \right\rangle = \left\langle \begin{pmatrix} s'^{p} \\ s'^{q} \end{pmatrix}_i \otimes \begin{pmatrix} s'^{p} \\ s'^{q} \end{pmatrix}_j^{*} \right\rangle = \begin{pmatrix} \left\langle s_i'^{p} \cdot s_j'^{*p} \right\rangle \\ \left\langle s_i'^{p} \cdot s_j'^{*q} \right\rangle \\ \left\langle s_i'^{q} \cdot s_j'^{*p} \right\rangle \\ \left\langle s_i'^{q} \cdot s_j'^{*q} \right\rangle \end{pmatrix}$$

  - These four correlations (*pp, pq, qp, qq*) map to Stokes (I,Q,U,V) visibilities
- A very useful property of outer products:

$$(A \otimes B)(A' \otimes B') = (AA') \otimes (BB')$$

  - (where *A,B,A',B'* are matrices and/or vectors of appropriate dimensions):

Signal Correlation and Matrices *(cont)*

- The outer product for the Jones matrix:

$$\overleftrightarrow{J}_i \otimes \overleftrightarrow{J}_j^{*} = \begin{pmatrix} J^{p\to p} & J^{q\to p} \\ J^{p\to q} & J^{q\to q} \end{pmatrix}_i \otimes \begin{pmatrix} J^{p\to p} & J^{q\to p} \\ J^{p\to q} & J^{q\to q} \end{pmatrix}_j^{*}$$

$$= \begin{pmatrix} J_i^{p\to p} J_j^{*p\to p} & J_i^{p\to p} J_j^{*q\to p} & J_i^{q\to p} J_j^{*p\to p} & J_i^{q\to p} J_j^{*q\to p} \\ J_i^{p\to p} J_j^{*p\to q} & J_i^{p\to p} J_j^{*q\to q} & J_i^{q\to p} J_j^{*p\to q} & J_i^{q\to p} J_j^{*q\to q} \\ J_i^{p\to q} J_j^{*p\to p} & J_i^{p\to q} J_j^{*q\to p} & J_i^{q\to q} J_j^{*p\to p} & J_i^{q\to q} J_j^{*q\to p} \\ J_i^{p\to q} J_j^{*p\to q} & J_i^{p\to q} J_j^{*q\to q} & J_i^{q\to q} J_j^{*p\to q} & J_i^{q\to q} J_j^{*q\to q} \end{pmatrix} = \overleftrightarrow{J}_{ij}$$

  - J_{ij} is a 4x4 *Mueller matrix*
  - Antenna and array design thankfully driven by minimizing off-diagonal terms

Signal Correlation and Matrices *(cont)*

- And finally, for fun, the correlation of corrupted signals:

$$\overleftrightarrow{J}_i \vec{s}_i \otimes \overleftrightarrow{J}_j^{*} \vec{s}_j^{*} = \left(\overleftrightarrow{J}_i \otimes \overleftrightarrow{J}_j^{*}\right)\left(\vec{s}_i \otimes \vec{s}_j^{*}\right)$$

$$= \begin{pmatrix} J_i^{p\to p} J_j^{*p\to p} & J_i^{p\to p} J_j^{*q\to p} & J_i^{q\to p} J_j^{*p\to p} & J_i^{q\to p} J_j^{*q\to p} \\ J_i^{p\to p} J_j^{*p\to q} & J_i^{p\to p} J_j^{*q\to q} & J_i^{q\to p} J_j^{*p\to q} & J_i^{q\to p} J_j^{*q\to q} \\ J_i^{p\to q} J_j^{*p\to p} & J_i^{p\to q} J_j^{*q\to p} & J_i^{q\to q} J_j^{*p\to p} & J_i^{q\to q} J_j^{*q\to p} \\ J_i^{p\to q} J_j^{*p\to q} & J_i^{p\to q} J_j^{*q\to q} & J_i^{q\to q} J_j^{*p\to q} & J_i^{q\to q} J_j^{*q\to q} \end{pmatrix} \begin{pmatrix} s_i^{p} \cdot s_j^{*p} \\ s_i^{p} \cdot s_j^{*q} \\ s_i^{q} \cdot s_j^{*p} \\ s_i^{q} \cdot s_j^{*q} \end{pmatrix}$$

$$= \begin{pmatrix} J_i^{p\to p} J_j^{*p\to p} s_i^{p} \cdot s_j^{*p} + J_i^{p\to p} J_j^{*q\to p} s_i^{p} \cdot s_j^{*q} + J_i^{q\to p} J_j^{*p\to p} s_i^{q} \cdot s_j^{*p} + J_i^{q\to p} J_j^{*q\to p} s_i^{q} \cdot s_j^{*q} \\ J_i^{p\to p} J_j^{*p\to q} s_i^{p} \cdot s_j^{*p} + J_i^{p\to p} J_j^{*q\to q} s_i^{p} \cdot s_j^{*q} + J_i^{q\to p} J_j^{*p\to q} s_i^{q} \cdot s_j^{*p} + J_i^{q\to p} J_j^{*q\to q} s_i^{q} \cdot s_j^{*q} \\ J_i^{p\to q} J_j^{*p\to p} s_i^{p} \cdot s_j^{*p} + J_i^{p\to q} J_j^{*q\to p} s_i^{p} \cdot s_j^{*q} + J_i^{q\to q} J_j^{*p\to p} s_i^{q} \cdot s_j^{*p} + J_i^{q\to q} J_j^{*q\to p} s_i^{q} \cdot s_j^{*q} \\ J_i^{p\to q} J_j^{*p\to q} s_i^{p} \cdot s_j^{*p} + J_i^{p\to q} J_j^{*q\to q} s_i^{p} \cdot s_j^{*q} + J_i^{q\to q} J_j^{*p\to q} s_i^{q} \cdot s_j^{*p} + J_i^{q\to q} J_j^{*q\to q} s_i^{q} \cdot s_j^{*q} \end{pmatrix}$$

- UGLY, but let's think about individual calibration components in the signal domain, where the matrices are a factor of 2 less complicated…..

Calibration Components

- 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

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

- Order of terms follows signal path
- Each term has matrix form of J_i with terms embodying its particular algebra (on- vs. off-diagonal terms, etc.)
- The full matrix equation (especially after correlation!) is daunting, but usually only need to consider the terms individually or in pairs, and rarely in open form (matrix formulation = shorthand)

Ionospheric Faraday Rotation, *F*

- The ionosphere is *birefringent*; one hand of circular polarization is delayed w.r.t. the other, introducing a phase shift:

$$\Delta f = 0.15 \; l^2 \int B_{\parallel} n_e ds \;\; \text{deg}$$

$$l \text{ in cm}, \; n_e ds \text{ in } 10^{14}\text{cm}^{-2}, \;\; B_{\parallel} \text{ in G}$$

  - Rotates the linear polarization position angle
  - More important at longer wavelengths:

$$TEC = \int n_e ds \sim 10^{14}\text{cm}^{-2}; \; B_{\parallel} \sim 1\text{G}; \; l = 20\text{cm} \rightarrow \Delta f \sim 60^{\circ}$$

  - More important at solar maximum and at sunrise/sunset, when ionosphere is most active
  - Beware of 'patchiness' and other variability (e.g., with elevation changes)
    - » Namir's lecture: "Long Wavelength Interferometry" (next Tuesday)

$$\overleftrightarrow{F}^{RL} = \begin{pmatrix} e^{i\Delta f} & 0 \\ 0 & e^{-i\Delta f} \end{pmatrix}; \; \overleftrightarrow{F}^{XY} = \begin{pmatrix} \cos\Delta f & -\sin\Delta f \\ \sin\Delta f & \cos\Delta f \end{pmatrix}$$

Tropospheric Effects, *T*

- The troposphere causes polarization-independent amplitude and phase effects due to emission/opacity and refraction, respectively
  - Typically 2-3m excess path length at zenith compared to vacuum
  - Most important at ν > 15 GHz where water vapor absorbs/emits
  - More important nearer horizon where tropospheric path length greater
  - Clouds, weather = variability in phase and opacity; may vary across array
  - Water vapor radiometry? Phase transfer from low to high frequencies?
    - » Claire's lecture: "mm-Wave Interferometry" (next Monday)

$$\overleftrightarrow{T}^{pq} = \begin{pmatrix} t & 0 \\ 0 & t \end{pmatrix} = t \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

Parallactic Angle, *P*

- Orientation of sky in telescope's field of view
  - Constant for equatorial telescopes
  - Varies for alt-az-mounted telescopes:

$$c\,(t) = \arctan\left(\frac{\cos(l)\sin(h(t))}{\sin(l)\cos(d) - \cos(l)\sin(d)\cos(h(t))}\right)$$

$$l = \text{latitude},\ h(t) = \text{hour angle},\ d = \text{declination}$$

  - Rotates the position angle of linearly polarized radiation (c.f. *F*)
  - Analytically known, and its variation provides leverage for determining polarization-dependent effects

$$\vec{P}^{RL} = \begin{pmatrix} e^{ic} & 0 \\ 0 & e^{-ic} \end{pmatrix};\ \vec{P}^{XY} = \begin{pmatrix} \cos c & -\sin c \\ \sin c & \cos c \end{pmatrix}$$

Antenna Voltage Pattern, *E*

- Antennas of all designs have direction-dependent gain
  - Important when region of interest on sky comparable to or larger than λ/D
    - » Kumar's lecture: "Wide Field Imaging I" (next Monday)
    - » Debra's lecture: "Wide Field Imaging II" (next Monday)
  - Important at lower frequencies where radio source surface density is greater and wide-field imaging techniques required
  - Beam squint: E^p and E^q not parallel, yielding spurious polarization
  - For convenience, direction dependence of polarization leakage (*D*) may be included in *E* (off-diagonal terms then non-zero)

$$E^{pq} = \begin{pmatrix} e^{p}(l,m) & 0 \\ 0 & e^{q}(l,m) \end{pmatrix}$$

Polarization Leakage, *D*

- Polarizer is not ideal, so orthogonal polarizations not perfectly isolated
  - Well-designed feeds have *d* ~ a few percent or less
  - A geometric property of the feed design, so frequency dependent
  - For *R,L* systems, total-intensity imaging affected as ~*dQ*, *dU*, so only important at high dynamic range (because *Q,U*~*d*, typically)
  - For *R,L* systems, linear polarization imaging affected as ~*dI*, so almost always important
    - » Greg's lecture: "Polarization in Interferometry" (today!)

$$\vec{D}^{pq} = \begin{pmatrix} 1 & d^{p} \\ d^{q} & 1 \end{pmatrix}$$

Electronic Gain, *G*

- Catch-all for most amplitude and phase effects introduced by antenna electronics (amplifiers, mixers, quantizers, digitizers)
  - Most commonly treated calibration component
  - Dominates other effects for standard observations
  - Includes scaling from engineering to radioastronomy units (Jy)
  - Often includes ionospheric and tropospheric effects which are typically difficult to separate unto themselves
  - Excludes frequency dependent effects (see *B*)

$$G^{pq} = \begin{pmatrix} g^{p} & 0 \\ 0 & g^{q} \end{pmatrix}$$

Bandpass Response, *B*

- *G*-like component describing frequency-dependence of antenna electronics, etc.
  - Filters used to select frequency passband not square
  - Optical and electronic reflections introduce ripples across band
  - Typically (but not necessarily) normalized

$$B^{pq} = \begin{pmatrix} b^{p}(n) & 0 \\ 0 & b^{q}(n) \end{pmatrix}$$

More-sophisticated effects

- Errors in geometric/clock models in correlator cause poor phase compensation
  - Routine problem in VLBI solved by fringe-fitting: parameterization of *G* to include phase terms which are linear in time and frequency
    - » Craig's lecture: "VLBI" (Thursday)
- Baseline-based errors do not decompose into antenna-based components
  - Most digital correlators designed to limit such effects to well-understood and uniform scaling laws (absorbed in *G*)
  - Additional errors can result from averaging in time and frequency over variation in antenna-based effects and visibilities (practical instruments are finite!)
  - Correlated noise (e.g., RFI)
  - Virtually indistinguishable from source structure effects
  - Geodetic observers consider determination of radio source structure—a baseline-based effect—as a required *calibration* if antenna positions are to be determined accurately

Putting it all back together

- In the correlation of signals, like terms from the different antennas are conveniently grouped:

$$\overleftrightarrow{J}_i \otimes \overleftrightarrow{J}_j = \overleftrightarrow{B}_i \overleftrightarrow{G}_i \overleftrightarrow{D}_i \overleftrightarrow{E}_i \overleftrightarrow{P}_i \overleftrightarrow{T}_i \overleftrightarrow{F}_i \otimes \overleftrightarrow{B}_j^* \overleftrightarrow{G}_j^* \overleftrightarrow{D}_j^* \overleftrightarrow{E}_j^* \overleftrightarrow{P}_j^* \overleftrightarrow{T}_j^* \overleftrightarrow{F}_j^*$$
$$= \left(\overleftrightarrow{B}_i \otimes \overleftrightarrow{B}_j^*\right)\left(\overleftrightarrow{G}_i \otimes \overleftrightarrow{G}_j^*\right)\left(\overleftrightarrow{D}_i \otimes \overleftrightarrow{D}_j^*\right)\left(\overleftrightarrow{E}_i \otimes \overleftrightarrow{E}_j^*\right)\left(\overleftrightarrow{P}_i \otimes \overleftrightarrow{P}_j^*\right)\left(\overleftrightarrow{T}_i \otimes \overleftrightarrow{T}_j^*\right)\left(\overleftrightarrow{F}_i \otimes \overleftrightarrow{F}_j^*\right)$$
$$= \overleftrightarrow{B}_{ij} \overleftrightarrow{G}_{ij} \overleftrightarrow{D}_{ij} \overleftrightarrow{E}_{ij} \overleftrightarrow{P}_{ij} \overleftrightarrow{T}_{ij} \overleftrightarrow{F}_{ij}$$

- The total *Measurement Equation* has the form:

$$\vec{V}_{ij} = \overleftrightarrow{M}_{ij} \int \overleftrightarrow{B}_{ij} \overleftrightarrow{G}_{ij} \overleftrightarrow{D}_{ij} \overleftrightarrow{E}_{ij} \overleftrightarrow{P}_{ij} \overleftrightarrow{T}_{ij} \overleftrightarrow{F}_{ij}\, S \vec{I}_n(l,m)\, e^{-i2p\,(u_{ij} l + v_{ij} m)}\, dl\, dm + \vec{A}_{ij}$$

  - *S* maps the Stokes vector, *I*, to the polarization basis of the instrument
  - M_{ij} and A_{ij} are multiplicative and additive baseline-based errors, respectively
  - In general, all J_{ij} may be direction-dependent, so inside the integral….

Realizing practical calibration

- …but in practice, we often ignore the direction dependence of the calibration components and factor them out of the integral (dropping E_{ij}). The Measurement Equation then becomes a relation between the observed and ideal visibilities:

$$\vec{V}_{ij}^{obs} = \overleftrightarrow{B}_{ij} \overleftrightarrow{G}_{ij} \overleftrightarrow{D}_{ij} \overleftrightarrow{P}_{ij} \overleftrightarrow{T}_{ij} \overleftrightarrow{F}_{ij}\, \vec{V}_{ij}^{ideal}$$

- If the ideal visibilities are known (e.g., by choosing calibration source of known structure), we can solve for individual components using those we already know (if any), e.g.:

$$\left(\overleftrightarrow{G}_{ij}^{-1} \overleftrightarrow{B}_{ij}^{-1} \vec{V}_{ij}^{obs}\right) = \overleftrightarrow{D}_{ij} \left(\overleftrightarrow{P}_{ij} \overleftrightarrow{T}_{ij} \overleftrightarrow{F}_{ij}\, \vec{V}_{ij}^{ideal}\right)$$

Realizing practical calibration *(cont)*

- Formally, solving for any component is the same non-linear fitting problem:

$$\left(\vec{V}_{ij}^{corrected\cdot obs}\right) = \overleftrightarrow{J}_{ij}^{solvable} \left(\vec{V}_{ij}^{corrupted\cdot ideal}\right)$$

  - Algebraic particulars are stored safely and conveniently inside the matrix formalism (out of sight, out of mind!)
  - Viability of the solution relies on the underlying algebra (hard wired in calibration applications) and *proper calibration observations*
  - The relative importance of the different components enables deferring or even ignoring the more subtle effects

Planning for Good Calibration

- A priori calibrations (provided by the observatory)
  - Antenna positions, earth orientation and rate
  - Clocks
  - Antenna pointing, gain, voltage pattern
  - Calibrator coordinates, flux densities, polarization properties
- Absolute calibration?
  - Very difficult, requires heroic efforts by visiting observers and observatory scientific and engineering staff
- Cross-calibration a better choice
  - Observe nearby point sources against which calibration components can be solved, and transfer solutions to target observations
  - Choose appropriate calibrators for different components; usually point sources because we can predict their visibilities
  - Choose appropriate timescales for each component

Calibrator Rules of Thumb

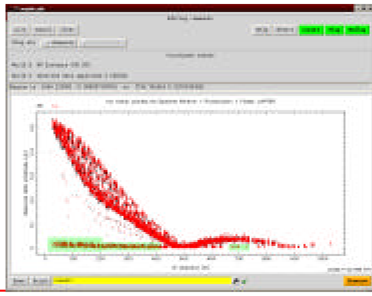
- *T, G:*
  - Strong and point-like sources, as near to target source as possible
  - Observe often enough to track phase and amplitude variations: calibration intervals of up to 10s of minutes at low frequencies (beware of ionosphere!), as short as 1 minute or less at high frequencies
  - Observe at least one calibrator of known flux density at least once
- *B:*
  - Strong enough for good sensitivity in each channel (often, *T, G* calibrator is ok)
  - If bandwidth is wide, should be point-like to avoid visibility changes across band
  - Observe often enough to track variations (e.g., waveguide reflections change with temperature and are thus a function of time-of-day)
- *D:*
  - Best calibrator is strong and unpolarized
  - If polarized, observe over a broad range of parallactic angle to disentangle *D*s and source polarization (often, *T, G* calibrator is ok)
- *F:*
  - Choose strongly polarized source and observe often enough to track variation
  - If ionosphere is stable, rely on ionosonde observations for empirical corrections

Data Examination and Editing

- After observation, initial data examination and editing very important
  - Will observations meet goals for calibration and science requirements?
  - Some real-time flagging occurred during observation (antennas off-source, LO out-of-lock, etc.). Any such bad data left over? (check operator's logs)
  - Any persistently 'dead' antennas ($J_i=0$ during otherwise normal observing)? (check operator's logs)
  - Amplitude and phase should be continuously varying—edit outliers
  - Any antennas shadowing others? Edit such data.
  - Be conservative: those antennas/timeranges which are bad on calibrators are probably bad on weak target sources—edit them
  - Periods of poor weather? (check operator's log)
  - Distinguish between bad data and poorly-calibrated data. E.g., some antennas may have significantly different amplitude response which may not be fatal—it may only need to be calibrated
  - Radio Frequency Interference (RFI)?
  - Choose reference antenna wisely (ever-present, stable response)

A Data Editing Example

- msplot in aips++

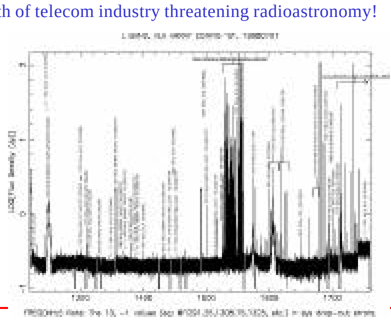


Radio Frequency Interference

- RFI originates from man-made signals generated in the antenna or by external sources (e.g., satellites, cell-phones, radio and TV stations, etc.)
  - Obscures natural emission in spectral line observations
  - Adds to total noise power in all observations, thus decreasing sensitivity to desired natural signal, and complicating amplitude calibration
  - Though a contribution to the n_i term, can correlate between antennas if of common origin or baseline short enough
- RFI Mitigation
  - Careful electronics design in antennas
  - Observatories world-wide lobbying for spectrum management
  - Various on-line and off-line mitigation techniques under study
  - Choose interference-free frequencies (try to find 50 MHz of clean spectrum in the 1.6 GHz band!)
  - Observe continuum experiments in spectral-line modes so bad channels can be edited

Radio Frequency Interference *(cont.)*

- Growth of telecom industry threatening radioastronomy!



Calibration Sequence I

- Observation: total intensity spectral line imaging of weak target
  - A weak target source (**1**)
  - A nice near-by point-like *G, T* calibrator (**2**), observed alternately, but too weak for good *B* calibration (flux density unknown)
  - Three observations of strong flux density calibrator (**3**) which is also good for *B* calibration
- Schedule (each digit is a fixed duration):
  - **33-2-111-2-111-2-111-2-111-2-33-2-111-2-111-2-111-2-111-2-111-2-33**
- Calibration sequence:
  - On **3**, solve for *G*: $\left(\vec{V}^{obs}_{ij(3)}\right) = \overset{\leftrightarrow}{G}_{ij(3)}\left(\vec{V}^{ideal}_{ij(3)}\right)$
  - On **3**, solve for *B*, using *G*: $\left(\vec{V}^{obs}_{ij(3)}\right) = \overset{\leftrightarrow}{B}_{ij(3)}\left(\overset{\leftrightarrow}{G}_{ij(3)}\vec{V}^{ideal}_{ij(3)}\right)$
  - On **2**, solve for *G*, using *B*: $\left(\overset{\leftrightarrow}{B}{}^{-1}_{ij(3)}\vec{V}^{obs}_{ij(2)}\right) = \overset{\leftrightarrow}{G}_{ij(2)}\left(\vec{V}^{ideal}_{ij(2)}\right)$
  - Scale **2**'s *G*s according to **3**'s *G*s: $\left|\overset{\leftrightarrow}{G}'_{i(2)}\right| = \left|\overset{\leftrightarrow}{G}_{i(2)}\right|\left(\left\langle\left|\overset{\leftrightarrow}{G}_{i(3)}\right|\right\rangle / \left\langle\left|\overset{\leftrightarrow}{G}_{i(2)}\right|\right\rangle\right)$
  - Transfer *B*, *G* to **1**: $\vec{V}^{corrected}_{ij(1)} = \left(\overset{\leftrightarrow}{G}{}'^{-1}_{ij(2)}\overset{\leftrightarrow}{B}{}^{-1}_{ij(3)}\vec{V}^{obs}_{ij(1)}\right)$

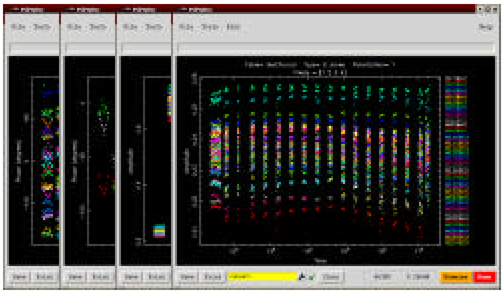
Calibration Sequence II

- Observation: full-polarization imaging of weak target
  - A weak target source (**1**)
  - A nice, near-by, point-like, *G, T* calibrator (**2**), observed alternately, ok for *D* calibration, too (flux density and polarization unknown)
  - Three observations of strong flux density calibrator
- Schedule (each digit is a fixed duration):
  - **33-2-1111-2-1111-2-1111-2-1111-2-33-2-1111-2-1111-2-1111-2-1111-2-33**
- Calibration sequence:
  - On **2** & **3**, solve for *G*, using *P*: $\left(\vec{V}^{obs}_{ij(2,3)}\right) = \overset{\leftrightarrow}{G}_{ij(2,3)}\left(\overset{\leftrightarrow}{P}_{ij(2,3)}\vec{V}^{ideal}_{ij(2,3)}\right)$
  - Apply *G* to **2**, get improved poln model: $\vec{V}^{ideal}_{ij(2)} = \left\langle\overset{\leftrightarrow}{P}{}^{-1}_{ij(2)}\overset{\leftrightarrow}{G}{}^{-1}_{ij(2)}\vec{V}^{obs}_{ij(2)}\right\rangle$
  - On **2**, solve for *D*, using *P, G,* & new model: $\left(\overset{\leftrightarrow}{G}{}^{-1}_{ij(2)}\vec{V}^{obs}_{ij(2)}\right) = \overset{\leftrightarrow}{D}_{ij(2)}\left(\overset{\leftrightarrow}{P}_{ij(2)}\vec{V}^{ideal}_{ij(2)}\right)$
  - Scale **2**'s *G*s according to **3**'s *G*s: $\left|\overset{\leftrightarrow}{G}'_{i(2)}\right| = \left|\overset{\leftrightarrow}{G}_{i(2)}\right|\left(\left\langle\left|\overset{\leftrightarrow}{G}_{i(3)}\right|\right\rangle / \left\langle\left|\overset{\leftrightarrow}{G}_{i(2)}\right|\right\rangle\right)$
  - Transfer *D, G* to **1**, use *P*: $\vec{V}^{corrected}_{ij(1)} = \left(\overset{\leftrightarrow}{P}{}^{-1}_{ij(1)}\overset{\leftrightarrow}{D}{}^{-1}_{ij(2)}\overset{\leftrightarrow}{G}{}'^{-1}_{ij(2)}\vec{V}^{obs}_{ij(1)}\right)$

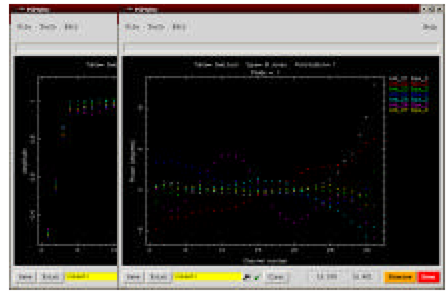
Evaluating Calibration Performance

- Are solutions continuous?
  - Noise-like solutions are just that—noise
  - Discontinuities indicate instrumental glitches
  - Any additional editing required?
- Are calibrator data fully described by antenna-based effects?
  - Phase and amplitude *closure errors* are the baseline-based residuals; see Chapter 5 in book
  - Are calibrators sufficiently point-like? If not, self-calibrate: model calibrator visibilities (by imaging, deconvolving and transforming) and re-solve for calibration; iterate to isolate source structure from calibration components
    - » Jim's lecture: "Self-Calibration" (Wednesday)
- Any evidence of unsampled variation? Is interpolation of solutions appropriate?
  - Self-calibration may be required, if possible

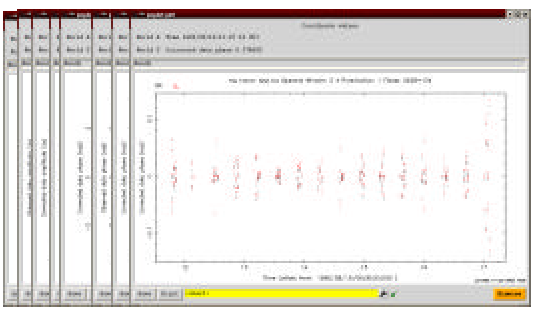
G Solution Examples



B Solution Examples

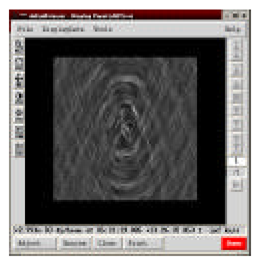


Effect of Calibration on Visibility Data

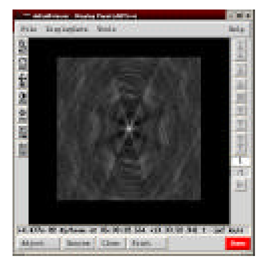


Effect of Calibration in the Image Plane

Uncalibrated



Calibrated



Summary

- Determining calibration is as important as determining source structure—can't have one without the other
- Data examination and editing and important part of calibration
- Calibration dominated by antenna-based effects
- Calibration formalism algebra-rich, but can be described piecemeal in comprehendible segments, according to well-defined effects
- Calibration determination is a single standard fitting problem
- Point sources are the best calibrators
- Observe calibrators according requirements of components
- Calibration sequences a juggling act of effects and corrections