High Dynamic Range Imaging

Craig Walker

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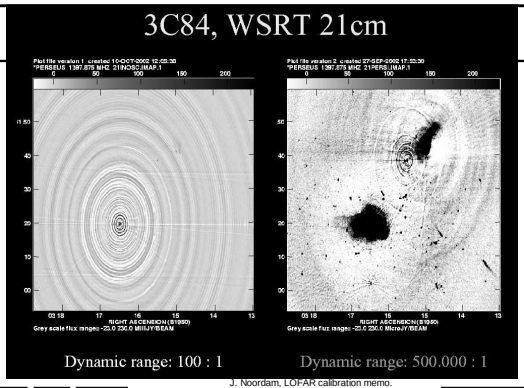
WHAT IS HIGH DYNAMIC RANGE IMAGING?

- High quality imaging of strong sources
  - Flux evolution of components
  - Motions of components
  - Detection of weak features
- Imaging of weak sources near strong sources
  - Deal with strongest sources in deep surveys
  - Deal with confusing sources near specific targets
- Imaging with high signal-to-noise
  - Usual calibration assumptions may be violated
  - Low level systematic errors matter
- Note some spectacular images have low dynamic range
  - Cygnus A, Cas A

QUALITY MEASURES

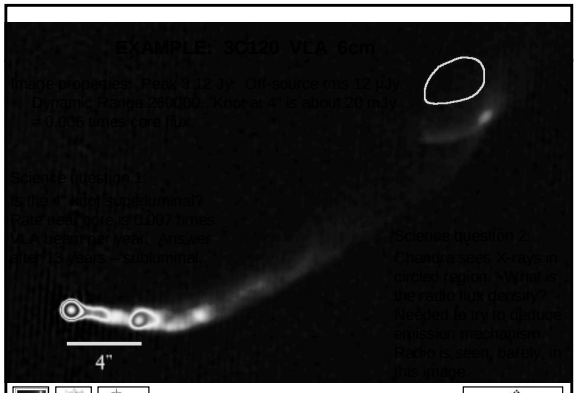
- Dynamic range:
  - Usually is ratio of peak to off-source rms
  - Easy to measure
  - A measure of the ability to detect weak features
  - Highest I am aware of: ~500,000 on 3C84 with WSRT
- Fidelity:
  - Error of on-source features
  - Important for motion measurements, flux histories etc.
  - Hard to measure – don't know the "true" source
    - Mainly good for simulations
- On-source errors typically much higher than off-source rms
  - Good fits to the data are not unique with incomplete sampling
- Highest dynamic ranges are achieved on simple sources

3C84, WSRT 21cm



J. Noordam, LOFAR calibration memo.

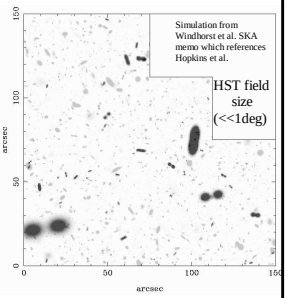
EXAMPLE: 3C120 VLA 6cm



EXAMPLE: SKA SURVEY

Survey 1 square degree to 20 nJy rms in 12 hr with 0.1" beam

- Required dynamic range 10^7
  - There will typically be a ~200 mJy source in the beam
  - Any long integration will have to deal with this problem
- Dense UV coverage required
  - About 10 sources per square arcsec above 100 nJy.



REQUIREMENTS FOR HIGH DYNAMIC RANGE IMAGING

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- Very clean, well calibrated data
  - Corrected for known degradations (sampling, smearing …)
  - Careful edit
  - Self-calibration (or redundancy calibration)
  - Calibration or avoidance of closure errors
    - These are violations of the antenna dependence of calibration
- Adequate UV coverage
  - Simple sources can be imaged with little UV coverage
  - Must sample more UV "cells" than there are beam areas on source
- Careful imaging and deconvolution
- Large fields have special issues
  - Most relate to spatial variations of gain

KNOWN DEGRADATIONS

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- Quantization correction (Van Vleck correction)
  - At high correlation, ratio of true/measured correlation is non-linear
  - A digital correlator effect for samples with few bits.
  - Worry when flux density >10% of SEFD
- Smearing due to averaging in frequency at wrong a priori delay
  - Delay error causes phase slope in frequency
  - VLA continuum system needs accurately set delays on-line
  - VLBI – software makes corrections based on fringe fit delay
  - Can reduce effect by keeping narrow band channels
- Smearing due to averaging in time
  - A problem with fast changing phases due to atmosphere or poorly known geometry or wide fields
  - VLBI – software makes corrections based on fringe fit rates
  - Can reduce effect with short averages

EDITING CONSIDERATIONS

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- Individual bad points don't have much effect
  - Each point divided by about the total number of points in image normalization
  - But, typically a bad point hurts more than a good point helps
- For typical data, phase errors are more important than amplitude errors
  - A fractional amp error is equivalent to a phase error of that fraction of a radian.
    - Example: a 5° phase error is equivalent to a 9% amplitude error
- Small systematic errors can have a big cumulative effect
  - Example: if each baseline has a constant error, it will only be reduced in the image by about the number of antennas (square root of number of baselines)
- Nearly all editing should be station based
  - Most data problems are due to a problem at an antenna
  - Most clipping algorithms don't do this, which is a problem
  - Exceptions often relate to spurious correlation
    - RFI, DC offsets, pulse cal tones ….

SELF-CALIBRATION

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- Self-calibration is required for high dynamic range
  - Atmosphere limits dynamic range to about 1000 for nodding calibration
  - Use of in-beam calibrator is a form of self-calibration
- High dynamic range is possible with just self-calibration
  - Nodding calibration is not required – get more time on-source
  - Typical VLBI case, but also true on VLA – see 3C120 example
  - But absolute position is not constrained – will match input model
- Many iterations may be needed
  - Most true for complex sources or poor UV coverage
  - Imagine finding the minimum in a lumpy χ^2 space with poor leverage
  - May need to vary parameters to help convergence
    - Robustness, UV range, taper, solution interval etc.

CLOSURE ERRORS

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- The measured visibility V'_{ij} for true visibility V_{ij} is:

  $V'_{ij} = g_i(t)\, g^*_j(t)\, G_{ij}(t)\, V_{ij}(t) + \varepsilon_{ij}(t) + \epsilon_{ij}(t)$

  From the self-calibration chapter
  - $g_i(t)$ is a complex antenna gain
    - Initially measured on calibrators
    - Improved with self-calibration
    - Could depend on sky position
  - $G_{ij}(t)$ is the portion of the gain that cannot be factored by antenna
    - These are the closure errors
    - The harmful variety are usually slowly or not variable
  - $\varepsilon_{ij}(t)$ is an additive offset term
    - For example spurious correlation of RFI etc.
    - These are also closure errors – the gain cannot be factored by antenna
    - Usually ignored
  - $\epsilon_{ij}(t)$ is the thermal noise

CLOSURE ERRORS: MISMATCHED BANDPASS EXAMPLE

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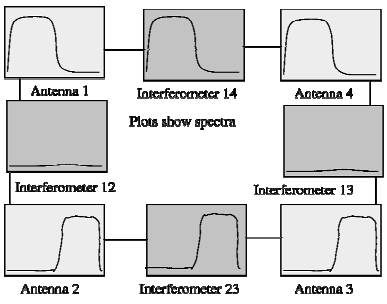
The average amplitudes on each baseline cannot be described in terms of antenna dependent gains



CLOSURE ERRORS: CAUSES

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- Mismatched bandpasses
- Instrumental errors
  - Non-orthogonality of real and imaginary signals from Hilbert transformer in VLA continuum. Raw phase dependent
- Uncorrected delay errors
- Uncorrected time average smearing
- Quantization error at high correlation coefficient
- Polarization leakage
- Poor coherence
- Correlation of RFI, pulse cal, DC offsets …

CLOSURE ERRORS: WHY THEY MATTER

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- Closure errors ($G_{ij}(t)$) are typically small
  - VLA continuum: of order 0.5%
  - VLBA and VLA line: less than 0.1%
  - Often smaller than data noise
- But the harmful closure errors are systematic
  - All data points on a given baseline may have the same offset
- Small systematic errors mount up
  - Any error in the data is reduced in the image by about $1/\sqrt{N}$ where N is the number of independent values
  - For noise, each data point is independent and N is the number of visibilities, which is large
  - For many closure errors, N is only the number of baselines
    - $\sqrt{N_{bas}} \approx N_{ant}$

AVOIDING CLOSURE ERRORS

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- Do a bandpass calibration
  - Only possible if spectral information is available
- Avoid excessive frequency or time averaging
- Be sure delay and rate smearing corrections are done
  - VLBI: If detected with fringe fit, done automatically in AIPS
  - VLA: Usually not needed – but EVLA may be different
- VLA continuum (for > 20,000 dynamic range):
  - Be sure delays are accurately set for observations (< 1ns)
  - Use array phasing to keep raw phases constant
    - Makes calibration of offsets from Hilbert transform devices possible
- Do full polarization calibration including effect on parallel hand data

CALIBRATING CLOSURE ERRORS

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- Baseline calibration on strong calibrator
  - Need high SNR
  - Do after best possible self-calibration
- Closure self-calibration
  - A baseline calibration on the target source
  - Depends on closure offsets being constant while UV structure is not
  - Will perfectly reproduce the model for snapshot
  - Some risk of matching the model even with long observations

UV COVERAGE

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- Obtain adequate UV coverage to constrain source
  - If divide UV plane into cells of about 1/(source size), need more sampled cells than there are beam areas covering the source
    - Source size in radians
    - In other words, you need more constraints than unknowns
    - Low level structures can cover many beam areas
- Avoid hidden distributions
  - Distributions whose transform is only large in UV holes
  - Avoid major holes
  - Sample short UV spacings
- Not much UV coverage is needed for simple sources
  - This includes a few widely separated simple sources

IMAGING ISSUES

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- Digital representation:
  - For CLEAN, negative components are required to represent an unresolved feature between cells
    - Don't stop CLEAN or self-cal at first negative
  - If possible, put bright points on grid cells
  - Need 5 or 6 cells per beam
  - 32 bit real numbers may not be adequate for SKA
- Use the most appropriate deconvolution algorithm
  - MEM for large, smooth sources
  - CLEAN for compact sources
  - NNLS best for partially resolved sources (avoid Briggs effect)
- Don't use CLEAN boxes that are too large
  - CLEAN can fit the noise with a few points and give spurious low rms
- May need to deal with sidelobes from confusing sources

LIMITS IMPOSED BY VARIOUS ERRORS

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Numbers are approximate max dynamic range

- Atmosphere without self-calibration: 1,000
- Closure errors VLA continuum: 20,000
- Closure errors VLA line or VLBA: >100,000
- Uncalibrated closure errors
  - VLA: >200,000
  - WSRT: >400,000
- Thermal noise > 10^6
  - Very few sources are bright enough to reach this limit with current instruments.
    - Bigger problem with EVLA and especially SKA

EXAMPLE: 3C273 VLA

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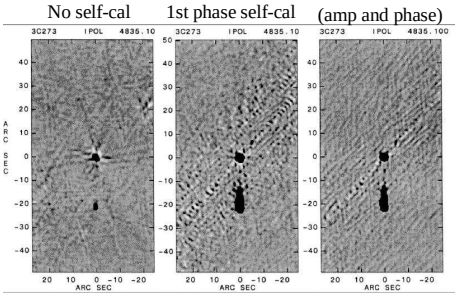
No self-cal | 1st phase self-cal | 2nd self-cal (amp and phase)

B Array

Rotated so jet is vertical



From R. Perley Synthesis Imaging Chapter 13.

3C273 RESIDUAL DATA

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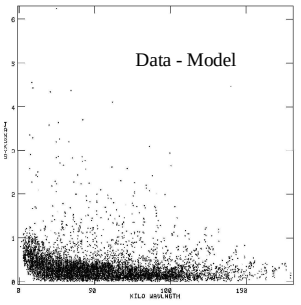
Points above 1 Jy from correlator malfunction.

Points below 1 Jy mostly show closure errors

1 Jy



UV Distance

EXAMPLE: 3C273 CONTINUED

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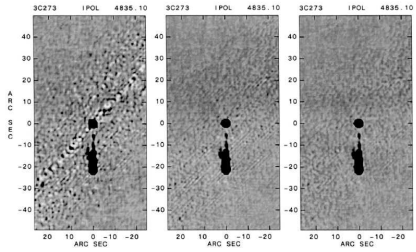
Bad baseline removed | Self-closure calibration | Clip residuals



EXAMPLE: VALUE OF SHORT BASELINES

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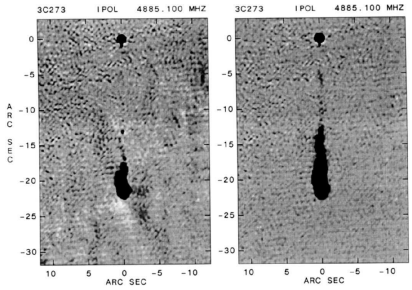
VLA A only | VLA A+B



BRIGGS EFFECT

Dan Briggs at the 1998 school, shortly before his death while skydiving

The Briggs effect is a deconvolution problem with partially resolved sources

- Interpolation between longest baselines poor
- Not seen on unresolved sources
- Not seen on well resolved sources
- Seen with all common deconvolution algorithms (CLEAN, MEM …)
- Dan developed the NNLS algorithm which works
  - Non-Negative Least Squares
  - Restricted to sources of modest size (computer limitations)

BRIGGS EFFECT EXAMPLE: 3C48 UV DATA

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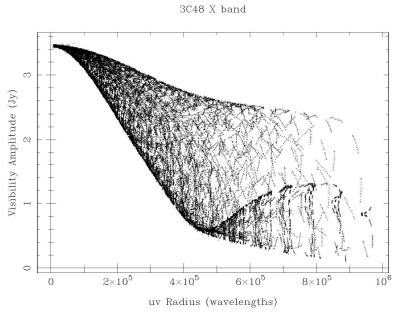

BRIGGS EFFECT EXAMPLE: 3C48 IMAGES

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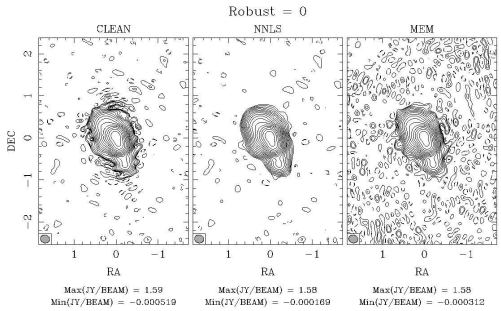

LARGE FIELD ISSUES

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- Position dependent gain
  - Primary beam – the sensitivity of the individual antennas
    - Scales with frequency
    - Pointing: relative gain across field varies with pointing fluctuations
    - Squint: RCP & LCP beams offset for asymmetric antennas (VLA, VLBA)
    - Parallactic angle effects with non-circular beams
  - Isoplanatic patch – ionosphere or troposphere variations in position
- Bandwidth and time average smearing away from center
  - Distant sources have large delay offsets
  - Distant sources have rapidly varying phases
  - Need to keep frequency channels narrow and time averages short
    - Big data sets!
- May need to deal with confusing sources
  - Can be outside primary beam – separate self-cal

WIDE FIELD EXAMPLE

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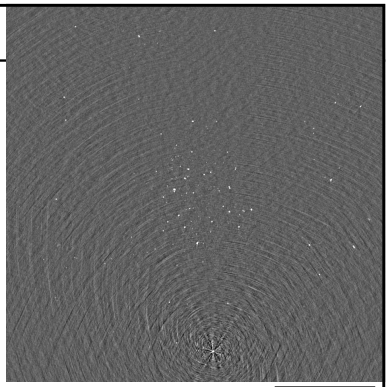
- Sources in cluster Abell 2192
  - Continuum from HI line cube (z=0.2)
    - Provided by Marc Verheijen
- Bright source in first primary beam sidelobe
  - 39 mJy after primary beam attenuation
  - Self-cal on the confusing source
  - Subtract from UV data
  - Self-cal on primary beam sources

WIDE FIELD EXAMPLE: EXTERNAL CALIBRATION ONLY

Confusing source outside primary beam near bottom



WIDE FIELD EXAMPLE: SAMPLE PRIMARY BEAMS

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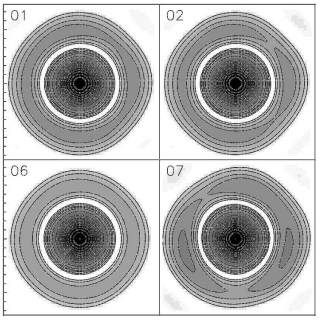
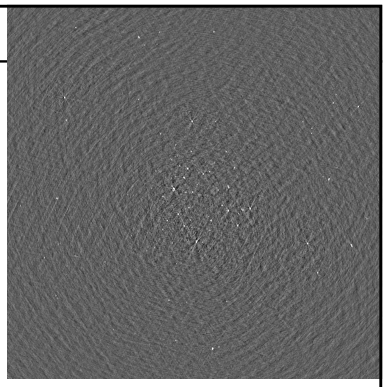
Beams from different antennas

Note variations far from center

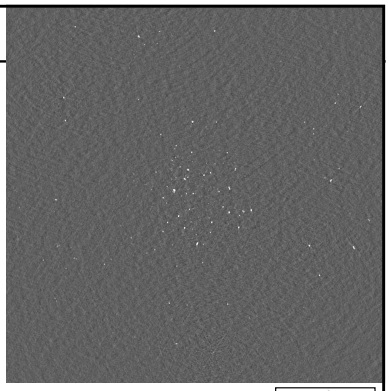


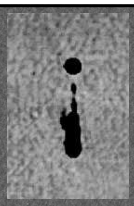
WIDE FIELD EXAMPLE: SELF-CAL ON CONFUSING SOURCE



WIDE FIELD EXAMPLE: FINAL IMAGE

Confusing source subtracted
Self-cal on primary beam sources





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