



HELGA DÉNES

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# CALIBRATION



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SEPTEMBER, 2017

# OUTLINE

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

# WHY IS CALIBRATION IMPORTANT?

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

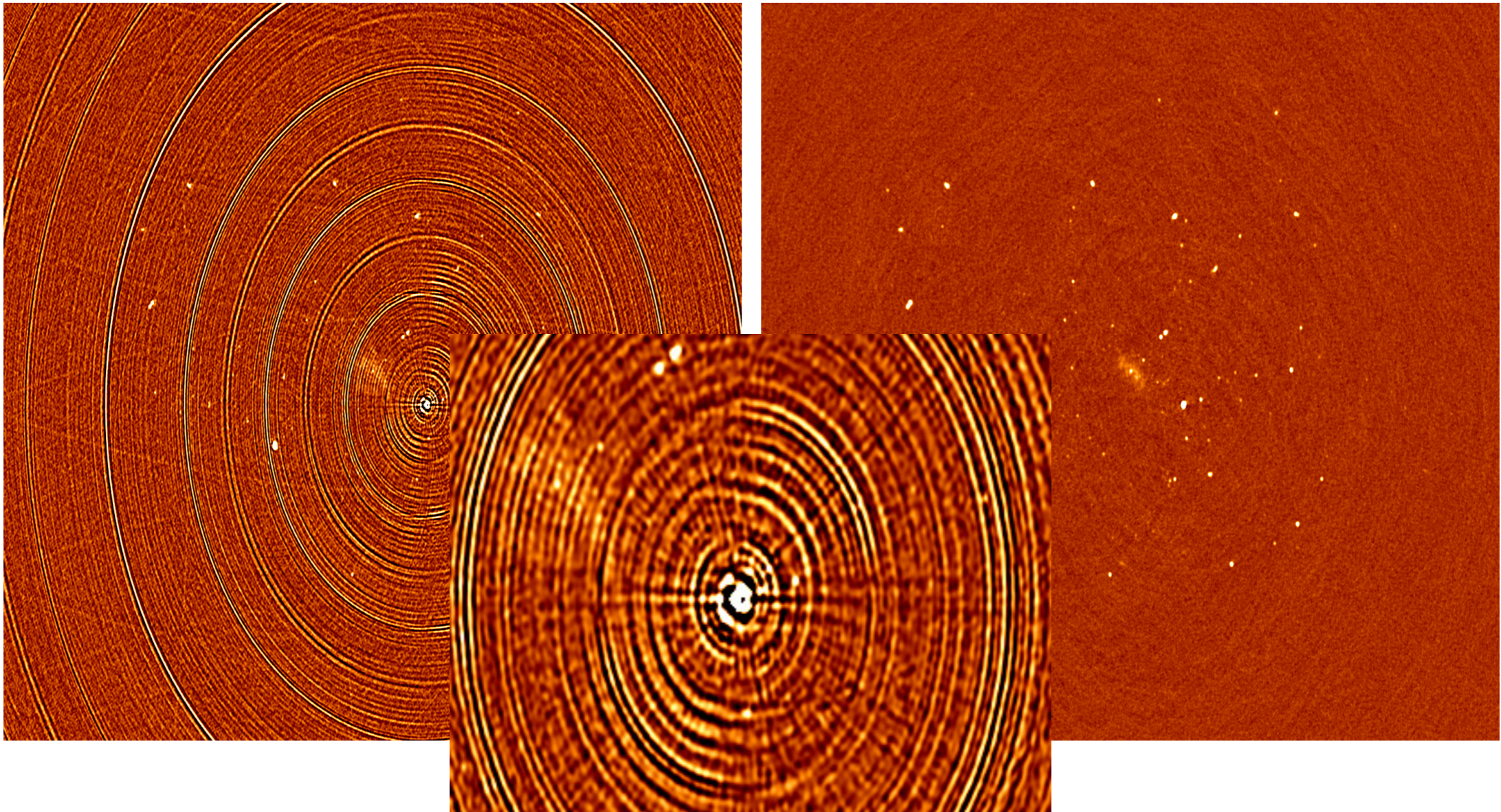


Image credit: George Heald's 2015 talk

# WHY IS CALIBRATION IMPORTANT?

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**FT(Observed Visibilities)  $\neq$  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

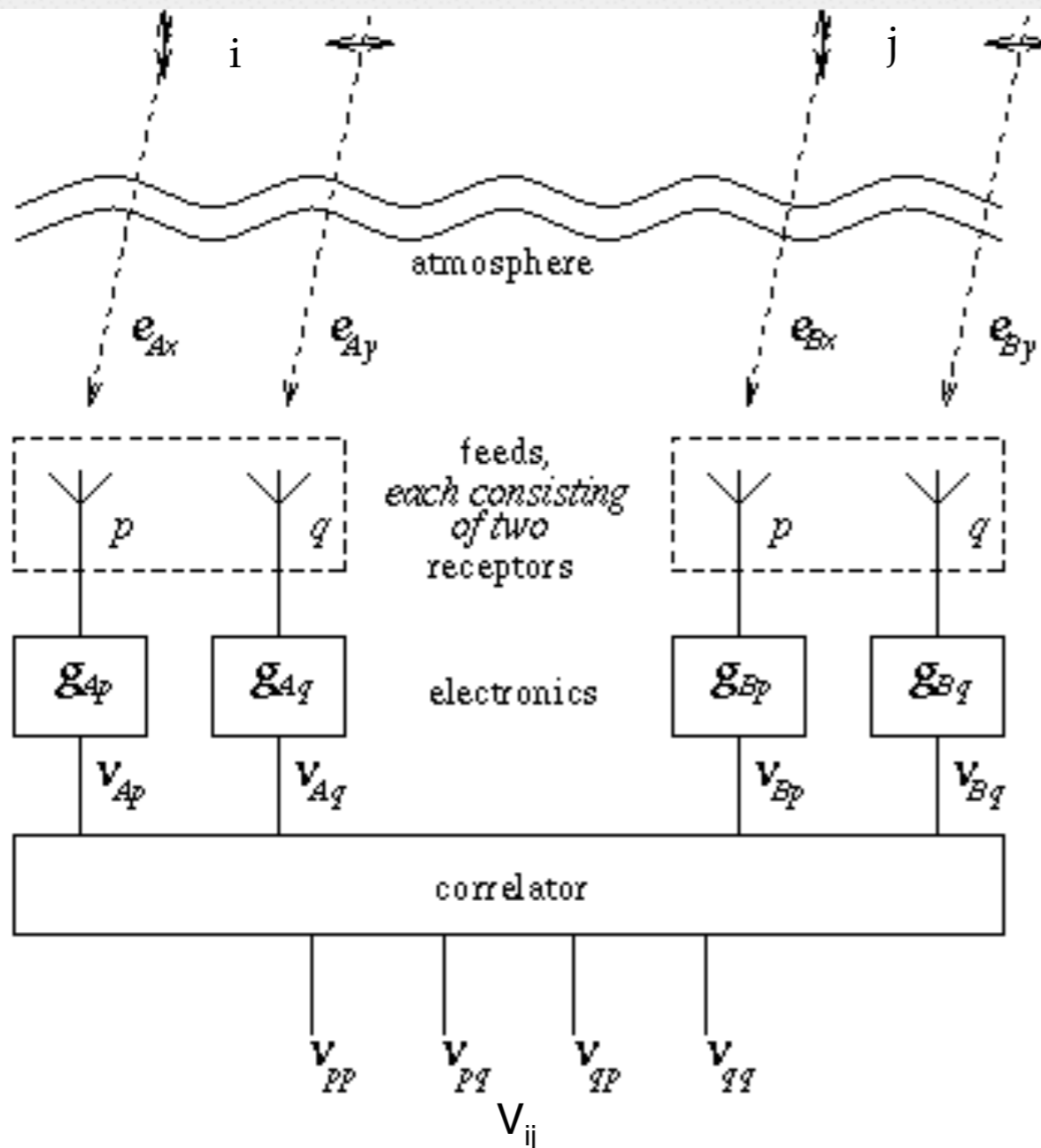
- ▶ **Antenna feed**
  - ▶ On-axis gain/sensitivity vs EI
  - ▶ Primary beam correction
  - ▶ Pointing
  - ▶ Position (location)

**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

$$\vec{V}_{ij} = X_{ij} \left( M_{ij} \left[ J^{\text{vis}}_i \otimes J^{\text{vis}}_j^* \right] \sum_k \left[ J^{\text{sky}}_i(\vec{\rho}_k) \otimes J^{\text{sky}}_j(\vec{\rho}_k)^* \right] S \vec{I}_k + \vec{A}_{ij} \right)$$



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

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

# THE MEASUREMENT EQUATION

Observed visibility

$$\vec{V}_{ij} = X_{ij} \left( M_{ij} \left[ J^{\text{vis}}_i \otimes J^{\text{vis}}_j{}^* \right] \sum_k \left[ J^{\text{sky}}_i(\vec{\rho}_k) \otimes J^{\text{sky}}_j(\vec{\rho}_k)^* \right] S \vec{I}_k + \vec{A}_{ij} \right)$$

**Antenna based:**

$$J^{\text{vis}} = B G D P$$

B = bandpass

G = complex gain

D = pol leakage

P = receptor pos angle

(2x2 matrices)

Sky intensity distribution

Polarization conversion

Antenna beam + pointing

Faraday Rotation

Baseline based gain errors  
correlation corrections

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

**Calibration is the process of perfecting the sky and instrument models**

# FLAGGING/EDITING

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- ▶ **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

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- ▶ **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 :**

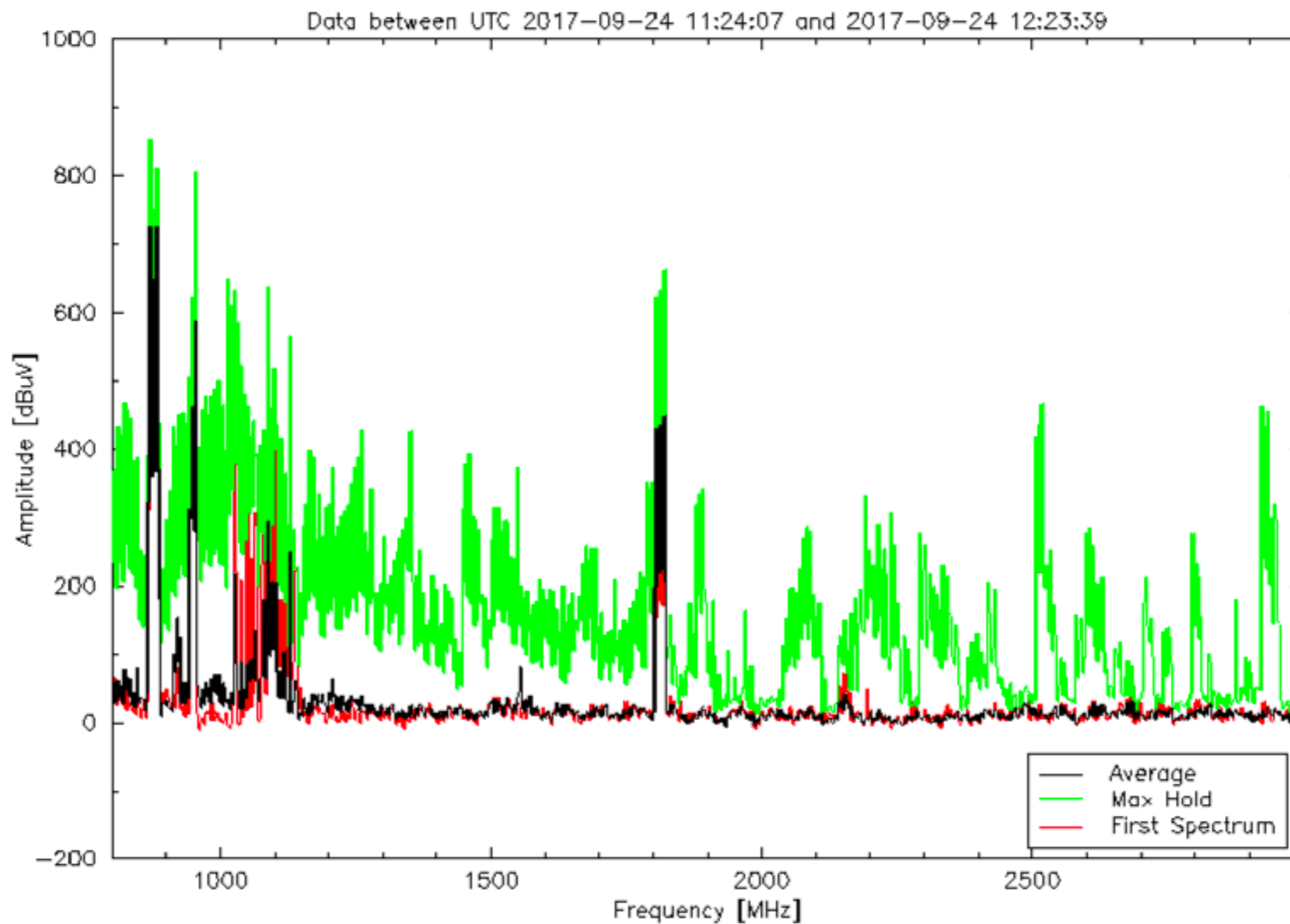
- ▶ one antenna (partially) blocked by another

# FLAGGING/EDITING

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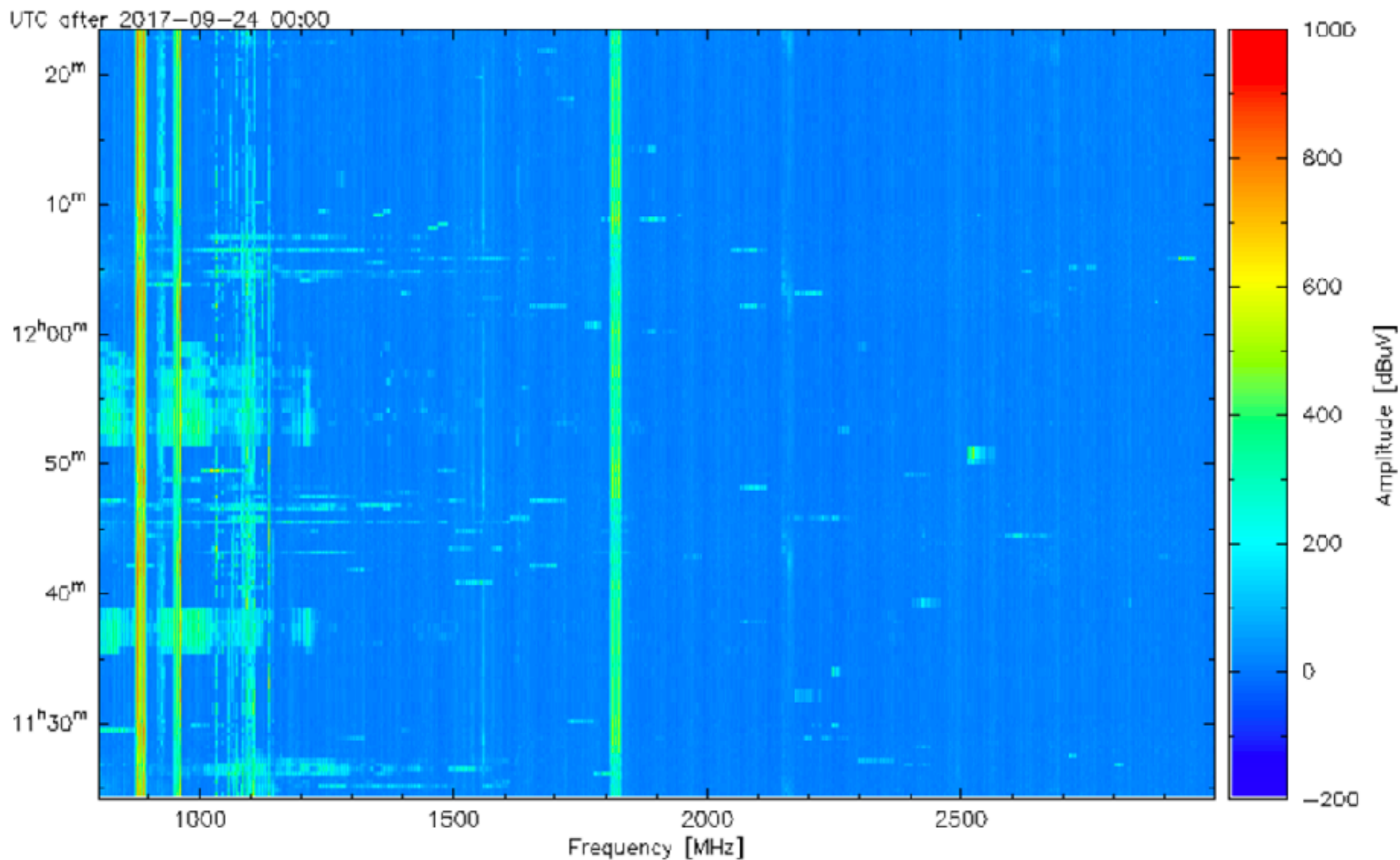
- ▶ **1<sup>st</sup> pass: use on-line flags (automatic)**
  - ▶ Flags when antennas are off source or correlator blocks offline.
- ▶ **2<sup>nd</sup> pass: Use the observing logbook! Saves lots of time later.**
  - ▶ Note which data is supposed to be good & discard data with setup calibration, failed antennas, observer typos etc.
- ▶ **3<sup>rd</sup> 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)
- ▶ **4<sup>th</sup> pass: Check calibrators - plot amp-time, phase-time, amp-frq**
  - ▶ investigate outliers & flag, flag source as well if you can't trust data
- ▶ **5<sup>th</sup> 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](https://www.narrabri.atnf.csiro.au/observing/rfi/monitor/rfi_monitor.html#atca)

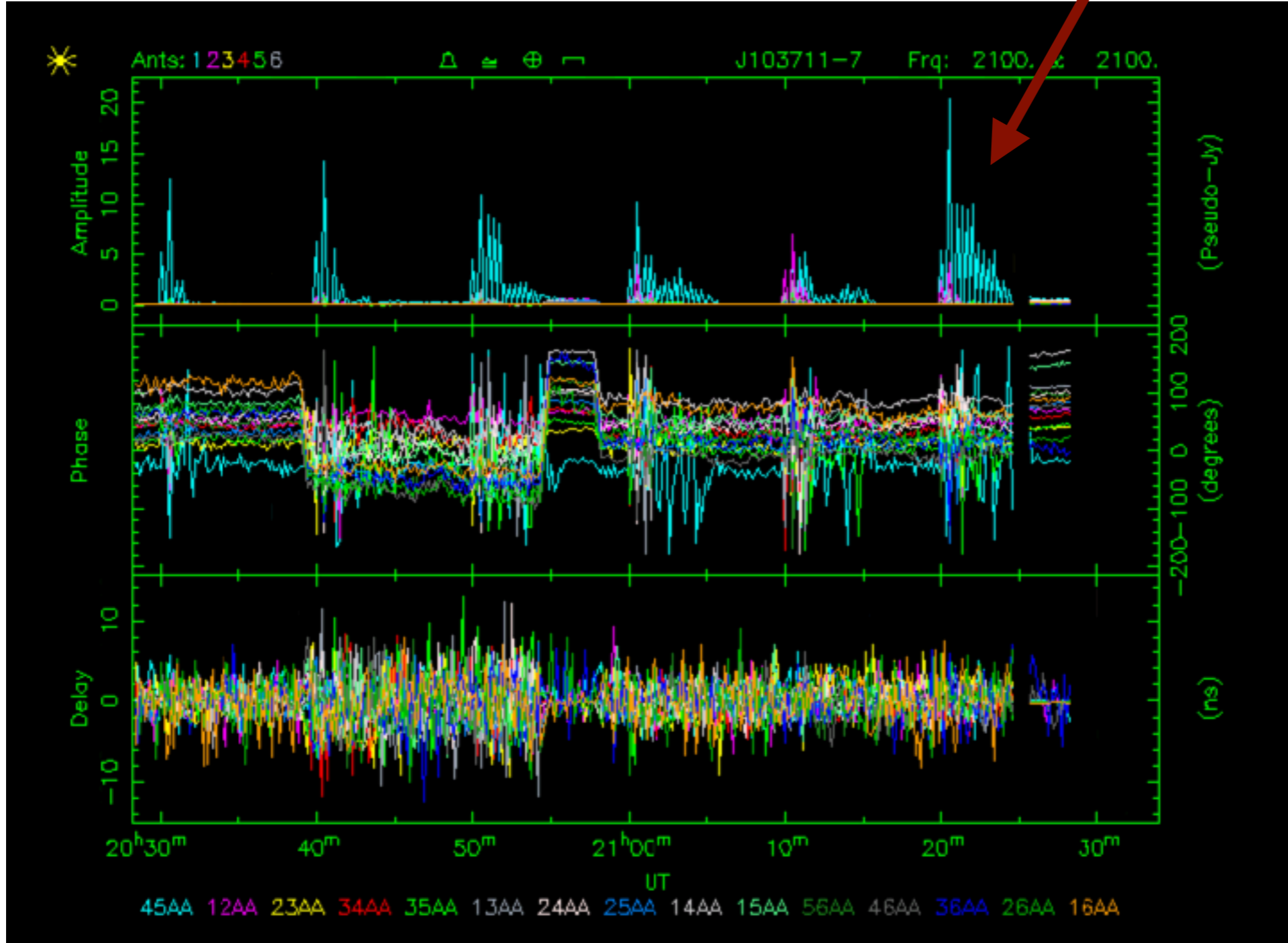
# RFI 1 - 3 GHz



[https://www.narrabri.atnf.csiro.au/observing/rfi/monitor/rfi\\_monitor.html#atca](https://www.narrabri.atnf.csiro.au/observing/rfi/monitor/rfi_monitor.html#atca)

# RFI 1 - 3 GHz

Weather radar



# ATCA CALIBRATION

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- ▶ **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

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- ▶ **antenna pointing** (global pointing model derived from sources in all Az/EI directions)
  - ▶ generally correct to better than 10", occasional 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

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- ▶ 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

Pointing calibrator



Target



Gain calibrator  
(phase, amplitude)



Flux calibrator  
(flux, bandpass, delay)



# ATCA & VLA CALIBRATOR LIST

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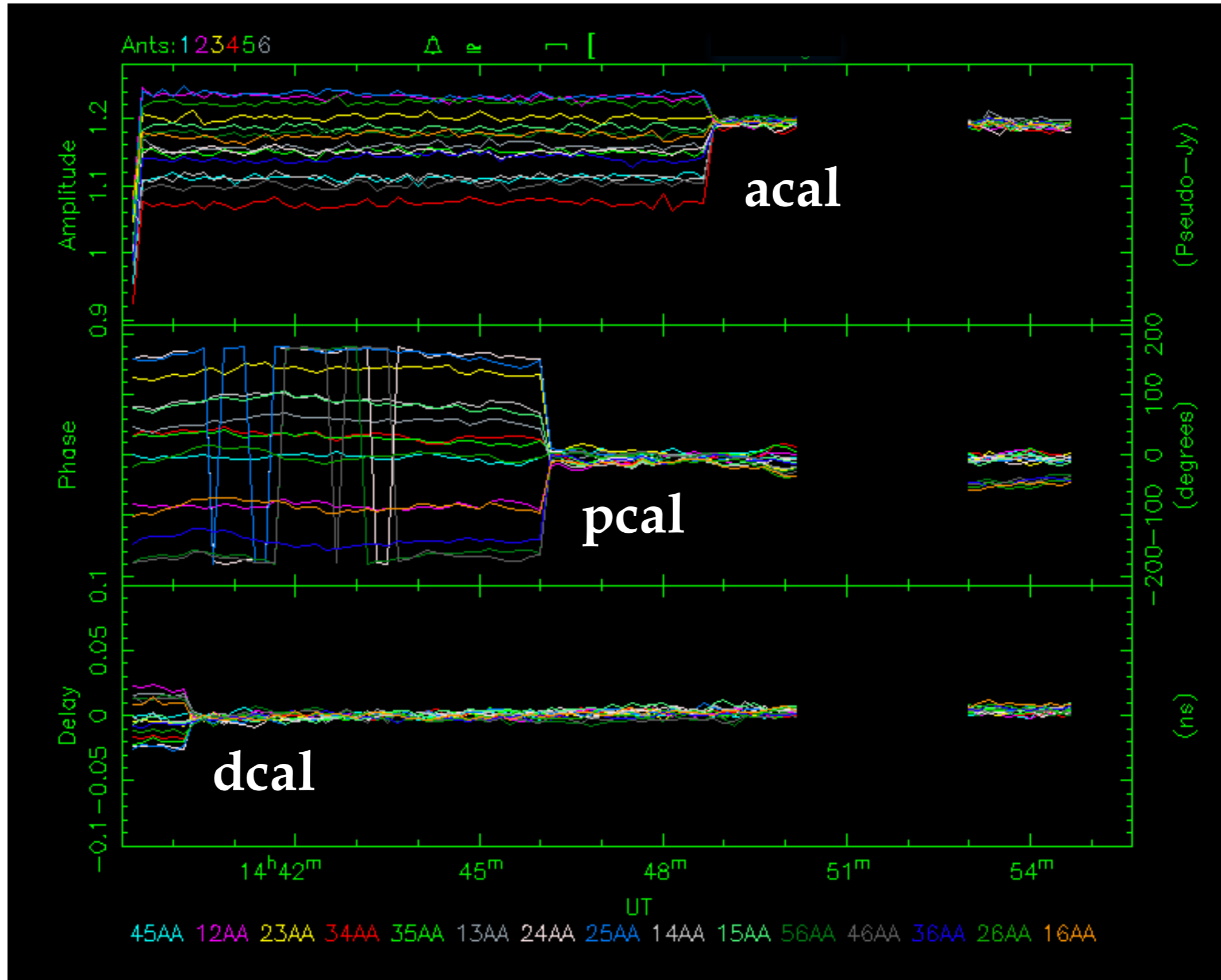
- ▶ Ideal **secondary calibrator** is strong, small ( $\theta < \lambda / B_{\max}$ ) and close to the target ( $< 15^\circ$ )
  - ▶ ATCA + VLA lists ~1000 sources
  - ▶ Calibrator database lets you make the optimal choice
- ▶ **Primary flux calibrators** are also stable with time:  
PKS1934-638, PKS0823-500
- ▶ 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

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- ▶ **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  $T_{\text{sys}}$  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

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- ▶ **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

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- ▶ **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

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- ▶ **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

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## **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](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](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



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**THANK YOU!**