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WORKSHOP 2020

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LECTURE 6: TYPICAL DATA ISSUES

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Typical Data Issues with VLBI

Identifying and Correcting Gain-related and Noise-related Problems

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CASA-VLBI Workshop 2020 — JIVE (Netherlands)

Typical Data Issues

- **Bad Gains.**
  - Effects on visibilities and images.
  - The "effective" PSF from bad gains. Dynamic-range limitations.
  - Amplitude vs. phase gain issues.
  - Locating problematic visibilities during deconvolution.
- **Bad Data.**
  - Sensitivity limitation.
  - Noise-dominated visibility distributions.
  - A "crazy" self-calibration.
- **Bad Sources.**
  - Bandwidth effects.

BAD GAINS

Back to the Origins

The *true* image brightness distribution, $\mathcal{I}^{\rm true}(x,y)$ is related to the visibility function, $\mathcal{V}(u,v)$ via the equation:

$$\mathcal{I}^{\rm true}(x,y) = \int_{(u,v)} \mathcal{V}(u,v)\, e^{2\pi j(ux+vy)} du\, dv$$

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However, we only measure $\mathcal{V}(u,v)$ in a finite set of (u,v) points, a.k.a. the uv-coverage, $\mathcal{C}(u,v)$. We thus reconstruct a dirty image, $\mathcal{I}^{\mathrm{dirty}}(x,y)$:

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Using the well-known *Convolution Theorem*: $\mathcal{I}^{\rm dirty}(x,y) = \mathcal{I}^{\rm true}(x,y) * B(x,y)$

$$\text{where } B(x,y) = \int_{(u,v)} \mathcal{C}(u,v)\, e^{2\pi j(ux+vy)} du\, dv$$

The Origins Revisited

We actually measure a somewhat *corrupted* version of $\mathcal{V}^{\rm obs}(u,v)$:

$$\mathcal{V}^{\rm obs}(u,v) = \mathcal{V}(u,v) \times (1 + \mathcal{G}(u,v))$$

Hence, the recovered image is:

$$\mathcal{I}^{\rm obs}(x,y) = \int_{(u,v)} \mathcal{V}(u,v)\,\mathcal{C}(u,v)(1 + \mathcal{G}(u,v))\, e^{2\pi j(ux+vy)} du\, dv$$

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From the *Convolution Theorem*, we get: $\mathcal{I}^{\mathrm{obs}}(x,y) = \mathcal{I}^{\mathrm{true}}(x,y) * (B(x,y) + G(x,y))$

$$\text{where } G(x,y) = \int_{(u,v)} \mathcal{C}(u,v)\,\mathcal{G}(u,v)\, e^{2\pi j(ux+vy)} du\, dv$$

The Gain Problem

The images $\mathcal{I}^{\rm obs}(x,y)$ and $\mathcal{I}^{\rm dirty}(x,y)$ are convolved with different PSFs.
However, we use the PSF of $\mathcal{I}^{\rm dirty}(x,y)$ to deconvolve $\mathcal{I}^{\rm obs}(x,y)$.
In other words, **we use the wrong point-spread function** for the deconvolution!:

$$\mathcal{I}^{\rm obs}(x,y) = \mathcal{I}^{\rm true}(x,y) * \left(B(x,y) + G(x,y)\right) \quad ; \quad \mathcal{I}^{\rm dirty}(x,y) = \mathcal{I}^{\rm true}(x,y) * B(x,y)$$

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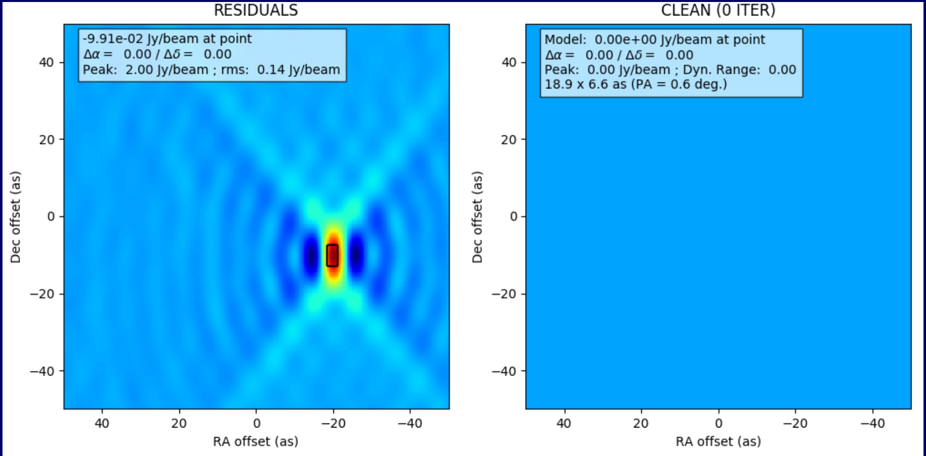
Wrong antenna gains have a convolution-like effect in the image plane. The true convolving PSF and the one computed from the uv-coverage are different.

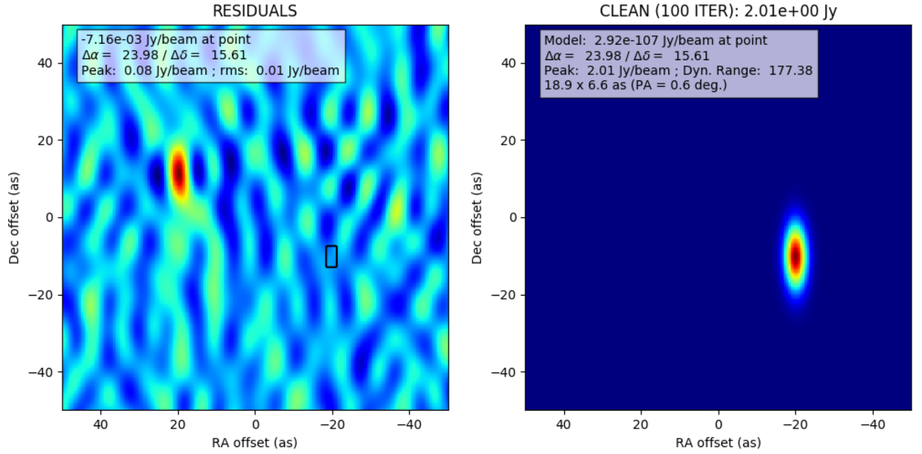
This introduces dynamic-range limitations in the image (i.e., the noise is proportional to the image peak, hence limiting the achievable contrast).

Gains and Dynamic Range



Point source with weak companion (CLEANing perfectly-calibrated data).

Gains and Dynamic Range



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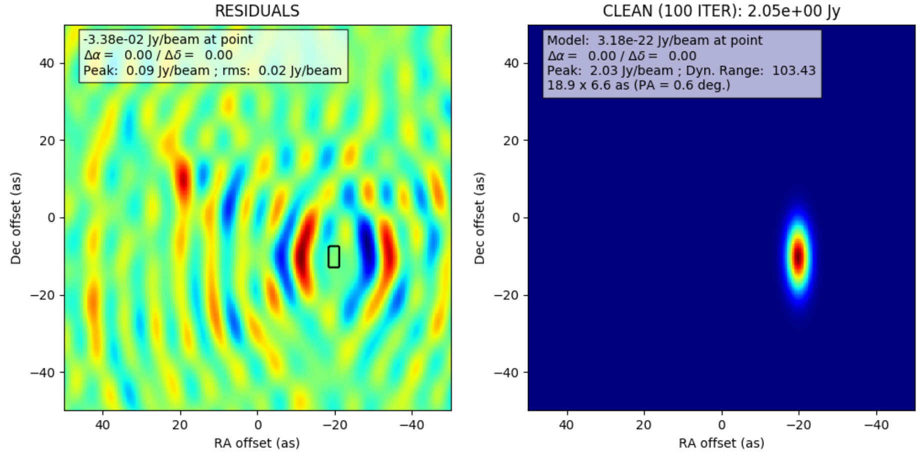
Gains and Dynamic Range



Point source with weak companion (CLEANing data with calibration issues).

Gain Effects in the Image Plane

How do $\mathcal{G}(u,v)$ and $G(x,y)$ behave?

- Amplitude gain: $\mathcal{G}(u,v)$ is real-valued and even. Hence, $G(x,y)$ is even.

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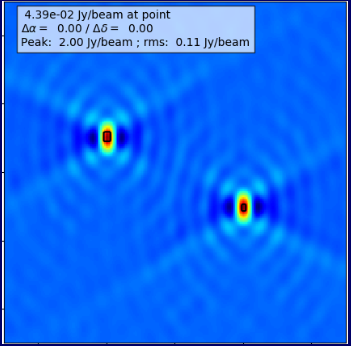
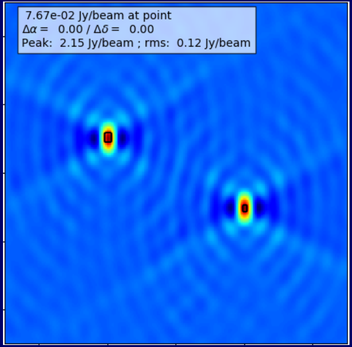
EXAMPLE: 6h with WSRT at 45° Declination (done with APSYNSIM):

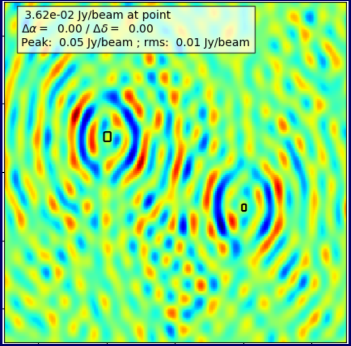
Perfect calibration



50% Amplitude in one antenna



CLEAN residuals



Gain Effects in the Image Plane

How do $\mathcal{G}(u,v)$ and $G(x,y)$ behave?

- Small Phase gain: $\mathcal{G}(u,v)$ is imaginary and odd. Hence, $G(x,y)$ is odd.

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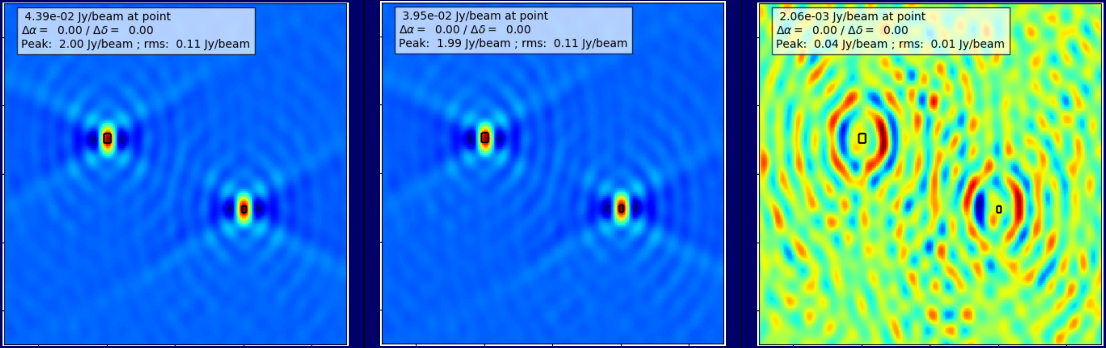
- Small Phase gain: $\mathcal{G}(u,v)$ is imaginary and odd. Hence, $G(x,y)$ is odd.

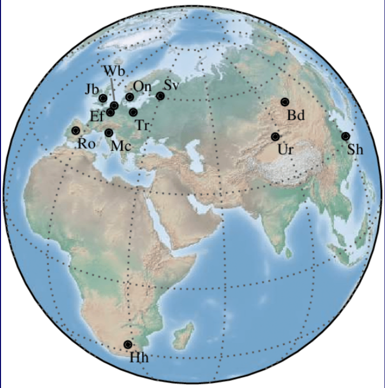
EXAMPLE: 6h with WSRT at 45° Declination (done with APSYNSIM):

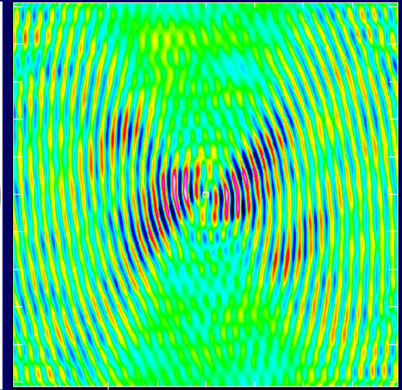
Perfect calibration	20° Phase in one antenna	CLEAN residuals



Quizzzz

Which EVN baseline and gain dominates these residuals?





- **A.** Jb - On. Amplitude gain.
- **B.** Jb - Ro. Phase gain.
- **C.** Sh - Ro. Amplitude gain.
- **D.** Hh - Mc. Phase gain.

Quizzzzz

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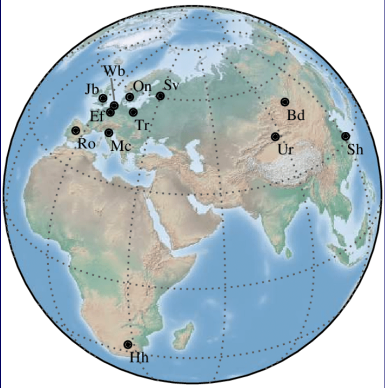
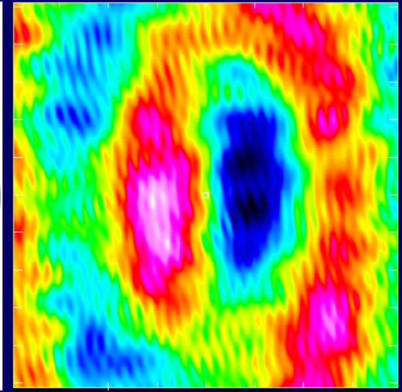
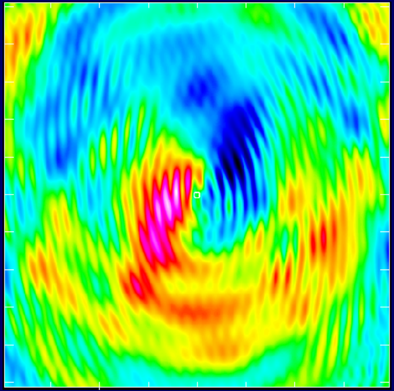




- **A.** Jb - Wb. Amplitude gain.
- **B.** Ro - Tr. Amplitude gain.
- **C.** Jb - Wb. Phase gain.
- **D.** Hh - Ur. Phase gain.

Reality is usually worse

How can we identify the bad gains in the general case?



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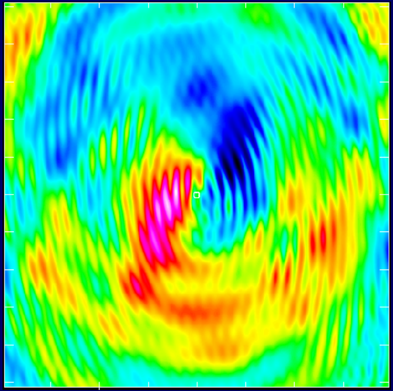
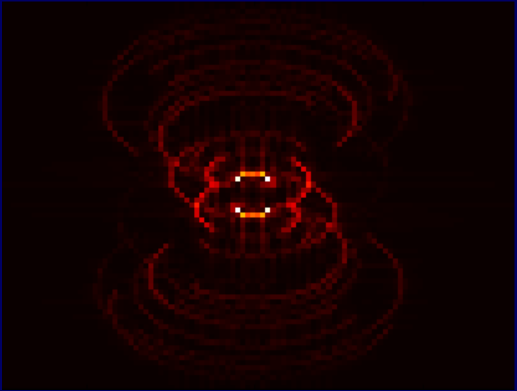
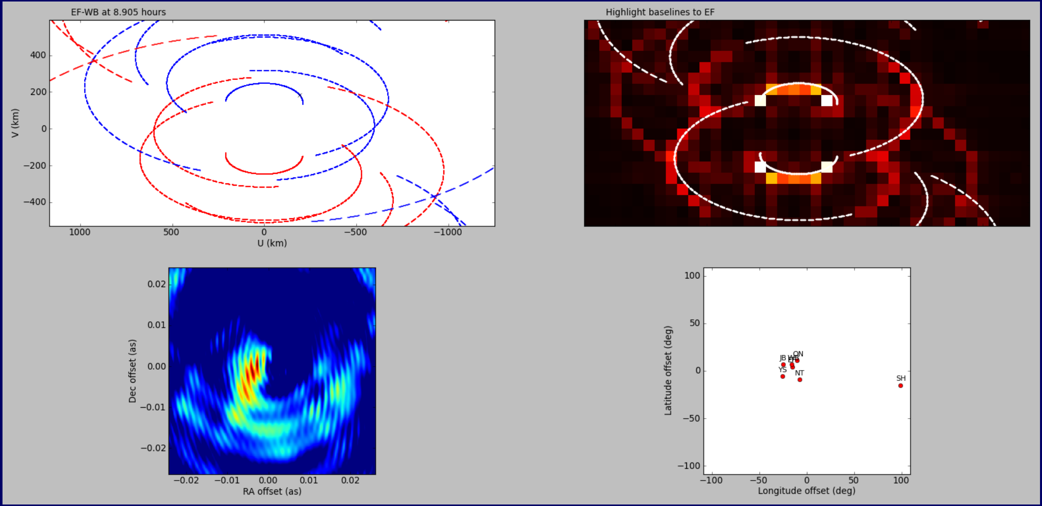


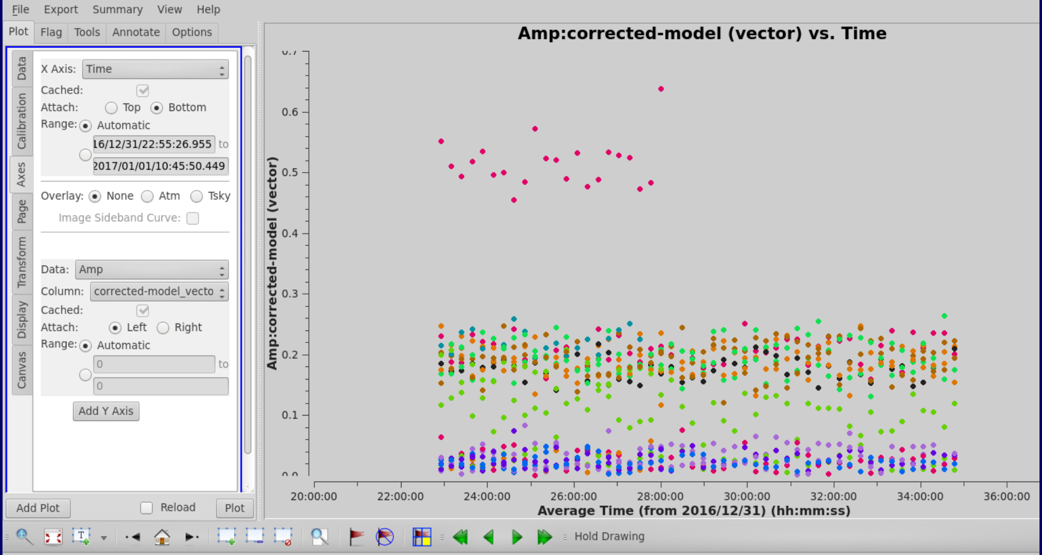


The residual image encodes the spatial frequencies of $G(x,y)$!

The “checkres” task (Nordic ARC Node)



The plotms task



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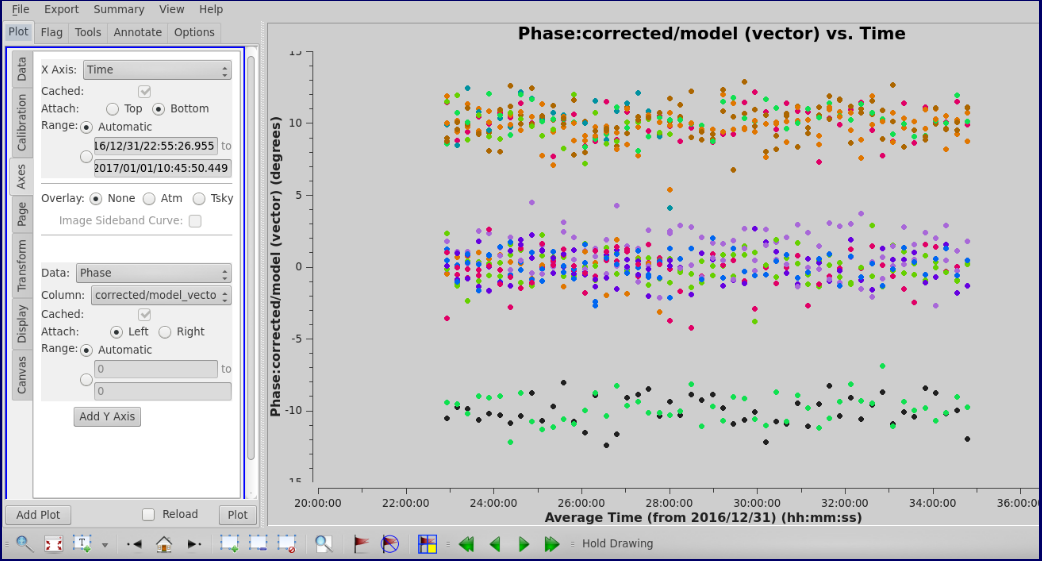

So, what do we do?

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SELF-CALIBRATION! Iterative hybrid imaging!

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SELF-CALIBRATION! Iterative hybrid imaging!

But remember: *with great power comes great responsibility*

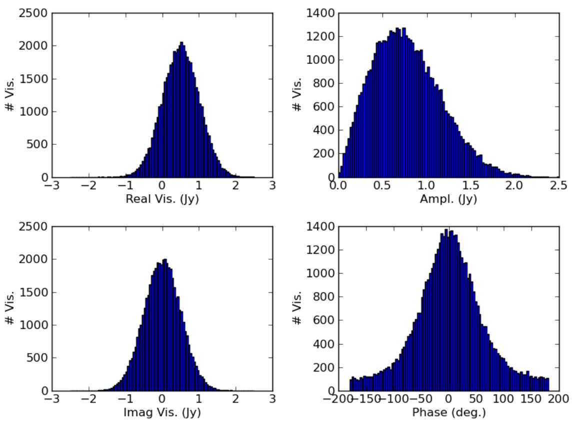
(see next slides)

BAD DATA

Bad data is worse than no data at all.
Alan Marsher

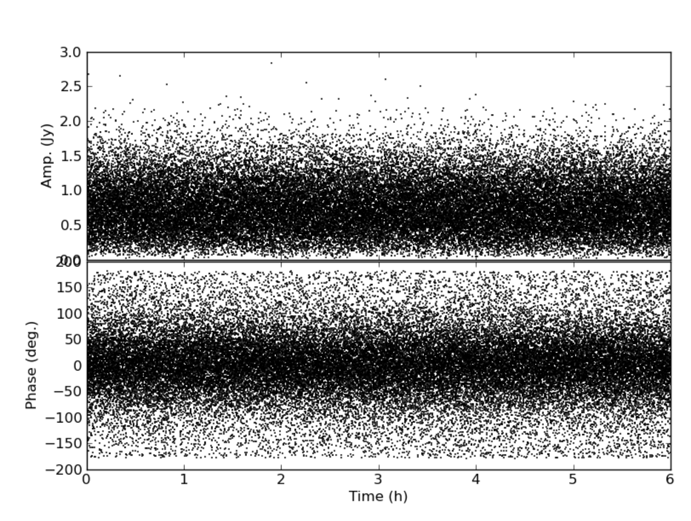
Noise in the visibilities

- Assuming a correct calibration, the real and imaginary parts of the visibilities have Gaussian and independent thermal noise.
- Hence, the amplitudes and phase do **NOT** have neither Gaussian nor independent noises.



Quizzzzz

What is the flux density of the point source in these observations?



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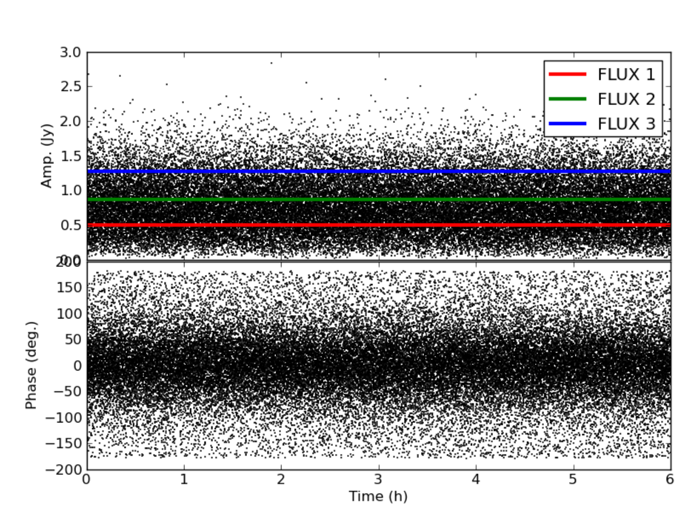
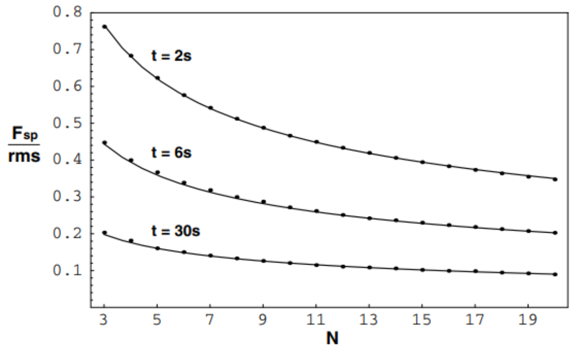


Beware of noisy selfcal!

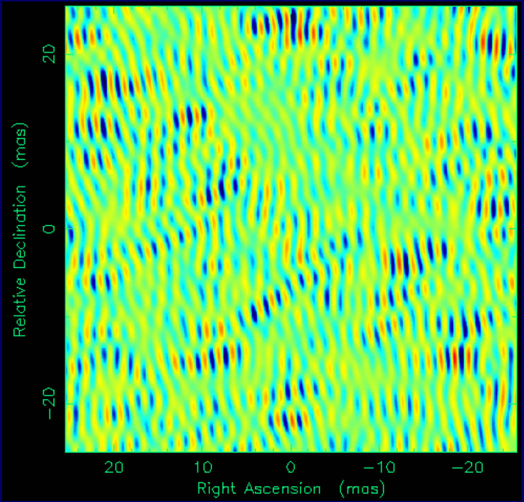


Self-calibrating on noisy data can create spurious sources with a flux density, F_{sp}, similar to the rms of the visibilities, ρ! (e.g., Martí-Vidal & Marcaide 2008).

$$F_{sp} \sim 0.7\rho\sqrt{\frac{t_{\mathrm{int}}}{t_{\mathrm{sol}}}}N_{\mathrm{ant}}^{-0.4}$$

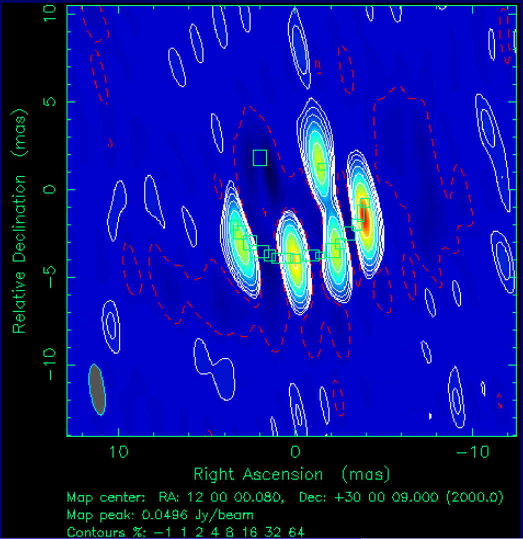
A crazy self-calibration

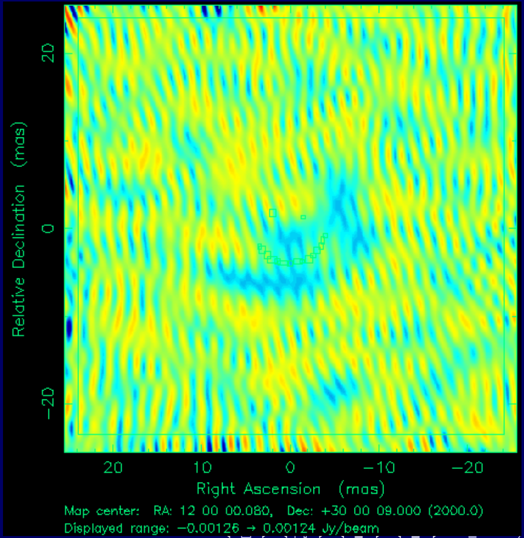
Pure thermal noise observed with the EVN (30° declination, 6h with optimum elevations).



A crazy self-calibration

Only phase self-calibration with an a-priori model. Pretty “harmless”, ain’t it?





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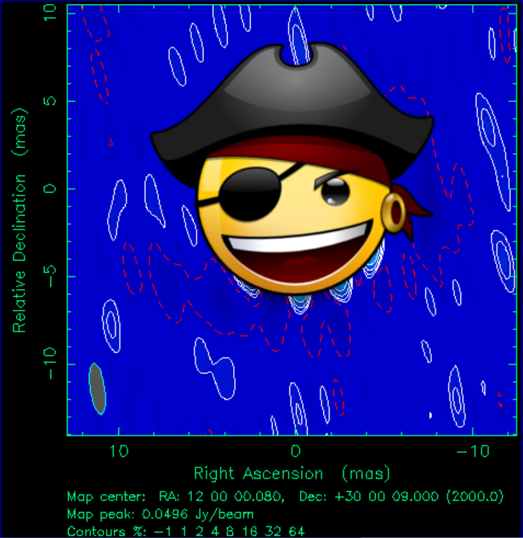
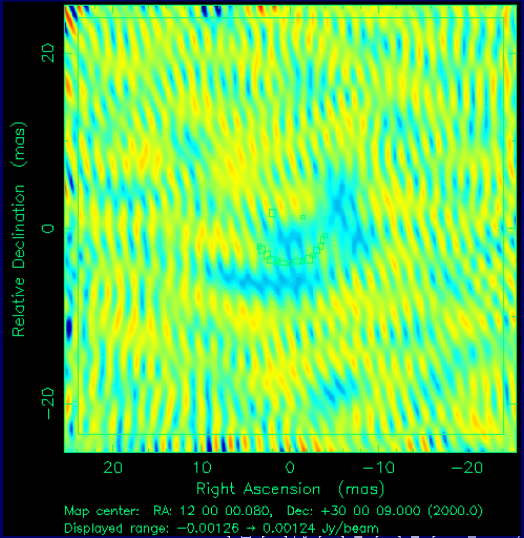




BAD SOURCES

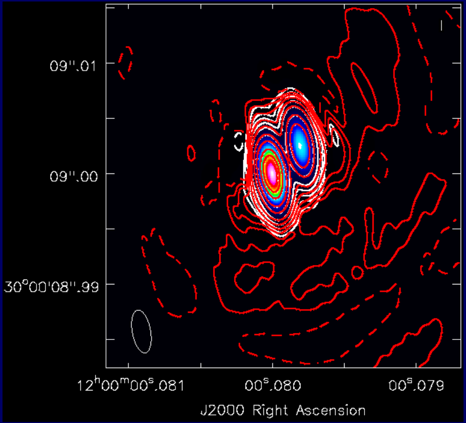
Increasing the SNR by averaging

- We can do averaging either in time or frequency (or both).
- Averaging in uv-space is a *convolution-like* operation (substitutes tracks and lines by points).
- From the convolution theorem, the effects in the image plane are "product-like".
  - Time Smearing and Bandwidth Smearing (baseline-dependent smearing of source components far from the phase center).

$$\mathrm{FoV(arcsec)} = \max\left[11\left(\frac{t_{\mathrm{int}}}{1\,\mathrm{s}}\right)^{-1}\;,\;4.8\left(\frac{\Delta\nu}{1\,\mathrm{MHz}}\right)^{-1}\right]\times\left(\frac{B_{\mathrm{max}}}{10^4\,\mathrm{km}}\right)^{-1}$$

Source frequency dependence

- For large bandwidths, the source's spectral distribution can limit the dynamic range.



Double source with different spectral indices ($\alpha = 0.0$ for the core; $\alpha = -1.0$ for the extension). In **red**, CLEAN in normal mode; In **white**, CLEAN in multi-frequency-synthesis (mfs) mode.

SUMMARY

- Images are limited by uv-coverage and antenna gains. Both have convolution-like effects.
- If there is an incorrect calibration, it is possible to identify the bad gains from the residuals:
  - Find out the bad spatial frequencies in the residual image and identify the bad points (e.g., the "checkres" task).
  - Check the residual visibilities and look for outliers: phases in data/model or amplitudes in data−model (the "plotms" task).
- Once the bad data are identified, we can correct them with self-calibration. BUT, special care has to be taken with noisy data.
- Even if the data are perfectly calibrated, we can still introduce artifacts, e.g.:
  - Smearing effects from visibility averaging.
  - Dynamic-range limitation by source spectral distribution in wideband observations.

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