High Fidelity Imaging of Extended Sources

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Expanded Very Large Array
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Very Long Baseline Array

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A Brief History of Calibration (VLA)

An Amazing Fact:

- The VLA was proposed, and funded, without any real concept of how to calibrate the data.
- Proof: When I arrived (in 1977 as a newly minted PhD with no real experience), my job assignment was 'Figure out how to calibrate this telescope'.
- In defense of NRAO: The VLA was such a major leap forwards from any existing array it is not surprising that there was much to learn on how to use it.
- Thus began the search for VLA calibrators, and how to use them.
- Little did I know where this would lead …

The Impact of Self-Calibration

- Early VLA imaging quickly demonstrated that Martin Ryle was right – atmospheric phase errors prevent imaging (at 6cm) beyond 5 km.
- But Martin (and the VLA's promoters) didn't know about self-calibration.
- By 1978, we had figured out simple (point-source) self-cal.
- By early 1980s, full model-based self-cal was well established.

Shown here is our 1989 X-band image of Cygnus A.

DR ~ 4500. Far poorer than expected.

Noise 10 – 100 x higher than thermal.

Fidelity – Point source vs. Extended source

- Testing of self-calibration on 1980s-era VLA data quickly established:
- For point-like, or very compact objects, DRs of 100,000 (down to thermal noise) could be easily reached.
- For extended objects – especially with bright compact structure at the extremities, DRs of ~5000 were the best one could get.
- Why the difference?
- One certainty: Not an SNR issue. This is about imaging fidelity.

The VLA's old correlator

- The VLA's original digital correlator was a beautiful – but imperfect – machine.
- From the point of view of High Fidelity imaging, its major shortcoming was:
  - `Closure Errors'.
- In short, basic self-calibration relies on the gains being factorable by antenna:

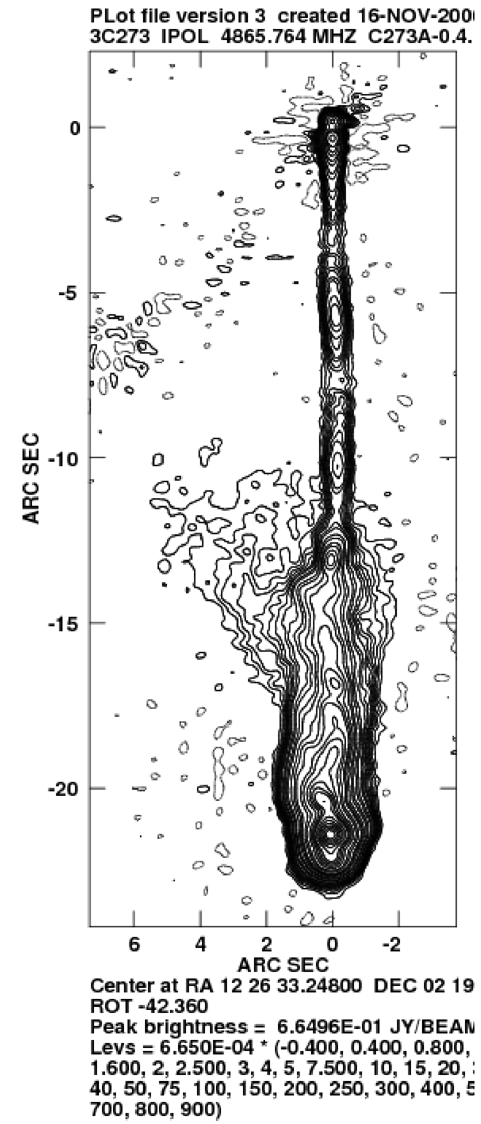
$$G_{ij} = G_i G_j$$

- But in reality, our old correlator (in 'continuum' mode) contained a significant baseline-dependent error:

$$G_{ij} = G_i G_j + g_{ij}$$

Removal of 'Closure' Errors

- It was quickly determined that these 'closure' errors were proportional to source strength, and were fairly constant in time.
- Software was soon developed ('BLCAL') to permit their estimation and removal.
  - But this calibration methodology is very dangerous!
- How well did this work? DRs over 100,000:1. But this could only be used on small, strong sources.
- But attempts to improve the Cygnus A images via application of these 'closure' corrections failed.
- Nevertheless, it's easy to blame your tools for your failure, so we awaited a new correlator…



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Solution? – A New Correlator.

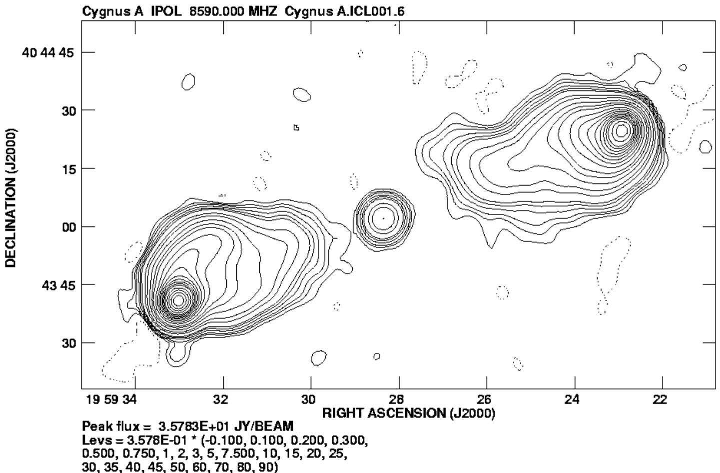
- The EVLA Project enabled a much better solution – A new wideband digitial correlator ('WIDAR').
- So far as I have been able to determine, there are NO `closure' errors from this machine.
  - Note upcoming caveats …
- Use of WIDAR on strong point sources (3C147) immediately provided DRs of 10^6 or so.
- Limitations now come from DD effects.
- Oleg has implemented DD calibration to push the DR limit to over 8×10^6:1.
- So we're happy now. Right?

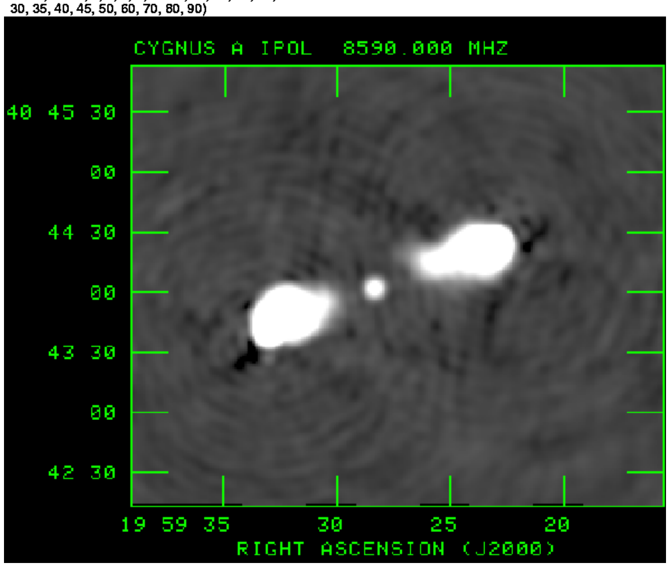
WRONG!

- In fact, imaging of Cygnus A-like objects is no better now than it was in the 1980s.
- We're missing something here …

Early WIDAR observations of Cygnus A

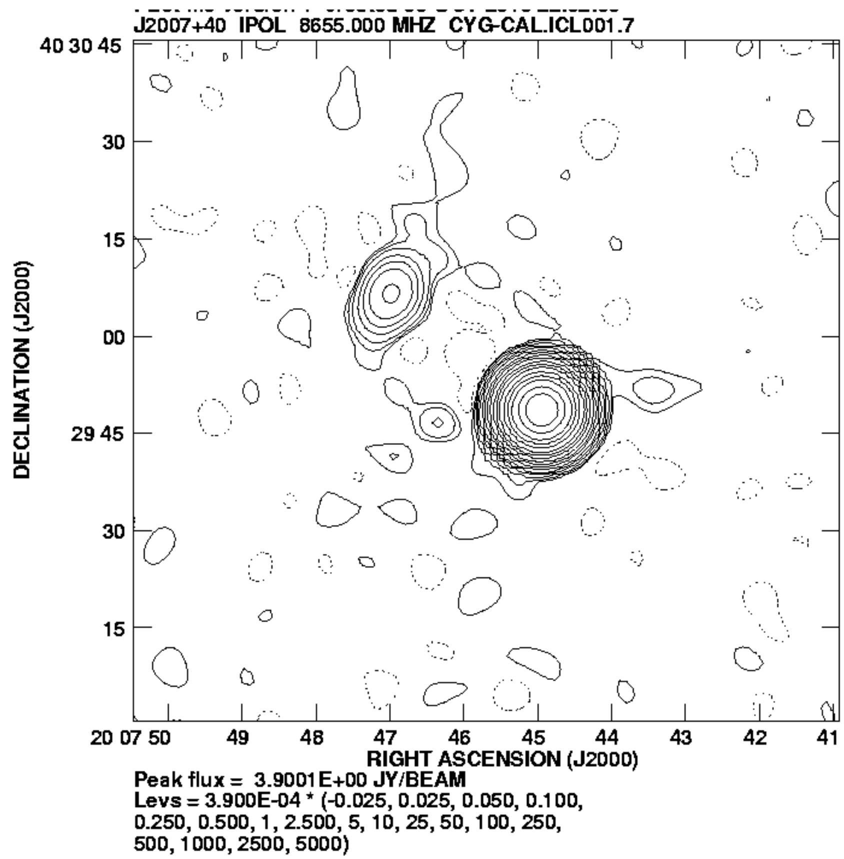
- Shown here – an early test of WIDAR.
- X-band synthesis on Cygnus A.
- D configuration. 512 MHz BW, 2 hours' integration.
- Normal self-calibration applied.
- DR ~ few x 1000.
- RMS noise ~ 3 mJy/beam.
- This ~500 x thermal. (!)
- No better than what we did in 1989!





It’s not the correlator -- J2007+4029

- This is the calibrator source.
- Only ~2 degrees away.
- Same integration time, bandwidth, day, weather, as for Cygnus A.
- DR: 650,000:1
- Noise level 6μJy/beam – thermal level.

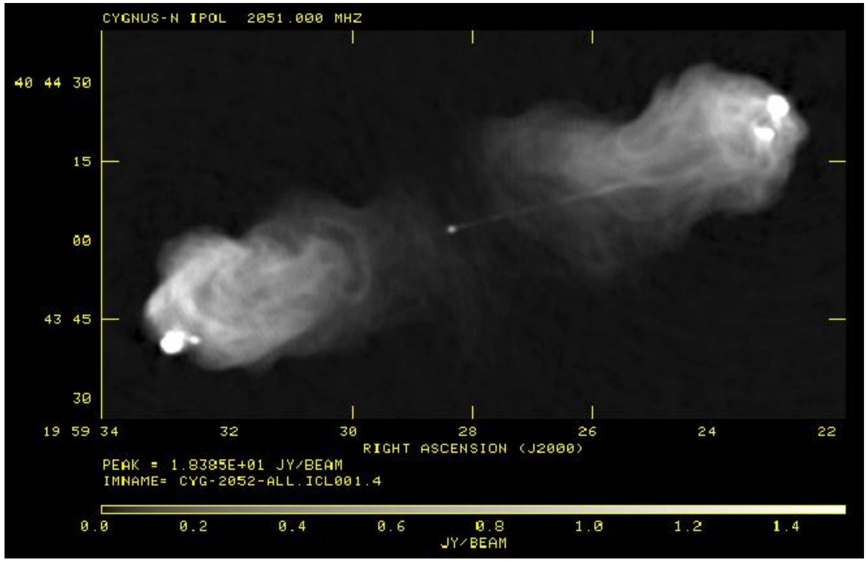


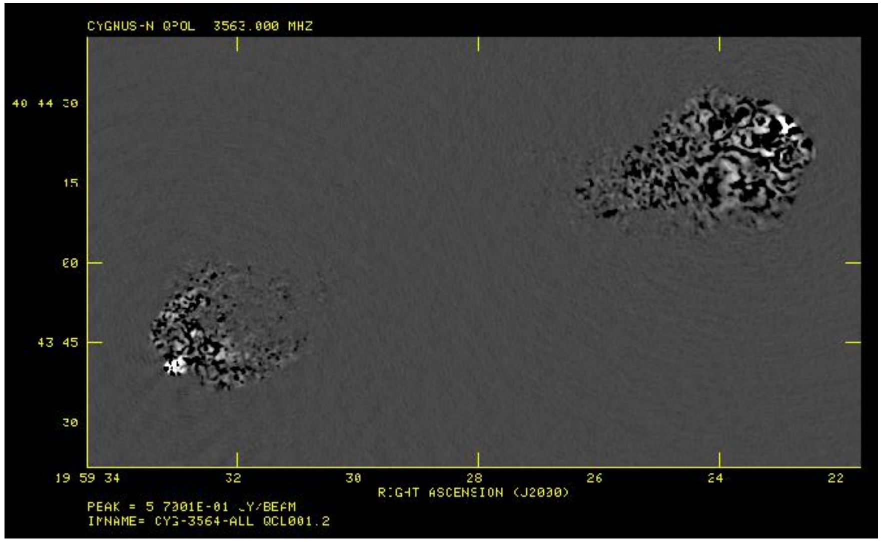
The New EVLA Cygnus A Campaign

- With the new wideband capabilities of the VLA, a new observational campaign has been undertaken.
- All four configurations, full frequency coverage across four frequency bands: 2.0 – 18 GHz.
- About 9200 individual frequency channels.
- Full polarization.
- Raw data occupy ~ 7 TB.
- Significant imaging challenge:
  - Source comprises ~10000 – 100000 beam elements
  - Stokes I, Q, U required
  - ~5000 individual frequency channels.
- We need fast, efficient, ‘correct’, easy-to-use deconvolution…

Cygnus A in I and Q

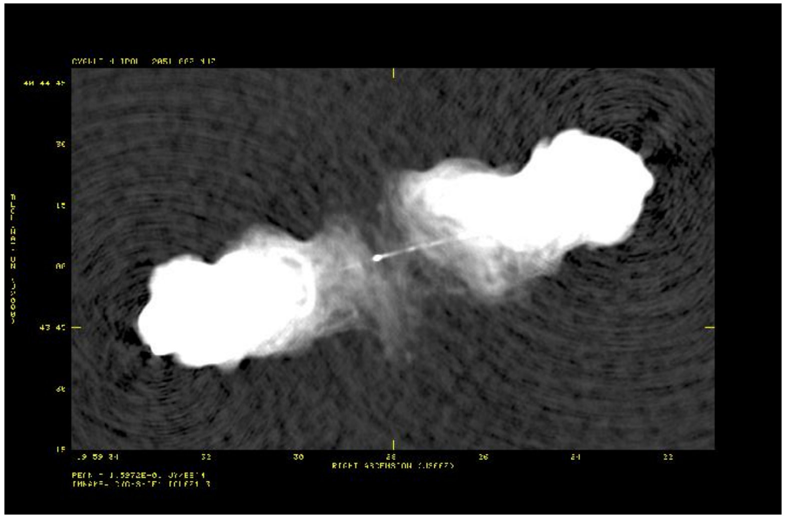
- Shown here are Cygnus A in I (top) at 2052 MHz, and Q (bottom) at 3564 MHz.
- Both were deconvolved with single-scale CLEAN.
- Clearly, 'I' would benefit by using MS-clean.
- But, in polarization, a single-scale CLEAN is remarkably efficient.
- Note: In 'I', the peak bringhtness of the hotpots is about 20 x the peak in the lobes.

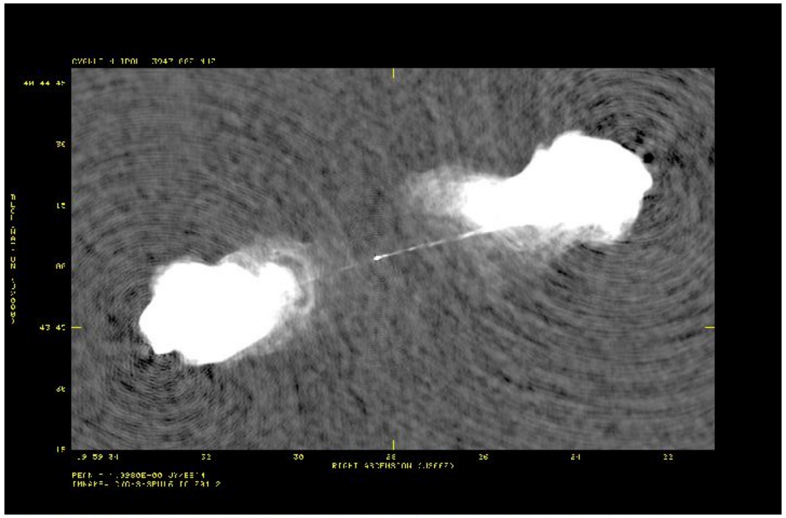




JVLA Imaging of Cygnus A : 2 – 4 GHz

- Shown are highly saturated grey-scale images of Cygnus A.
- These are single-channel (1 MHz).
- Single-solution self-cal applied.
- Top: 2052 MHz. DR = 32000
- Bottom: 3952 MHz. DR = 12000
- Surprising trend: Fidelity steadily worsens with increasing frequency.
- The 'swirls' in the error patterns indicate:
  - Imaging of the hotspots dominate the errors
  - The errors vary slowly over time.





Degradation over S-band …

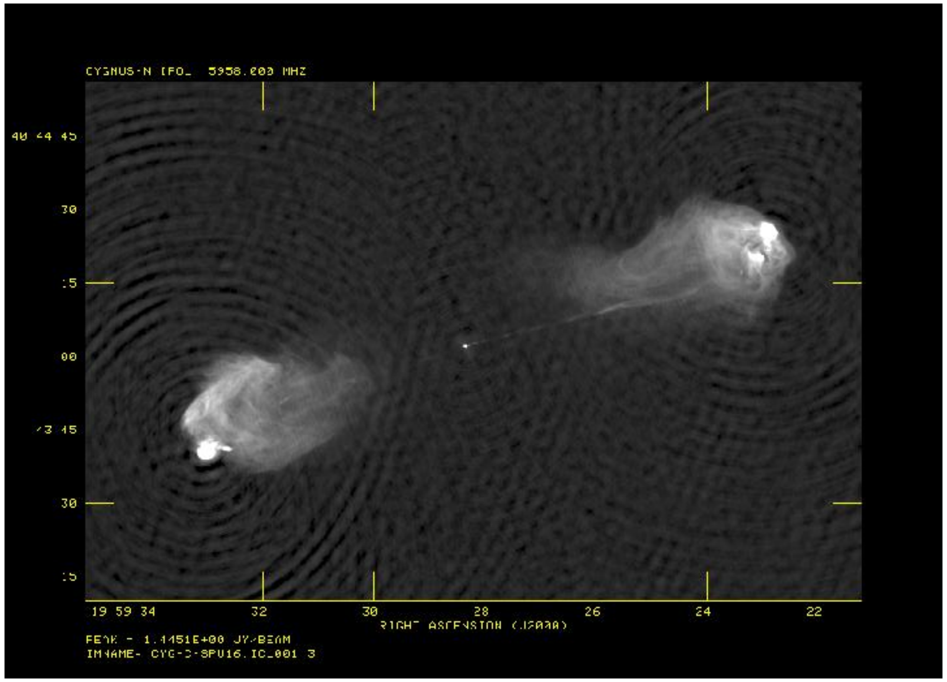
- Over the past year, Cygnus A has been intensively observed, from 2 through 18 GHz, all four configurations.
- Imaging now (slowly) underway.
- A remarkable trend was discovered at S-band.
- DR drops precipitously across the band (2 – 4 GHz).

	2052	2308	2564	2820	3052	3308	3564	3820	
Peak	16.0	12.4	9.31	7.11	8.12	6.44	5.30	4.49	Jy/b
Rms	0.46	0.45	0.39	0.33	0.48	0.47	0.42	0.40	mJy/b
`DR’	**34.5**	**27.4**	**23.9**	**21.7**	**16.2**	**13.8**	**12.8**	**11.3**	**x1000**

- The trend continues through C-band – DR at 6 GHz down to 2500!

It gets worse at C-band (4 – 8 GHz)

- This image (5948MHz) is actually significantly worse than our 1984 result!
- DR only about 4000:1.
- What has gotten worse since then?
- But … X-band (8 – 12 GHz) appears to be better …



So … What is the problem now?

- So why is imaging of large objects – especially those with sharp, bright structure at distance – no better than before?
- The error pattern clearly points to a non-random, slowly-varying origin with significant frequency dependence.
- A long list of potential suspects:
  1. DDE – atmospheric gradients
  2. Antenna pointing errors
  3. Antenna beam ellipticity
  4. Antenna beam squint
  5. Variation of amplitude/phase within the main beam.
  6. Cross-polarization leakage
  7. Non-coplanar baselines
  8. Regularly gridded brightness representation.

Atmospheric Phase Gradients

- Perhaps there's a significant phase screen across the array.
- Would certainly be more significant at higher frequencies.

- If this were the primary origin, the images in 'D' configuration should, overall, be much better than those in 'A'.
- No such dependency is observed.
  – In fact, it's more the other way around …
- Cygnus A is small (2 arcminutes, full width), and significant atmospheric/ionospheric gradients on that scale are not expected.

Non-Coplanar Baselines

- At the offset of the Cygnus A hotspots (1 arcmin), the phase error due to not accounting for this effect can be significant.
- Phase error proportional to: $\phi \sim \theta^2 \sin Z\, B / \lambda$
- For the 1 arcminute offset of the Cygnus A hotspots, we have

$$\phi \sim 0.12 B_{km} \upsilon_G \sin z \quad \text{degrees}$$

- The maximum error increases from 4 degrees at 2 GHz to 120 degrees at 45 GHz.
- But we know how to manage this problem, (W-Projection, Faceted Imaging).
- Doing this shows that (at least for the lowest three bands), this is not the origin of the poor imaging results.

Regularly Gridded Representation

- No secret that using regularly gridded Clean components for self-calibration will lead to errors in the solution.
  - E.g. Noise-free point source located between two grid cells needs an infinite number of 'clean components' to correctly describe its visibility.
- But the results of this error should not increase with frequency – as the edges become properly resolved, the errors must decrease.
- But the question remains – how important is this error for Cygnus-A type sources, and how do we best avoid it?

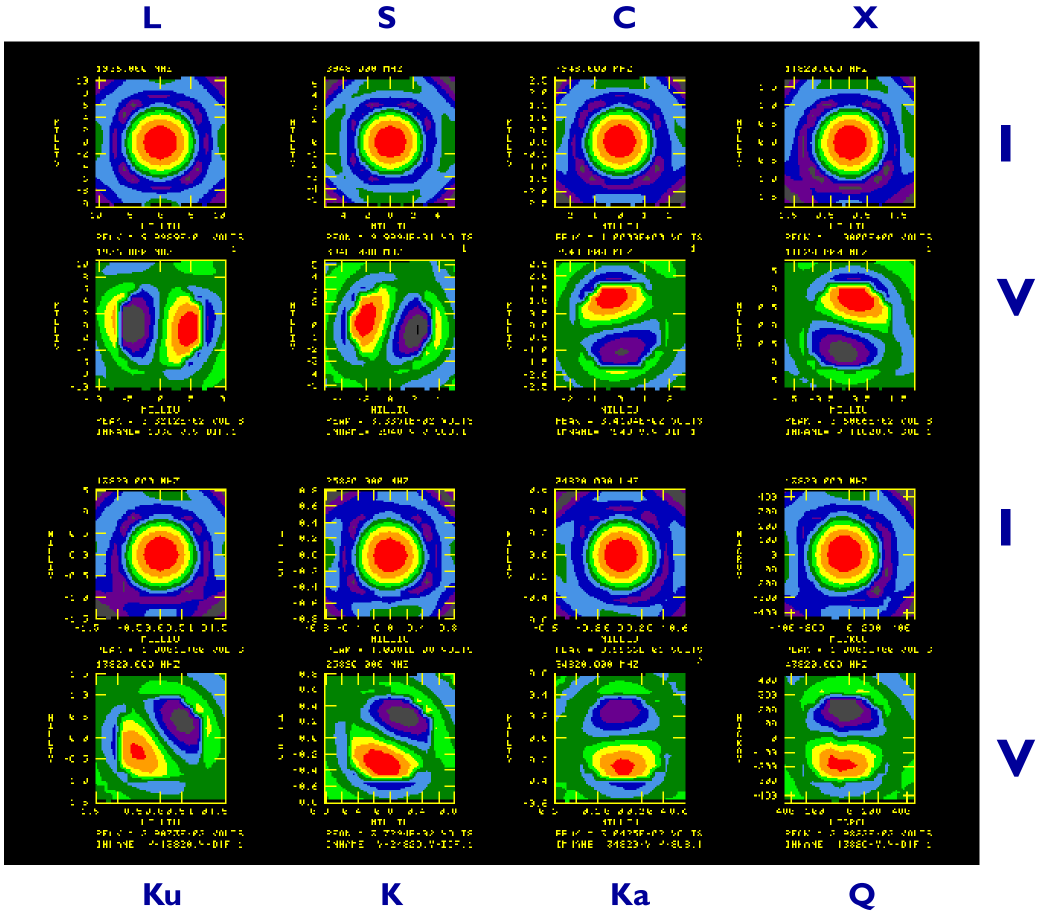
Antenna Beam Squint

- The VLA's off-axis feeds, and use of circular polarization, leads to a 'squint" – the LCP and RCP beams are separated on the sky.
- The beams (for all bands) are separated by 5.5% of the FWHM, with the axis of separation perpendicular to the position angle of the feed on the feed ring.
- But the effect on 'I', from averaging the R and L visibilities is very small – less than 0.4% in amplitude.
- Of course, the effect on 'V' is huge!

VLA Beam Squint -- Measurements

- The VLA's I and V beams, at each band.
- Arranged by frequency: left -> right,

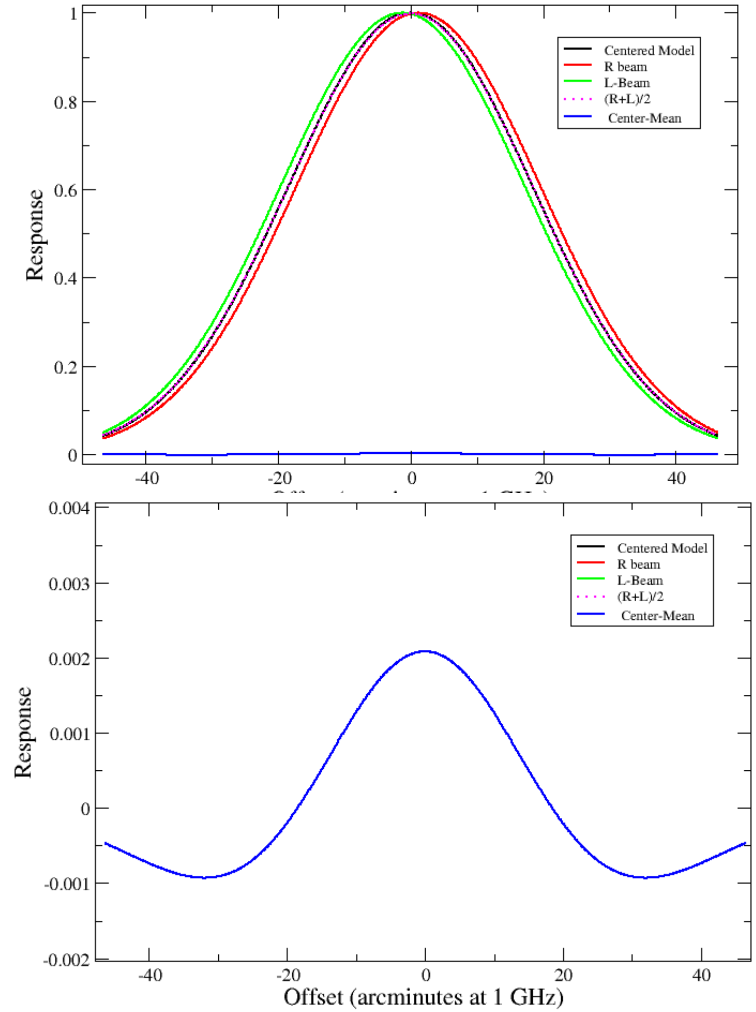
  top -> bottom.
- V>0 -> RCP
- V<0 -> LCP
- Line of separation is orthogonal to offset of Cassegrain feed.
- Separation is 5.5% of FWHM.



- Images arranged so these are the beams as seen from behind the antenna.
- V defined using IEEE/IAU definition(!)

Beam Squint – Not a problem for I imaging.

- The top panel shows a normalized model of the VLA's beam, with RCP and LCP beams separated by 5.5% of the FWHM.
- The bottom line is the difference (error) between the average of RCP and LCP, and the beam model.
- Maximum excursion is just 0.3%.



Antenna Ellipticity and Phase Variations

- VLA antenna beam measurements show the RCP and LCP beams are not perfectly circular.
  - Ellipticities of up to 5% are seen.
- Phase gradients within the RR and LL beams also present.
  - Deviations of up to 4 degrees (at FWHM) are observed.
- Due to focus and alignment errors in the horns and subreflector
- All antennas are different.
- In principle, we know the beam parameters in advance, and could correct via A-projection, or the equivalent.
- But for the small offsets of Cygnus A hotspots, I doubt these are responsible for the poor imaging.

Antenna Pointing Errors

- Pointing errors are typically 15 arcseconds. Some as large as 30 arcseconds!
- Unquestionably a major effect at high frequencies.
  - At 45 GHz, primary beam ~60 arcseconds FWHM.
- To control this, 'referenced pointing' developed
  - Use the local calibrator to determine/apply 'local' offsets.
- This works well (except when it doesn't …)
  - In good conditions, accuracies of 3 – 5 arcseconds achieved.
  - Cygnus A calibrator only 2 degrees away – ideal.
- But – in multiple-band observations, corrections normally made at one frequency, and applied to all.
  - Errors in band-dependent pointing offsets (collimation offsets) are retained.

Antenna Pointing Errors (cont)

- But I doubt this is our problem.
- Simple model – Gaussian beam, presume 10 and 30 arcsecond pointing errors.
- Fractional error in hotspot brightness at 1 arcminute offset.

Band	10”	30”
S (3GHz)	0.1%	0.4%
C (6 GHz)	0.3%	1.5%
X (10 GHz)	0.9%	5.1%
Ku (15 GHz)	1.6%	8.7%

Cross-Polarization

- AIPS images (also CASA?) for Stokes 'I' are not corrected at all for cross-polarization leakage.
- Although 2nd order, this can be large when the polarizers are poor, and the source structure is highly linearly polarized.

$$V_{r1r2} = I(1 + D_{lr1} D^*_{lr2}) + Q(D_{lr1} e^{i2\Psi_p} + D^*_{lr2} e^{-i2\Psi_p}) - iU(D_{lr1} e^{i2\Psi_p} - D^*_{lr2} e^{-i2\Psi_p})$$

$$V_{l1l2} = I(1 + D_{rl1} D^*_{rl2}) + Q(D_{rl1} e^{-i2\Psi_p} + D^*_{rl2} e^{i2\Psi_p}) + iU(D_{rl1} e^{-i2\Psi_p} - D^*_{rl2} e^{i2\Psi_p})$$

- Note: I, Q, U are *Visibilities*, not brightnesses.
- It is not necessarily true that |Q|, |U| << |I| (!!!!!)
- D.D* terms constant in time ('closure error'), Q.D terms slowly variable.

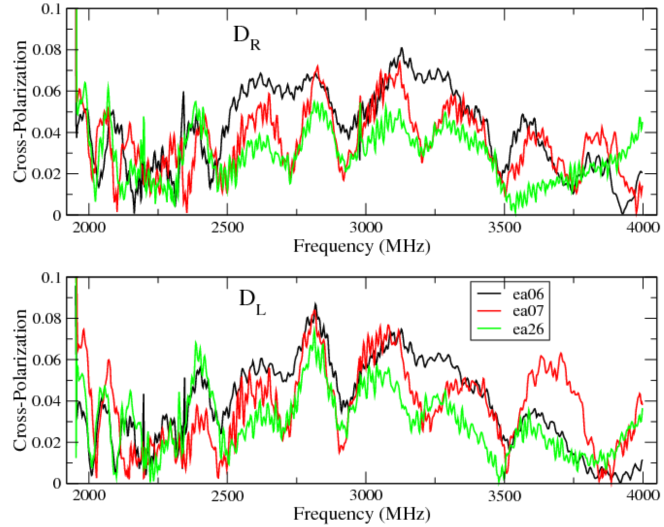
VLA's Polarizers are not very good …

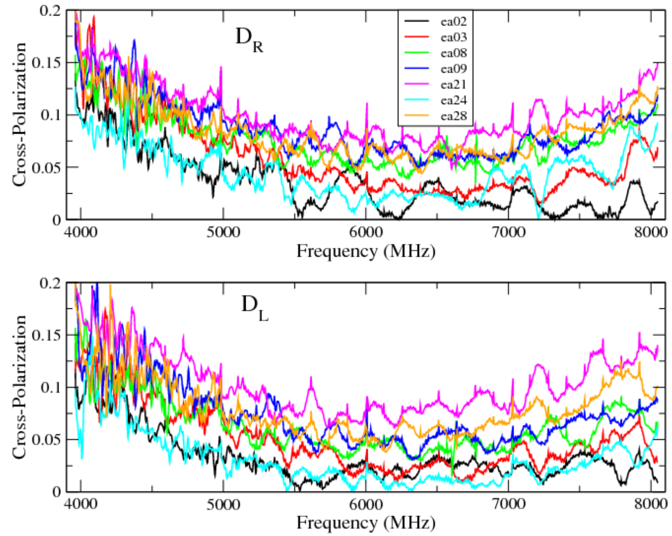
- Use of circular polarization greatly eases basic (parallel-hand) gain calibration.
- But a cost of wide-band receivers is that the conversion from the native linearly polarized feeds to circular results in relatively high cross polarization.
- In other words, the VLA's native polarization is significantly elliptical.

- How bad are they?

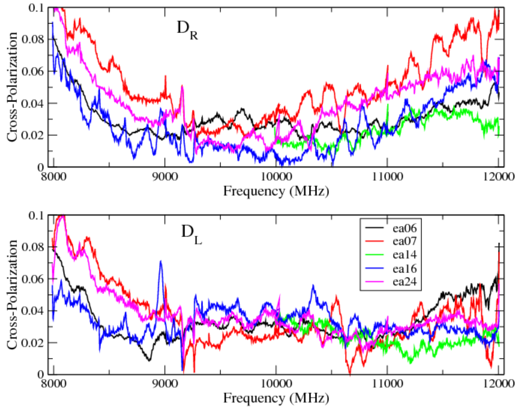
How bad are the JVLA's polarizers?

- Not as good as we would like …
- Typical polarizations are 5%, but reaches 15% or more for some antennas as C-band.
- Hotspot polarization visibilities can easily exceed 30% of I visibilities.
- Will increase with frequency as the RM gradients resolve out.
- Is this the origin of our troubles?





If so – we should do much better at X-band:



Cross-Polarization (cont.)

- Obvious solution: Apply the polarization leakage parameters to the parallel-hand data!
- A complication:
  - Can we get away with the easy-to-determine 'relative' D-term solutions?
  - Or must we utilize the hard-to-determine 'absolute' D-terms?

Cross-Polarization – what to do?

- 5 --15% cross-pol, and 30% source polarization is possible.
- This means a 2 -- 5% contribution to Stokes 'I' – which is slowly time variable (function of parallactic angle).
- Answer is elementary: Determine the true cross-polarizations, and apply the full Polarization Mixing matrix to correct the visibilities.
- Easy to say, harder to do:
  - Determining 'relative' D-terms is easy.
  - Determining 'true' D-terms is much harder.
    - Except for ASKAP (3rd-axis rotation is brilliant!)
  - Real antennas have spatially (and likely time) variant cross-polarizations.

Summary

- Fidelity in our imaging limited by a 'host' of effects.
- The major ones are known and largely controlled.
- These work well for small, compact objects.
- Fidelity in imaging extended objects has not improved.
- There are many possible origins.
- It is likely that all are involved, but in different combinations for different bands and different sources.
  - Pointing effects clearly important at high frequencies.
  - DD gains, beam variability important at high freq.
  - Cross-polarization at all bands.
- Realistic simulations will be very useful.
- Much work lies ahead to understand/control these.