Data Analysis in the Radio

Emma Storm

Astr 257: Modern Astronomical Techniques

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Radio Data Analysis

- interferometers measure antenna gains (voltages)
- antenna gains are related to sky brightness via fourier transforms
- only have access to raw, uncalibrated data
- need to manually calibrate
- image processing depends on science goals

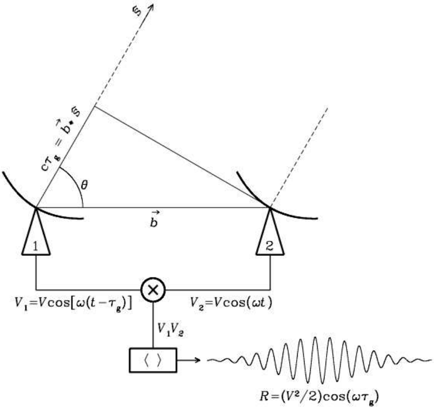
The VLA

- VLA → EVLA → JVLA
- 27 25m-diameter telescopes (351 baselines!)
- 4 configurations (A>B>C>D)
- frequency range: 1-50 GHz in 8 bands (L,S,C,X,Ku,K,Ka,Q)

Image courtesy of NRAO/AUI

Interferometry Basics

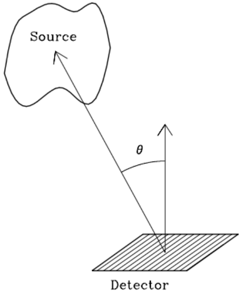
- Interferometers measure **Visibility Functions**
  - correlated antenna gains for each baseline (antenna pair)
  - reported as a complex number: phase and amplitude at a given position in (u,v) space:
  - $u = \frac{b_x}{\lambda}$, $v = \frac{b_y}{\lambda}$



From ERA online course (see references).

Interferometry Basics

- Astronomers want **Brightness Distributions**
  - $I_\nu(l, m)$, where
  - $l = sin\theta_x$, $m = sin\theta_y$



From ERA online course (see references).

Interferometry Basics

- How to get from Visibilities to Brightness: Fourier Transform!
- (u,v) plane $\leftrightarrow$ (l,m) plane

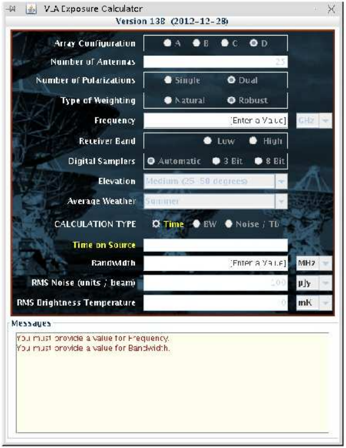
$$V(u,v) = \int I_\nu(l,m) \mathrm{e}^{2\pi i(ul+vm)} \mathrm{d}l \mathrm{d}m$$

VLA Basics

- synthesized beam: $\theta_{sb} \sim \frac{\lambda}{b_{max}}$
  - 1.5 GHz (L), A config: 1.3"
  - 1.5 GHz (L), D config: 46"
- primary beam: $\theta_{pb} \sim \frac{\lambda}{D}$
  - 1.5 GHz (L): 1700"
- largest angular size: $\theta_{LAS} \sim \frac{\lambda}{b_{min}}$
  - 1.5 GHz (L), A config: 36"
  - 1.5 GHz (L), D config: 970"
- Sensitivity? Exposure Calculator

VLA Exposure Calculator

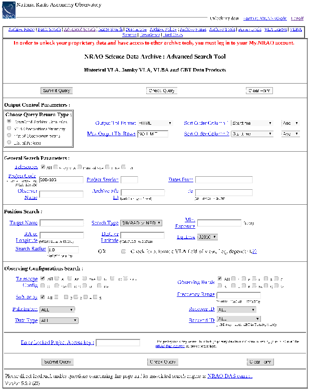
- theoretical thermal noise:
- $\sigma_{th} = \dfrac{SEFD}{\eta_c \sqrt{n_{pol} N(N-1) t_{int} \Delta\nu}}$
  - η_c: correlator efficiency (>0.92 for VLA)
  - n_{pol}: number of polarizations = 2
  - N: number of antennas
  - t_{int}: total time on source
  - $\Delta\nu$: bandwidth in Hz
  - SEFD: system equivalent flux density = flux density of a radio source that doubles system temp
  - See OSS for VLA SEFDs



science.nrao.edu/facilities/vla/caltools/exposure

Getting NRAO telescope data

- for VLA, GBT, VLBA, ALMA
- JVLA data sets are huge! 10s to 100s of GB
- Data Analysis Tools:
  - **CASA:** measurement sets
  - **AIPS:** fits files



NRAO Archive page:
archive.nrao.edu/archive/advquery.jsp

CASA: Common Astronomy Software Applications

- new(ish): for JVLA and ALMA
- The Measurement Set: series of binary tables
- C++ tools bundled under a python interface:
  - can run interactively via ipython interface
  - can run non-interactively via python scripts
- see CASA tutorials and cookbooks via nrao website

Data Reduction

- Look at your data!
- Lots of manual flagging, calibration, hand tuning of images
- General Steps:
  1. Initial flagging, smoothing
  2. A priori calibration
  3. Initial Calibration
  4. More flagging
  5. Calibration Round 2
  6. More flagging and calibration, if needed
  7. Apply the Calibration
  8. Imaging: highly iterative
  9. Self Calibration?
  10. More imaging (and/or flagging and/or calibrating and/or imaging...)
- New: VLA pipeline (only for HF continuum observations)
  - science.nrao.edu/facilities/vla/data-processing/pipeline

Calibrators in Observations

- Flux Calibrator
  - strong, steady source with known flux
- Bandpass, Phase, Gain Calibrators
  - nearby target, scans interspersed with those of target
  - LF: $\sim$ 10 or more min scans
  - HF: $\sim$ 1 min scans

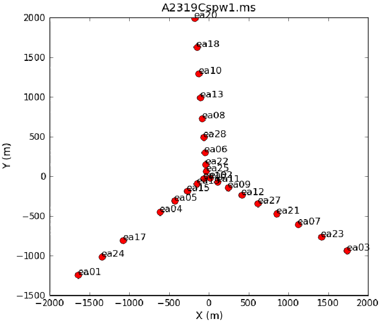
Source	Cal Code	Start Time	Stop Time	Sys	TOS (sec)	Intrvl (sec)	Scan Intent	Spect Win	Obs_Freq (MHz)	Bandw (MHz)	Polar	Spect chans
J1331+3030		10-Oct-08 01:02:56	10-Oct-08 01:03:55	UTC	58.8	0.997	TRACK	CD_0:SW_0 CD_0:SW_1	1284.000000 1796.000000	128.000 128.000	RR,RL,LR,LL RR,RL,LR,LL	64 64
J1331+3030		10-Oct-08 01:03:55	10-Oct-08 01:13:53	UTC	598.4	1	TRACK	CD_0:SW_0 CD_0:SW_1	1284.000000 1796.000000	128.000 128.000	RR,RL,LR,LL RR,RL,LR,LL	64 64
J1845+4007		10-Oct-08 01:13:53	10-Oct-08 01:18:52	UTC	299.2	1	TRACK	CD_0:SW_0 CD_0:SW_1	1284.000000 1796.000000	128.000 128.000	RR,RL,LR,LL RR,RL,LR,LL	64 64
A2319_A		10-Oct-08 01:18:52	10-Oct-08 01:24:51	UTC	359	1	TRACK	CD_0:SW_0 CD_0:SW_1	1284.000000 1796.000000	128.000 128.000	RR,RL,LR,LL RR,RL,LR,LL	64 64
A2319_A		10-Oct-08 01:24:51	10-Oct-08 01:30:50	UTC	359	1	TRACK	CD_0:SW_0 CD_0:SW_1	1284.000000 1796.000000	128.000 128.000	RR,RL,LR,LL RR,RL,LR,LL	64 64
A2319_B		10-Oct-08 01:30:50	10-Oct-08 01:36:49	UTC	359	1	TRACK	CD_0:SW_0 CD_0:SW_1	1284.000000 1796.000000	128.000 128.000	RR,RL,LR,LL RR,RL,LR,LL	64 64
A2319_B		10-Oct-08 01:36:49	10-Oct-08 01:42:48	UTC	359	1	TRACK	CD_0:SW_0 CD_0:SW_1	1284.000000 1796.000000	128.000 128.000	RR,RL,LR,LL RR,RL,LR,LL	64 64
J1845+4007		10-Oct-08 01:42:48	10-Oct-08 01:47:48	UTC	299.2	0.997	TRACK	CD_0:SW_0 CD_0:SW_1	1284.000000 1796.000000	128.000 128.000	RR,RL,LR,LL RR,RL,LR,LL	64 64
A2319_A		10-Oct-08 01:47:48	10-Oct-08 01:57:46	UTC	598.4	1	TRACK	CD_0:SW_0 CD_0:SW_1	1284.000000 1796.000000	128.000 128.000	RR,RL,LR,LL RR,RL,LR,LL	64 64
A2319_B		10-Oct-08 01:57:46	10-Oct-08 02:07:44	UTC	598.4	1	TRACK	CD_0:SW_0 CD_0:SW_1	1284.000000 1796.000000	128.000 128.000	RR,RL,LR,LL RR,RL,LR,LL	64 64
J1845+4007		10-Oct-08 02:07:44	10-Oct-08 02:12:44	UTC	299.2	0.997	TRACK	CD_0:SW_0 CD_0:SW_1	1284.000000 1796.000000	128.000 128.000	RR,RL,LR,LL RR,RL,LR,LL	64 64
A2319_A		10-Oct-08 02:12:44	10-Oct-08 02:22:42	UTC	598.4	1	TRACK	CD_0:SW_0 CD_0:SW_1	1284.000000 1796.000000	128.000 128.000	RR,RL,LR,LL RR,RL,LR,LL	64 64
A2319_B		10-Oct-08 02:22:42	10-Oct-08 02:32:40	UTC	598.4	1	TRACK	CD_0:SW_0 CD_0:SW_1	1284.000000 1796.000000	128.000 128.000	RR,RL,LR,LL RR,RL,LR,LL	64 64
J1845+4007		10-Oct-08 02:32:40	10-Oct-08 02:37:39	UTC	299.2	1	TRACK	CD_0:SW_0 CD_0:SW_1	1284.000000 1796.000000	128.000 128.000	RR,RL,LR,LL RR,RL,LR,LL	64 64
A2319_A		10-Oct-08 02:37:39	10-Oct-08 02:47:38	UTC	598.4	0.999	TRACK	CD_0:SW_0 CD_0:SW_1	1284.000000 1796.000000	128.000 128.000	RR,RL,LR,LL RR,RL,LR,LL	64 64
A2319_B		10-Oct-08 02:47:38	10-Oct-08 02:57:36	UTC	598.4	1	TRACK	CD_0:SW_0 CD_0:SW_1	1284.000000 1796.000000	128.000 128.000	RR,RL,LR,LL RR,RL,LR,LL	64 64
J1845+4007		10-Oct-08 02:57:36	10-Oct-08 03:02:35	UTC	299.2	1	TRACK	CD_0:SW_0 CD_0:SW_1	1284.000000 1796.000000	128.000 128.000	RR,RL,LR,LL RR,RL,LR,LL	64 64
A2319_A		10-Oct-08 03:02:35	10-Oct-08 03:12:34	UTC	598.4	0.999	TRACK	CD_0:SW_0 CD_0:SW_1	1284.000000 1796.000000	128.000 128.000	RR,RL,LR,LL RR,RL,LR,LL	64 64
A2319_B		10-Oct-08 03:12:34	10-Oct-08 03:22:32	UTC	598.4	1	TRACK	CD_0:SW_0 CD_0:SW_1	1284.000000 1796.000000	128.000 128.000	RR,RL,LR,LL RR,RL,LR,LL	64 64
J1845+4007		10-Oct-08 03:22:32	10-Oct-08 03:27:31	UTC	299.2	1	TRACK	CD_0:SW_0 CD_0:SW_1	1284.000000 1796.000000	128.000 128.000	RR,RL,LR,LL RR,RL,LR,LL	64 64
A2319_A		10-Oct-08 03:27:31	10-Oct-08 03:37:30	UTC	598.4	0.999	TRACK	CD_0:SW_0 CD_0:SW_1	1284.000000 1796.000000	128.000 128.000	RR,RL,LR,LL RR,RL,LR,LL	64 64

List of observation scans.

Data Reduction: Visibility Plane

Initial Look and A Priori Calibration

- Look to observing log for antenna issues to flag immediately
- Calibration of antenna positions, antenna gain vs elevation, weather (opacity)

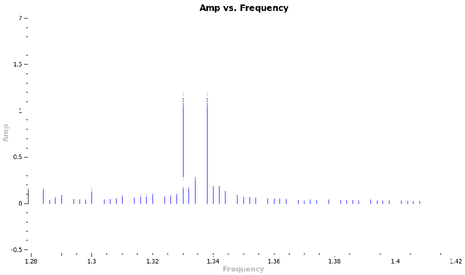


Antenna Positions.

Data Reduction: Visibility Plane

Low Frequency Issue: Radio Frequency Interference (RFI)

- RFI from humans wipes out large frequency bands in LF observations
- dealt with by smoothing data, autoflagging tools

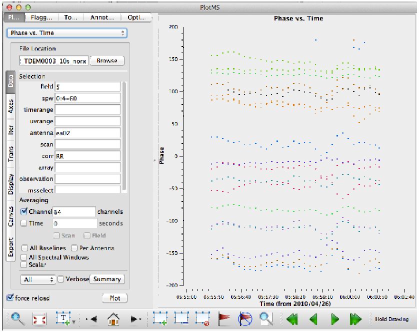


Badly RFI affected data.

Data Reduction: Visibility Plane

High Frequency Issue: Rapid Phase Variations

- atmospheric turbulence causes changes in phase over short timescales
- dealt with by observing phase calibrator in short intervals, careful phase calibration

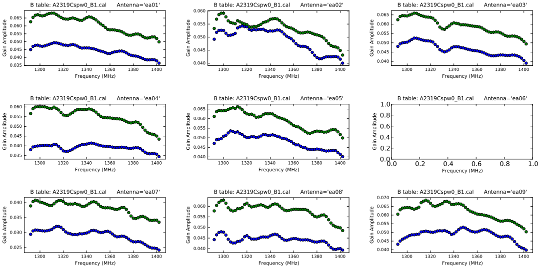


Phase variations in HF data. From IRC+10216 tutorial, casaguides.nrao.edu

Data Reduction: Visibility Plane

Bandpass, Gain, Flux Calibration

- bandpass shape: amp and phase vs frequency per antenna
- antenna gain: amp and phase vs time per antenna
- flux: scale flux of target relative to flux calibrator



Bandpass shape for first 9 antennas.

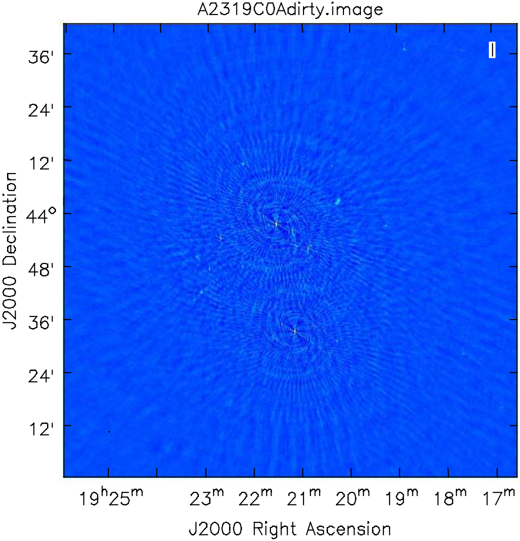
Data Reduction: Image Plane

CLEAN Algorithm

- FT of visibility = source map convolved with psf ("dirty map")
- Clean task takes care of this, assumes source map is collection of point sources
- CLEAN Algorithm:
  1. deconvolves source map from psf map (leftover: "residual map")
  2. finds highest peak in residuals
  3. subtracts out some percentage of peak
  4. adds the location and subtracted amplitude to a "model map" + clean component list
  5. iterate over hundreds to thousands components...
  6. add back clean components to residuals, convolve with weighted "clean" beam
- Extended emission? – options to deal with this (e.g. boxes, multiscale cleaning...)

Data Reduction: Image Plane

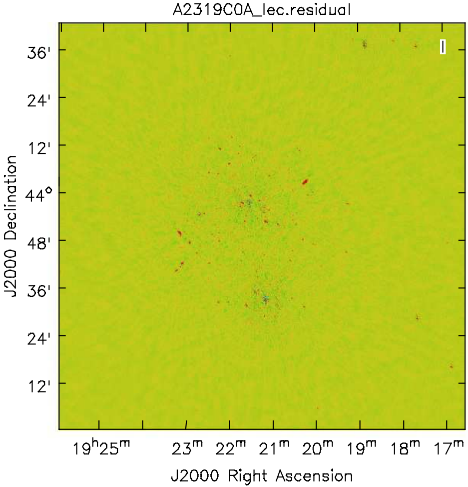
Dirty Image



No clean components.

Data Reduction: Image Plane

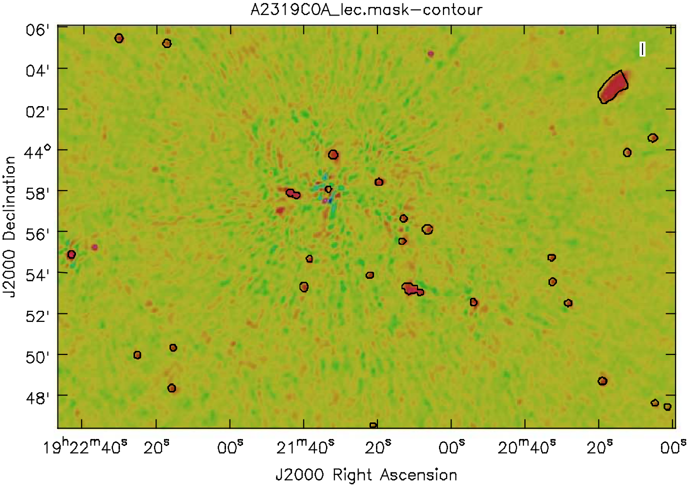
Interactive Cleaning



Residuals after 1000 clean components.

Data Reduction: Image Plane

Masking

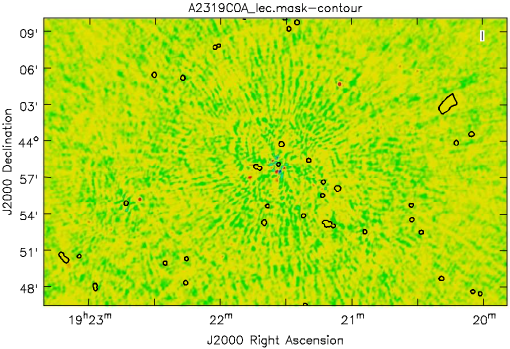


Residuals with masks on point sources.

Data Reduction: Image Plane

When to Stop

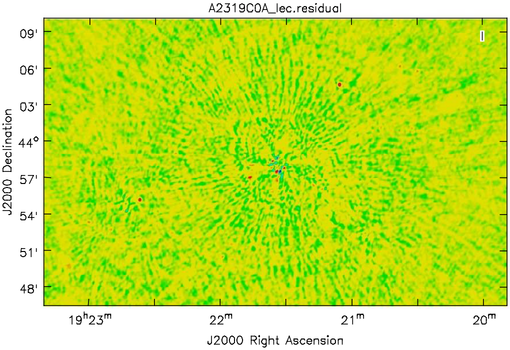
- set cleaning threshold to some multiple of theoretical rms noise
- interactively clean until the image looks good! (e.g., point sources appear to be cleaned down to background noise level)



Data Reduction: Image Plane

Image Quality

- flux scale (do your fluxes match those from e.g., NVSS?)
- rms noise near sources and far away
- dynamic range: maximum flux over rms noise
  - JVLA data capable of dynamic range in the thousands



Data Reduction: Image Plane → Visiblity Plane

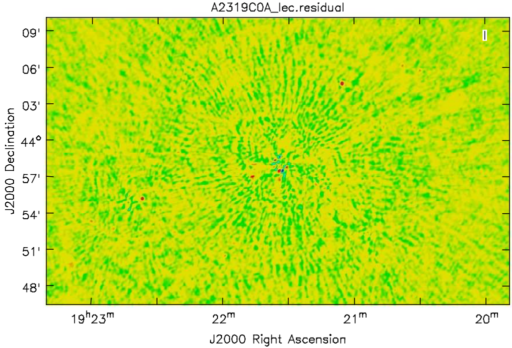
Self Calibration

- re-calibrate antenna gain using target itself, rather than gain calibrator
- if self-cal increases dynamic range, good!
- typically requires many iterations

Data Reduction: Image Plane

Image Quality: Patterns in the Residuals

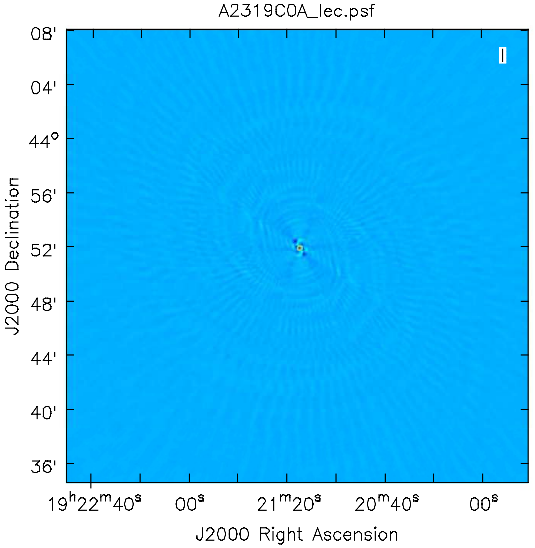
- residuals should be random!
- think in fourier space



PSF artifacts around point sources, due to imperfect UV coverage.
Not much you can do.

Data Reduction: Image Plane

Image Quality: PSF Shape

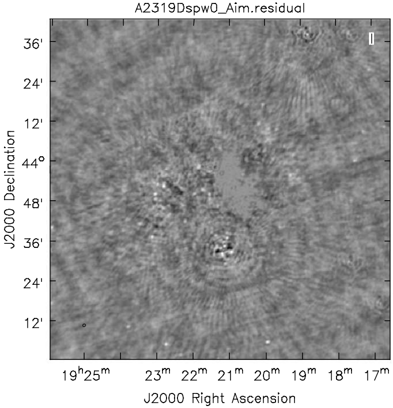


PSF for previous image. Lots of structure!

Data Reduction: Image Plane → Visibility Plane

Image Quality: Patterns in the Residuals

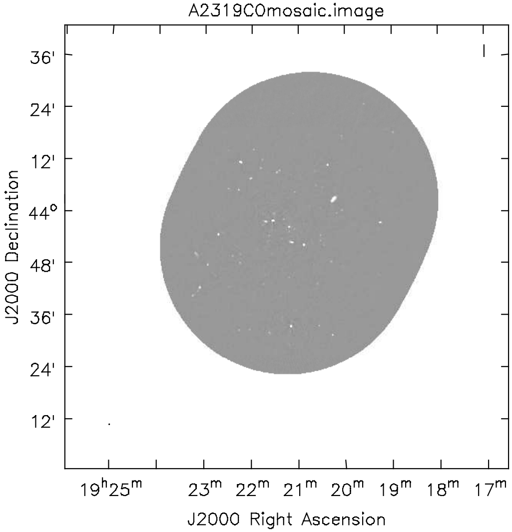
- some artifacts require going back to visiblity plane
- more flagging, etc.



Stripes, due to bad baseline or antenna, or RFI. Can remove this by going back to visiblity data.

Data Reduction: Image Plane

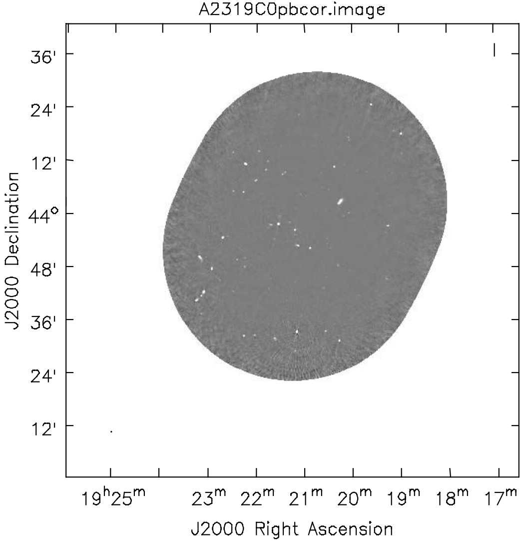
Fancier Options: Mosaicing



Multiple pointings put together into one image.

Data Reduction: Image Plane

Primary Beam Correction



Primary beam corrected. Flux weighted based on primary beam shape.

Data Reduction: Image Plane

More Options

- Wide Field Clean
  - baselines are not really in 2D plane
  - Wide Field clean takes 3D nature of baselines into account
  - can reduce artifacts far from center of primary beam
- Multifrequency Clean
  - simultaneously images and fits for instrinsic source spectrum
  - useful for wide band observations (e.g. >few hundred MHz bandwidth)
- Multiscale Clean
  - for known extended emission
  - no set method, need to play around
  - good starting point: set scales to point source, 2-3x synthesized beam, 2-3x expected extended emission sizes

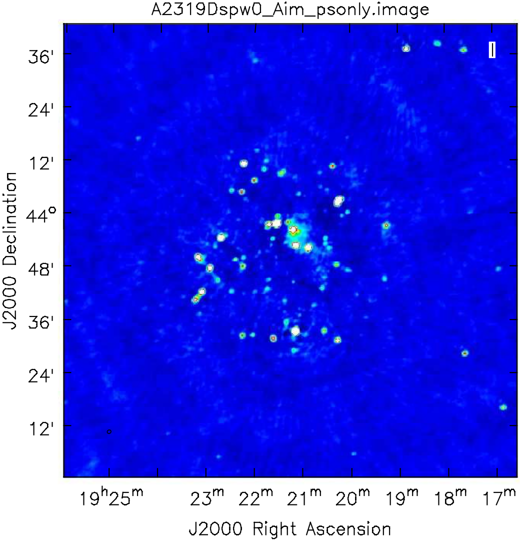
Data Reduction: Image Plane

Finalizing the Image

- lots of image manipulation tools: add, subtract, scale, make contours, etc
- export to fits format for manipulation in e.g., ds9

Data Reduction: Image Plane

Case Study: Imaging the halo of A2319



Clean point sources.

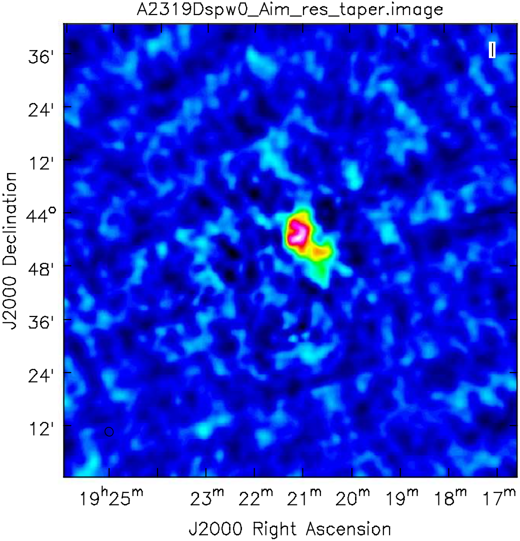
Data Reduction: Image $\rightarrow$ Visibility Plane

Case Study: Imaging the halo of A2319

- Subtract point source model from data, to be left with residuals and the halo. This is done in the visibility plane.
- Convolve the image down to 2 arcmin, so emission from halo is smoothed out.

Data Reduction: Image Plane

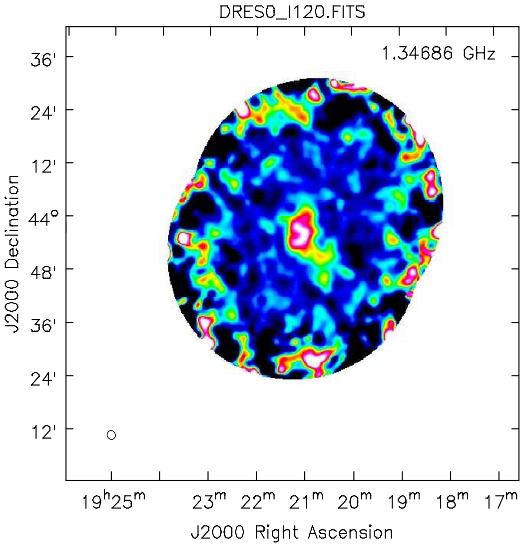
Case Study: Imaging the halo of A2319



Clean the smoothed residual+halo image. Repeat for other pointing.

Data Reduction: Image Plane

Case Study: Imaging the halo of A2319



Mosaic the two pointings, including primary beam correction. Note: this was done in AIPS.

Summary

- Measureable of interferometers: visiblity functions (=correlated antenna gains)
- Fourier Transform visibility to get image brightness
- manual calibration of visibility data necessary
- science goals determine image generation

References

- Essential Radio Astronomy: www.cv.nrao.edu/course/astr534/ERA.shtml
- NRAO website: nrao.edu
- NRAO synthesis imaging + single dish summer schools: science.nrao.edu/opportunities/courses
- VLA Observational Status Summaries: science.nrao.edu/facilities/vla/oss
- CASA downloads, user manuals, etc: casa.nrao.edu/
- CASA tutorials: casaguides.nrao.edu
- AIPS downloads, manuals, etc: www.aips.nrao.edu/index.shtml