HELGA DÉNES

CALIBRATION

CSIRO RADIO ASTRONOMY SCHOOL
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OUTLINE

- Game
- Calibration
    - The tutorials will give you hands on experience

WHY IS CALIBRATION IMPORTANT?

- To get meaningful accurate data/results
- To remove the effects of instrumental and atmospheric factors

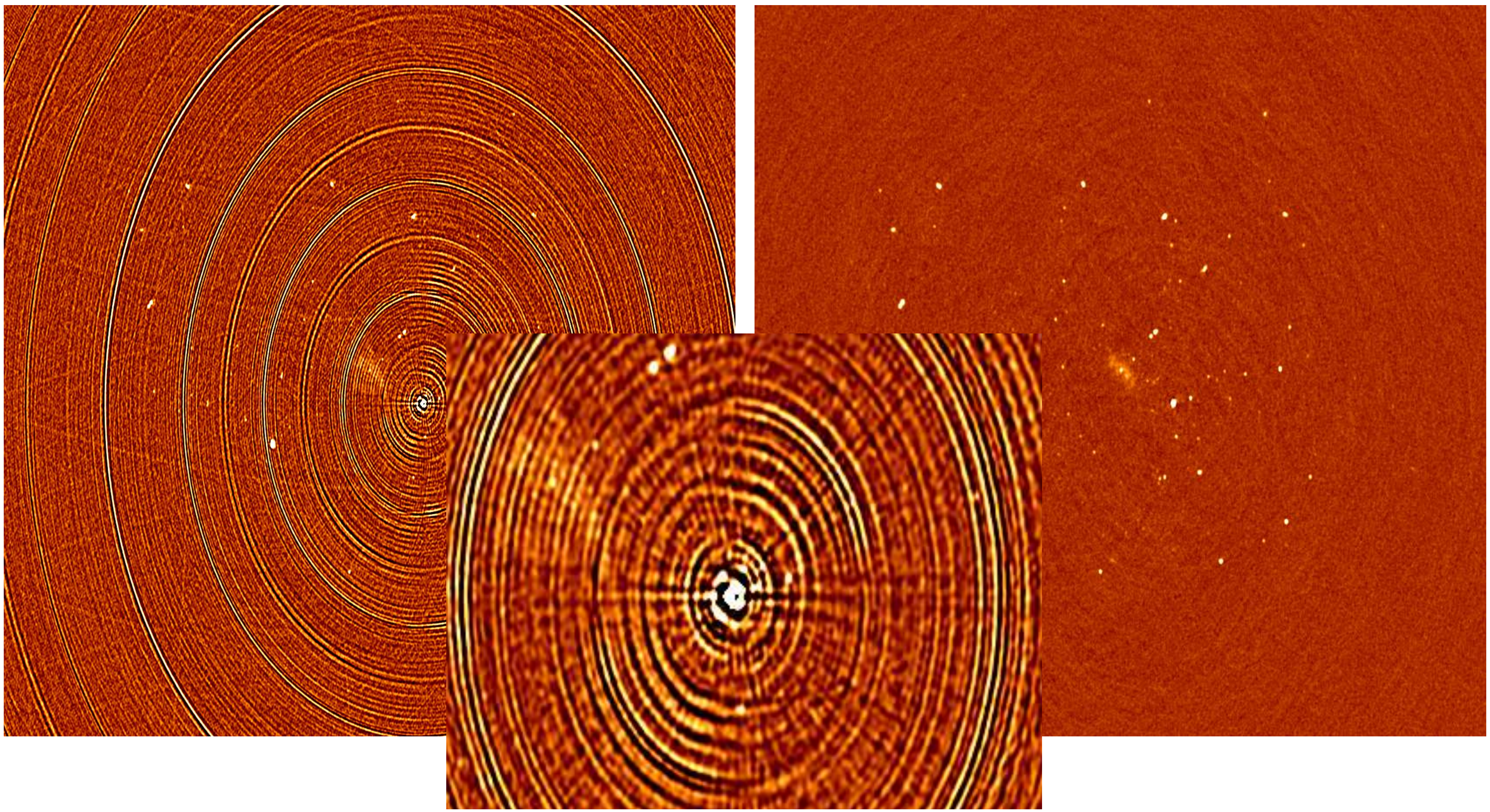


Image credit: George Heald's 2015 talk

WHY IS CALIBRATION IMPORTANT?

FT(Observed Visibilities) ≠ Pretty Images

Relevant physical effects:

- **Atmosphere**
  - Ionosphere
  - Troposphere

- **Digitiser/Correlator**
  - Auto leveling
  - sampling efficiency
  - Birdies (internal RFI)

Measurables:
Amplitude
Phase
Delay
Polarization
Spectrum

- **LNA + conversion chain**
  - Clock
  - Gain, phase, delay
  - frequency response

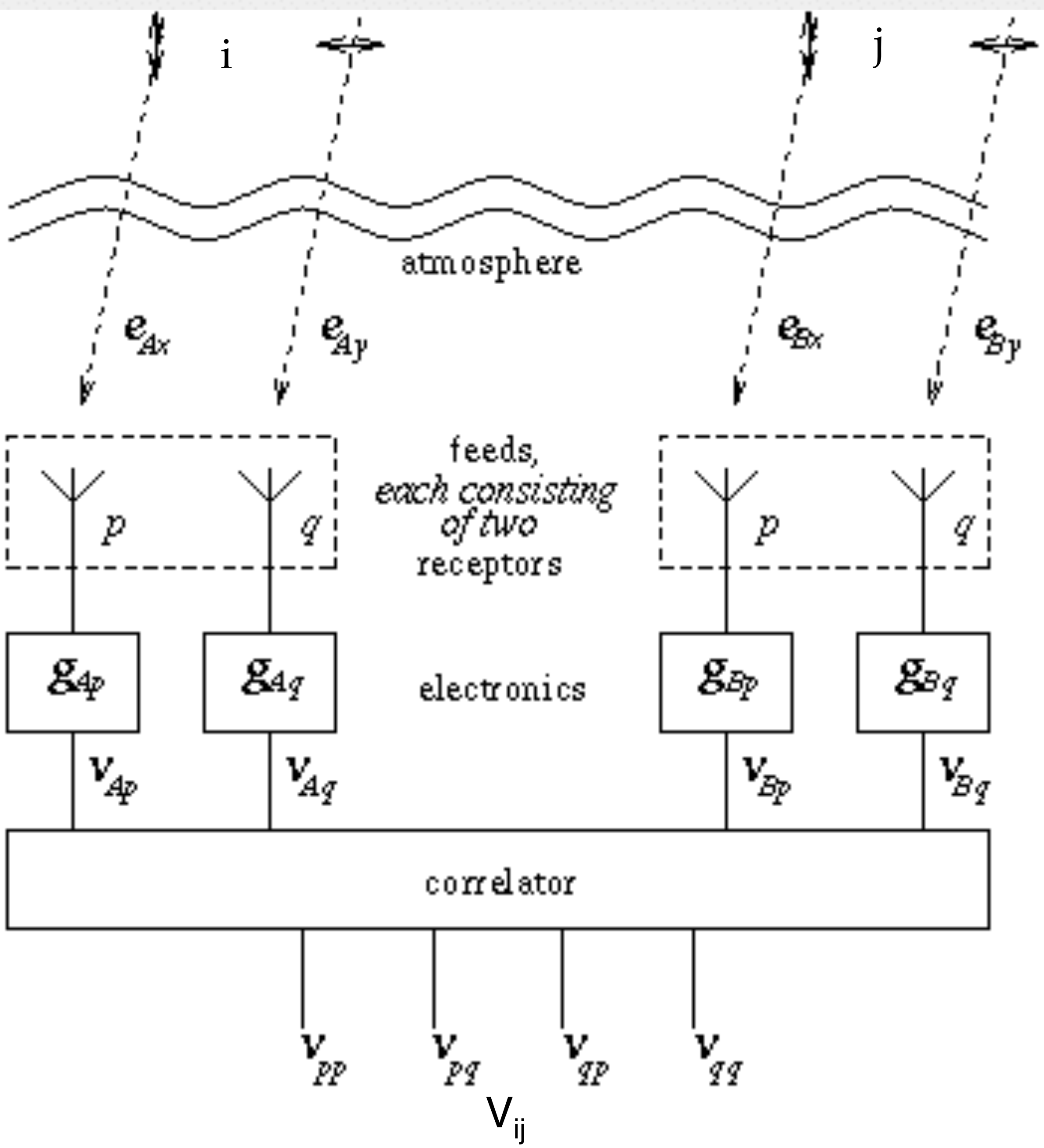
- **Antenna feed**
  - On-axis gain/sensitivity vs El
  - Primary beam correction
  - Pointing
  - Position (location)

Key factors: corresponding timescales, frequency dependence, polarimetric properties, **order in signal path**, ...

THE MEASUREMENT EQUATION

The measurement equation (Hamaker, Bregman & Sault) is a matrix formalism for expressing the polarimetric response of an interferometer

$$\vec{V}_{ij} = X_{ij}\left(\mathsf{M}_{ij}\left[\mathsf{J}^{vis}{}_{i} \otimes \mathsf{J}^{vis}{}_{j}{}^{*}\right]\sum_{k}\left[\mathsf{J}^{sky}{}_{i}\,(\vec{\rho}_k) \otimes \mathsf{J}^{sky}{}_{j}\,(\vec{\rho}_k)^{*}\right]\mathsf{S}\;\vec{I}_k + \vec{A}_{ij}\right)$$



$$V_{ij} = \begin{matrix} V_{pp} \\ V_{pq} \\ V_{qp} \\ V_{qq} \end{matrix}$$

$$J_i = \begin{matrix} J_p \\ J_q \end{matrix}$$

THE MEASUREMENT EQUATION

Observed visibility

$$\vec{V}_{ij} = X_{ij}\left(\mathrm{M}_{ij}\left[\mathrm{J}^{vis}{}_{i} \otimes \mathrm{J}^{vis}{}_{j}{}^{*}\right]\sum_{k}\left[\mathrm{J}^{sky}{}_{i}\,(\vec{\rho}_k) \otimes \mathrm{J}^{sky}{}_{j}\,(\vec{\rho}_k)^{*}\right]\mathrm{S}\,\vec{I}_k + \vec{A}_{ij}\right)$$

Antenna based:
J^{vis} = B G D P
B = bandpass
G = complex gain
D = pol leakage
P = receptor pos angle
(2x2 matrices)

Sky intensity distribution

Polarization conversion

Baseline based gain errors
correlation corrections

Antenna beam + pointing
Faraday Rotation

Baseline based additive
A_{ij} = noise + RFI + offsets

Calibration is the process of perfecting the sky and instrument models

FLAGGING/EDITING

- **Don’t be afraid to throw out data**
  - Corrupted data can reduce the image quality significantly
  - Effect of missing data (even 25%) is often minor and easily corrected in deconvolution
- **Flag data you know is bad early**
  - Save your sleuthing skills for the hard stuff
    - See “Error recognition” talk
- **Visualise your data**
  - Detailed visual inspection of all data is rapidly becoming impossible
  - Collapse, average, difference & automate using scripts

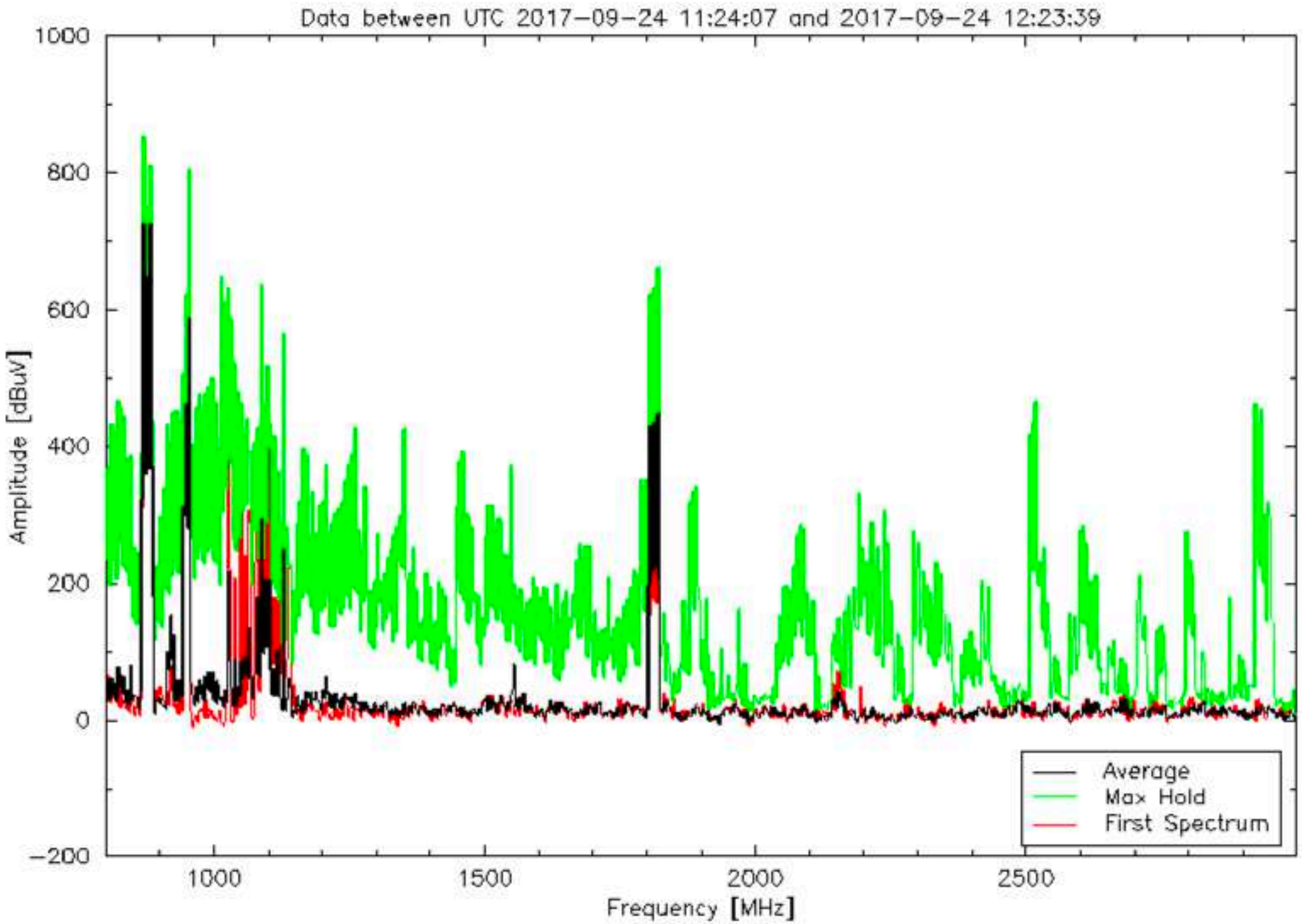
VISIBILITY CORRUPTION

- **RFI – interference:**
  - Transmitters, Lightning, Solar, Internal RFI
- **Antenna/Receiver/Correlator failures :**
  - no signal, excess noise, artificial spectral features
- **Bad weather:**
  - effects get worse for higher freq.
  - decorrelation, noise increase, signal decrease (opacity)
- **Shadowing :**
  - one antenna (partially) blocked by another

FLAGGING/EDITING

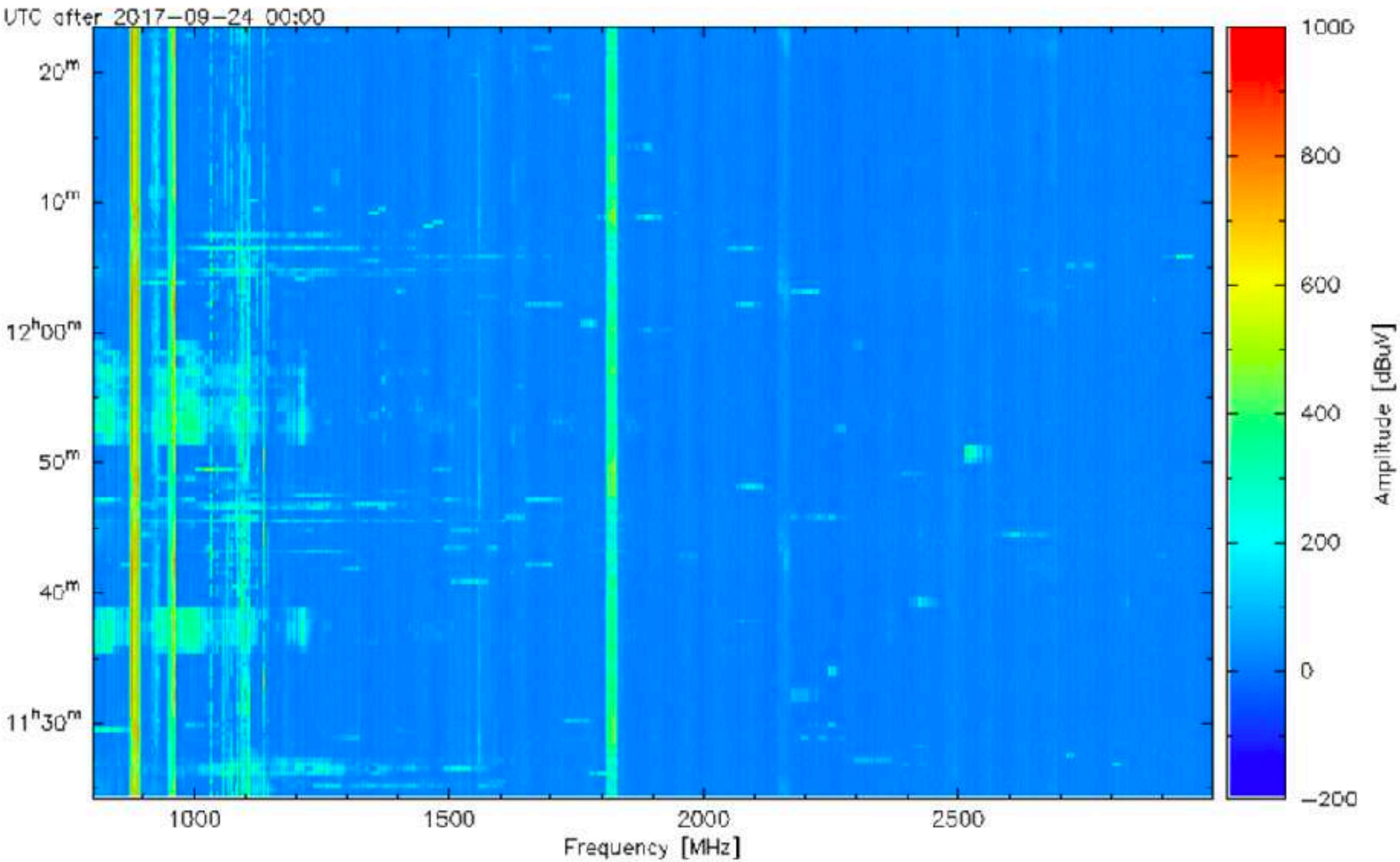
- **1st pass: use on-line flags (automatic)**
  - Flags when antennas are off source or correlator blocks offline.
- **2nd pass: Use the observing logbook! Saves lots of time later.**
  - Note which data is supposed to be good & discard data with setup calibration, failed antennas, observer typos etc.
- **3rd pass: Use automatic flags**
  - Correlator birdies, Common RFI sources (options=birdie, rfiflag)
  - Shadowed data: select=shadow(25)
  - Data with bad phase stability: select=seeing(300)
- **4th pass: Check calibrators - plot amp-time, phase-time, amp-frq**
  - investigate outliers & flag, flag source as well if you can't trust data
- **5th pass: (After calibration) Inspect & flag source data**
  - Use Stokes V to flag data with strong sources

RFI 1 - 3 GHZ



https://www.narrabri.atnf.csiro.au/observing/rfi/monitor/rfi_monitor.html#atca

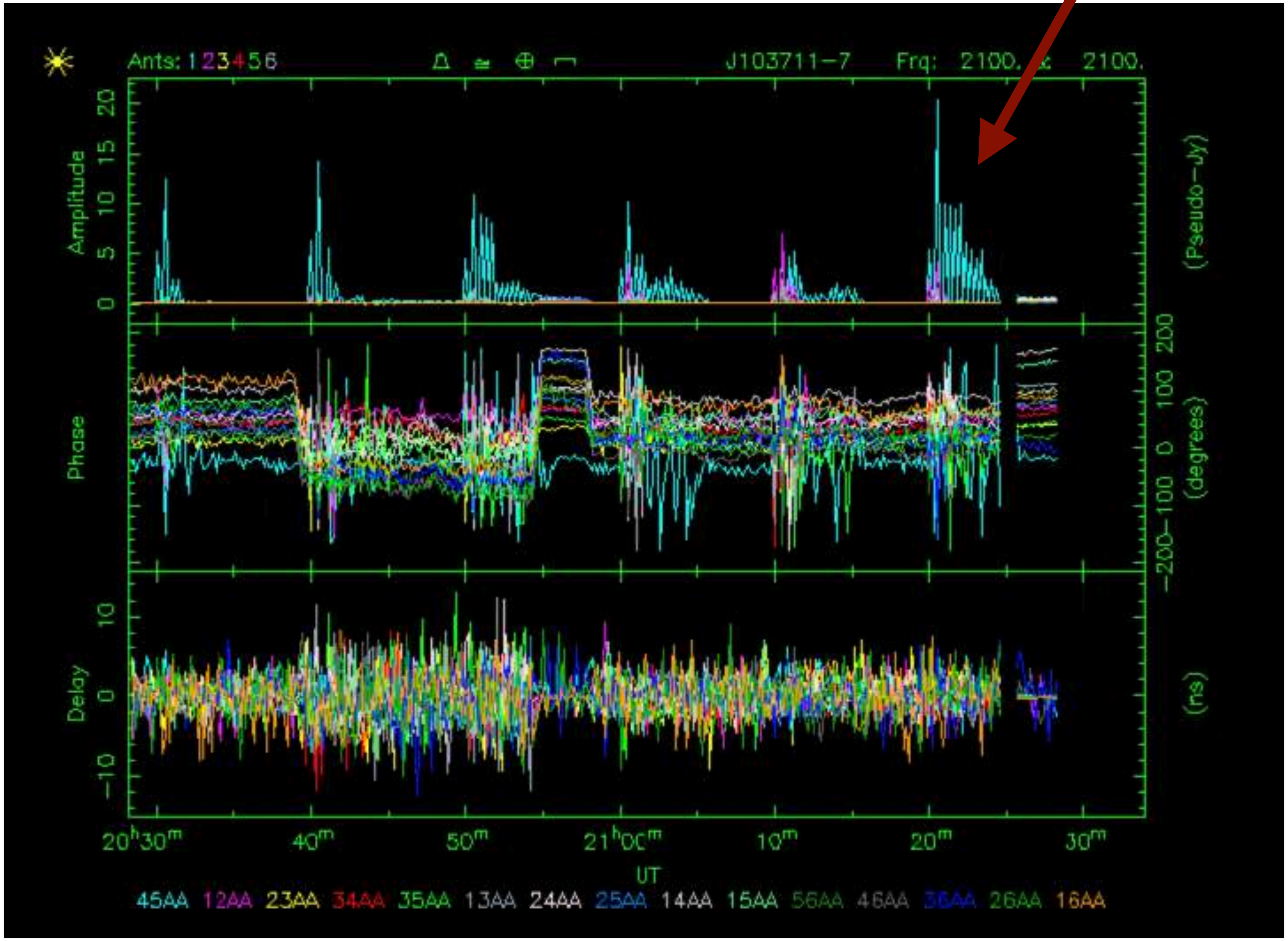
RFI 1 - 3 GHZ



https://www.narrabri.atnf.csiro.au/observing/rfi/monitor/rfi_monitor.html#atca

RFI 1 - 3 GHZ

Weather radar



ATCA CALIBRATION

- **Observatory – done after reconfiguration**
  - Bulk delay (cable lengths)
  - Baseline (antenna location) – good to 1-5 mm
  - Antenna Pointing – good to 10″-20″

- **User**
  - Schedule preparation (observing strategy)
  - dcal/pcal/acal: "Real-time" first-pass approximation
  - Post-observation calibration

CALIBRATION AT RECONFIGURATION

- **antenna pointing** (global pointing model derived from sources in all Az/El directions)
  - generally correct to better than 10", occassional 20" error single antenna
  - may need reference pointing with nearby cal above 10 GHz

- **baseline lengths** (relative antenna positions)
  - generally correct to better than 1-2 mm (depending on weather)
  - error significant at 3mm - correct phase with nearby calibrator

- **global antenna delay** (bulk transmission delay in cables)

CALIBRATION - SCHEDULE PLANING

- **Observe primary calibrator 1934-638(cm), Uranus(mm)**
  - 5-15 min, to calibrate the absolute fluxscale
  - cm/1934: can also solve for polarization leakage and bandpass
  - mm:
    - Observe separate bandpass calibrator
    - Use secondary for polarization leakage

- **Observe secondary calibrator (close to target)**
  - 1-2 min every 15-60 min (dependent on wavelength)
  - Atmospheric, instrumental phase variation,
  - System gain variations; optional: solve leakage, bandpass

- **Observe pointing calibrator (for mm observations)**
  - a POINTing scan every 30-60 minutes

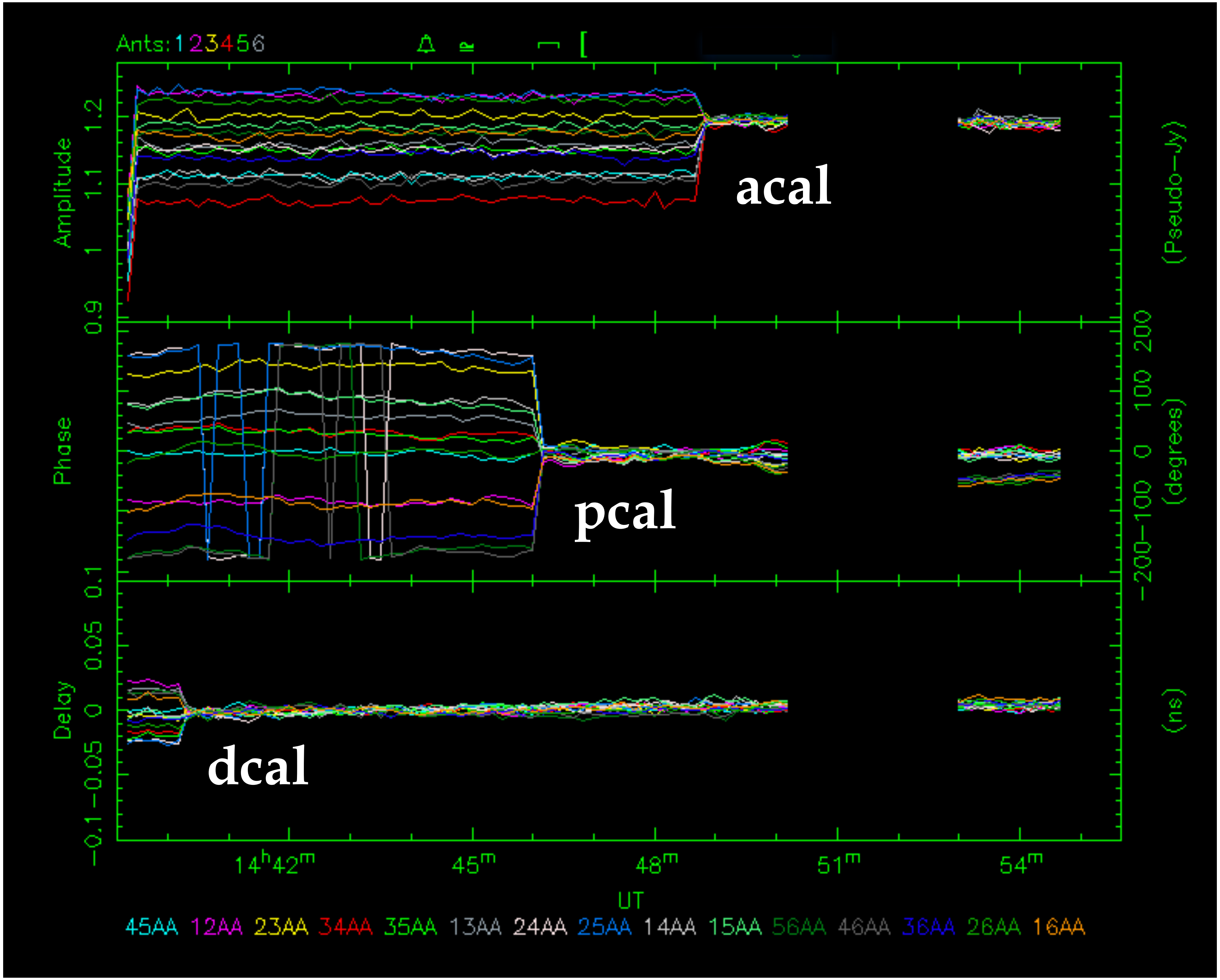
ATCA & VLA CALIBRATOR LIST

- Ideal **secondary calibrator** is strong, small ($\theta<\lambda/B_{max}$) and close to the target (<15°)
  - ATCA + VLA lists ~1000 sources
  - Calibrator database lets you make the optimal choice
- **Primary flux calibrators** are also stable with time: PKS1934-638, PKS0823-500
- Above 20GHz , the planets are essentially the only primary flux calibrators
  - all bright compact sources seem to vary at high freq
  - Planets not ideal – resolved on longer baselines / seasonal variation

CALIBRATION - STARTING UP

- **Calibration done at start of observation (usually on the primary calibrator):**
  - **Delay calibration**
    - Correct residual path length for your particular frequency & correlator setup
    - Fixes phase slope across band
  - **Amplitude & Phase**
    - Equalize gains, zero phases, sets Tsys scale
      - helps to detect problems during observation.
  - **Polarization**
    - zero delay & phase difference between X & Y feeds
    - uses noise source on reference antenna to measure phase.
    - generally correct to a few degrees at 3-20cm

INITIAL ARRAY CALIBRATION



CALIBRATION - DURING THE OBSERVATION

- **Observations of secondary calibrator [+ pointing cal]**

- **Tsys correction**
  - estimates system temp from injected noise
  - corrects for e.g., ground pickup & elevation, but not for atmospheric absorption
  - At 3mm: use Paddle scan calibration instead

- **Calibration data recorded during the observation:**
  - Tsys – system temperature
  - XY-phase difference on each antenna
  - (experimental) Water Vapour Radiometer path length

CALIBRATION RECIPE

- **After you have all your data:**
- **Primary calibrator**
  - Solve for complex gain vs time
  - Solve bandpass gain vs frequency
  - Solve polarization leakage (crosstalk between feeds)
- **Secondary calibrator(s)**
  - Apply bandpass and leakage from primary
  - Solve for complex gain vs time
  - Bootstrap absolute flux scale (from primary)
- **Sources of interest**
  - Apply bandpass and leakage from primary and complex gains from secondary
  - Use calibrated data in subsequent imaging and analysis

CALIBRATION

- **There are different calibration techniques and strategies for**
  - different instruments
  - different science goals
    - different frequencies
    - wide band vs. narrow band
    - spectral line - continuum observations

RESOURCES

This talk is based on:

- Mark Wieringa's 2012 talk
- George Heald's 2015 talk

Resources:

- **The ATCA User Guide** (Section 4.3.6. http://www.narrabri.atnf.csiro.au/observing/users_guide/html/atug.html#Calibration2)
- **Online available tutorials: e.g. Miriad and CASA tutorials** (http://www.atnf.csiro.au/computing/software/miriad/tutorials.html https://casaguides.nrao.edu/index.php/Main_Page)

Books:

- Interferometry and Synthesis in Radio Astronomy
- Tools of Radio Astronomy
- Synthesis Imaging in Radio Astronomy II

THANK YOU!