High Dynamic Range Imaging

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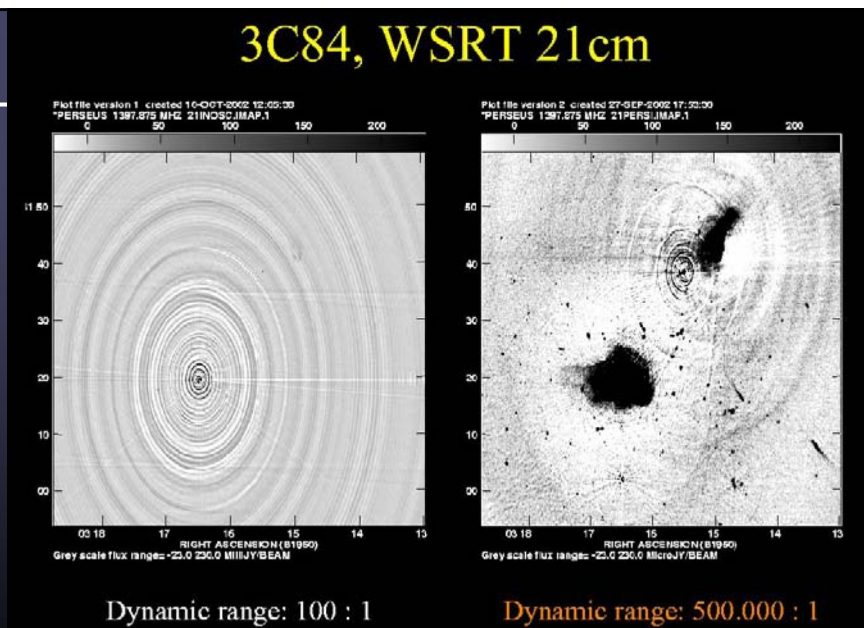
Tenth Summer Synthesis Imaging Workshop
University of New Mexico, June 13-20, 2006

WHAT IS HIGH DYNAMIC RANGE IMAGING? AND WHY DO IT?

- Accurate imaging with a high brightness ratio.
  - 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
  - Note some spectacular images have low dynamic range
    - Cygnus A, Cas A

QUALITY MEASURES

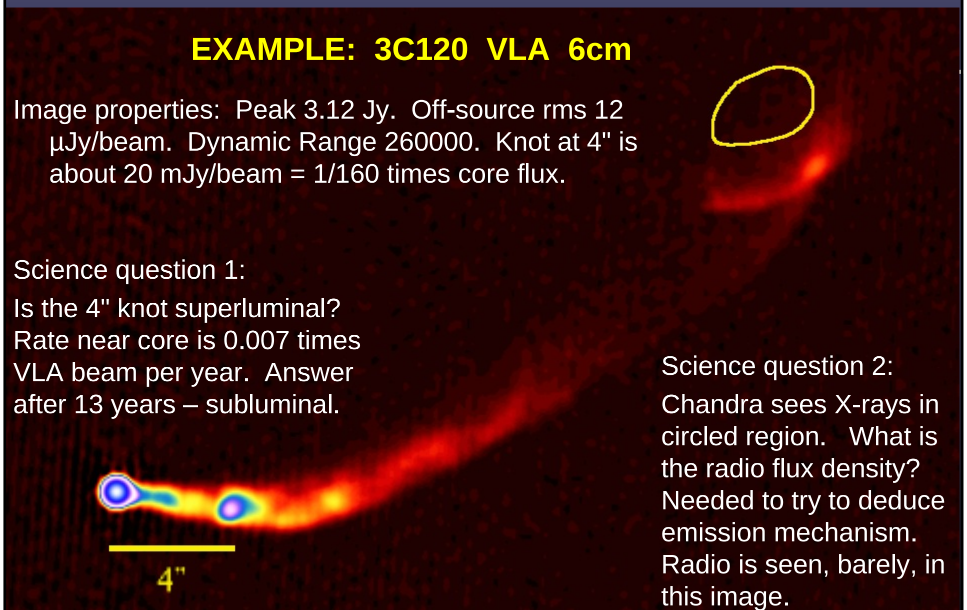
- Dynamic range:
  - Usually is ratio of peak to off-source rms
  - Easy to measure
  - A measure of the ability to detect weak features
  - Highest I am aware of as of 2004: ~500,000 on 3C84 with WSRT
- Fidelity:
  - Error of on-source features
  - Important for motion measurements, flux histories etc.
  - Hard to measure – don't know the "true" source
    - Mainly good for simulations
- On-source errors typically much higher than off-source rms
- Highest dynamic ranges are achieved on simple sources



J. Noordam, LOFAR calibration memo.

EXAMPLE: 3C120 VLA 6cm

Image properties: Peak 3.12 Jy. Off-source rms 12 µJy/beam. Dynamic Range 260000. Knot at 4" is about 20 mJy/beam = 1/160 times core flux.



Science question 1:

Is the 4" knot superluminal? Rate near core is 0.007 times VLA beam per year. Answer after 13 years – subluminal.

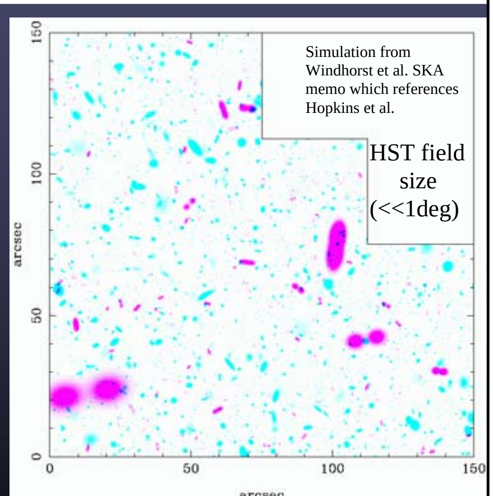
Science question 2:

Chandra sees X-rays in circled region. What is the radio flux density? Needed to try to deduce emission mechanism. Radio is seen, barely, in this image.

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 field
  - Any long integration will have to deal with this problem
- Dense UV coverage required
  - About 10 sources per sq. deg. above 100 nJy.
  - Significant fraction of sky filled
- The EVLA will face the same issues, although to a lesser degree



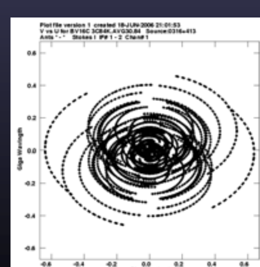
BASIC REQUIREMENTS FOR HIGH DYNAMIC RANGE IMAGING

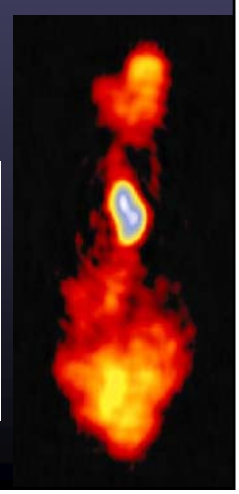
- A way to view the problem:

  It must be possible to subtract the model from the data with high accuracy
- The model must be a good description of the sky
  - Typically clean components or MEM image
- Need very good calibration and edit
- Deal with commonly ignored effects
  - Closure errors
  - Spurious correlation, RFI etc.
  - Finite bandwidth and sources with spatial variations in spectral index
  - Position dependent gains due to primary beam shape and pointing
  - Position dependent gains due to troposphere and ionosphere
  - 3D effects for wide fields
- Avoid digital precision effects (mostly a future issue)

UV COVERAGE

- 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
    - In other words, you need more constraints than unknowns
    - As dynamic range increases, beam areas with emission usually does too.
- Avoid hidden distributions
  - Big UV holes
  - Missing short spacings
- Can do simple sources with poor UV coverage
- Example - 3C84 on the VLBA is a marginal case





EDITING CONSIDERATIONS

- A few individual bad points don't have much effect
- For typical data, phase errors are more important than amplitude errors
  - Example: a 5° phase error is equivalent to a 9% amplitude error
- Small systematic errors can have a big cumulative effect
- 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

- High dynamic range imaging requires self-calibration
  - Atmosphere limits dynamic range to about 1000 for nodding 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 and/or poor UV coverage
  - May need to vary parameters to help convergence
    - Robustness, UV range, taper, solution interval etc.

CLOSURE ERRORS

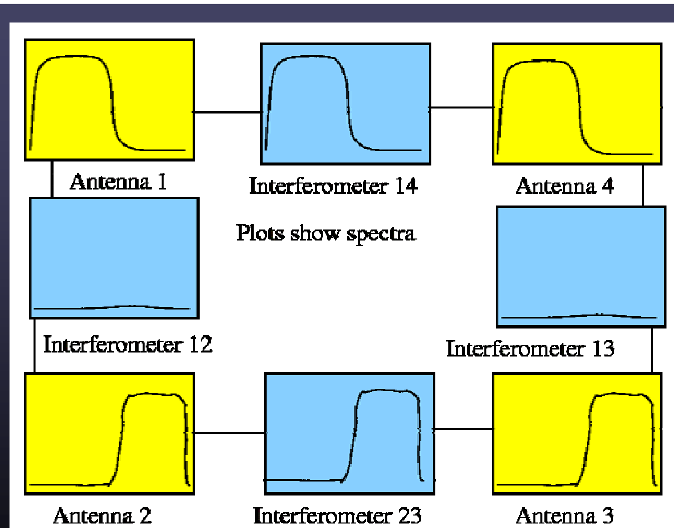
- The measured visibility V'_{ij} for true visibility V_{ij} is:

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

  From the self-calibration chapter
  - $g_i(t)$ is a complex antenna gain
    - Initially measured on calibrators
    - Improved with self-calibration
    - Depends on sky position for large fields (comparable to primary beam)
  - $G_{ij}(t)$ 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: EXTREME MISMATCHED BANDPASS EXAMPLE

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



CLOSURE ERRORS: WHY THEY MATTER

- 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 data error 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 (1)

- Use accurate delays and/or narrow frequency channels
  - A delay error causes a phase slope with frequency
    - Averaging can cause baseline dependent smearing - does not close
  - Instrumental delays need to be removed accurately
    - VLA continuum system needs accurately set delays on-line
  - Delay changes with sky position, so wide fields need narrow channels
- Use sufficiently short time averages to avoid smearing
  - Such smearing is baseline dependent - does not close
  - Troposphere, Ionosphere, Poor geometric model
  - Offset positions in wide field imaging
- Well matched bandpasses
  - Mismatched bandpasses cause closure errors
  - Use bandpass calibration to reduce effect

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AVOIDING CLOSURE ERRORS (2)

- Avoid spurious correlations at low total fringe rate
  – Signals that can correlate: RFI, clipper offsets, pulse cal tones
    - VLA uses orthogonal Walsh functions to prevent correlation of clipper offsets. EVLA will use small frequency offsets
  – Happens on short baselines, polar sources and near V=0
    - Can even be a problem for VLBI
- Quantization correction (Van Vleck correction)
  – At high correlation, ratio of true/measured correlation is non-linear
  – This is a digital correlator effect for samples with few bits.
  – A concern when flux density >10% of SEFD
- Avoid or calibrate the effect of polarization impurity on the parallel hand data
  – May be current VLA limiting factor

AVOIDING CLOSURE ERRORS (3)

- Avoid or calibrate instrumental errors
  – Example: Non-orthogonality of real and imaginary signals from Hilbert transformer in VLA continuum causes closure errors.
    - Raw phase dependent
    - Limits VLA continuum system dynamic range to about 20,000
    - Can hold constant by using array phasing
    - Calibrate on strong source
- Avoid poor coherence - causes closure errors
  – Keep calibration solution intervals short compared to coherence time

CALIBRATING CLOSURE ERRORS

- Avoid closure errors if possible by using appropriate observation parameters
- Baseline calibration on strong calibrator
  - After best self cal, assume time averaged residual on each baseline is a closure error
  - Need high SNR
  - Errors in the calibrator model can transfer to data
    - Most problematic for polar sources and snaphot calibrator observations
- 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

IMAGING ISSUES FOR HIGH DYNAMIC RANGE

- 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

LARGE FIELD IMAGING ISSUES

- Position dependent gain:
  - Primary beam
    - Scales with frequency
    - Varies with pointing
    - Squint: RCP & LCP beams offset for asymmetric antennas (VLA, VLBA)
    - Rotates with hour angle
  - Isoplanatic patch – ionosphere or troposphere variations in position
- Bandwidth and time average smearing away from center
- May need to deal with confusing sources
  - Can be outside primary beam main lobe – separate self-cal
  - Bigger problem as sensitivity increases (serious for SKA)
  - Serious problem at low frequencies
- Topic of active research in algorithms

LIMITS IMPOSED BY VARIOUS ERRORS

Numbers are approximate maximum dynamic range

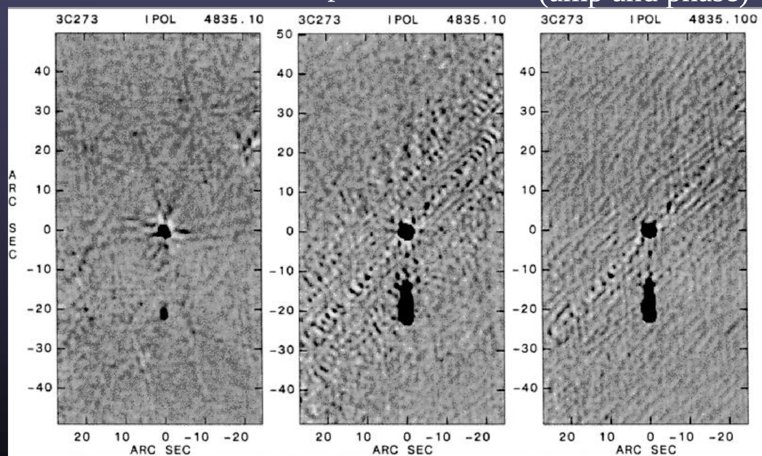
- Atmosphere without self-calibration: 1,000
- Closure errors VLA continuum: 20,000
- Closure errors VLA line or VLBA: >100,000
- Uncalibrated closure errors (after baseline calibration)
  - VLA: >200,000
  - WSRT: >400,000
- Thermal noise + maximum source strength > 10^6
  - Very few sources are bright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

EXAMPLE: 3C273 VLA

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

B Array

Rotated so jet is vertical



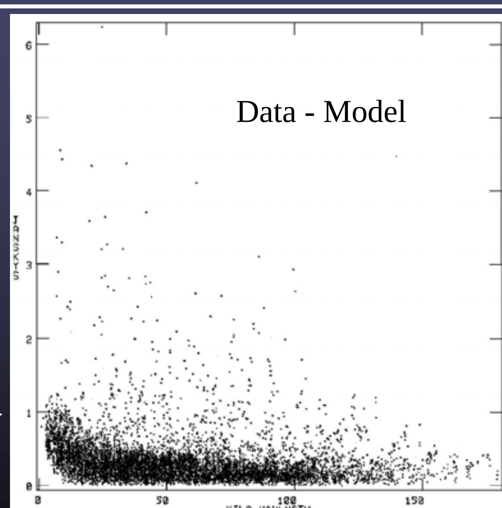
From
R. Perley
Synthesis Imaging
Chapter 13.

3C273 RESIDUAL DATA

Points above 1 Jy from correlator malfunction.

Points below 1 Jy mostly show closure errors

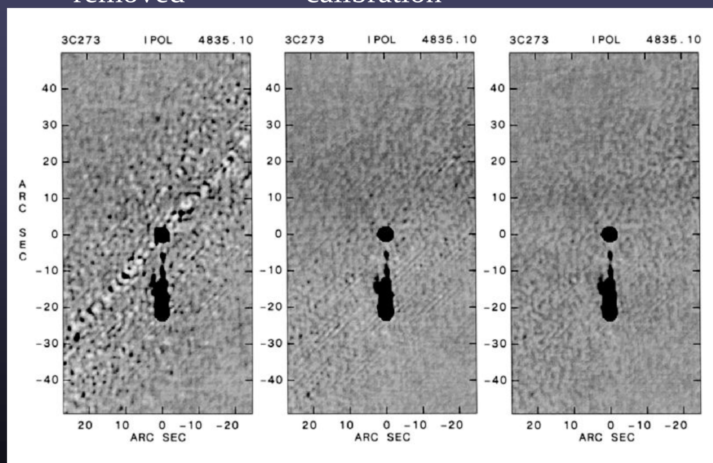
1 Jy



UV Distance

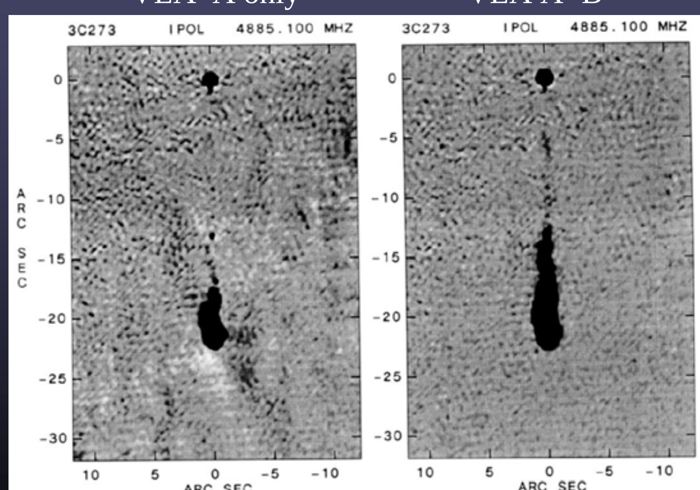
EXAMPLE: 3C273 CONTINUED

Bad baseline removed | Self-closure calibration | Clip residuals



EXAMPLE: VALUE OF SHORT BASELINES

VLA A only | VLA A+B

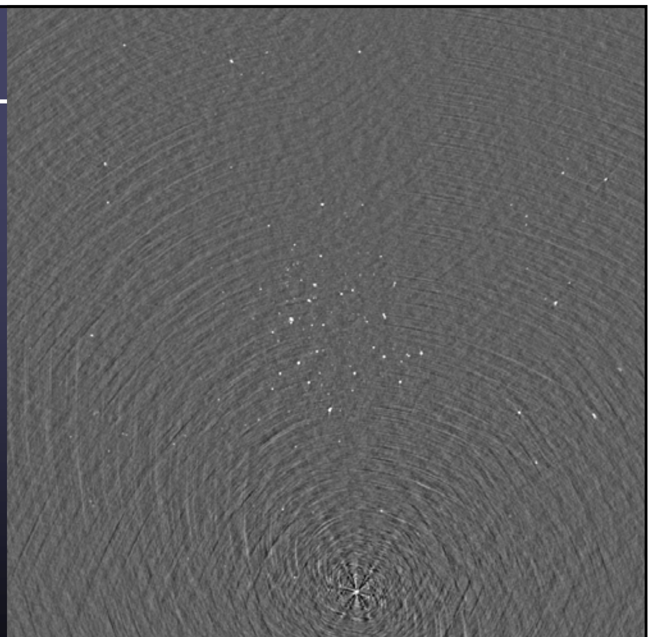


WIDE FIELD EXAMPLE

- 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

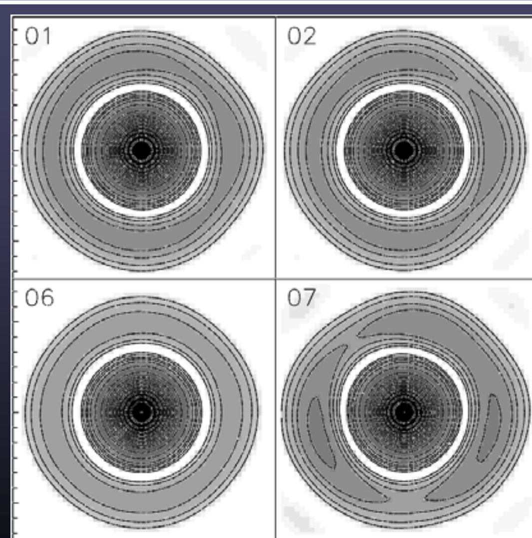
Confusing source outside primary beam near bottom



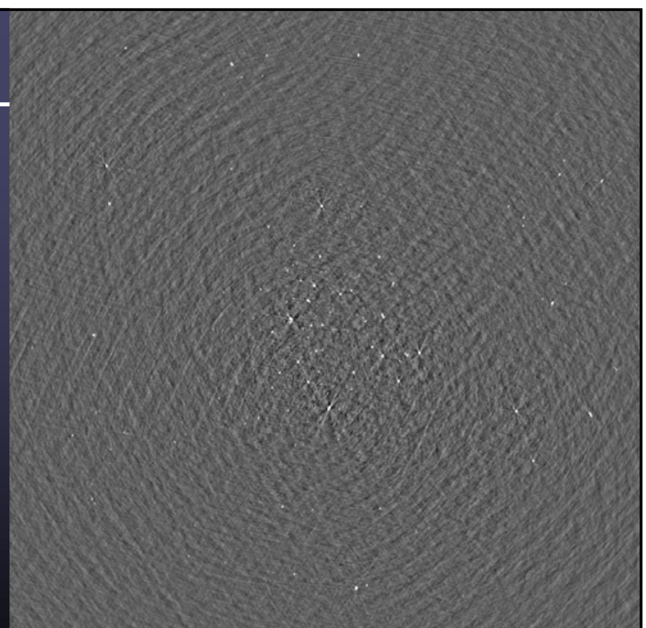
WIDE FIELD EXAMPLE: SAMPLE PRIMARY BEAMS

Beams from different antennas

Note variations far from center

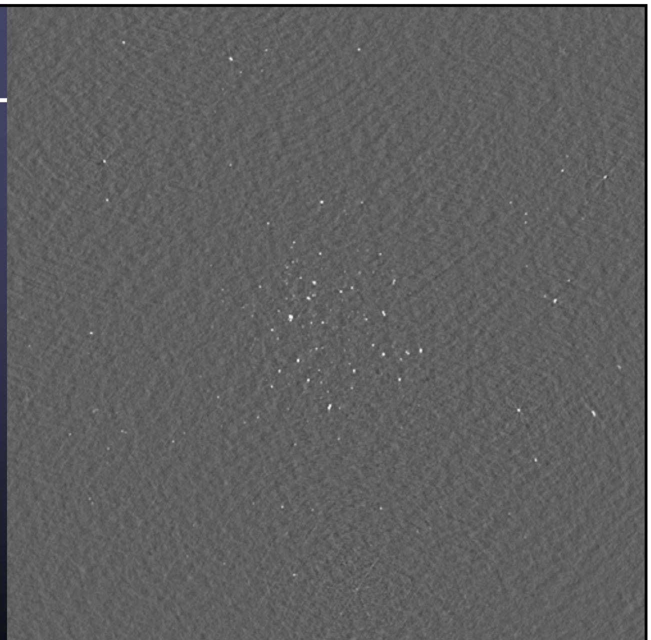


WIDE FIELD EXAMPLE: SELF-CAL ON CONFUSING SOURCE



WIDE FIELD EXAMPLE: FINAL IMAGE

Confusing source subtracted
Self-cal on primary beam sources



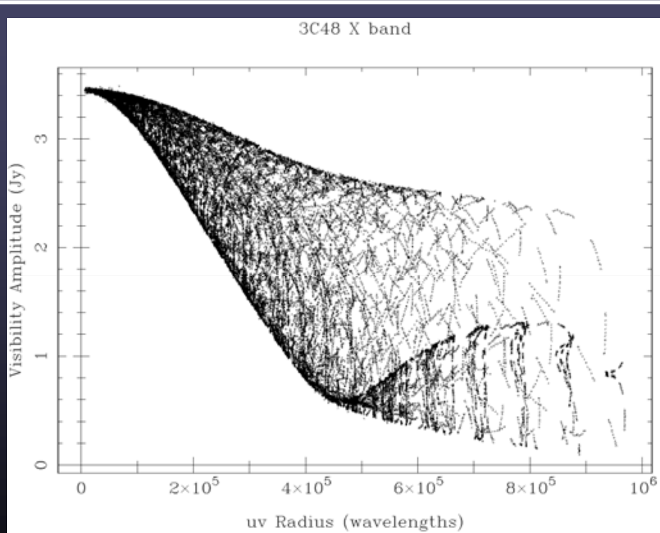
BRIGGS EFFECT

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

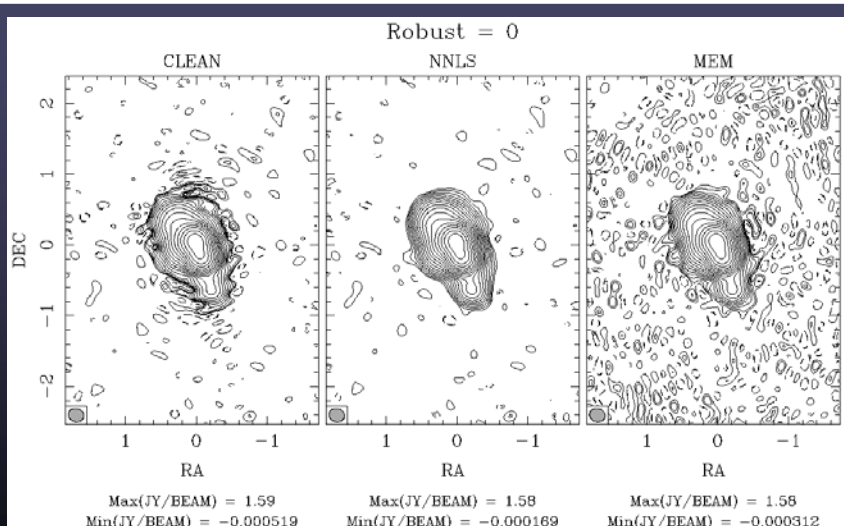
The Briggs effect is a deconvolution problem with partially resolved sources

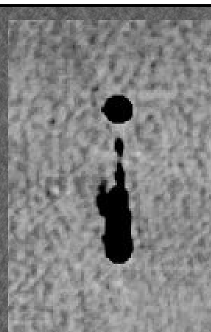
- Interpolation between longest baselines poor
- Not seen on unresolved sources
- Not seen on well resolved sources
- Seen with all common deconvolution algorithms (CLEAN, MEM …)
- Dan developed the NNLS algorithm which works
  - Non-Negative Least Squares
  - Restricted to sources of modest size (computer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

BRIGGS EFFECT EXAMPLE: 3C48 UV DATA



BRIGGS EFFECT EXAMPLE: 3C48 IMAGES





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