High Dynamic Range Imaging

EVLA

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Expanded Very Large Array
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Very Long Baseline Array

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Dynamic Range vs. Image Fidelity

- Dynamic Range on an image is usually defined as:

  DR = Peak/Noise

- This makes sense for a field comprising unresolved objects.
- DR is an excellent diagnostic of instrumental performance and calibration methodology.

- For complicated extended objects, we think of the 'Fidelity' – which is (with apologies to Stephen Colbert) the 'Truthiness' of an image.
- In addition to calibration issues, Image Fidelity can be limited by:
  - Gaps in the spatial frequency ('u-v') coverage
  - Errors or insufficiency in the deconvolution/selfcalibration proces
- These are important, but separate, questions.

Why Bother with 'Macho Imaging'?

- Are efforts to get > 10^6 fidelity a waste of time?
- For the VLA, most observing fields (especially at high frequency) are completely noise limited.
  - For example – at L-band with the VLA, a typical field has ~50 mJy/beam maximum background source brightness.
  - With a (deep) noise of 1 μJy/beam, only need > 50,000:1 DR. Easy!
  - Only ~ 2% of the sky is within a VLA beam of the 1000 strongest sources.
- But imagine a `VLA on steroids' (SKA?) with 10 nJy/beam sensitivity
  - Then a DR > 5×10^6 needed – even for an 'average' field.
- This issue is greatly exacerbated by smaller dishes.
- So my best answer to the question posed is:
  - **Instrumental:** Understanding the telescope in depth. Subtle problems can bite you. Instruments impose signatures on the data.
  - **Calibration Methodology:** Needed to implement understanding of the instrument, in order to reach the limits of performance.

A Simple Scalar Model (for starters)

- For simplicity, we pretend the sky emission has a single 'scalar' polarization.
- A very general formalism connecting the observed visibilities V_{ij} to the true visibilities S_{ij}

$$V_{ij} = G_i G_j^* (1 + C_{ij}) S_{ij} + O_{ij} + n_{ij}$$

- The baseline-based gain is separated into an antenna-based factor, G_i, and a baseline-based factor, C_{ij}, commonly called a 'closure error'.
- We allow for an additive baseline component O_{ij}, and random noise n_{ij}.

Signatures of Additive Errors

- An additive error simply means a constant complex value is added to the correlation.
- Easy to see the effect
  - The (2-d transform of the) error is added to the image.
  - Error is independent of source strength
  - If only one baseline, a Bessel-like function will be seen (it makes a 'bulls-eye' pattern, with circular rings, suggesting an explosion)
- Additive errors will be most easily detected when doing deep integrations on blank fields.
- No offset-style errors have yet been found in Jansky VLA data.
  - But the best test would be a deep integration at the NCP.

Multiplicative Errors

- These produce a signal proportional to the strength of the visibility.
- Most easily seen on strong sources, particularly for point-sources, since all baselines contribute about equally.
- VLA's old correlator had significant multiplicative errors when the 'continuum mode' was utilized.
- So far as we can tell, the new WIDAR correlator is nearly perfect.
- But as there are many other possible origins of this error (if indeed it is an error …), we press on …

Deep Integrations on 3C147 at L-band

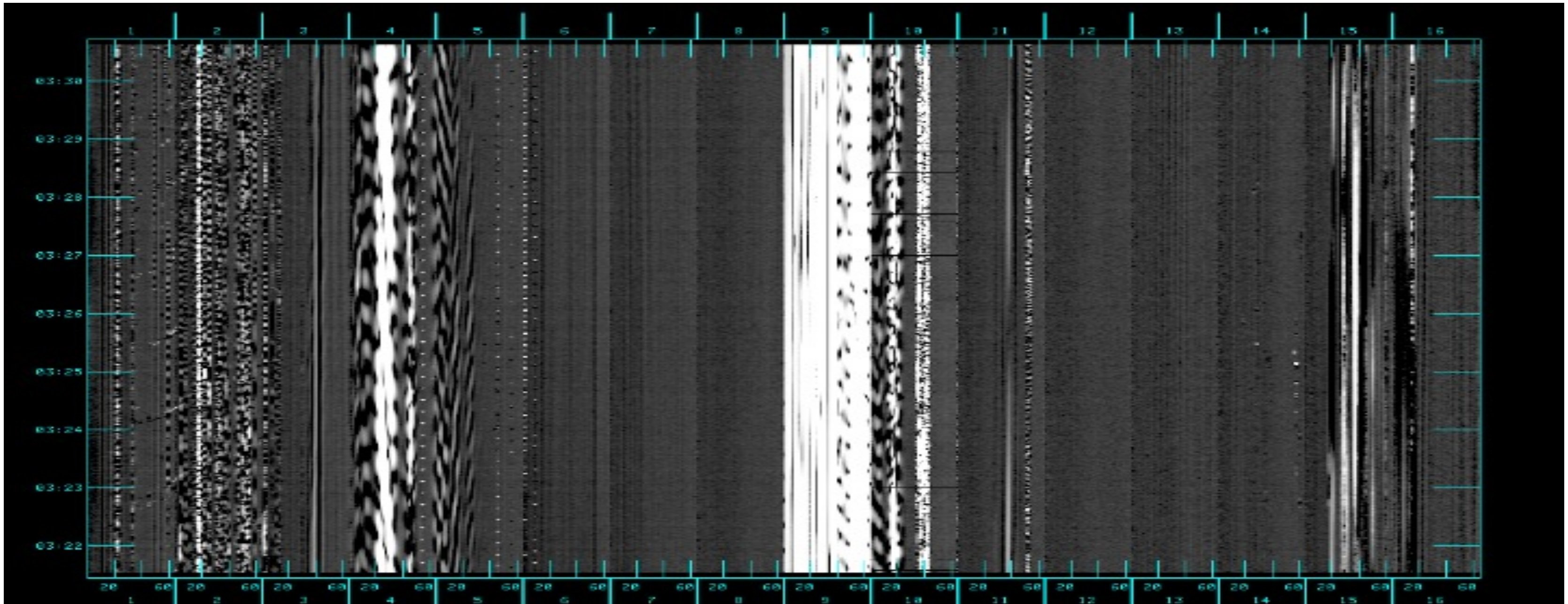
- To explore calibration effects on imaging, we observed 3C147 with the VLA at L-band, in the full-bandwidth mode (BW = 1024 MHz)
- 3C147 (J0542+4951) is very strong (22 Jy), quite compact (~ 700 mas), and almost completely unpolarized.
- Two observing sessions:
  - D-configuration (45" resolution): 6 hours.
  - C-configuration (15" resolution): 8 hours.
- Time resolution was 1 second, spectral resolution 1 MHz. Full polarization – a total of 1024 channels/polarization/baseline.
- In addition, short observations of 3C48, 3C138, 3C286, and 3C196.
- A nearby 'dot' calibrator, J0555+3948, was observed for calibration purposes once every ~10 minutes.

Calibration Basics

- These data were edited for the usual obvious problems, and calibrated on the new 'PB' flux density scale.
- All sources, (except 3C196) are unresolved, so basic editing and calibration are very straightforward.
- Note that 3C147 is unusual in that the total background flux within the primary beam is considerably less than usual – less than 1% of the total flux is from the background objects.
- RFI at L-band is definitely an issue (see next slide).
- For this work, we utilized the two nearly RFI-free 'chunks' shown on the next slide. Each is 196 MHz wide.
- Basic dataset will be made publicly available for all to try their hand at …

RFI Spectrum from 30-meter Baseline

1000 MHz 1510 2024

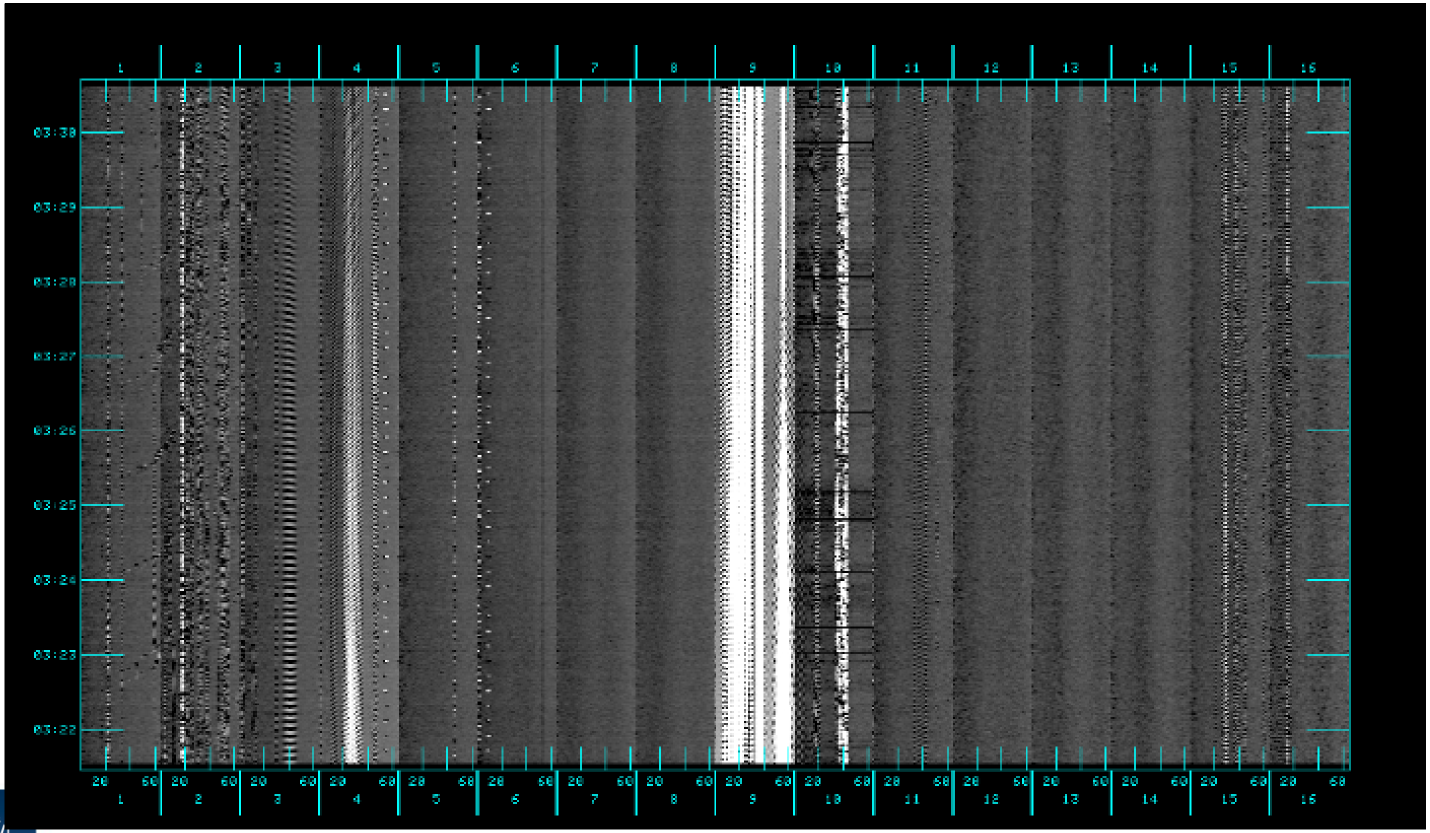


Aircraft (DME) GPS LO Inmarsat, GPS Glonass HI Cellphones

- 1 second, 1 MHz resolution.
- 30 meter baseline (the shortest!)
- 16 spectral windows, each 64 MHz wide.

Another RFI spectrum – 1 Km baseline

- This one is from a 1 Km baseline (1 second, 1 MHz)
- Strong baseline effect – for 10 or more Km, RFI effects nearly eliminated.



Stepping through Calibration …

- We now present a series of images of 3C147, using a single 1 MHz channel, at 1500 MHz, using the D configuration data.
- These illustrate the effects of various stages of calibration.

No Calibration!

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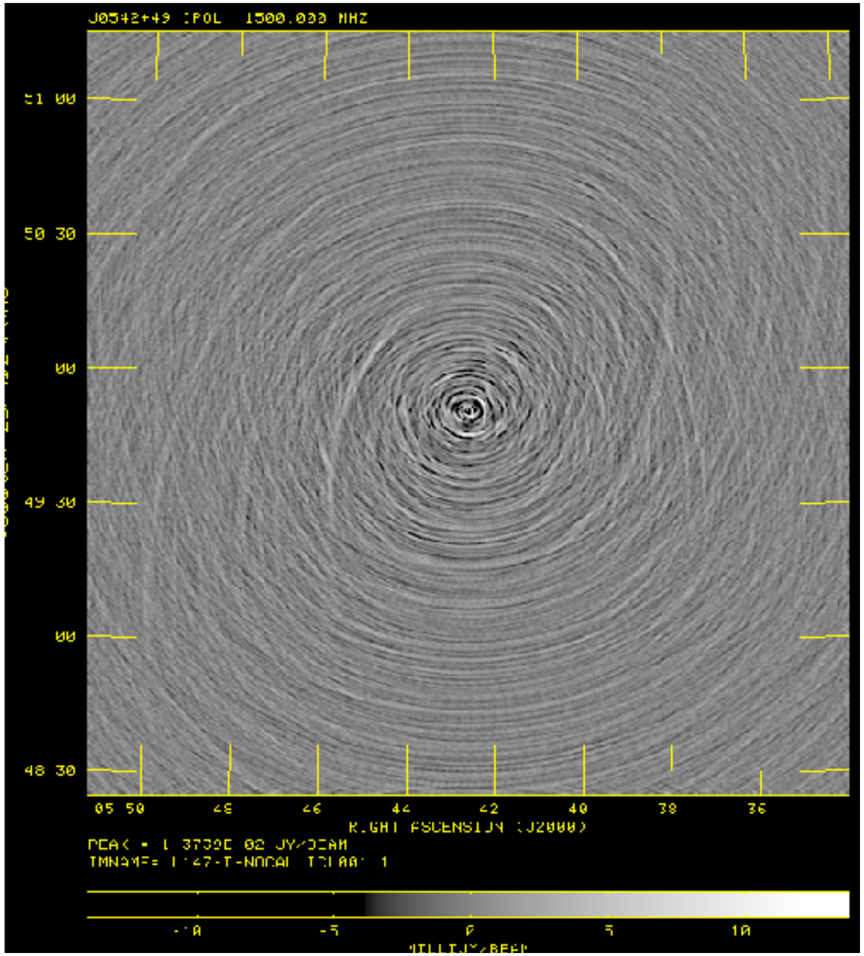
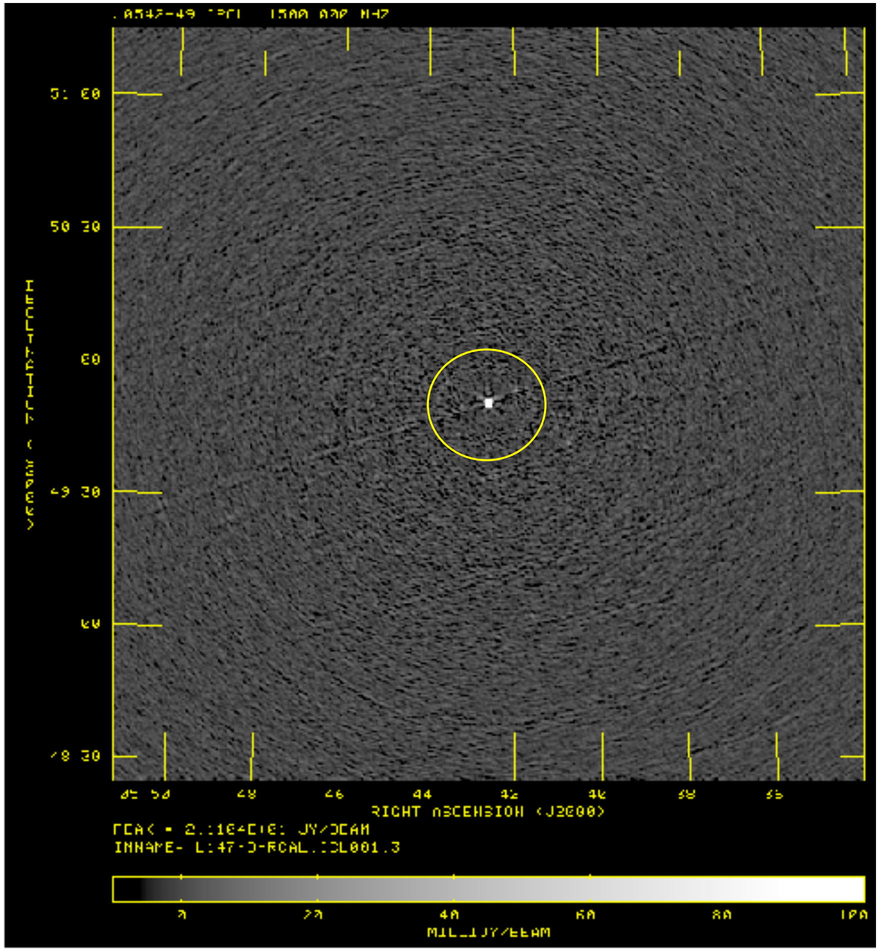
- Suppose we don't calibrate at all …
- D-configuration – peak = .014 Jy, rms = 1.2 mJy/beam. DR ~ 12.
- This is not a random noise image because the (incorrect) amplitudes and phases for each baseline are quite constant over time.
- Each baseline contributes a rough Bessel-function, centered at the origin.



No Calibration: DR ~12

Regular Calibration

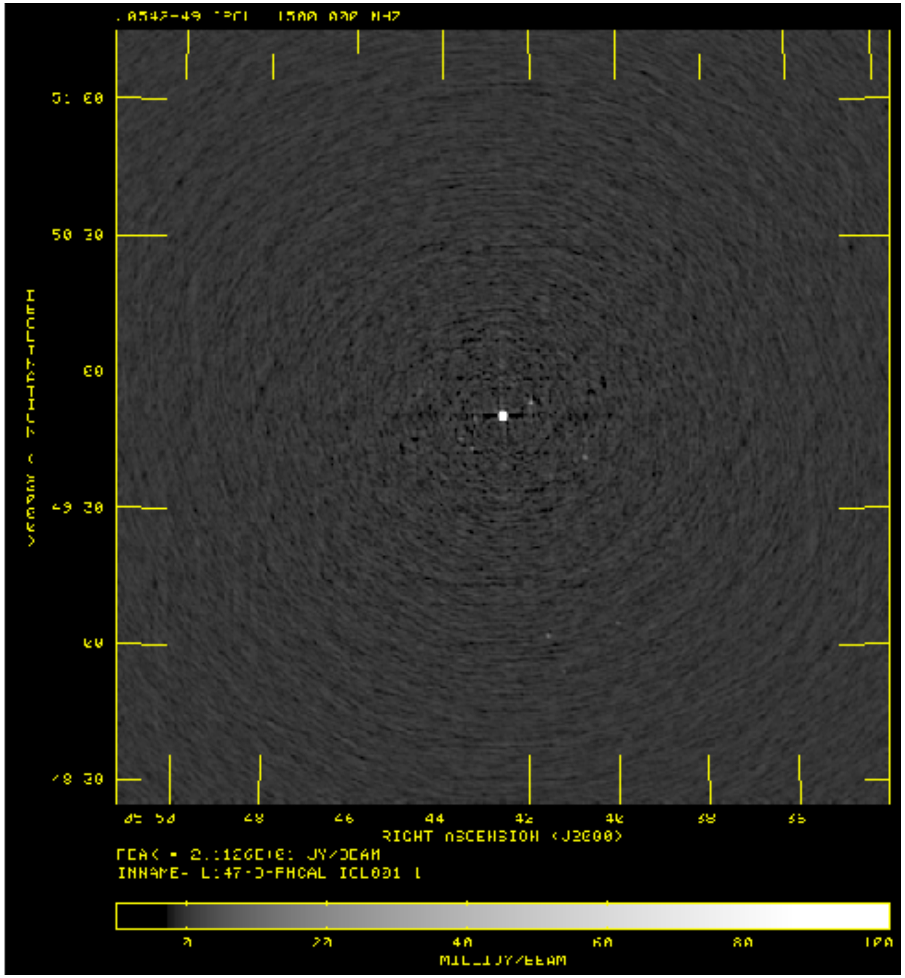
- Now we calibrate using the nearby point source.
- A nice image – but the background sources are barely visible.
- Pk – 21.07 Jy/beam
- Rms – 4.2 mJy/beam
- DR ~ 5000
- This is typical for a ‘regular calibration’ regimen.



Regular Calibration: DR ~5000

Phase Self-Calibration

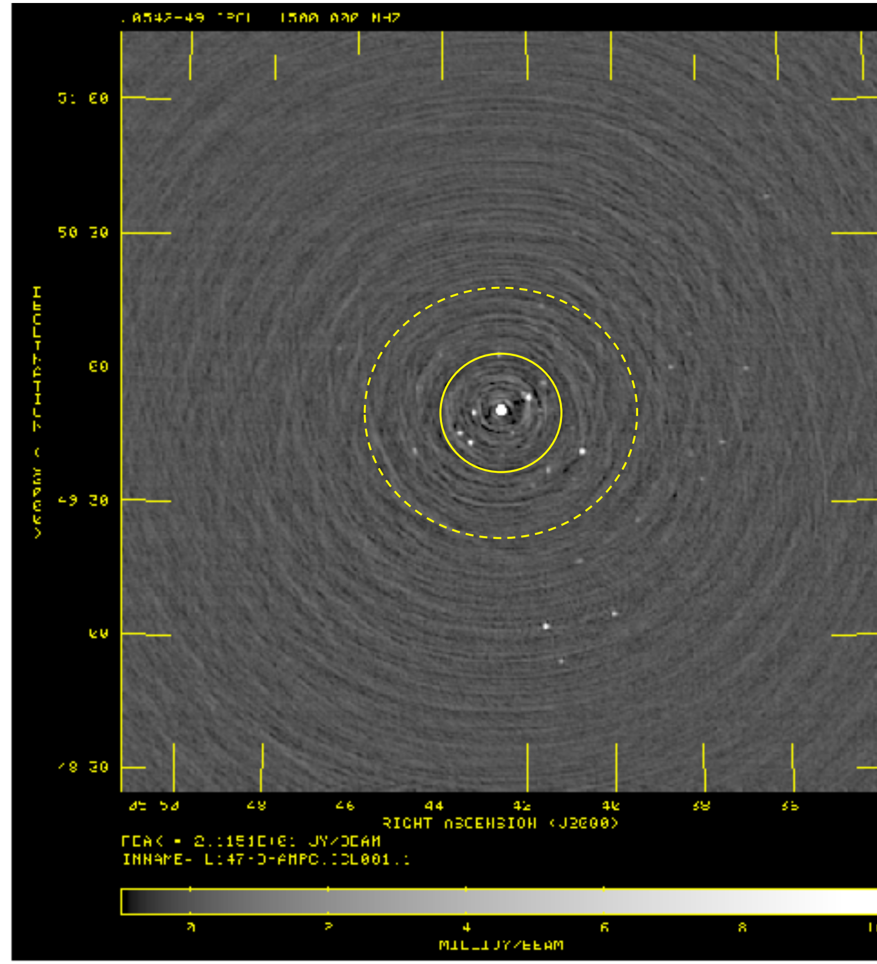
- The technique of self-calibration is well-suited to the VLA.
- 3C147 so dominates the field that a simple point-source model is sufficient.
- Solutions made every second.
- Image much better – but still far from what we aim for.
- Pk = 21.13 Jy/beam
- Rms = 0.7 mJy/beam
- DR = 30,000



Phase Self-Calibration: DR ~30000

Amplitude Self-Calibration

- Normally, amplitude self-calibration results in only small improvements –
- But at L-band, phase stability is quite good, approximately as stable as the amplitudes.
- Amplitude self-calibration again triples the DR:
- Pk = 21.15 Jy/beam
- Rms = 0.31 Jy/beam
- DR = 68,000
- More self-calibration loops, using this model, do not improve the image!



Amp and Phase Self-Calibration: DR ~68000

Baseline-based calibration

- The image is far from sensitivity limited – the rms expected is about 0.09 mJy/beam – we're short by a factor of at about 4.
- The 'swirly' pattern provides a strong clue of what the problem is – this looks like the pattern in the uncalibrated image.
- Such patterns occur when an error is specific to a baseline, and is constant over time.
- Postulate a small 'closure' error, specific to each baseline, unchanging in time.
- AIPS provides a nice baseline-based calibration task: BLCAL
- Give it a try – using the best image so far, and solving for a single time-invariant multiplicative baseline-dependent solution.

Baseline-Based Calibration

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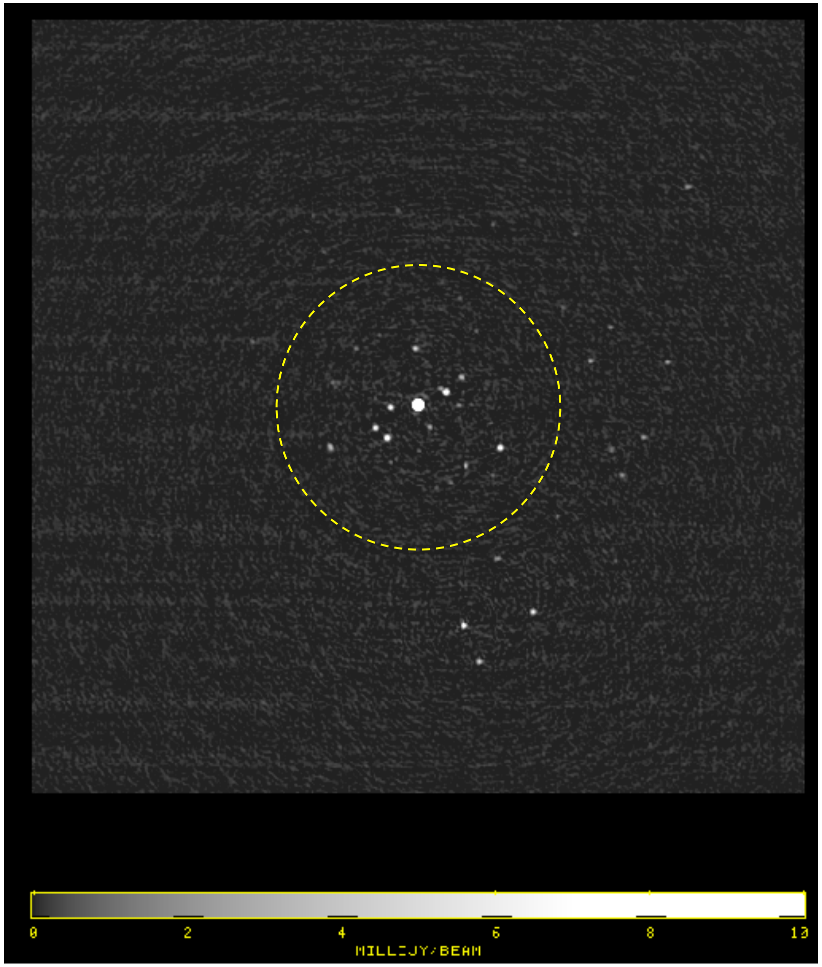
- Doing this makes a big improvement:
- Pk = 21.15 Jy/beam
- Rms .09 mJy/beam
- DR = 230,000
- This image is close to noise limited everywhere.
- So this really works!
- And if we have ~200 channels, we might expect to reach a DR of about 3,000,000.
- Can we?



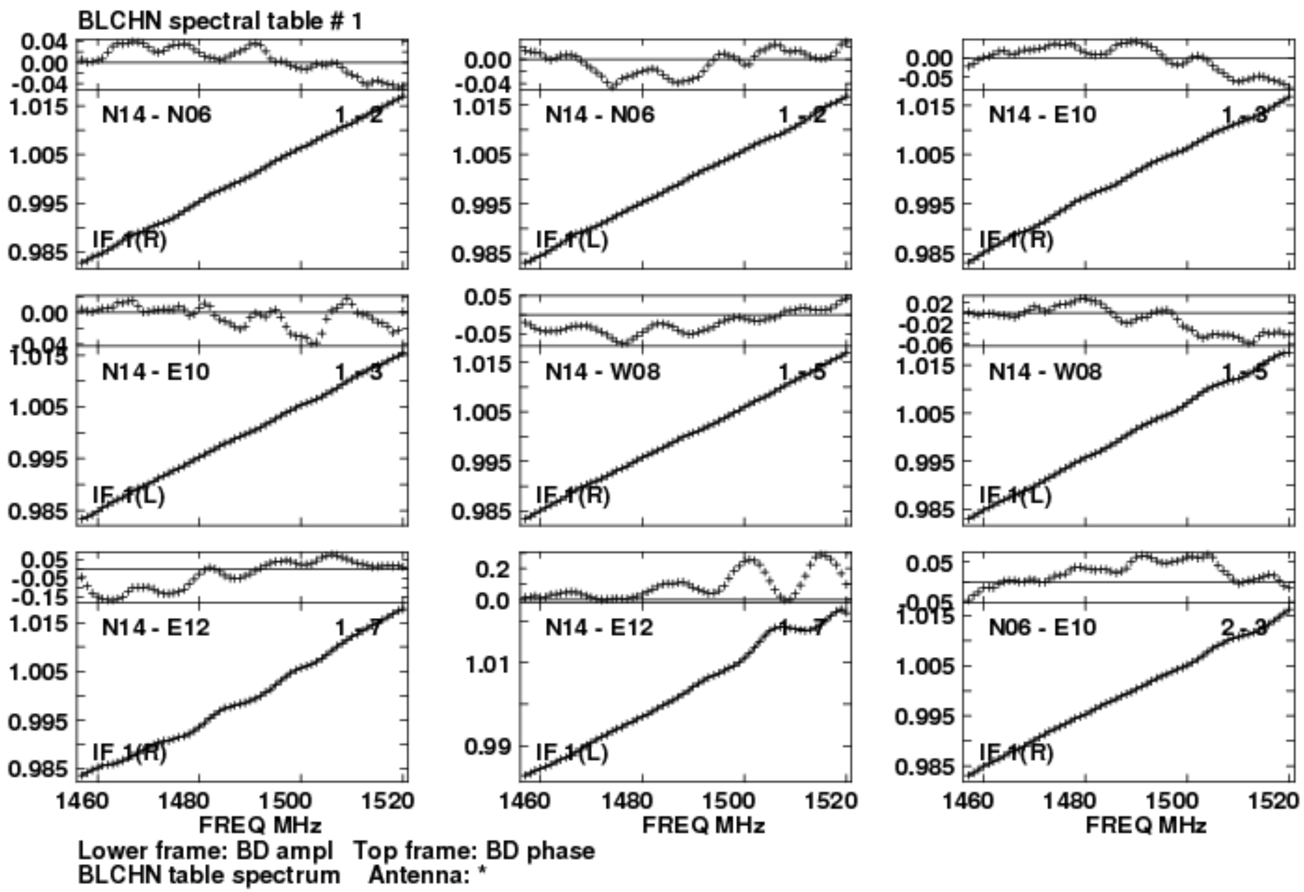
Closure Calibration: DR ~230000

How large are these errors?

Shown here are the closure solutions, over a 64 MHz-wide subband, for nine baselines. Each shows the phase (top) and amplitude (bottom).

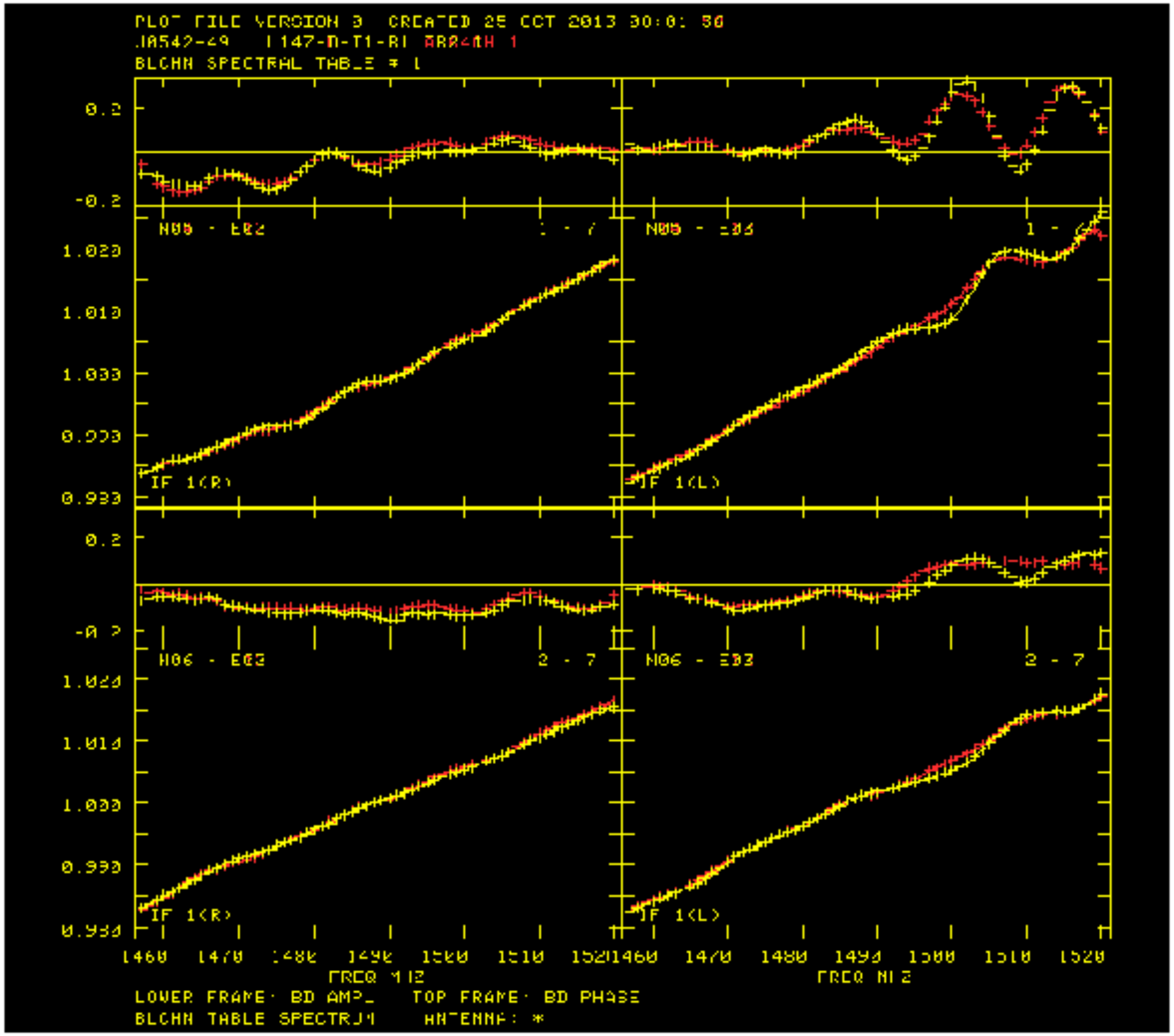
- The amplitude solutions mostly show the spectral index gradient.

  (Software fix needed – will be done).
- Typical errors are ~.05 degrees -- .001 radian, and .001 in amplitude.
- What might be the origin?



Errors are Stable over Months!

- Shown here are the errors for the C (red) and D (yellow) configurations
- Data taken 8 months apart
- These errors are very stable
- Another clue as to their origin.



Possible Origins of these Errors

There are many possibilities. Here are a few:

1. Uncorrected delay errors, when data have been subsequently averaged over frequency.
   - Not here. The delays were corrected for each individual record.
2. Uncorrected temporal phase changes, when data have been subsequently averaged over time.
   - Not a change. Phase corrected for each 1 second record.
3. Unrecognized (undersampled) structure in the field or the source.
   - 3C147 is a (nearly) perfect point source.
4. Faults in the correlator.
   - Cannot rule out – but no evidence to favor.
5. Polarization leakage (cross-coupling)
   - A possibility – see next slide.

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Antenna Cross-Polarization

- The VLA's L-band polarizers are pretty good, but not perfect.
- Imperfect polarizers bleed a little RCP into LCP, and vice versa.

- Can show, for properly calibrated data, that the RR correlator response is

$$R_{r1r2} = I(1 + D_{r1}D^{*}_{r2}) + V(1 - D_{r1}D^{*}_{r2}) + Q(e^{2i\Psi}D_{r1} + e^{-2i\Psi}D^{*}_{r2}) - iU(e^{2i\Psi}D_{r1} - e^{-2i\Psi}D^{*}_{r2})$$

where 'D' is the off-diagonal Jones' matrix element – the instrumental cross-polarization.

- For an unpolarized source, V = Q = U = 0, and things looks easier:

$$R_{r1r2} = I(1 + D_{r1}D^{*}_{r2})$$

- For a decent polarizer, |D|~0.03. We'll see a ~0.1% offset in R – which is different for every baseline, is proportional to I, and should be constant in time.

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Not all 'D's are the same …

- The 'D' terms solved by the standard 'AIPS' and 'CASA' polarization solvers are not these.
- These programs solve for 'relative' D-terms – they are referenced to an arbitrary standard ($D_{r1} = 0$).
- These solvers utilize only the 1st order expansion of the cross-polarization result: (for an unpolarized source)

$$R_{L1R2} = (D_{L1} + D^*_{R2})I$$

- This referencing of the cross-polarization to an arbitrary value is sufficient for 99% of VLA polarimetry (so little pressure to change).
- But we want to do better …

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How to Get those 'Real Ds'

I know of three 'easy' ways to specifically target and find the real D terms. (See memos by Perley and Sault in EVLA Memo Series for details)

1) **The 'Antenna Rotation Trick'**: Observe an unpolarized source twice:

a) With all antennas in normal orientation. $$R_{r1l2} = I(D_{r1} + D^*_{l2})$$

b) With one antenna rotated by 90 degrees. $$R_{r1l2} = I(D_{r1} - D^*_{l2})$$

The true Ds are found by sums and differences of the cross-hand visibilities.

2) **Observe a Strong Linearly Polarized Source:** Presuming V = 0, the parallel hand visibilities contain a small signature of the true D terms:

$$R_{r1r2} = I(1 + D_{r1}D^*_{r2}) + e^{2i\Psi} D_{r1}(Q - iU) + e^{-2i\Psi} D^*_{r2}(Q + iU)$$

If the polarization is known, and the source observed over a large range in parallactic angle, the Ds can be recovered.

3) **Observe a Strong Unpolarized Source:** Then the parallel hand visibilities are:

$$R_{r1r2} = I(1 - D_{r1}D^*_{r2})$$

so the D terms can be solved for from the 'closure' terms ($1-D_{r1}D_{r2}^*$)

Full Jones Matrix Calibration

- A general approach is to calibrate with a full 'Jones matrix' formalism, applicable with a full knowledge of the calibrators Stokes.
- Generalization of the last two mentioned before.
- Unknown is how many sources, how long, accuracy, etc…
- So these data were sent to Oleg, to be processed in his MeqTrees formalism.
- But before we show the glorious results, we must point out a few more things …

Going Deeper adds Additional Problems

- Utilizing other channels means wide-band imaging. Doing this at low frequencies means wide-field imaging. We must include:
- **Variable primary beams. This includes:**
  - Beam profiles scale with wavelength.
  - Beam is not circularly symmetric – esp. beyond the half power.
  - Beam pointing is not stable – antennas 'wobble' as they track.
  - Beam polarization (Q,U,V) does not scale with I beam.
- **Spectral index effects.**
  - Source spectra not flat – imaging needs to know (or solve) for this.
  - All sources have their own spectra.
  - Primary beam attenuation enhances this effect.
- **Calibrator sources are not perfect 'dots'.**
  - Need model with much higher resolution than your data.
- **Non-coplanar baselines.**
  - A geometric effect, well understood.

It's (Nearly) All In MeqTrees

Oleg's MeqTrees calibration formalism contains all of this:

1. On-axis (DI) gains, for the primary calibrator(s).
2. Off-axis (DD) gains, for specified objects not on the beam axis.
3. Jones matrix formalism, to handle antenna cross-polarization.

What it (currently) doesn't know about are:

1. Knowledge of the VLA's I, Q, U, or V beam responses.
2. Knowledge of the sources' spectral indices.

(Both of these will then come out as strongly channel-dependent gain variations).

Oleg's Process

1. Use initial full-polarization (I,Q,U,V) model of 3C147 from Ger (VLBI origin) to calibrate G Jones-matrix gains.
2. Remove 3C147, make residual image and deconvolve. Find next ~60 components.
3. Do DD-calibration (6 – 10 directions) together with G recalibration. Make new residual image, deconvolve, find next ~300 components, add to model.
4. Repeat #3 one more time (improving G and DD solutions), subtract entire accumulated sky model, make residual image, deconvolve
5. Restore sky model into residual image.

- Note: Nowhere in the process so far is there any input information on the beamshape in any Stokes parameter.

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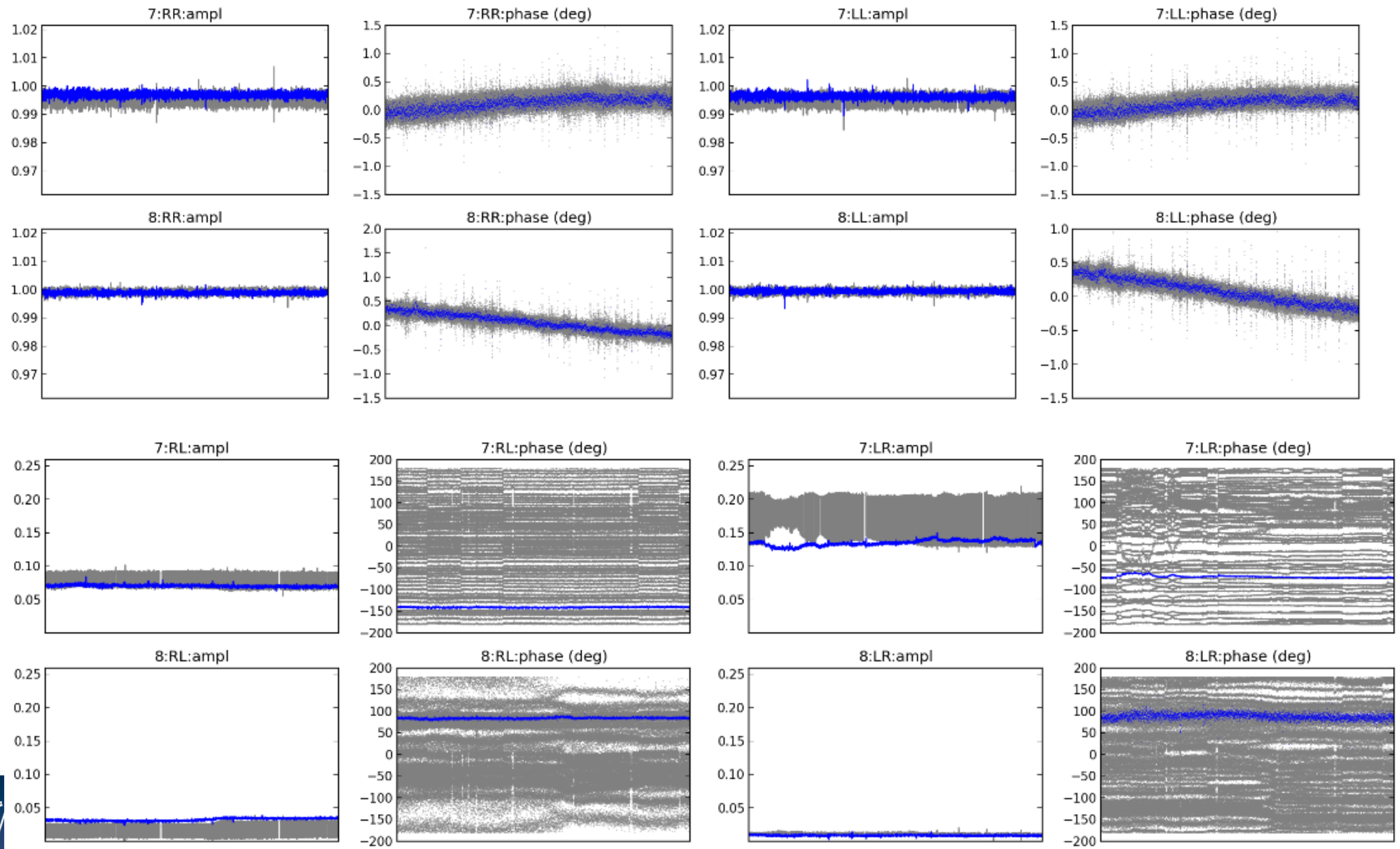
The Gain Solutions make Physical Sense

- Gjones gains are as expected.



dD Gains show expected variations

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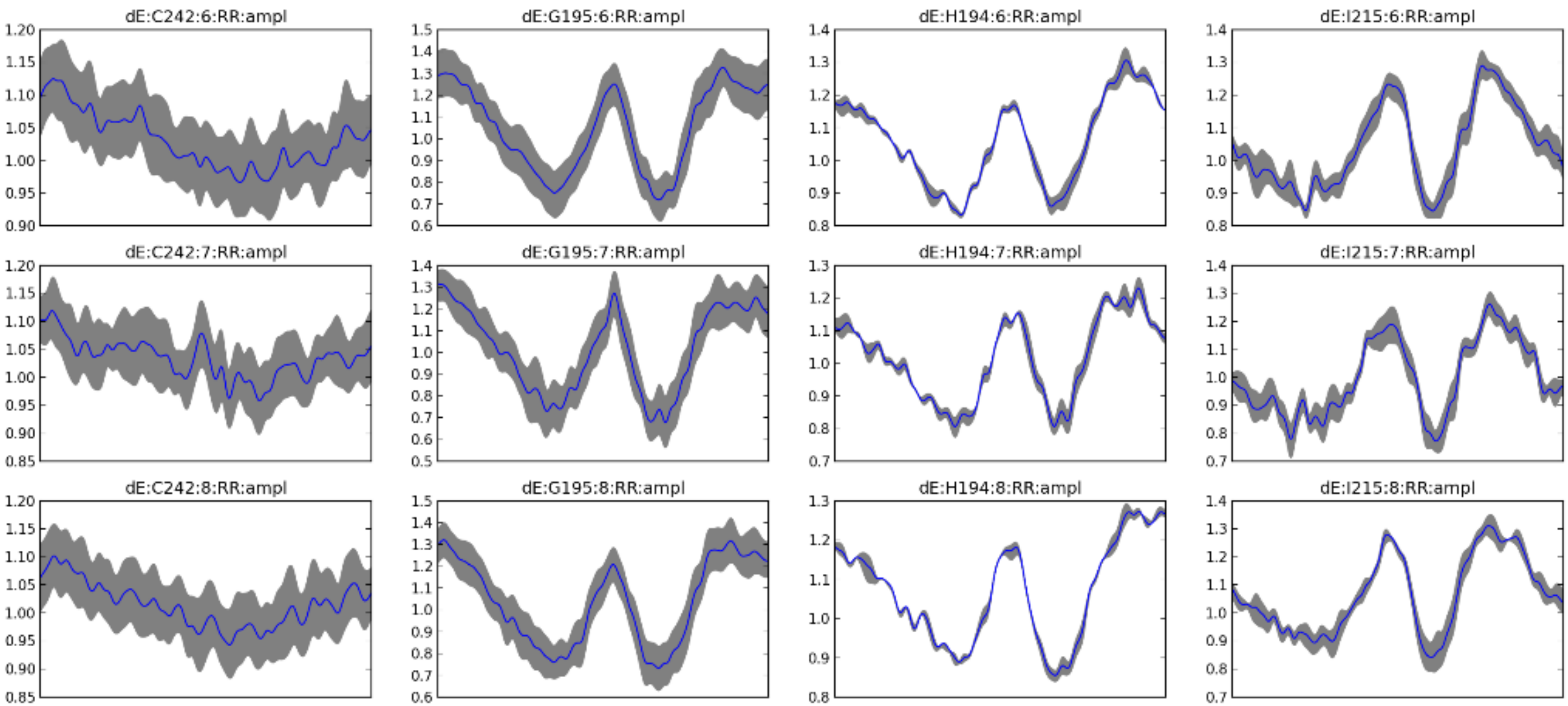

Rick's Best – No DD gains, 64 MHz BW

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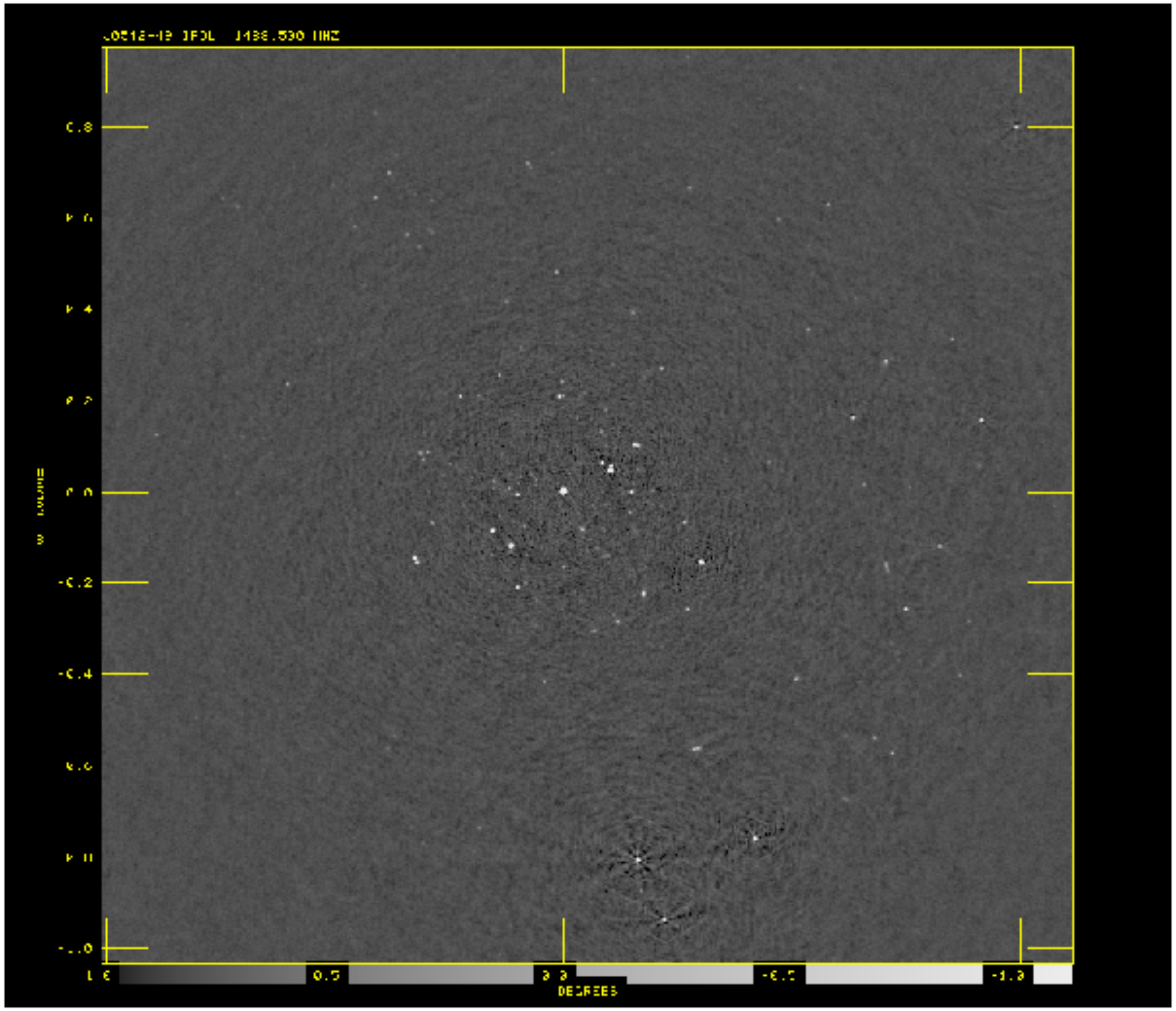
- C+D config data
- 3C147 spectrum flattened.
- BW = 64 MHz
- Rms = 26 μJy/b
- Rms in corners: 12 μJy/beam
- DR = 1.76 million
- Note the disturbances at the bottom – in the first sidelobe.



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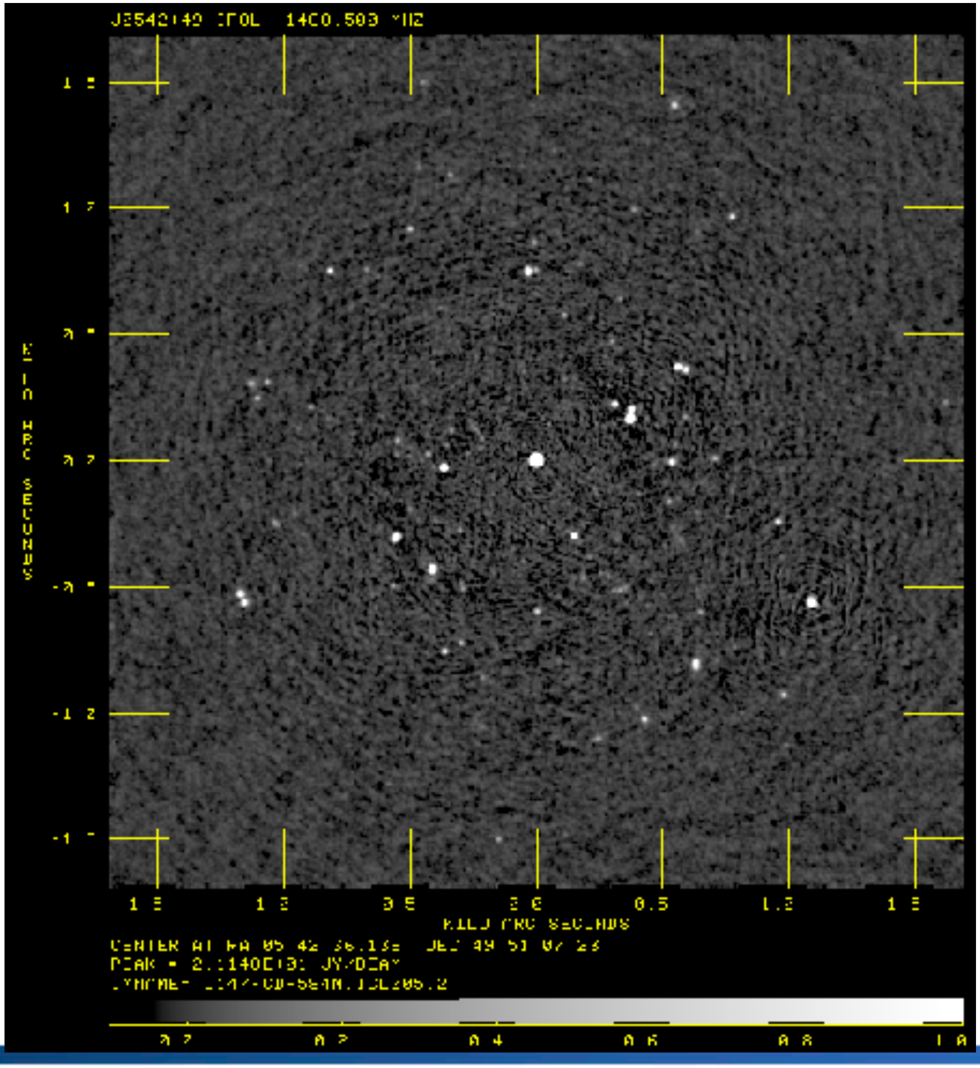
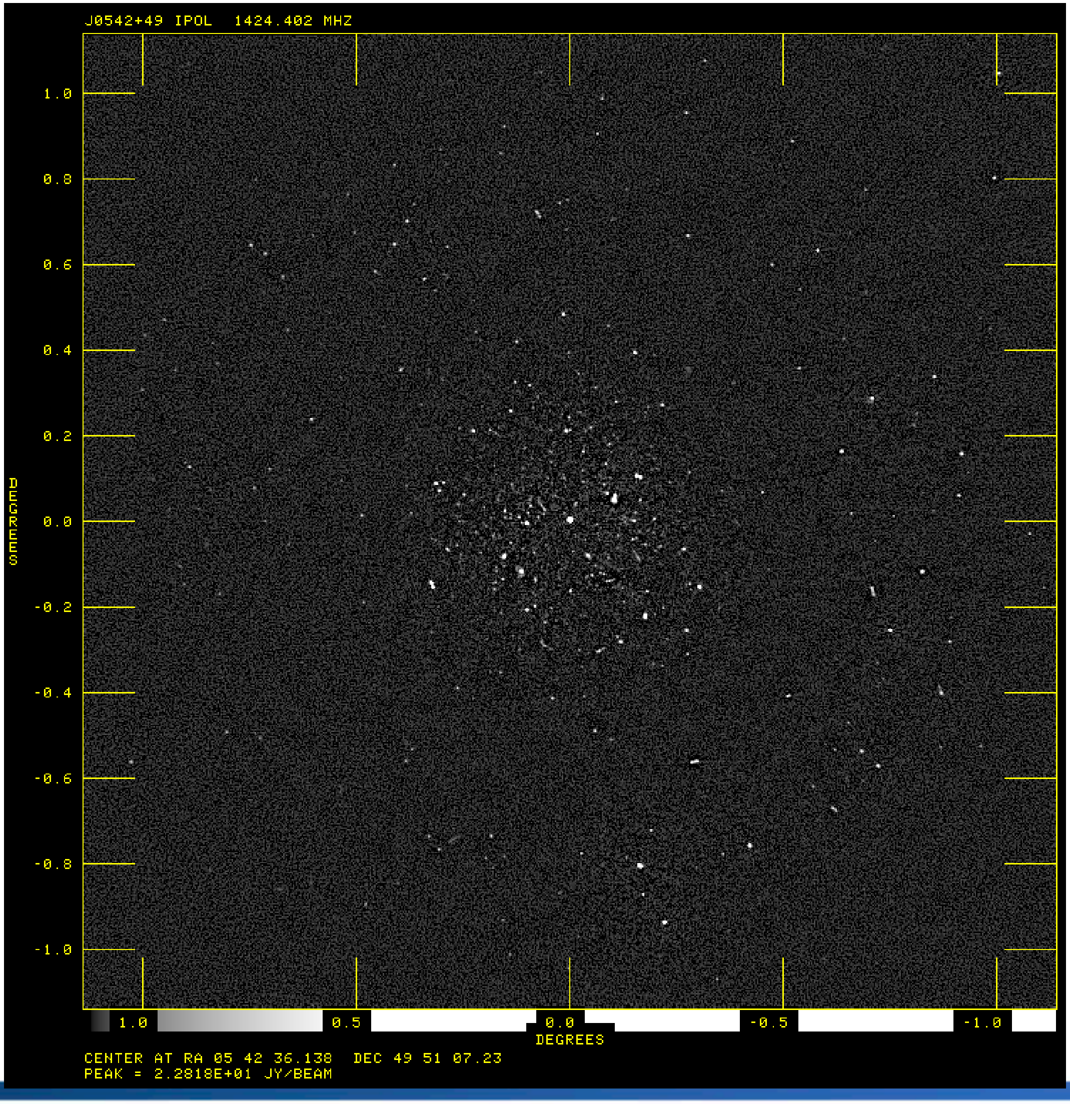
Rick's best – main beam:



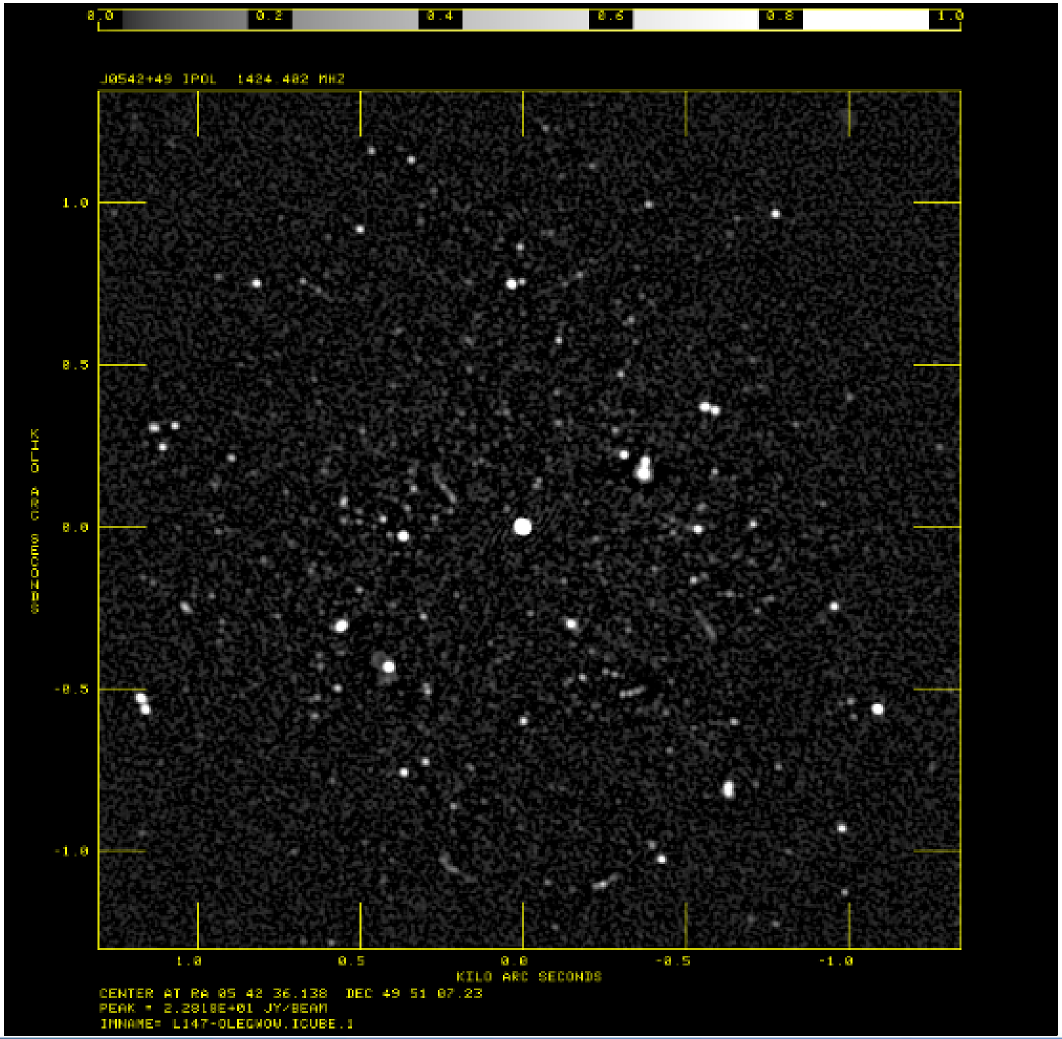
Oleg's Best – three subbands

- Rms in center: <10 μJy/beam
- Rms at edge: 7 μJy/b
- DR: 3.2e6
- Easy seen – the background sources in the first main-beam sidelobe.
- Even some sources in the 2nd sidelobe.

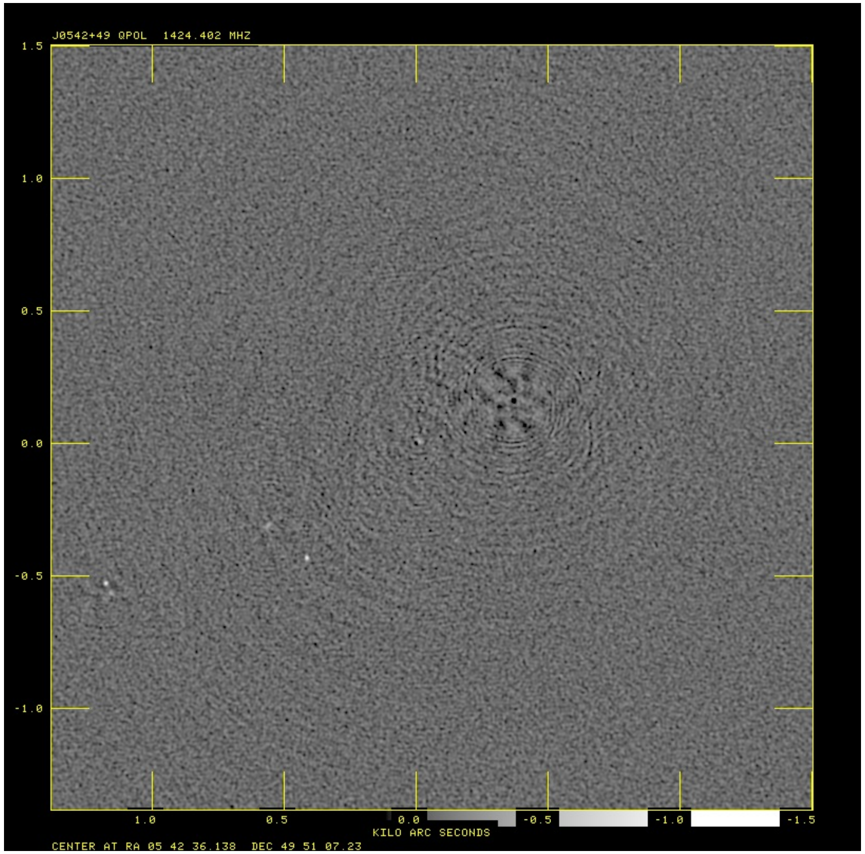


Oleg's Best – main beam

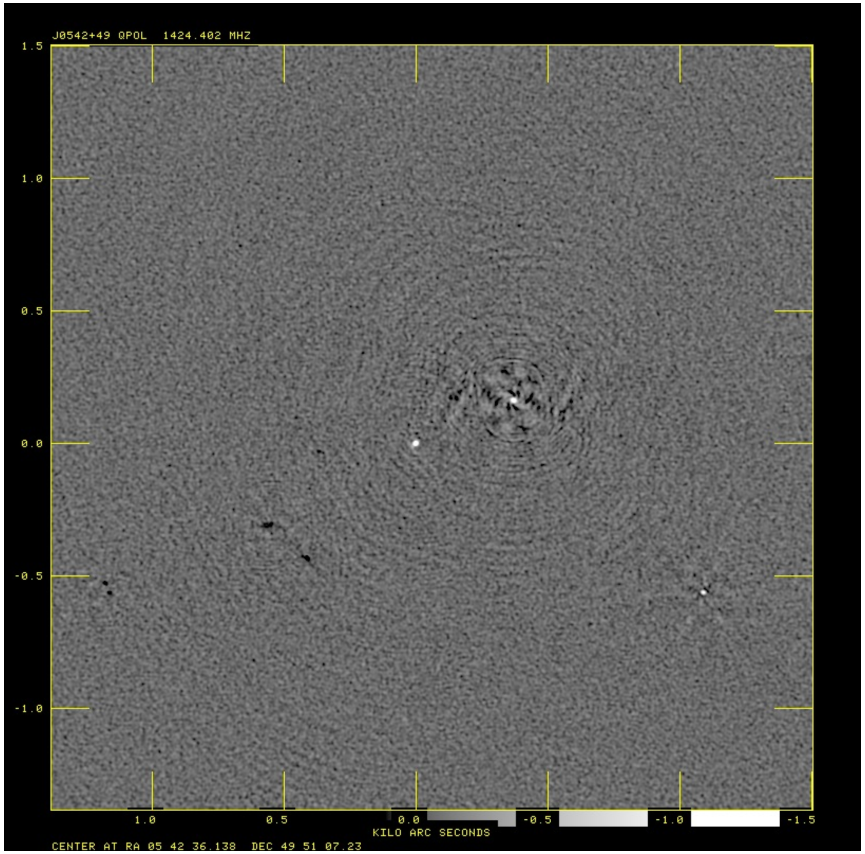
- Wow …



Stokes Q and U … (not right yet …)



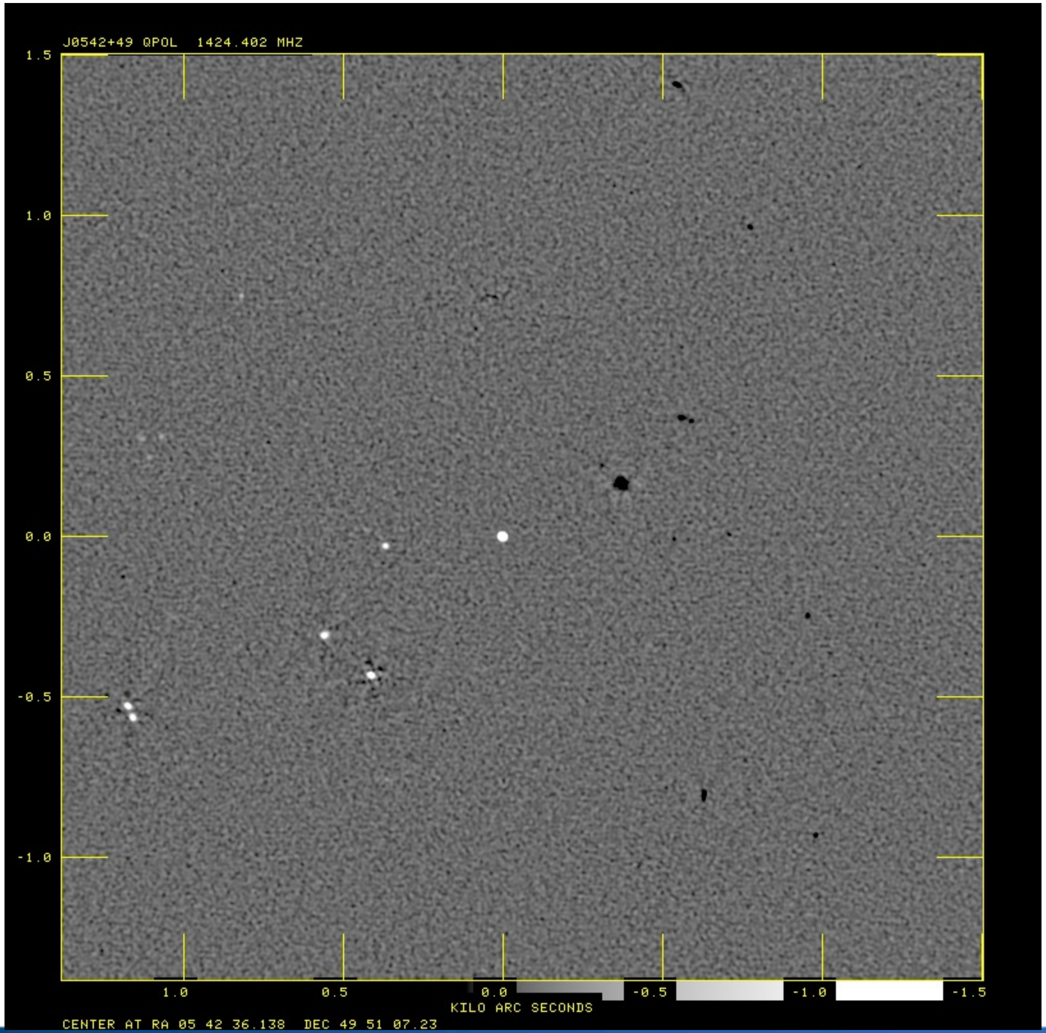
250MICROJY/BEAM



250MICROJY/BEAM

Stokes V

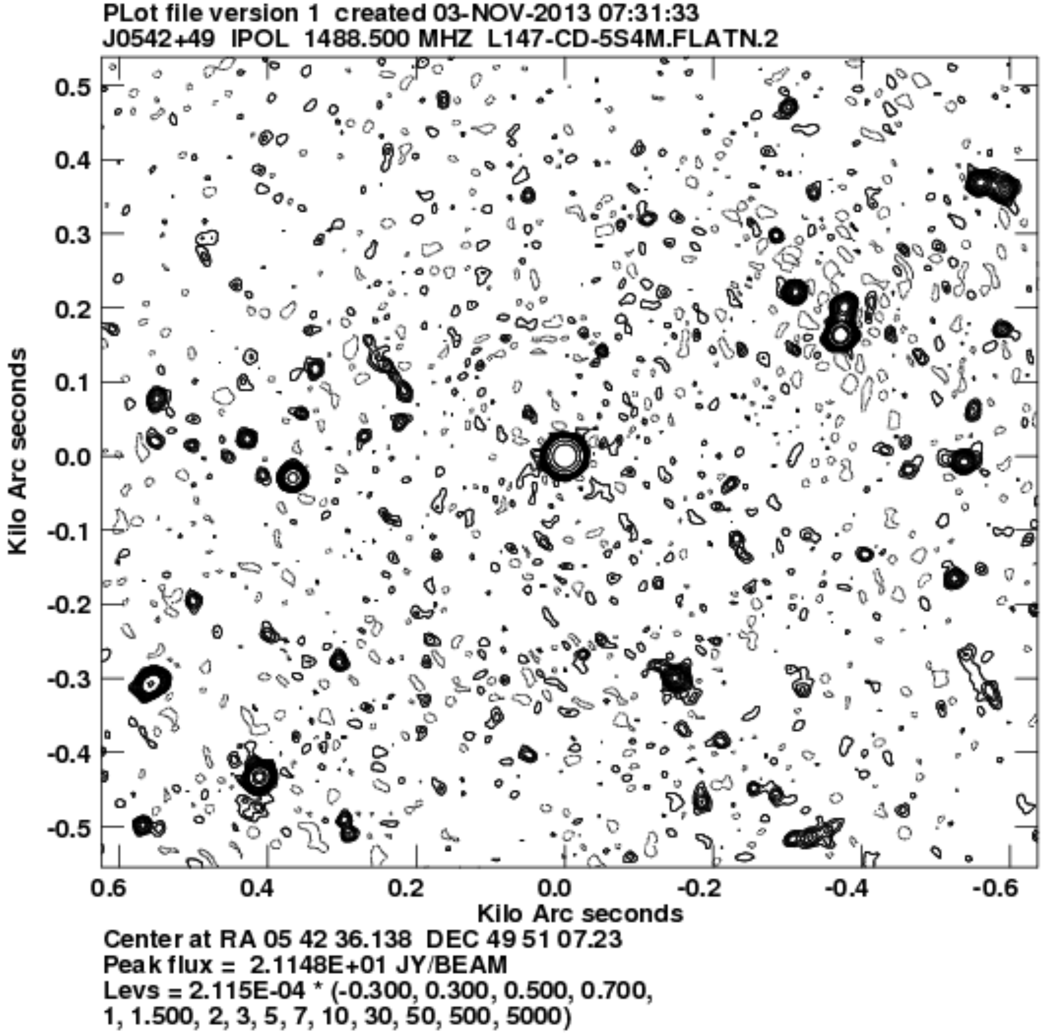
- No beam model included.
- Shown is the mean VLA beam squint.



250MICROJY/BEAM

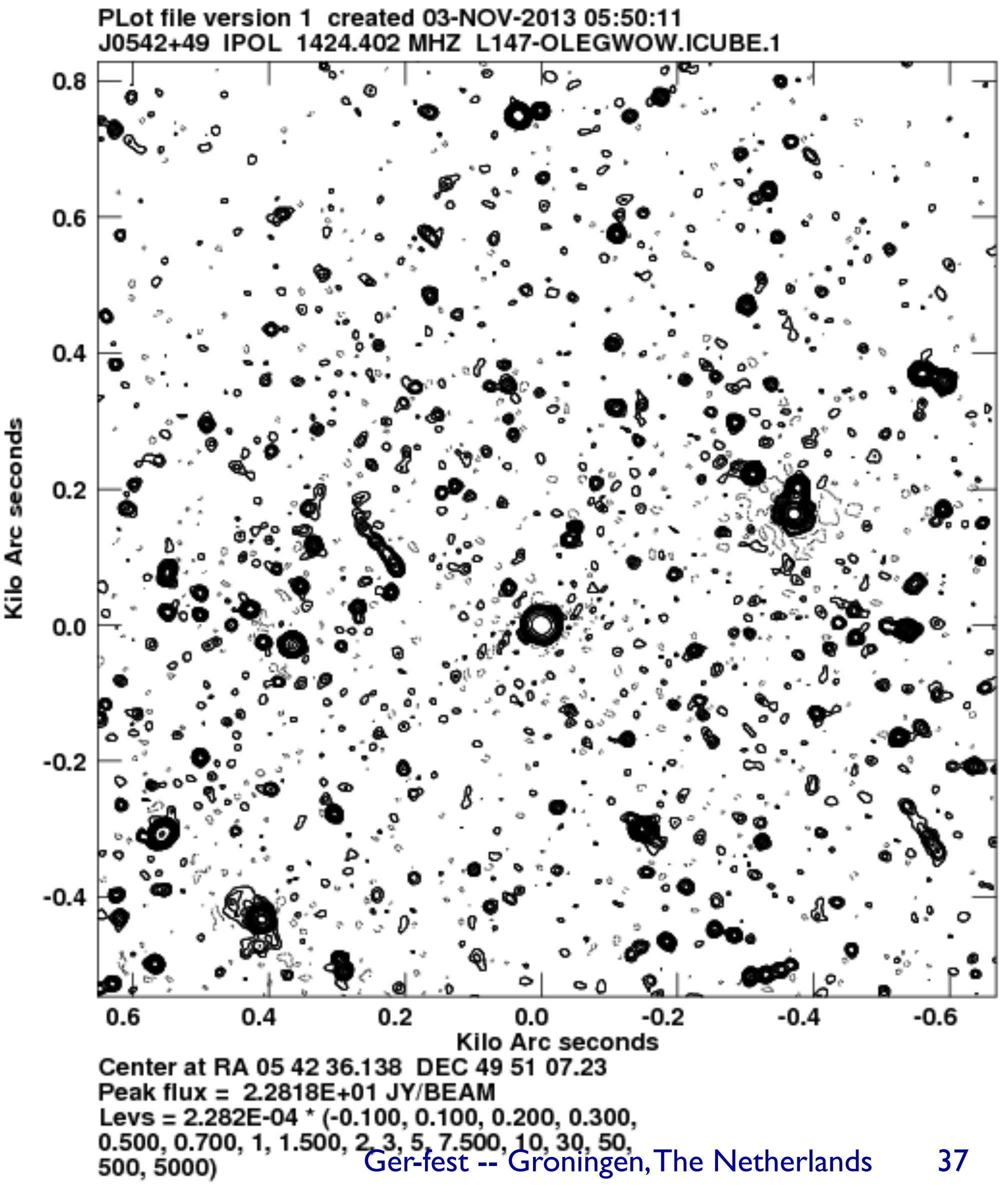
Contours plots .

- Rick's best (64 MHz)



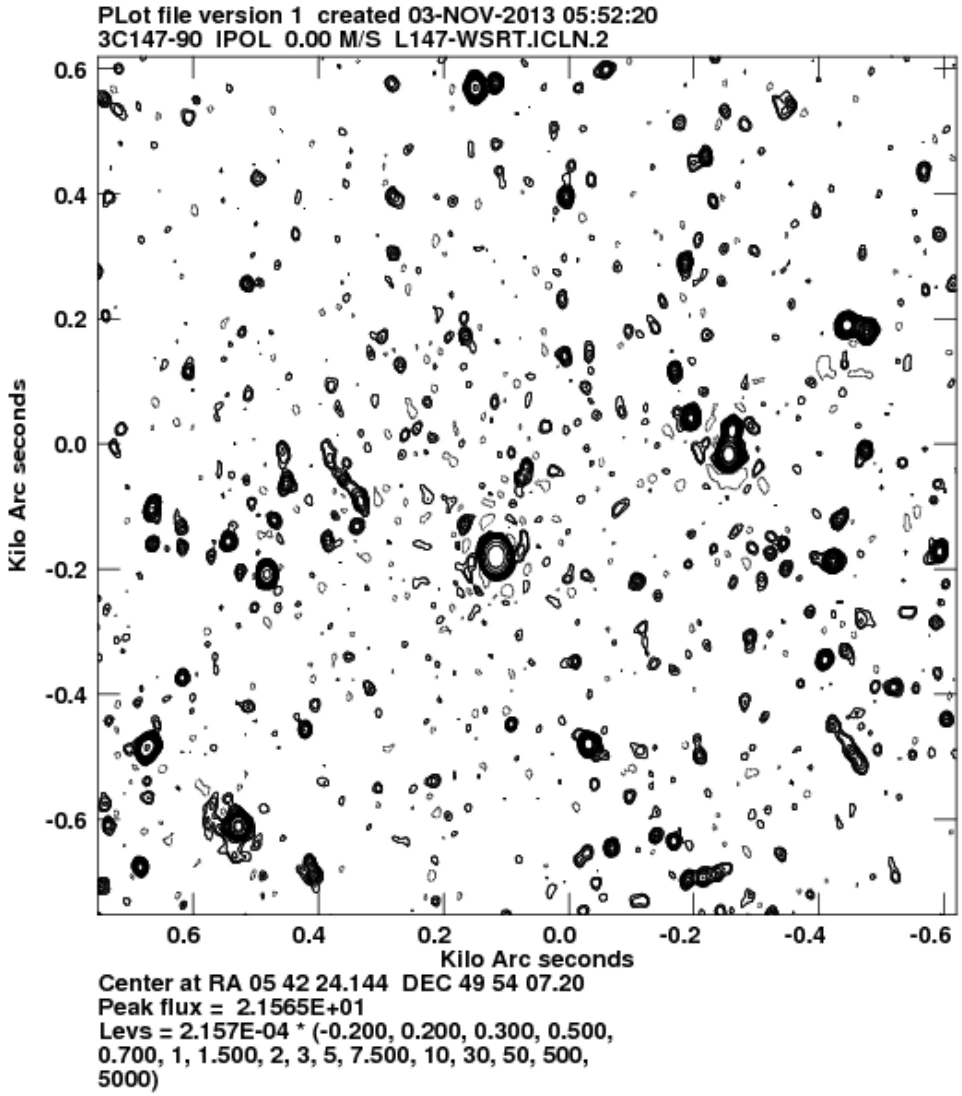
Oleg's Best

- C+D Configuration
- 192 MHz BW
- Lowest contour 3X below previous plot!



WSRT results:

- BW - ??
- Time = ??
- Contour level 2X higher than Oleg's



Summary

- We can achieve noise-limited performance even in the most demanding of circumstances.
- The Jones-matrix calibration formalism enables accurate full-polarization visibility data calibration.
  - (but, some problems remain in Q, U,V)
- DD, DI, and J calibration solutions appear physically reasonable, at least to the 2^{nd} sidelobe.
- Better, and more accurate results will come after proper beam I, Q, U, and V maps are made.