Calibration and Editing

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Outline

• Why calibrate and edit?
• How to calibrate
• What to Edit
• Practical Calibration Planning
• Calibration Evaluation
• A Dictionary of Calibration Components
• More on editing and RFI
• Summary

This lecture is complementary to Chapter 5 of ASP 180 and is based on a lecture by George Moellenbrock
Why Calibration and Editing?

- Synthesis radio telescopes, though well-designed, are not perfect (e.g., surface accuracy, receiver noise, polarization purity, stability, etc.)
- 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 limited to “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:

\[
V(u,v) = \int_{\text{sky}} I(l,m) e^{-i2\pi(u l + v m)} \, dl \, dm
\]

- In practice, we correlate (multiply & average) the electric field (voltage) samples, \(x_i\) & \(x_j\), received at pairs of telescopes \((i,j)\)
  - Averaging duration is set by the expected timescales for variation of the correlation result (typically 10s or less for the VLA)
- 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, $n_i(t)$:

$$x_i(t) = \int_{\text{sky}} J_i(t,l,m)s_i(t,l,m) \, dl \, dm + n_i(t)$$

$$= s'_i(t) + n_i(t)$$

- $J_i(t,l,m)$ is the product of a host of effects which we must calibrate
- In some cases, effects implicit 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
- Usually, $|n_i| >> |s_i|$
The Measurement Equation

- We can now write down the calibration situation in a general way - the Measurement Equation:

\[ \vec{V}_{ij}^{obs} = \int_{\text{sky}} \left( \vec{J}_i \otimes \vec{J}_j^* \right) \vec{I}(l, m) e^{-i2\pi(u_{ij}l + v_{ij}m)} dldm \]

- …and consider how to solve it!
The Measurement Equation - Simplified

\[ \tilde{V}_{ij}^{\text{obs}} = \int \left( \tilde{J}_i \otimes \tilde{J}_j^* \right) \tilde{I}(l,m)e^{-i2\pi(u_{ij}l+v_{ij}m)} \, dldm \]

- First, isolate non-direction-dependent effects, and factor them from the integral:

\[ \left( \tilde{J}_i^{\text{vis}} \otimes \tilde{J}_j^{\text{vis}*} \right) \int \left( \tilde{J}_i^{\text{sky}} \otimes \tilde{J}_j^{\text{sky}*} \right) \tilde{I}(l,m)e^{-i2\pi(u_{ij}l+v_{ij}m)} \, dldm \]

- Next, we recognize that it is often possible to assume \( J^{\text{sky}} = 1 \), and we have a relationship between ideal and observed Visibilities:

\[ \left( \tilde{J}_i^{\text{vis}} \otimes \tilde{J}_j^{\text{vis}*} \right) \int \tilde{I}(l,m)e^{-i2\pi(u_{ij}l+v_{ij}m)} \, dldm \]

\[ \tilde{V}_{ij}^{\text{obs}} = \left( \tilde{J}_i^{\text{vis}} \otimes \tilde{J}_j^{\text{vis}*} \right)\tilde{V}_{ij}^{\text{ideal}} \]
Solving the Measurement Equation

- The $J$ terms can be factored into a series of components representing physical elements along the signal path:

\[
\vec{V}_{ij}^{\text{obs}} = (\vec{J}_i^1 \otimes \vec{J}_j^1^*) (\vec{J}_i^2 \otimes \vec{J}_j^2^*) (\vec{J}_i^3 \otimes \vec{J}_j^3^*) (\vec{J}_i^{\text{...}} \otimes \vec{J}_j^{\text{...}}^*) \vec{V}_{ij}^{\text{ideal}}
\]

- Depending upon availability of estimates for various $J$ terms, we can re-arrange the equation and solve for any single term, if we know $\vec{V}_{\text{ideal}}$:

\[
\begin{bmatrix}
(\vec{J}_i^2 \otimes \vec{J}_j^2^*)^{-1} (\vec{J}_i^1 \otimes \vec{J}_j^1^*)^{-1} \vec{V}_{ij}^{\text{obs}}
\end{bmatrix}
= (\vec{J}_i^{\text{solve}} \otimes \vec{J}_j^{\text{solve}}^*) \begin{bmatrix}
(\vec{J}_i^4 \otimes \vec{J}_j^4^*) (\vec{J}_i^{\text{...}} \otimes \vec{J}_j^{\text{...}}^*) \vec{V}_{ij}^{\text{ideal}}
\end{bmatrix}
\]

- After obtaining estimates for all relevant $J$, data can be corrected:

\[
\vec{V}_{ij}^{\text{corrected}} = (\vec{J}_i^{\text{...}} \otimes \vec{J}_j^{\text{...}}^*)^{-1} (\vec{J}_i^3 \otimes \vec{J}_j^3^*)^{-1} (\vec{J}_i^2 \otimes \vec{J}_j^2^*)^{-1} (\vec{J}_i^1 \otimes \vec{J}_j^1^*)^{-1} \vec{V}_{ij}^{\text{obs}}
\]
Solving the Measurement Equation

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

\[
\vec{V}_{ij}^{\text{corrected.obs}} = \left( \vec{J}_i^{\text{solve}} \otimes \vec{J}_j^{\text{solve}*} \right) \vec{V}_{ij}^{\text{corrupted.ideal}}
\]

- Algebraic particulars are stored safely and conveniently inside the matrix formalism (out of sight, out of mind!)

- Viability of the solution depends on the underlying algebra (hardwired in calibration applications) and relies on proper calibration observations
Antenna-based Calibration

- Success of synthesis telescopes relies on antenna-based calibration
  - N antenna-based factors, N(N-1) visibility measurements
  - Fundamentally, only information that cannot be factored into antenna-based terms is believable as being of astronomical origin

- Closure: calibration-independent observables:
  - Closure phase (3 baselines):
    \[ \phi_{ij}^{\text{obs}} + \phi_{jk}^{\text{obs}} + \phi_{ki}^{\text{obs}} = \phi_{ij}^{\text{real}} + (\theta_i - \theta_j) + \phi_{jk}^{\text{real}} + (\theta_j - \theta_k) + \phi_{ki}^{\text{real}} + (\theta_k - \theta_i) \]
    \[ = \phi_{ij}^{\text{real}} + \phi_{jk}^{\text{real}} + \phi_{ki}^{\text{real}} \]

  - Closure amplitude (4 baselines):
    \[ \begin{vmatrix} V_{ij}^{\text{obs}} V_{kl}^{\text{obs}} \\ V_{ik}^{\text{obs}} V_{jl}^{\text{obs}} \end{vmatrix} = \begin{vmatrix} J_{ij} J_{j}^{\text{real}} V_{ij}^{\text{real}} J_{k} J_{l}^{\text{real}} V_{kl}^{\text{real}} \\ J_{ik} J_{k}^{\text{real}} V_{ik}^{\text{real}} J_{jl} J_{l}^{\text{real}} V_{jl}^{\text{real}} \end{vmatrix} = \begin{vmatrix} V_{ij}^{\text{real}} V_{kl}^{\text{real}} \\ V_{ik}^{\text{real}} V_{jl}^{\text{real}} \end{vmatrix} \]
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 flux calibration
  - True calibration very difficult, requires great effort
  - Substitute is to reference to a source of known flux (e.g., 3C286)

- Cross-calibration
  - Observe nearby point sources against which calibration components can be solved, and transfer solutions to target observations
  - Choose appropriate calibrators for different components; usually strong point sources because we can predict their visibilities
  - Choose appropriate timescales for each component

- Simple (common) example, Gain and Bandpass:

\[
\tilde{V}_{ij}^{\text{obs}} = (\tilde{B}_i \otimes \tilde{B}_j^*) (\tilde{G}_i \otimes \tilde{G}_j^*) \tilde{V}_{ij}^{\text{ideal}}
\]

\[
= \tilde{B}_{ij} \tilde{G}_{ij} \tilde{V}_{ij}^{\text{ideal}}
\]
“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 VLA observations
  - Includes scaling from engineering (correlation coefficient) to radio astronomy units (Jy), by scaling solution amplitudes according to observations of a flux density calibrator
  - Often also includes ionospheric and tropospheric effects which are typically difficult to separate unto themselves
**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
  - Often assumed time-independent, but not necessarily so
  - Typically (but not necessarily) normalized
### Typical VLA observation

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Frequency</th>
<th>Band</th>
<th>Central Elevation</th>
<th>Altitude</th>
<th>Azimuth</th>
<th>Right Ascension</th>
<th>Declination</th>
</tr>
</thead>
<tbody>
<tr>
<td>1331+305=3C286</td>
<td>13h 31m 6.28798s</td>
<td>33496MHz</td>
<td>1.04</td>
<td>70.8d</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J2000</td>
<td>(3) Ka band</td>
<td>30d 30' 32.9569''</td>
<td>---</td>
<td>33824MHz</td>
<td>1.09</td>
<td>71.2d</td>
<td>00:03:00</td>
<td></td>
</tr>
<tr>
<td>1331+305=3C286</td>
<td>13h 31m 6.28798s</td>
<td>33496MHz</td>
<td>1.09</td>
<td>71.2d</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J2000</td>
<td>(2) myOwide</td>
<td>30d 30' 32.9569''</td>
<td>---</td>
<td>7796MHz</td>
<td>1.14</td>
<td>71.6d</td>
<td>00:02:40</td>
<td></td>
</tr>
<tr>
<td>1331+305=3C286</td>
<td>13h 31m 6.28798s</td>
<td>33496MHz</td>
<td>1.14</td>
<td>71.6d</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J2000</td>
<td>(1) K band</td>
<td>30d 30' 32.9569''</td>
<td>---</td>
<td>2230MHz</td>
<td>1.19</td>
<td>72.0d</td>
<td>00:02:40</td>
<td></td>
</tr>
<tr>
<td>J1516+1932</td>
<td>J1516+1932 K</td>
<td>15h 16m 56.79619e</td>
<td>---</td>
<td>2230MHz</td>
<td>-0.57</td>
<td>-26.0d</td>
<td>00:02:40</td>
<td></td>
</tr>
<tr>
<td>J2000</td>
<td>(1) K band</td>
<td>19d 32' 12.9919''</td>
<td>---</td>
<td>22524MHz</td>
<td>-0.51</td>
<td>-23.4d</td>
<td>00:01:05</td>
<td></td>
</tr>
<tr>
<td>3C_321</td>
<td>3C_321 K</td>
<td>15h 31m 43.5s</td>
<td>---</td>
<td>2230MHz</td>
<td>-0.75</td>
<td>-42.0d</td>
<td>00:02:22</td>
<td></td>
</tr>
<tr>
<td>J2000</td>
<td>(1) K band</td>
<td>24d 4' 19.0''</td>
<td>---</td>
<td>22524MHz</td>
<td>-0.70</td>
<td>-40.2d</td>
<td>00:02:22</td>
<td></td>
</tr>
<tr>
<td>J1516+1932</td>
<td>J1516+1932 C_wide</td>
<td>15h 16m 56.79619e</td>
<td>---</td>
<td>4196MHz</td>
<td>-0.46</td>
<td>-21.4d</td>
<td>00:01:22</td>
<td></td>
</tr>
<tr>
<td>J2000</td>
<td>(2) myOwide</td>
<td>19d 32' 12.9919''</td>
<td>---</td>
<td>7796MHz</td>
<td>-0.42</td>
<td>-19.9d</td>
<td>00:01:22</td>
<td></td>
</tr>
<tr>
<td>3C_321</td>
<td>3C_321 C_wide</td>
<td>15h 31m 43.5s</td>
<td>---</td>
<td>4196MHz</td>
<td>-0.67</td>
<td>-38.9d</td>
<td>00:02:21</td>
<td></td>
</tr>
<tr>
<td>J2000</td>
<td>(2) myOwide</td>
<td>24d 4' 19.0''</td>
<td>---</td>
<td>7796MHz</td>
<td>-0.62</td>
<td>-36.9d</td>
<td>00:02:21</td>
<td></td>
</tr>
<tr>
<td>J1516+1932</td>
<td>J1516+1932 Ka</td>
<td>15h 16m 56.79619e</td>
<td>---</td>
<td>33496MHz</td>
<td>-0.37</td>
<td>-17.8d</td>
<td>00:01:51</td>
<td></td>
</tr>
<tr>
<td>J2000</td>
<td>(3) Ka band</td>
<td>19d 32' 12.9919''</td>
<td>---</td>
<td>33824MHz</td>
<td>-0.33</td>
<td>-15.9d</td>
<td>00:01:51</td>
<td></td>
</tr>
<tr>
<td>3C_321</td>
<td>3C_321 Ka</td>
<td>15h 31m 43.5s</td>
<td>---</td>
<td>33496MHz</td>
<td>-0.58</td>
<td>-35.1d</td>
<td>00:02:21</td>
<td></td>
</tr>
<tr>
<td>J2000</td>
<td>(3) Ka band</td>
<td>24d 4' 19.0''</td>
<td>---</td>
<td>33824MHz</td>
<td>-0.53</td>
<td>-32.8d</td>
<td>00:02:21</td>
<td></td>
</tr>
</tbody>
</table>
Uncalibrated spectra on 3C286

Plot file version 2 created 07-MAR-2011 07:58:58
MULTI.UVDATA.1
Freq = 22.5240 GHz, Bw = 128.000 MH No calibration applied and no bandpass applied

Lower frame: Milli Ampl Jy  Top frame: Phas deg
Scalar averaged cross-power spectrum  Several baselines displayed
Timerange: 00/14:06:00 to 00/14:07:00
Bandpass solutions

Plot file version 48 created 07-MAR-2011 08:07:20
MULTI.UVDATA.1
Freq = 22.3960 GHz, Bw = 128.000 MH Bandpass table # 1

Lower frame: BP ampl  Top frame: BP phase
Bandpass table spectrum  Antenna: *
Timerange: 00/14:01:08 to 00/14:04:08
Spectra after Fringe-fit and bandpass calibration

Plot file version 70  created 07-MAR-2011 08:17:42
MULTI.UVDATA.1
Freq = 22.3960 GHz, Bw = 128.000 MH  Calibrated with CL # 2 and BP # 1 (BP mode 1)

Lower frame: Milli Ampl Jy  Top frame: Phas deg
Scalar averaged cross-power spectrum  Several baselines displayed
Timerange: 00/14:02:01 to 00/14:04:01
Observed Data vs. UV dist

me name: g192.me

Observed data amplitude (Jy)

0
0.2
0.4
0.6
0.8
1
0
200

Observed data phase (rad)

0
2
-2
0
200
400
600
800
1000

UV Distance (m)

Spectral Window: 1
Polarization: 1
Fields: 05309+13319
Observed Data – Phase vs. Time
Observed Data – Amplitude Spectrum
Gain Amp/Phase Solutions (B calibrator)
Bandpass Solutions

Table: cal.B  Type: B Jones  Polarization: 1
Fields = 4

Ant_1 Spw_1
Ant_2 Spw_1
Ant_3 Spw_1
Ant_4 Spw_1
Ant_5 Spw_1
Ant_6 Spw_1
Ant_7 Spw_1
Ant_8 Spw_1
Ant_9 Spw_1
Ant_10 Spw_1
Ant_11 Spw_1
Ant_12 Spw_1
Ant_13 Spw_1
Ant_14 Spw_1
Ant_15 Spw_1
Ant_16 Spw_1
Ant_17 Spw_1
Ant_18 Spw_1
Ant_19 Spw_1
Ant_20 Spw_1
Ant_21 Spw_1
Ant_22 Spw_1
Ant_23 Spw_1
Ant_24 Spw_1
Ant_25 Spw_1
Ant_26 Spw_1
Ant_27 Spw_1
Bandpass-Calibrated Data (Amplitude)
Gain Amp/Phase Solutions
Corrected Data vs. UV dist

ma name: g192.me
Spectral Window: 1
Polarization: 1
Fields: 05309+13319

Corrected data amplitude (Jy)
Corrected data phase (rad)

UV Distance (m)
Effect of Calibration in the Image Plane

Uncalibrated

Calibrated
A Dictionary of 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
  - $K =$ geometric compensation

- Order of terms follows signal path (right to left)
- Direction-dependent terms involve FT in solution

\[ J_i = K_i B_i G_i D_i E_i P_i T_i F_i \]
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
  - Higher noise contribution, less signal transmission: Lower SNR
  - Most important at $\nu > 15$ 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?
Parallactic Angle, \( P \)

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

\[
\chi(t) = \arctan \left( \frac{\cos(l) \sin(h(t))}{\sin(l) \cos(\delta) - \cos(l) \sin(\delta) \cos(h(t))} \right)
\]

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

- Rotates the position angle of linearly polarized radiation
- Analytically known, and its variation provides leverage for determining polarization-dependent effects
Antenna Voltage Pattern, $E$

- Antennas of all designs have direction-dependent gain
  - Important when region of interest on sky comparable to or larger than $\lambda/D$
  - 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)
Polarization Leakage, $D$

- Polarizer is not ideal, so orthogonal polarizations not perfectly isolated
  - Well-designed feeds have $D \sim$ a few percent or less
  - A geometric property of the feed design, so frequency dependent
  - For $R,L$ systems, total-intensity imaging affected as $\sim DQ, DU$, so only important at high dynamic range ($Q,U \sim D \sim$ few %, typically)
  - For $R,L$ systems, linear polarization imaging affected as $\sim DI$, so almost always important
“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 VLA observations
  - Includes scaling from engineering (correlation coefficient) to radio astronomy units (Jy), by scaling solution amplitudes according to observations of a flux density calibrator
  - Often also includes ionospheric and tropospheric effects which are typically difficult to separate unto themselves
  - Excludes frequency dependent effects
**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
  - Often assumed time-independent, but not necessarily so
  - Typically (but not necessarily) normalized
Geometric Compensation, $K$

- Must get geometry right for Synthesis Fourier Transform relation to work in real time; residual errors here require “Fringe-fitting”
  - Antenna positions (geodesy)
  - Source directions (time-dependent in topecenter!) (astrometry)
  - Clocks
  - Electronic pathlengths
  - Importance scales with frequency and baseline length
Non-closing Effects:

- Correlator-based errors which do not decompose into antenna-based components
  - Most digital correlators designed to limit such effects to well-understood and uniform scaling laws (absorbed in $G$)
  - Simple noise
  - Additional errors can result from averaging in time and frequency over variation in antenna-based effects and visibilities (practical instruments are finite!)
  - 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
Calibrator Rules of Thumb

- **T, G, K:**
  - 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 (beeware 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), point-like if visibility might change 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 for full calibration is strong and pointlike
  - If polarized, observe over a broad range of parallactic angle to disentangle Ds and source polarization (often, T, G calibrator is ok)

- **F:**
  - Choose strongly polarized source and observe often enough to track variation
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 (hopeless) 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
## Radio Frequency Interference

- RFI originates from man-made signals generated in the antenna electronics or by external sources (e.g., satellites, cell-phones, radio and TV stations, automobile ignitions, microwave ovens, etc.)
  - Adds to total noise power in all observations, thus decreasing sensitivity to desired natural signal, possibly pushing electronics into non-linear regimes
  - As a contribution to the $n_i$ term, can correlate between antennas if of common origin and baseline short enough (insufficient decorrelation via geometric delay)
  - When RFI is correlated, it obscures natural emission in spectral line observations
Radio Frequency Interference

- Has always been a problem (Reber, 1944, in total power)!
Radio Frequency Interference (cont)

- Growth of telecom industry threatening radioastronomy!

FREQ(MHz) Note: The 13, -1 values (e.g.: 1291.25, 1308.75, 1325, etc.) = sys drop-cut errors.
Radio Frequency Interference (cont)

- RFI Mitigation
  - Careful electronics design in antennas, including notch filters
  - High-dynamic range digital sampling
  - Observatories world-wide lobbying for spectrum management
  - Choose interference-free frequencies: try to find 50 MHz (1 GHz) of clean spectrum in the VLA (EVLA) 1.6 GHz band!
  - Observe continuum experiments in spectral-line modes so affected channels can be edited

- Various off-line mitigation techniques under study
Summary

- Determining calibration is as important as determining source structure —can’t have one without the other
- Calibration dominated by antenna-based effects, permits separation of calibration from astronomical information
- Calibration formalism algebra-rich, but can be described piecemeal in comprehensible segments, according to well-defined effects
- Calibration determination is a single standard fitting problem
- Calibration an iterative process, improving various components in turn
- Point sources are the best calibrators
- Observe calibrators according requirements of components
- Data examination and editing an important part of calibration
Further Reading

- http://www.nrao.edu/whatisra/mechanisms.shtml
- http://www.nrao.edu/whatisra/
- www.nrao.edu

- Synthesis Imaging in Radio Astronomy
- ASP Vol 180, eds Taylor, Carilli & Perley