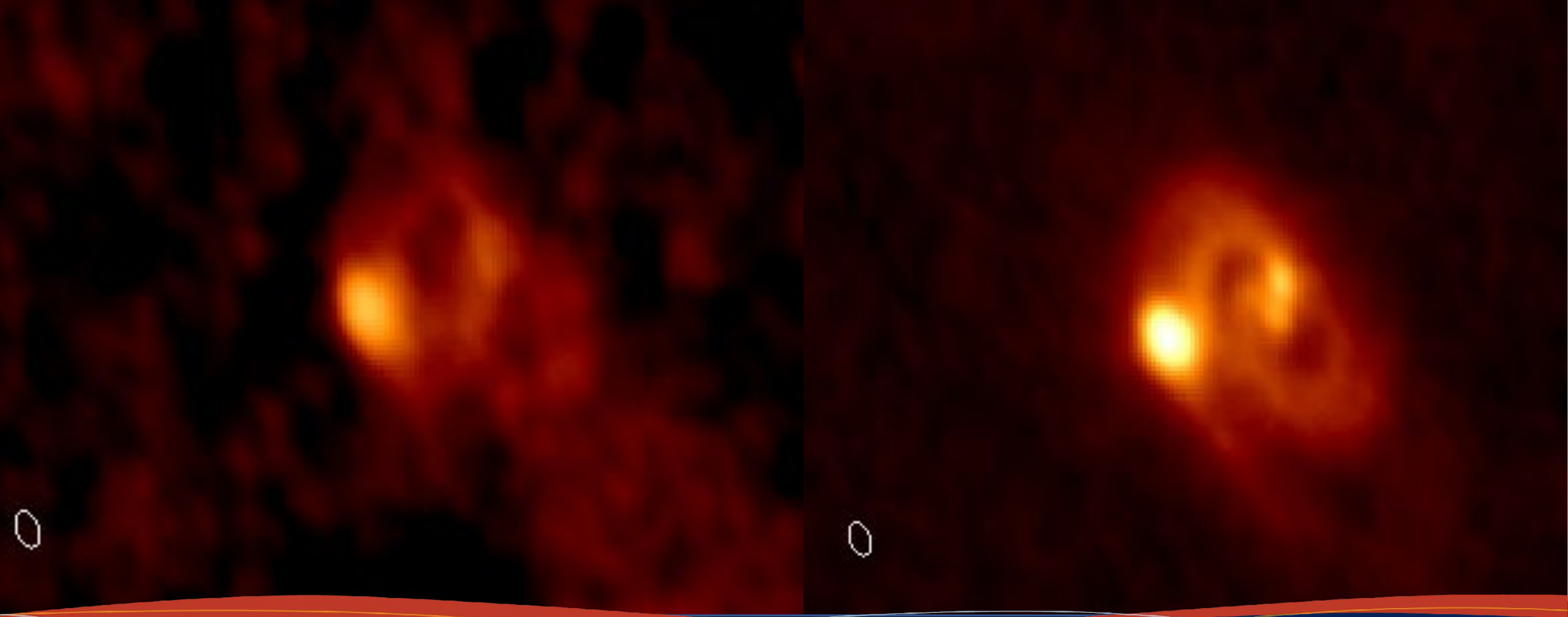


Self-Calibration

Patrick Sheehan

29 September 2023

A Quick review of calibration

Interferometers measure “visibilities”: the amplitude and phase information of the cross-correlated signals between pairs of antennas.

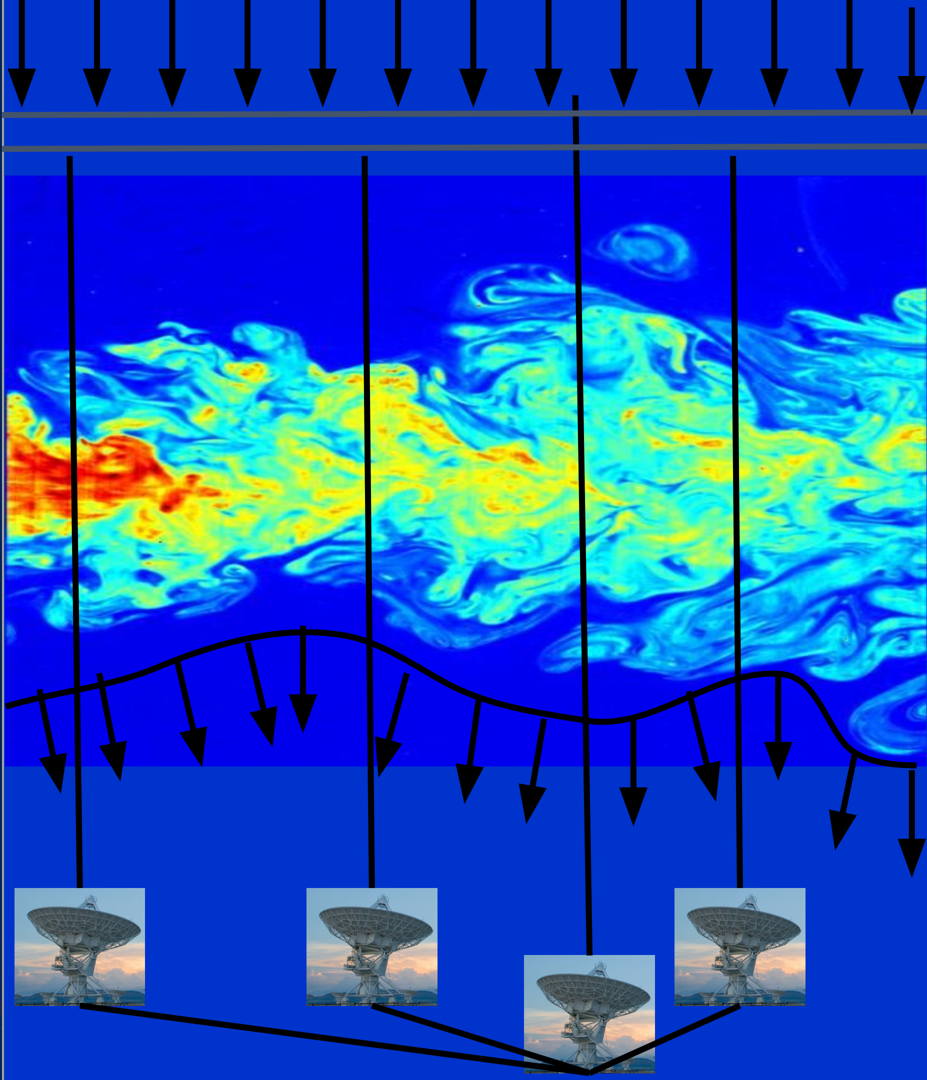
The true visibility is corrupted by many effects:

Antenna based:

- Atmospheric attenuation
- Radio “seeing”
- Variable pointing offsets
- Variable delay offsets
- Electronic gain changes
- Electronic delay changes
- Electronic phase changes

Baseline based:

- Radiometer noise
- Correlator malfunctions
- Most Interference signals



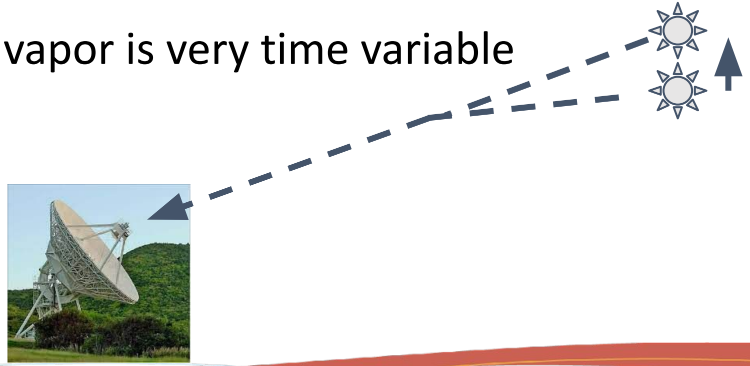
Mean Effect of Atmosphere on Phase - Refraction

- Index of refraction of atmosphere ≠ 1, an EM wave will experience refraction
- The phase change is related to the index of refraction of air and the distance travelled by $\delta\varphi = 2\pi/\lambda \times n\, D$
- $N = (n-1)\times 10^6$ is typically separated into 'dry' air and water vapor components

  $N_{dry} = 2.2\times10^5 \rho_{tot}$ $\qquad \rho_{tot} \sim 700 - 1000$ g m^{-3}

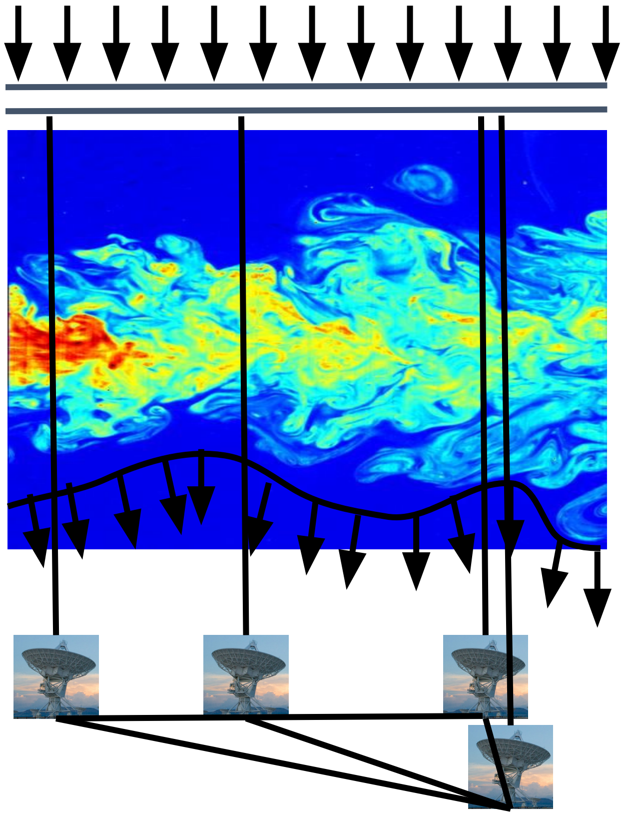
  $N_{H2O} = 1.7\times10^9 \rho_{H2O}/T_{atm}$ $\qquad \rho_{H2O} \sim 0.01 - 0.001\rho_{tot}$ and $T_{atm} \sim 270$ K

- Dry air dominates the refraction by ~10x, but water vapor is very time variable
- $\delta\varphi \cong 6.3 \times 2\pi/\lambda \times W$ where W is the PWV in mm



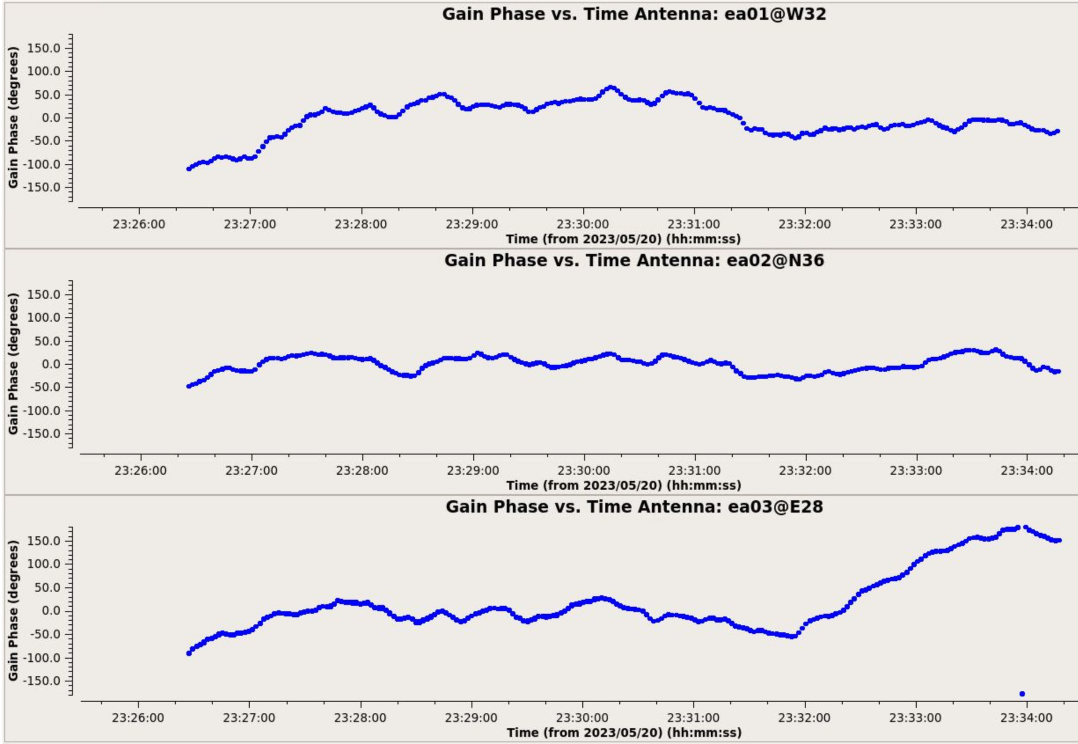
Mean Effect of Atmosphere on Phase - Refraction

- Patches of air with different water vapor content (and hence index of refraction) affect the incoming wavefront differently.
- Spatial and temporal variations in the amount of PWV causes phase variations, which are worse at higher frequencies:
- You can observe in apparently excellent submm weather (low PWV) and still have terrible "seeing", i.e. phase stability.



Mean Effect of Atmosphere on Phase - Refraction

- As a result of these temporal variations, a time-variable phase is added into the data collected from an given antenna in the array.
  - This phase is “antenna-based”, each antenna sees a different variation.
- This leads to:
  - Loss of coherence (reduced detected signal)
  - radio ‘seeing’ typicalling 0.1 - 1” at 1.3 mm
  - Anomalous pointing and delay offsets

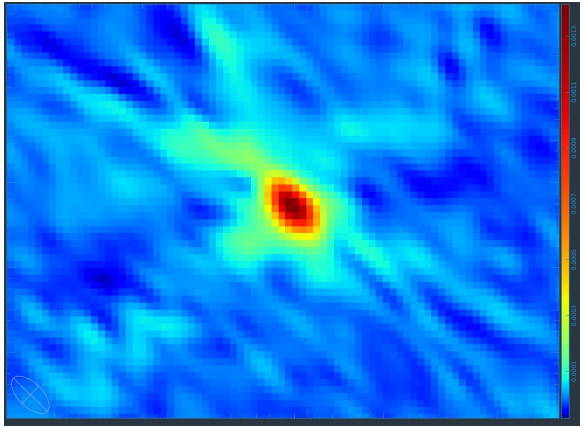


Phase vs. time on bandpass calibrator for VLA K-band observations - mediocre weather

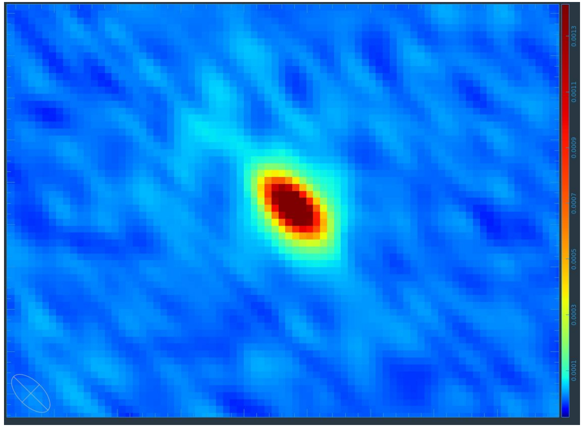
Mean Effect of Atmosphere on Phase

- Important points to note about these effects:
  - Decoherence does not (always) manifest in RMS noise for science target
  - Overall image RMS may not change but peak intensity is reduced
- Example: VLA Ka-band data, C-config
  - ~7 minute cycle time

VLA Ka-band observations; C-config. 16A-197;HOPS-87



Standard phase referencing:
Peak = 1.35 mJy/bm
rms ~11.2 uJy/bm

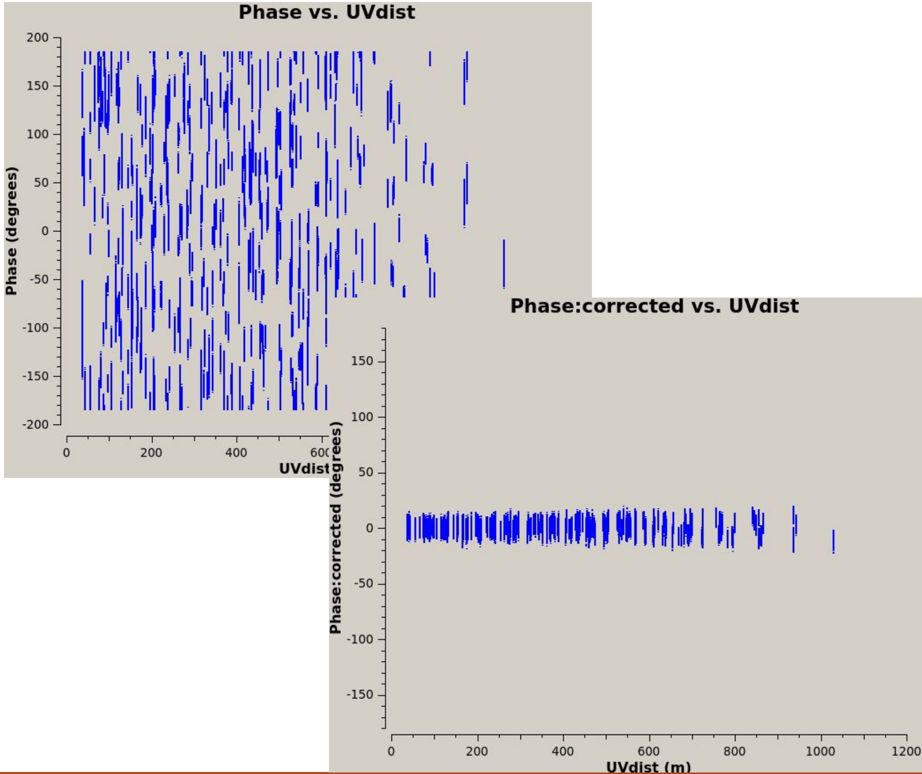


Self-calibration 12s
Peak = 2.31 mJy/bm
rms ~10.2 uJy/bm

A Quick review of calibration

We calibrate data by determining the complex gains (amplitude and phase) and the frequency response (bandpass) for each antenna. To do this, we observe a bandpass, flux, and phase calibrator

What is special about the calibrators?



Phase vs UVdist

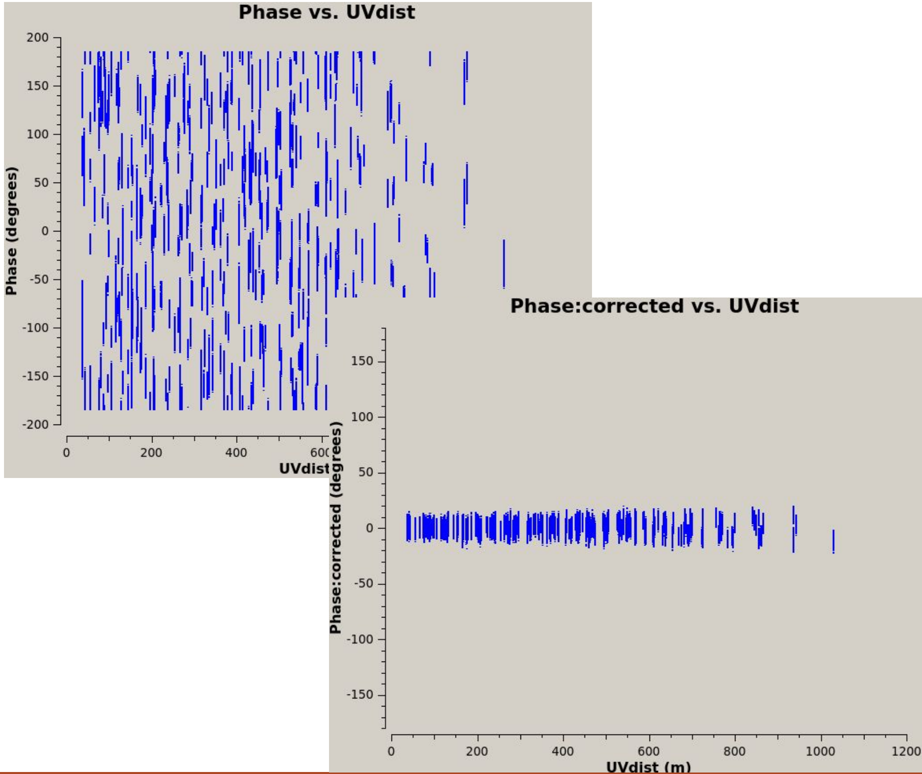
VLA Flux Calibrator 3C138

A Quick review of calibration

We calibrate these data by determining the complex gains (amplitude and phase) and the frequency response (bandpass) for each antenna. To do this, we observe a bandpass, flux, and phase calibrator

What is special about the calibrators?

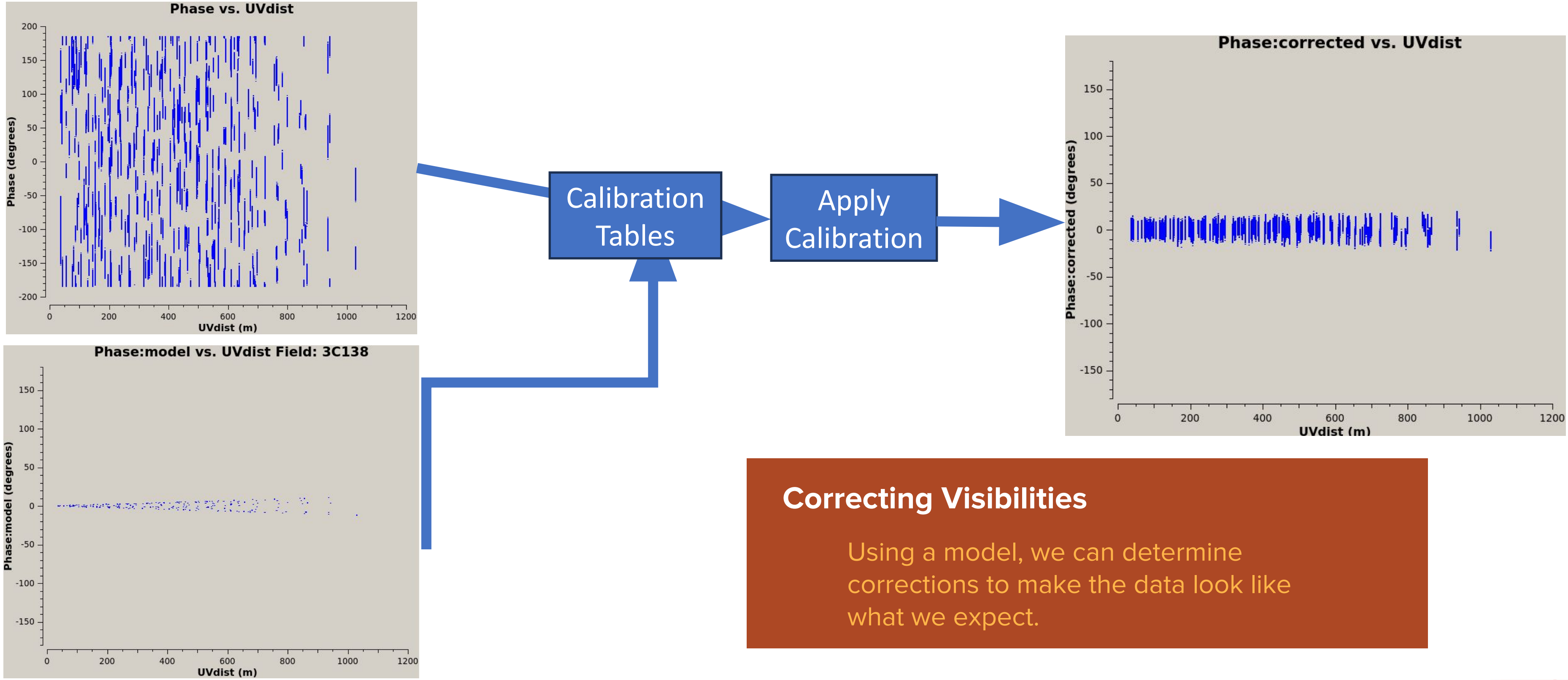
- Sources are monitored
- Well known Flux and structure
  - High SNR
  - Point source (preferred)
  - No spectral Features (Bandpass)
  - No short term variability



Phase vs UVdist

VLA Flux Calibrator 3C138

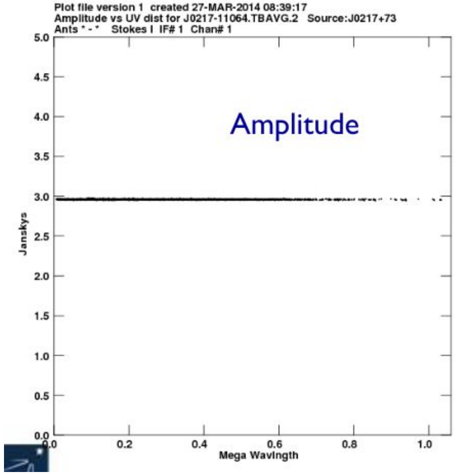
A Quick Review of Calibration

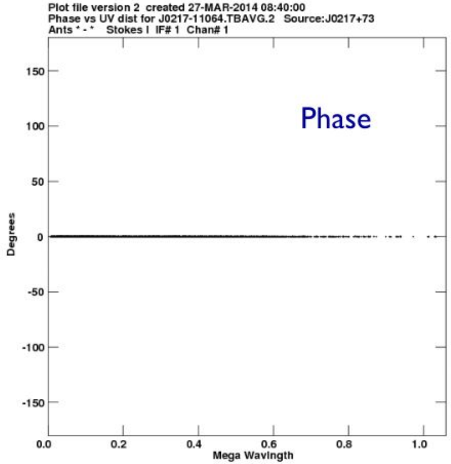


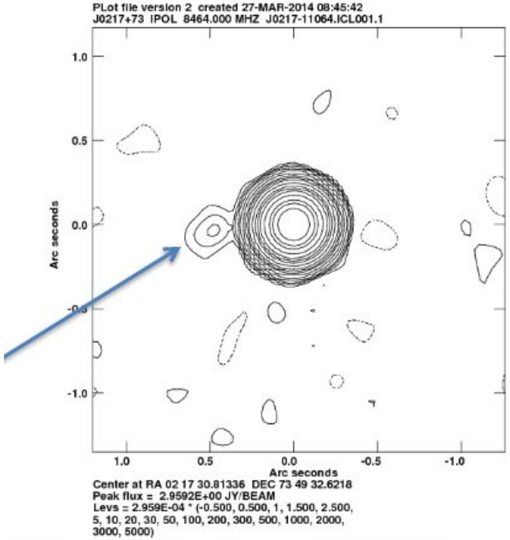
Correcting Visibilities

Using a model, we can determine corrections to make the data look like what we expect.

Examples of Calibrator Models





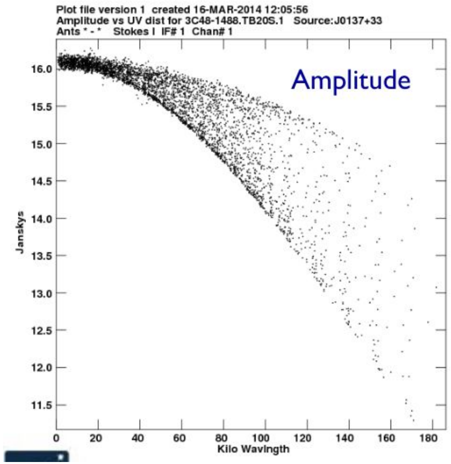


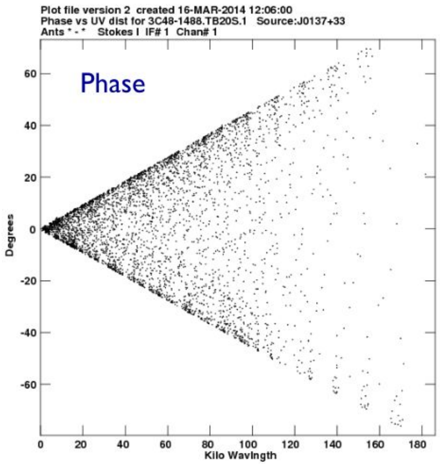
Models: Point Source

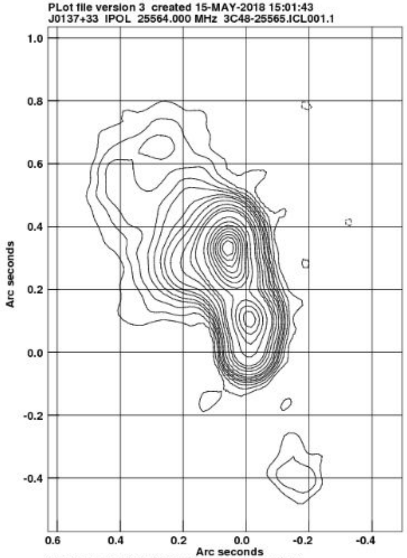
Fundamental Radio Astronomy II, Synthesis Imaging Workshop 2023, Rick Perley, NRAO/Socorro

National Radio Astronomy Observatory

Examples of Calibrator Models





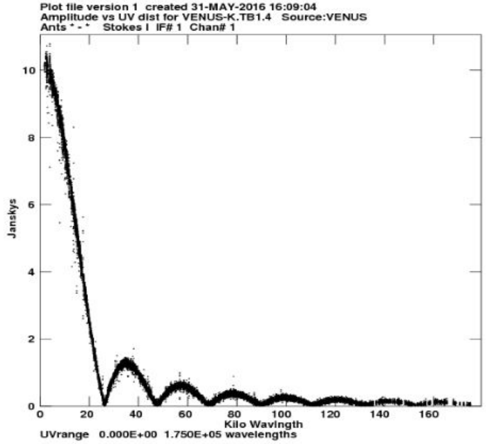


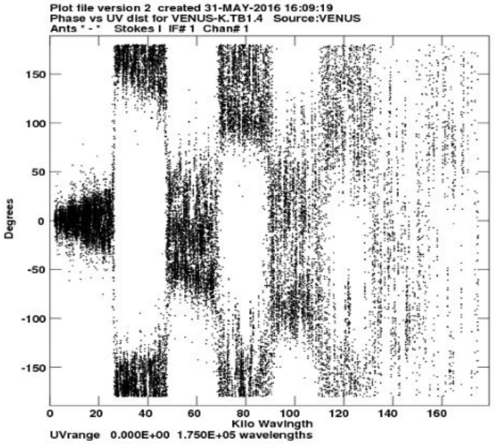
Models: Slightly resolved source

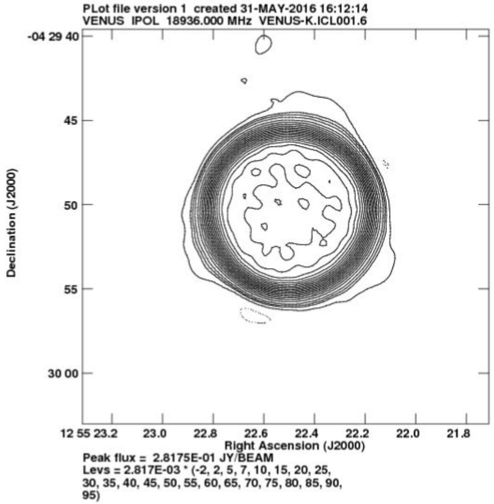
Fundamental Radio Astronomy II, Synthesis Imaging Workshop 2023, Rick Perley, NRAO/Socorro

National Radio Astronomy Observatory

Examples of Calibrator Models







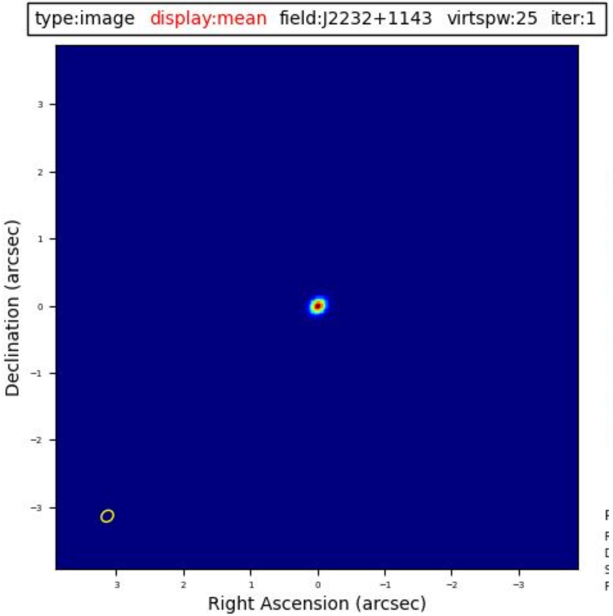
Models: Disk

Fundamental Radio Astronomy II, Synthesis Imaging Workshop 2023, Rick Perley, NRAO/Socorro

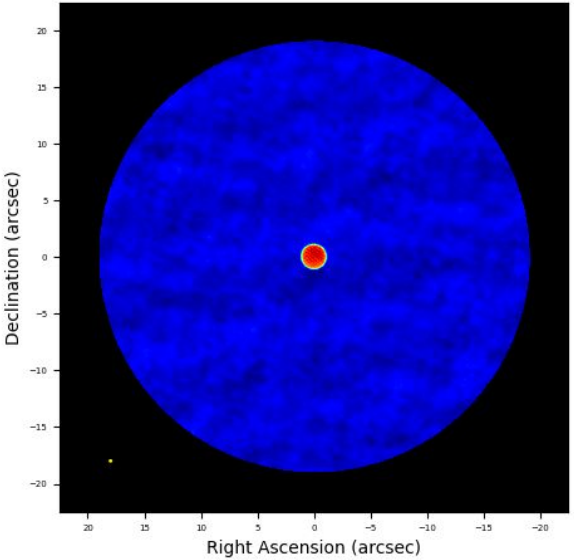
National Radio Astronomy Observatory

Examples of Calibrator Models

Calibrator 1

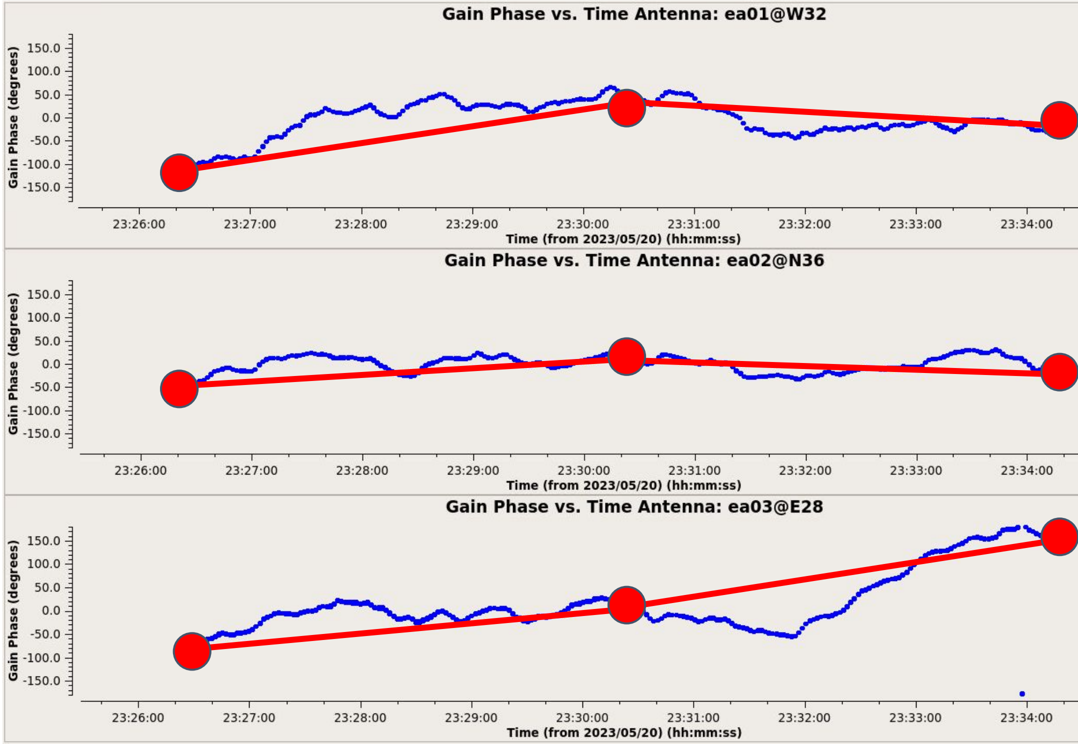


Calibrator 2



Residual Phase and Decorrelation

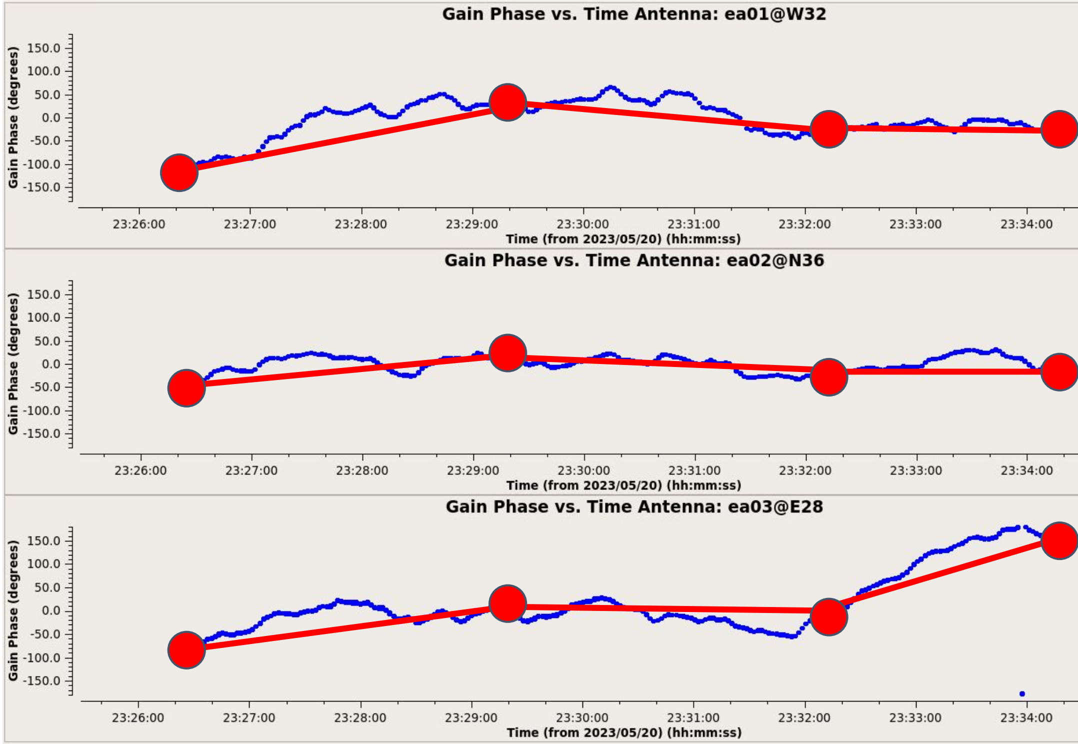
- Observe the phase calibrator at regular intervals to measure the difference between the known phase of the calibrator source and the measured phase of the calibrator source as a function of time.



Phase vs. time on bandpass calibrator for VLA K-band observations - mediocre weather

Residual Phase and Decorrelation

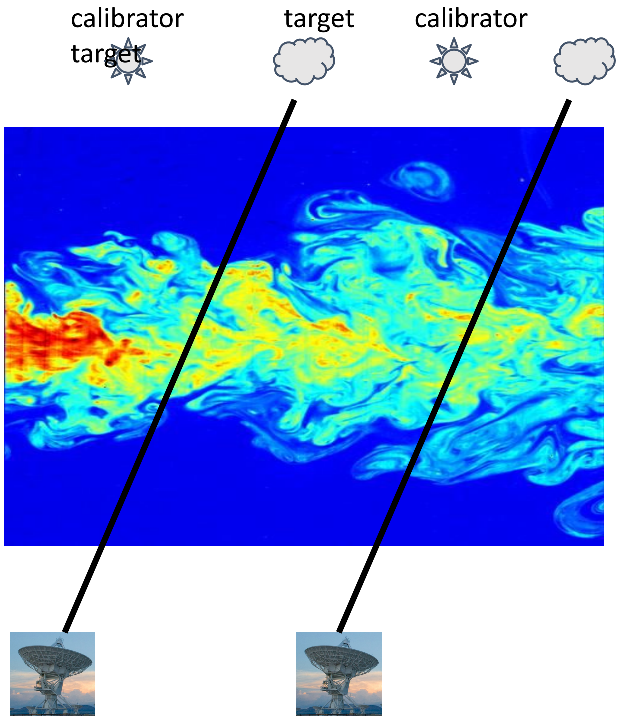
- Observe the phase calibrator at regular intervals to measure the difference between the known phase of the calibrator source and the measured phase of the calibrator source as a function of time.
- Atmosphere needs to be stable enough such that residual phase is not too large



Phase vs. time on bandpass calibrator for VLA K-band observations - mediocre weather

Calibrator-Source Separation

- Distance from source to calibrator can be an important consideration
  - Further from target, the more “different” the atmosphere will be
- Becomes more important at higher frequencies
  - VLA - slew time becomes non-negligible if ‘fast’ switching



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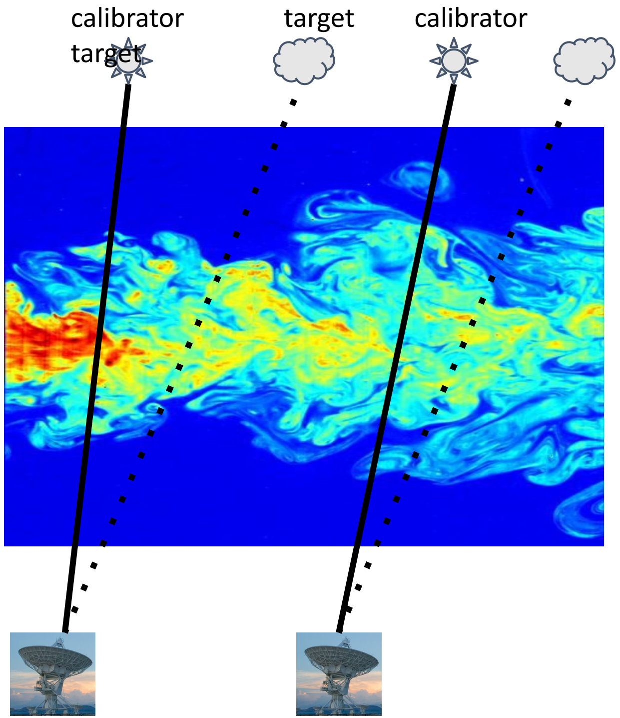
- Also for greater separations antenna positions need to be more accurate (in absence of self-calibration)
- See also L. Maud - High Frequency Observations



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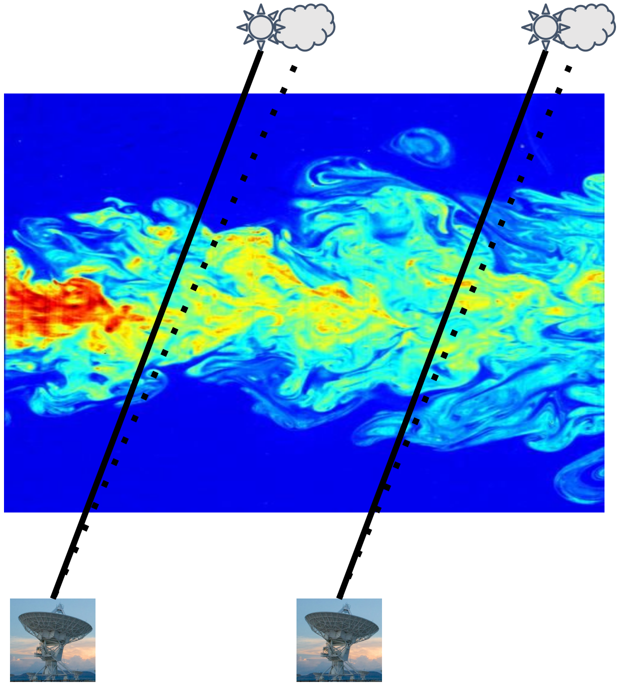
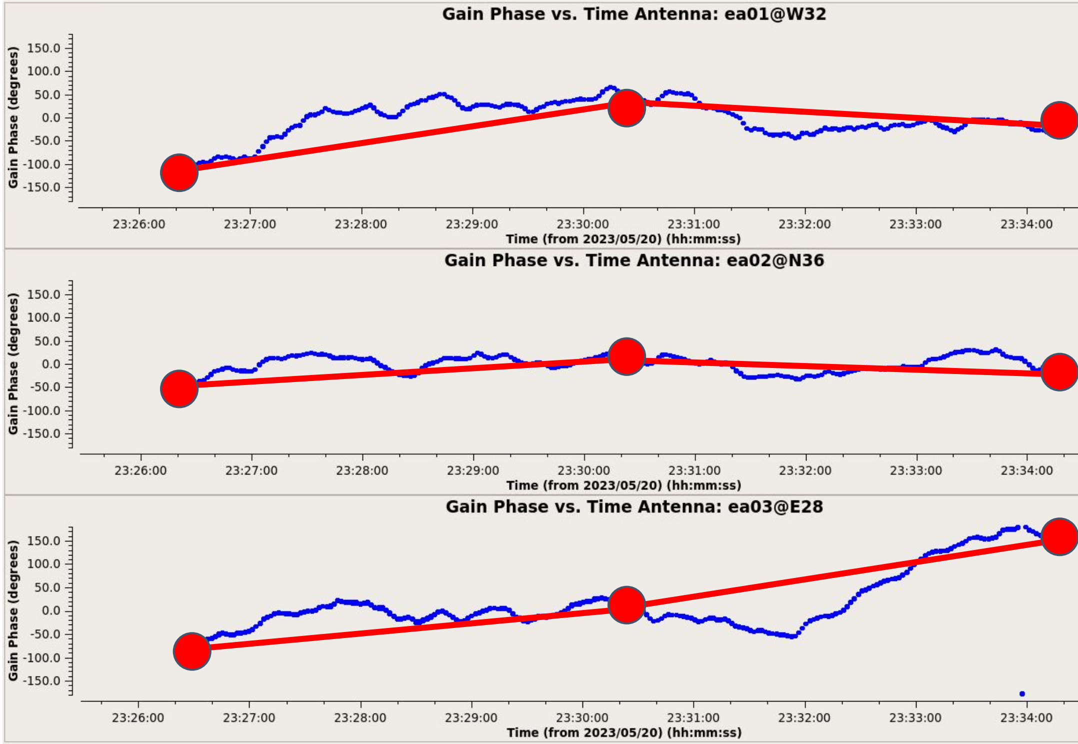


Residual Phase and Decorrelation

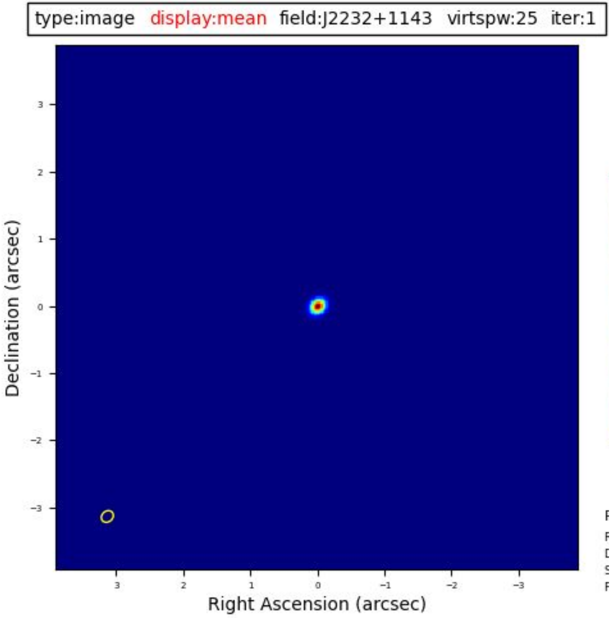
- Coherence = [vector avg]/[true vis amp] = $\langle V\rangle/V_o$ where, $V=V_o e^{i\phi}$
- $\langle V\rangle = V_o\langle e^{i\phi}\rangle = V_o e^{-\phi_{rms}^2/2}$ (Gaussian phase fluctuations)
- Example: if ϕ_{rms} = 1 radian (~60°), coherence = $\langle V\rangle$ = $0.60V_o$
  - ϕ_{rms} = 30° coherence ~0.9 V_o
  - Decorrelation on shortest calibration timescale can introduce fluxscale errors



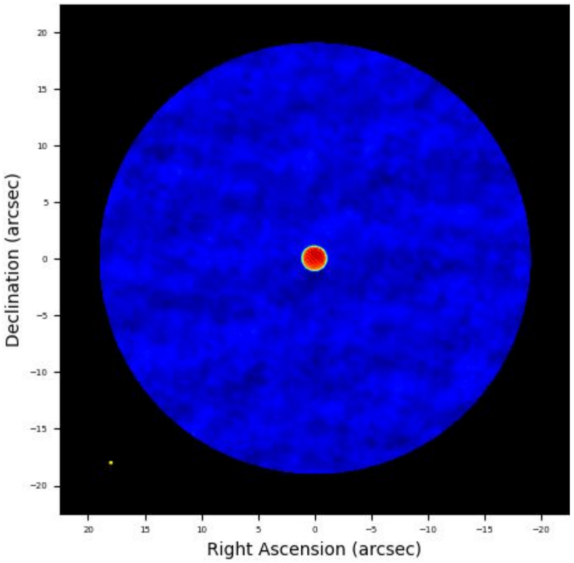
Phase vs. time on bandpass calibrator for VLA K-band observations - mediocre weather

Examples of Calibrator Models

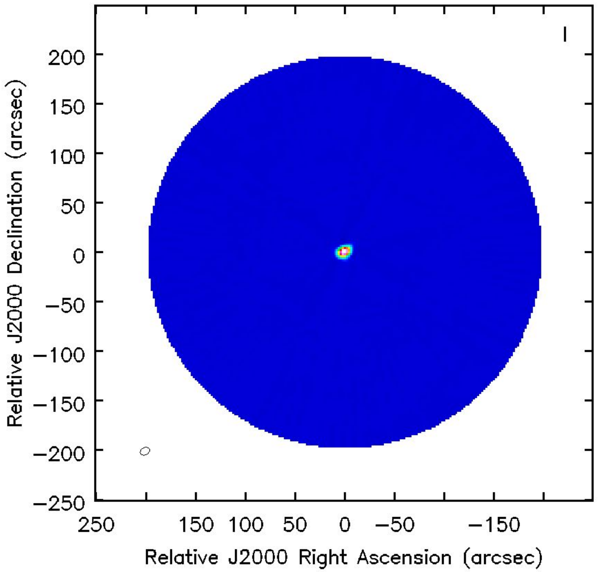
Calibrator 1



Calibrator 2

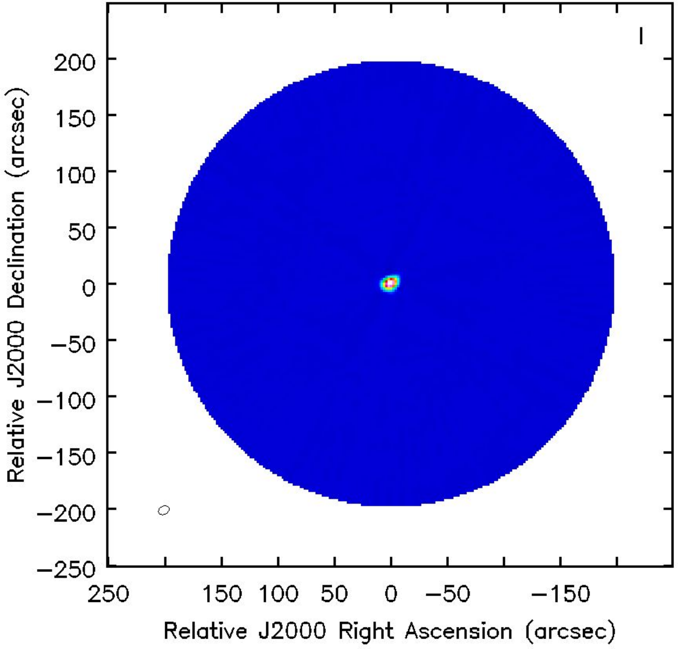


Calibrator 3 (Off Center)



Not a calibrator!

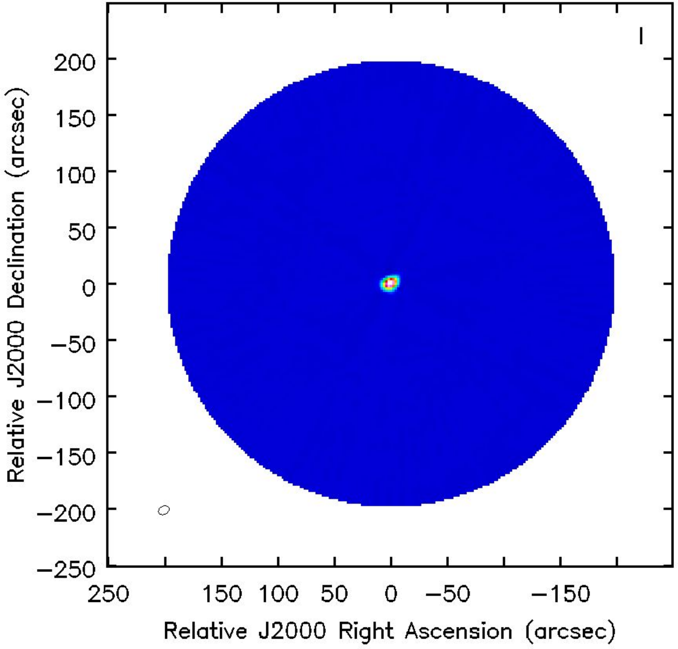
- This source is not a calibrator, it is a science target.
- **What is stopping you from using this source as a calibrator?**



Not a calibrator!

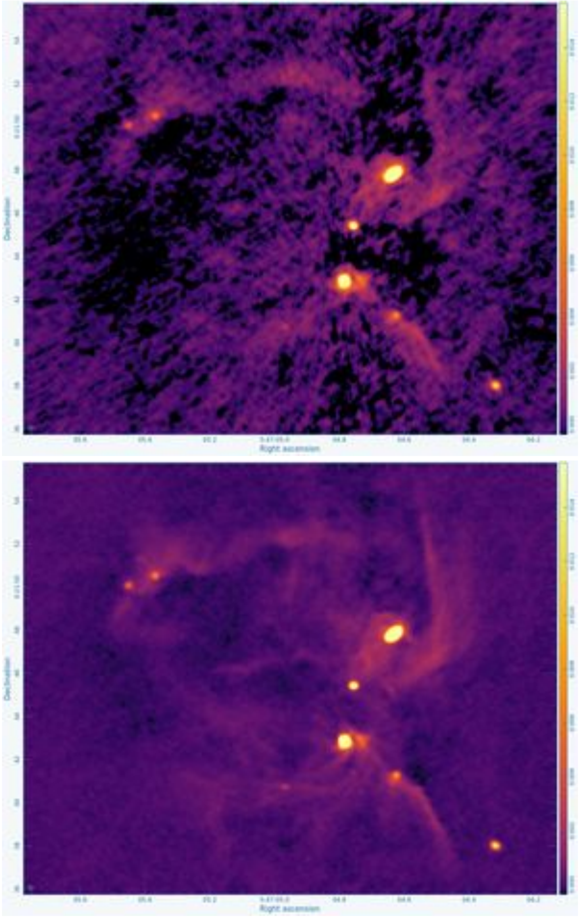
- This source is not a calibrator, it is a science target.
- **What is stopping you from using this source as a calibrator?**

- Good news! YOU CAN!
  - Any source can be a calibrator if you have a good model of the source.
  - “Self-calibration”



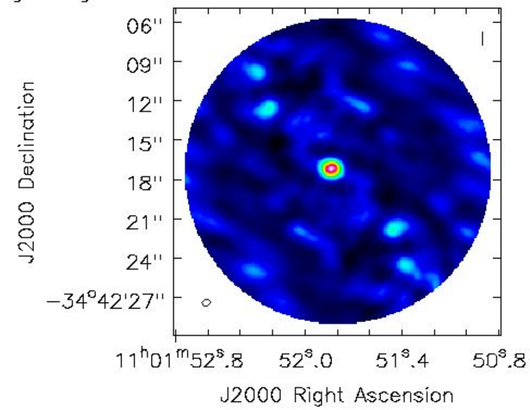
Why self calibration?

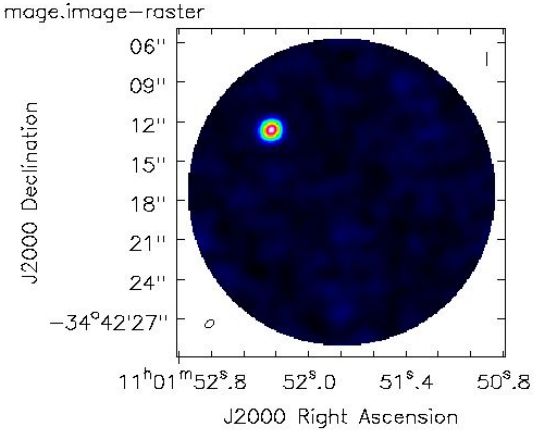
- ALMA (and the JVLA) have such impressive sensitivity that what you achieve is often limited by residual calibration errors!
- To surpass this, many objects have enough Signal-to-Noise (S/N) that they can be used to calibrate ***themselves*** to obtain a better image. This is self-calibration.
  - Sometimes, the increase in effective sensitivity may be an *order of magnitude!*
- It is not a circular trick to produce the image that you want.
  - It works because the number of baselines is much larger than the number of antennas so that an approximate source image does not stop you from determining a better temporal gain calibration which leads to a better source image.



Creating your own model

- Tclean creates models using the clean components when running.
  - **<u>If</u>** what you clean is real, you can use the model for calibration.
  - CAUTION: If you add sources that are not real, you can create fake structure in your data.
    - This is more of a concern if the array has a small number of antennas such as the ACA, GMVA, EHT, or VLBA





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SNR for self-calibration:

- **For phase only self-cal:** Need to detect the target with a S/N > 3 in a solution time (**solint**) less than the time for significant phase variations for all baselines to **a single antenna.**
- Make an initial image, cleaning it conservatively
  - Measure rms in emission free region
  - $rms_{Ant} = rms_{im}\sqrt{N-3}$ where N is # of antennas
  - $rms_{self} = rms_{Ant}\sqrt{\frac{t_{total}}{t_{solint}}}$
  - If $\frac{S_{peak}}{rms_{self}} > 3$:try phase only self-cal

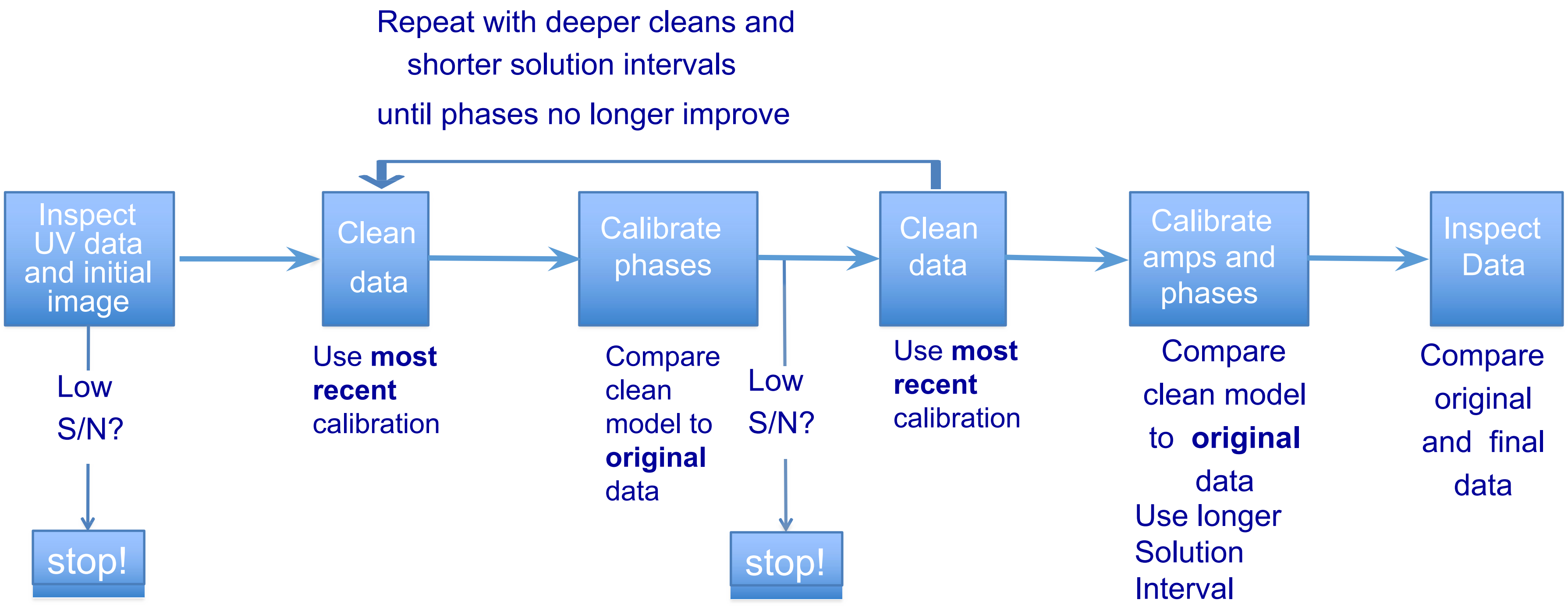
- CAVEAT 1: If dominated by extended emission,estimate what the flux will be on the longer baselines (by plotting the uv-data) instead of the image
  - If the majority of the baselines in the array cannot "see" the majority of emission in the target field (i.e. emission is resolved out) at a S/N of about 3, the self-cal will fail in extreme cases (though bootstrapping from short to longer baselines is possible, but it can be tricky).

- CAVEAT 2: If severely dynamic range limited (poor uv-coverage), it can also be helpful to estimate the rms noise from uv-plots

SNR for self calibration:

- **For amplitude self-cal:** Need to detect the target with a S/N > 10 with only the baselines to a single antenna in a solution time (solint) less than the time for significant amplitude variations. For 25 antennas, an antenna based S/N > 10 will lead to a 10% amplitude error.
  - Amplitude corrections are more subject to deficiencies in the model image. Check results carefully!
  - For example, if clean model is missing significant flux compared to uv-data, give uvrange for amplitude solution that excludes short baselines.

Outline of Self-Calibration Process:



How to proceed with self-calibration?

- **What is a good $\text{solint}_{\text{self}}$ to start with?**

- Best practice is to start self-calibration gently with long solints, cleaning deeper with successive solution intervals as the data are corrected and model is improved

  - Best Starting solution interval is long, length of full observation of a single source for ALMA (~90 minutes) or ~1-2 hours for VLA; if observation length is longer, split into ~1 hour intervals
    - neet to use solint='inf' and combine='scan' in *gaincal*

  - This coarse solution interval will enable primarily direction-dependent errors to be corrected; i.e., antenna position errors which result in errors from phase referencing
    - The level of improvement can be surprising from such a coarse correction

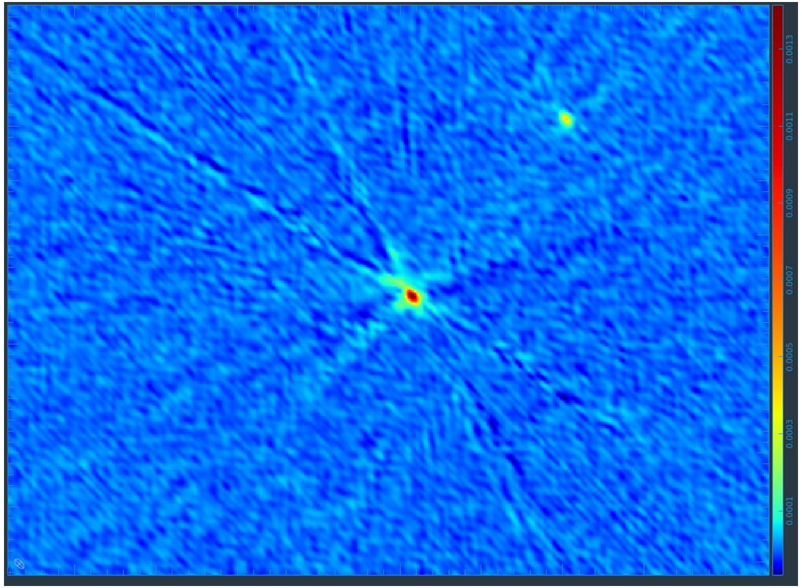
  - Then solution interval should be shortened to length of 1 scan (solint='inf' and omit combine='scan')
    - Solints spanning multiple scans not generally helpful since those corrections are taken care of by phase referencing

How to proceed with self-calibration? -cont’d

- Then proceed to solution intervals shorter than a single scan
  - Most scans have similar length of time
  - Given S/N of data what subdivision of scan lengths would most likely be successful?
    - Generally dividing typical scan length by 2 or 3 repeatedly until solint=’int’ (single integration works well
    - For example, if a scan is 60s
      - 30s (30.25s)
      - ~15s (18.15s or 12.1s)
      - ~8s (or 6.05s)
      - int
      - Tip: When solution interval only has a few integrations, try to use an integer number of integrations in the solution interval
    - Beware *gaincal* and uneven division of scans
      - For example, if you have 45s scans, and do solint=’20s’, *gaincal* will divide the scan into 2x 20s solints and 1x 5s solint which will have a factor of 2 lower S/N

How to proceed with self-calibration? -cont'd

- How deep to clean in each solution interval?
- General rule is to clean conservatively at the beginning,
  - avoid artifacts and do not clean below their level
  - artifacts: symmetric or things that look like artificial patterns



How to proceed with self-calibration? -cont'd

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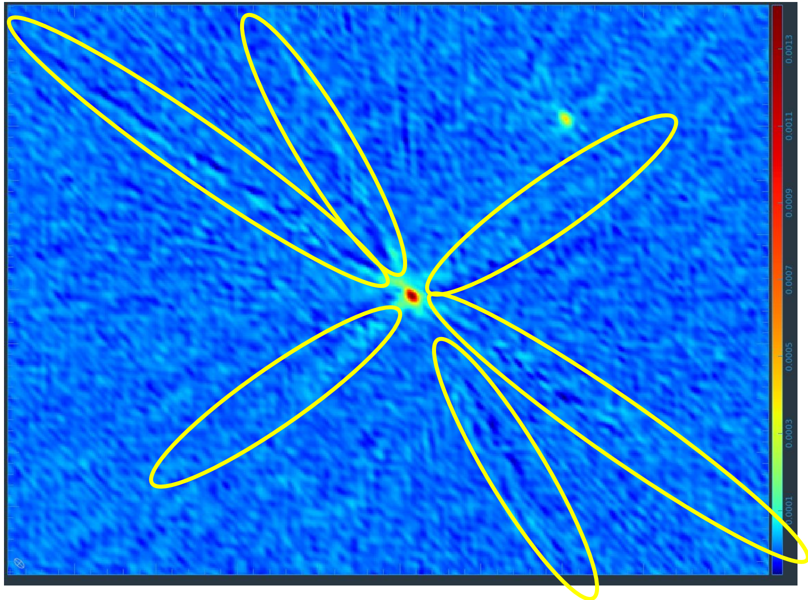
- Good idea to clean interactively at first to get a feel for self-calibration and model creation



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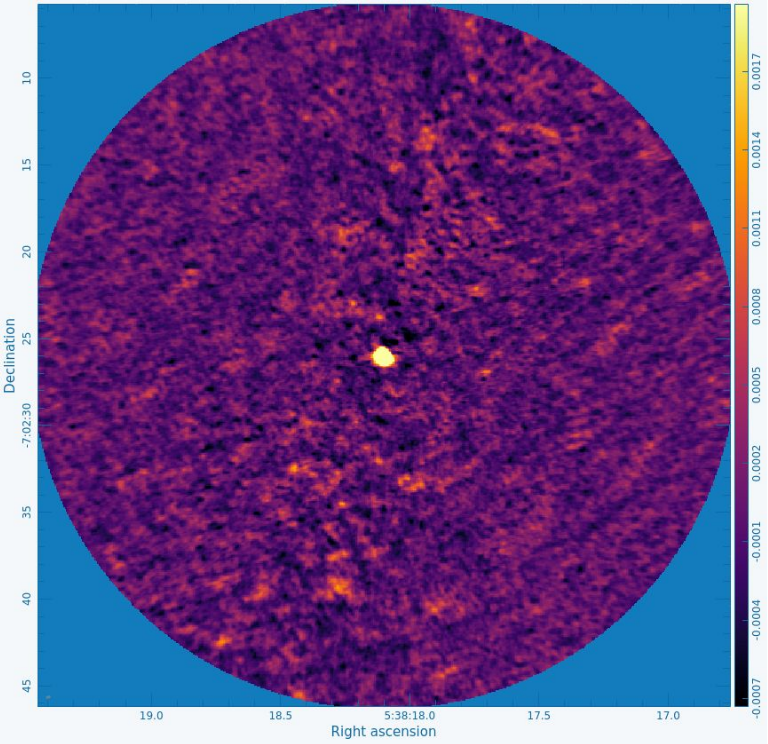

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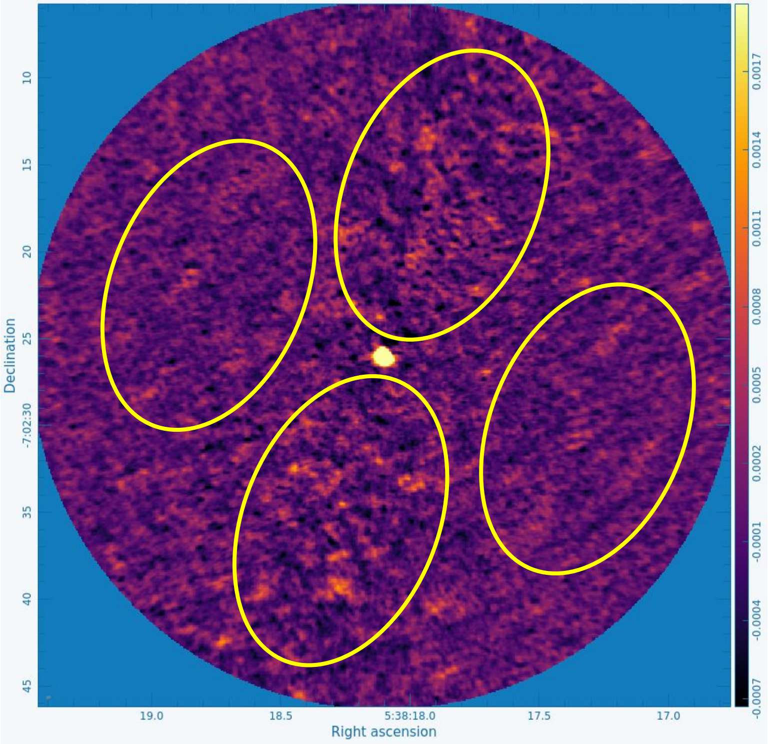
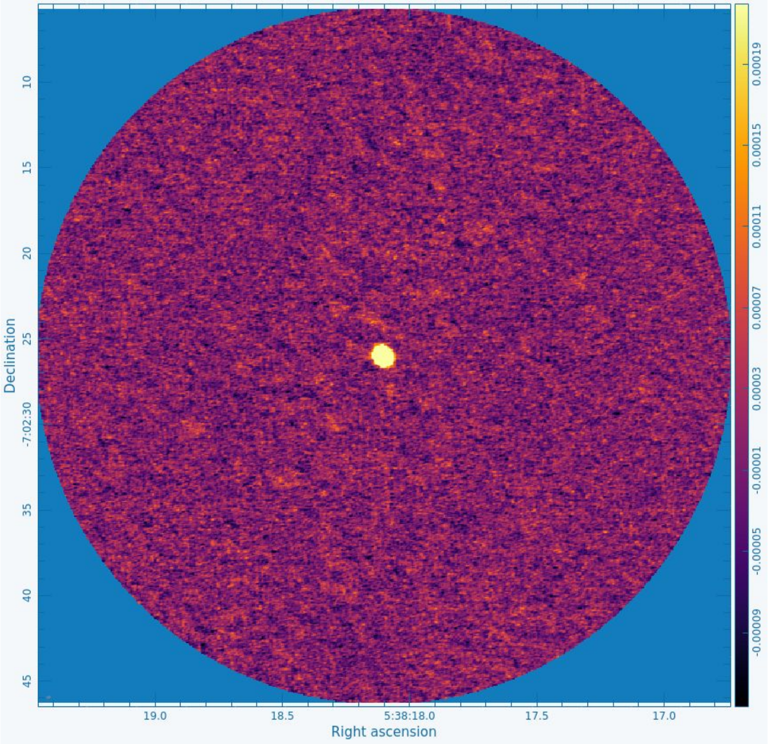


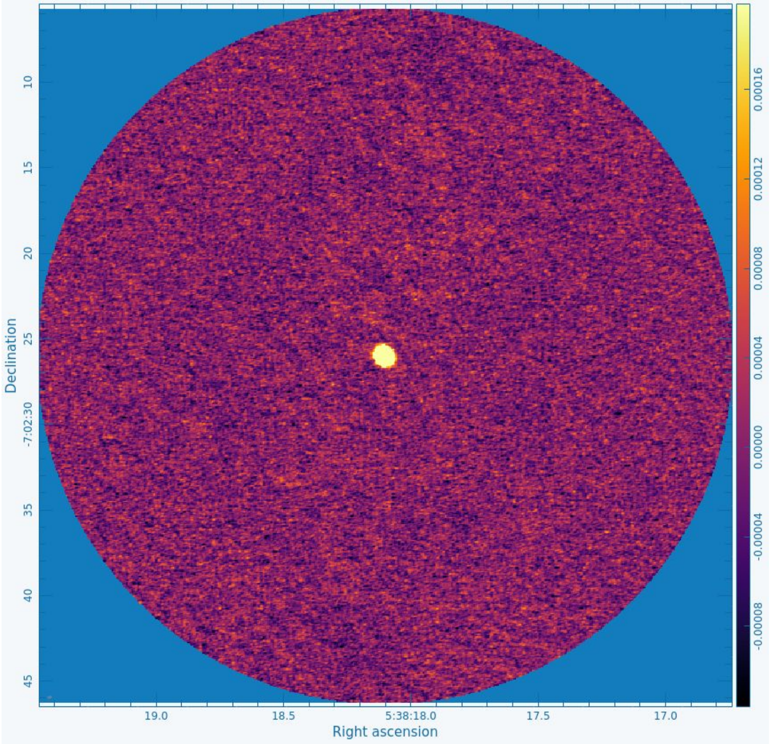
Where to Stop?

- As long as you are seeing bonafide improvments in each successive solution interval, it’s safe to continue
  - Peaks are not decreasing (adding phase noise in)
  - RMS is not increasing (sign of adding noise or over flagging)
  - artifacts are not emerging inexplicably
  - beam is not changing significantly
- Best practice: After each round of selfcal, should make a ‘post-solint’ image, cleaned to exactly the same depth as the image for model creation
  - Evaluate basic metrics above
  - If metrics pass, try another, shorter solint
  - If metrics fail, previous solution interval should be your final one

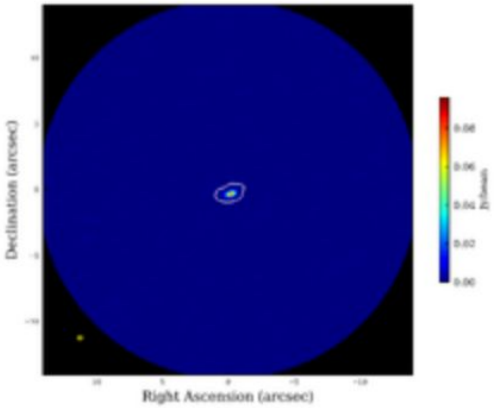
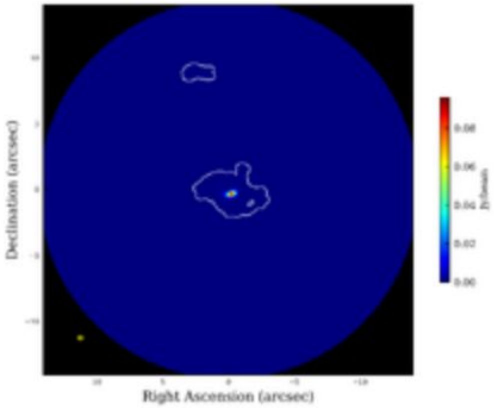


Other tips and tricks

- If you need more S/N for your solutions (gaincal is flagging them)
  - solint is too short
  - Use gaintype='T' (combines the orthogonal polarizations)
  - use combine='spw', combines data from all spws to create the gain solution (need to use spwmap parameter in applycal)
  - If high dynamic range (>~500) for ALMA, try using deconvolver='mtmfs',nterms=2; the spectral shape of the emission may limit dynamic range with deconvolver='hogbom'



hif_selfcal: Automated Self-Calibration

Data Type	Initial	Final
Image		
Integrated Flux	193.219 ± 2.278 mJy	200.061 ± 2.276 mJy
SNR	482.931	3050.983

Triggering criteria and inputs into hif_selfcal task

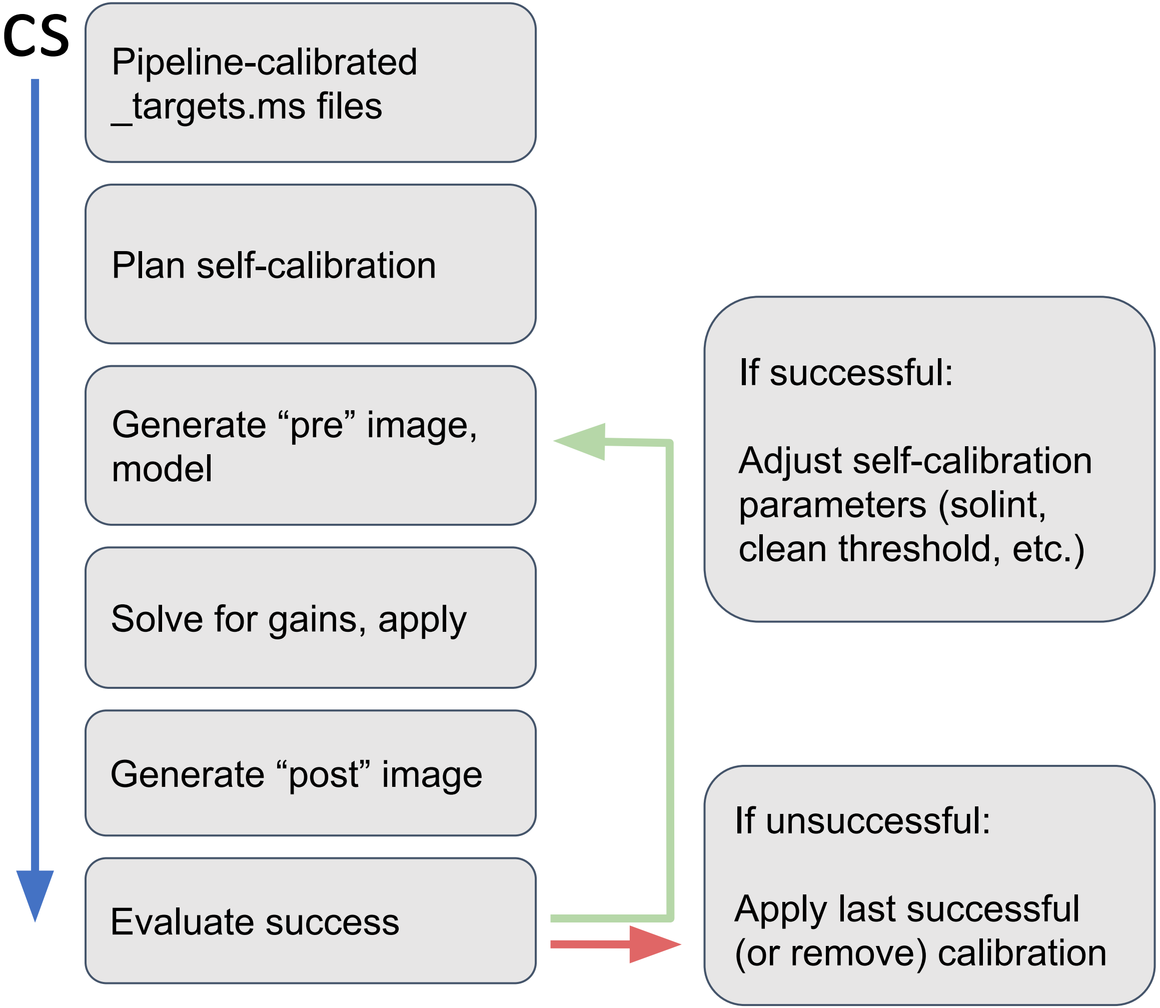
- Will run on all single field targets
  - hif_selfcal will no-op if it calculates selfcal will be of no benefit
    - Estimates the gaincal solution SNR on a per solution interval, per antenna basis and only proceeds with a solution interval if above a threshold (default=3)

- Tunable parameters:
  - field (string) - field names to self-calibrate e.g., "HL_Tau"; default = "" which will self-calibrate all sources
  - apply_cal_mode_default (string) - Apply mode to use for *applycal* task during self-calibration; default = 'calflag'; options: 'calflag' ,'calonly', 'calflagstrict'
  - amplitude_selfcal (boolean) - Attempt amplitude self-calibration following phase-only self-calibration; default = False
  - gaincal_minsnr (float) - Minimum S/N for a solution to not be flagged by gaincal; default = 2.0
  - minsnr_to_proceed (float) - Minimum estimated self-cal S/N computed on a per solution interval, per per antenna basis, used to determine whether to attempt self-calibration for a source at a given solution interval; default = 3.0
  - delta_beam_thresh (float) - Allowed fractional change in beam area for self-calibration to accept results of a solution interval; default = 0.05

See https://science.nrao.edu/srdp/self-calibration-preview for more details

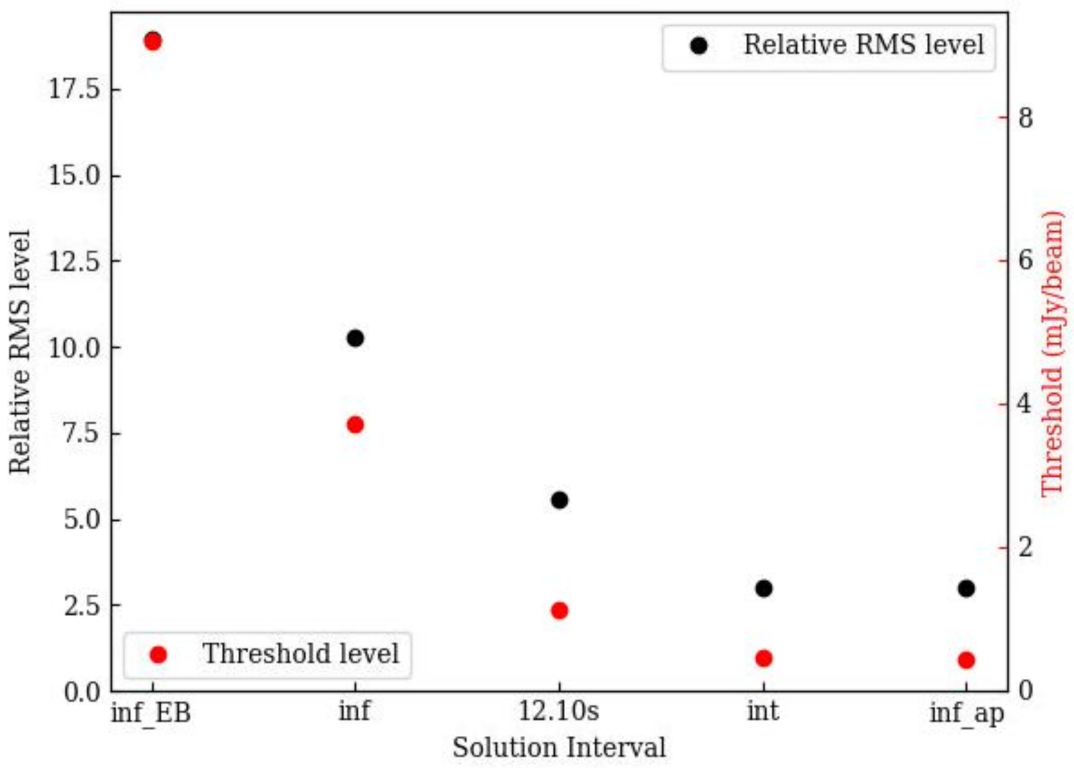
hif_selfcal heuristics

- Designed to mimic an interactive self-calibration workflow
- Heuristics added/developed to automate the process



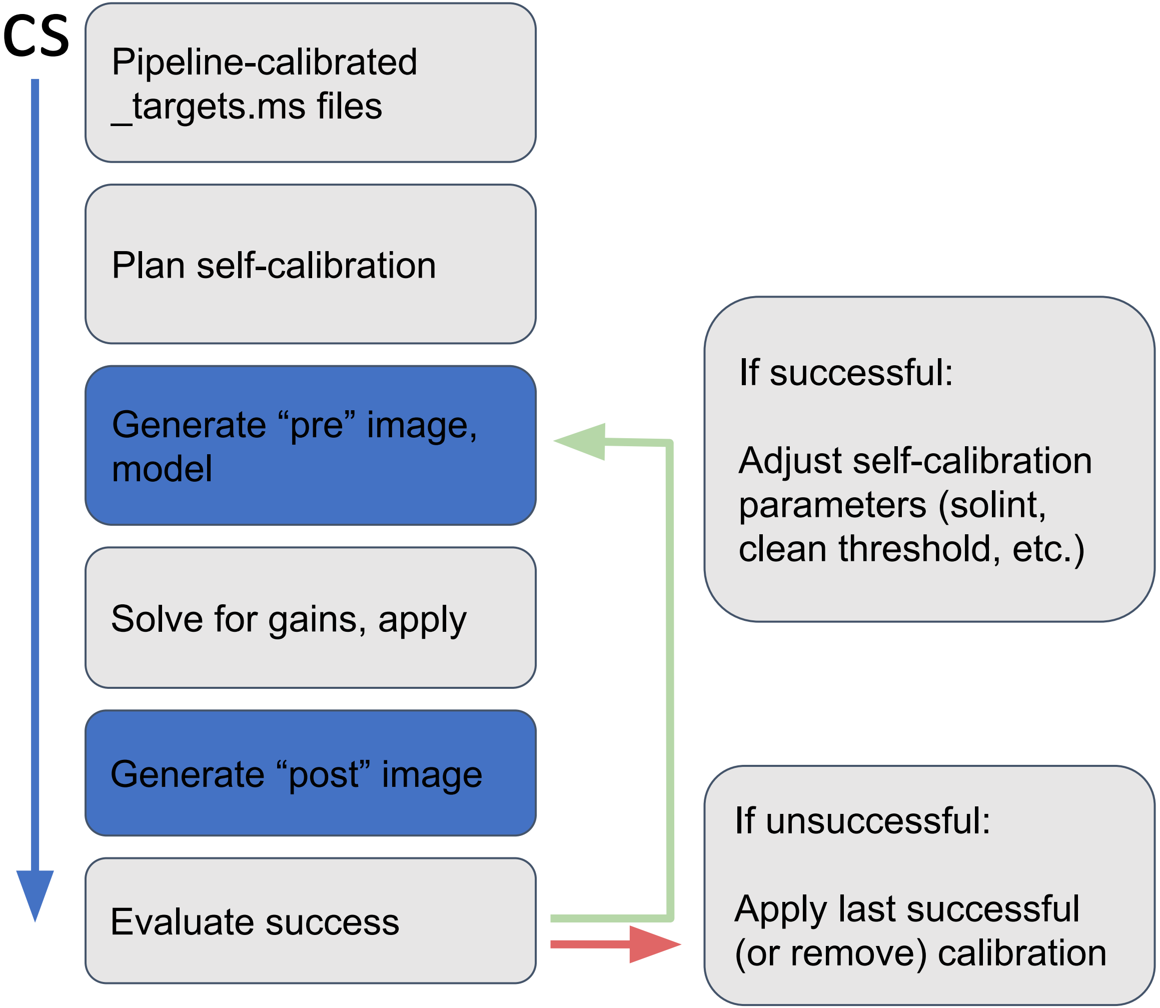
hif_selfcal heuristics

- Designed to mimic an interactive self-calibration workflow
- Self-calibration plan is set prior to executing self-calibration. This includes determining:
    - Self-calibration solution intervals
        - Start with long intervals (“inf”), shorten until (‘int’)
    - Clean threshold for each interval
        - Start shallow, increase depth



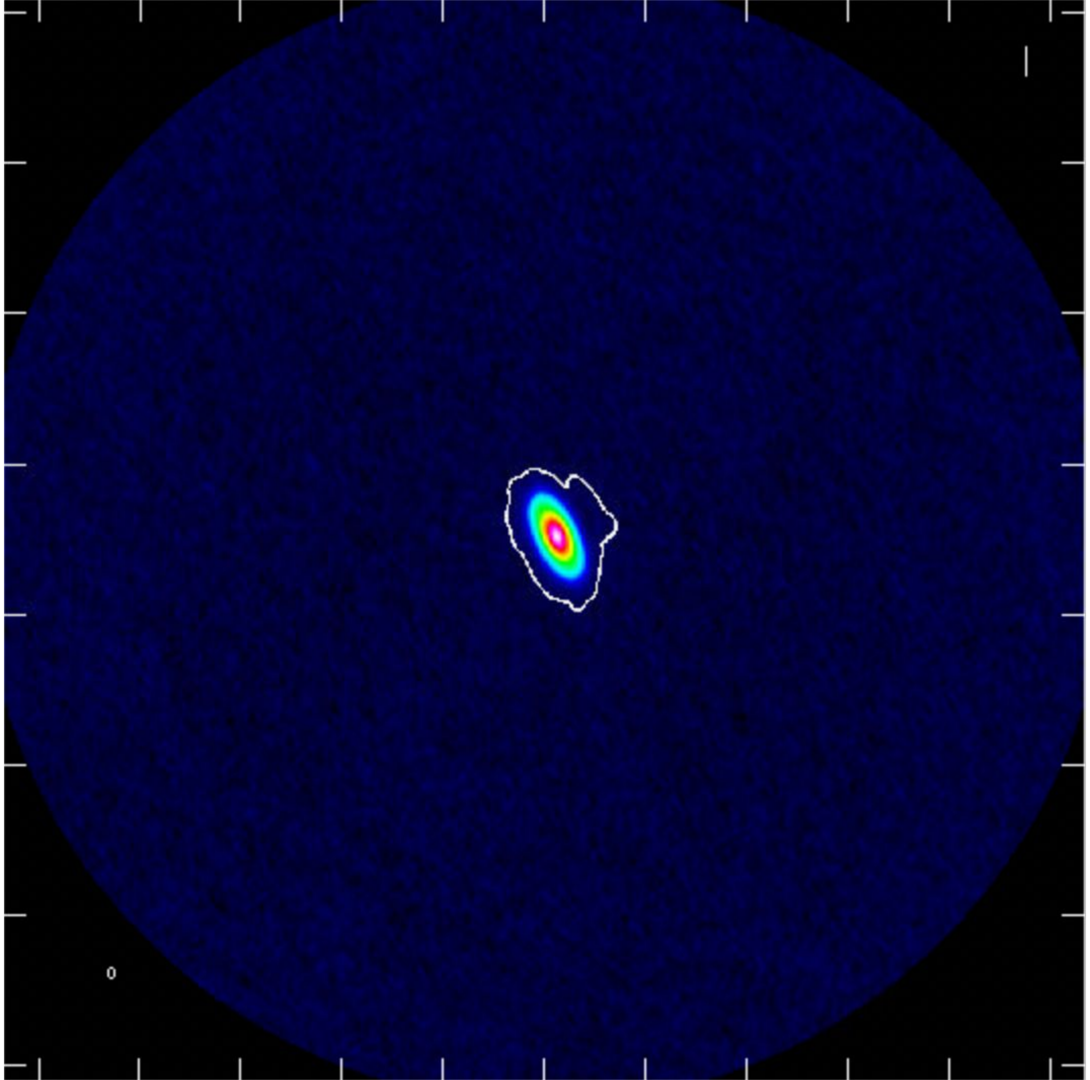
hif_selfcal heuristics

- Designed to mimic an interactive self-calibration workflow
- Generate an image prior to calibration, save the model to use for calculating gain tables.
- Automated using:
  - Pre-defined clean thresholds
  - Auto-masking to define regions to clean

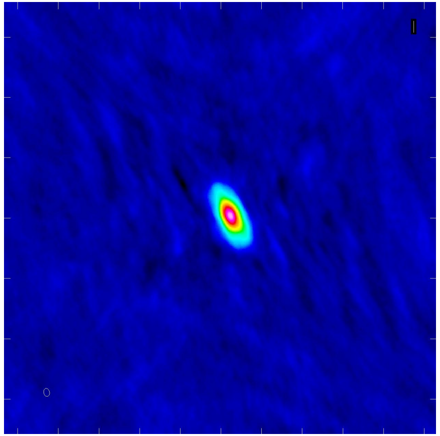


hif_selfcal heuristics

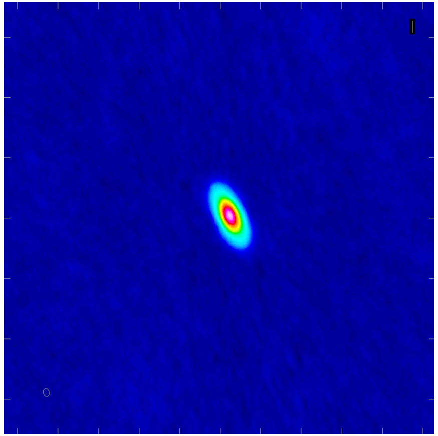
- Designed to mimic an interactive self-calibration workflow
- Metrics evaluated to determine the success of the calibration:
    - Pre-vs-post SNR
        - Evaluated outside the "*post*" clean mask
    - Pre-vs-post beam size
- Pre-vs-post "near-field" SNR calculated but not a decision point at this time
    - SNR with the noise calculate near to sources in the image



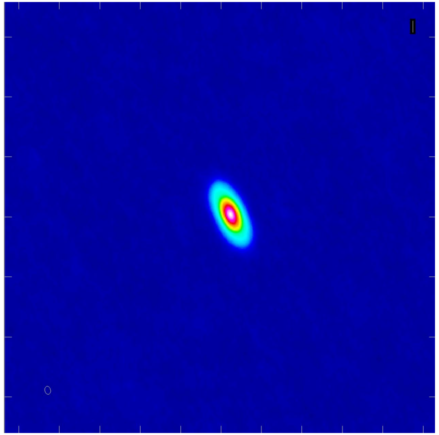
Example of improvement in image quality



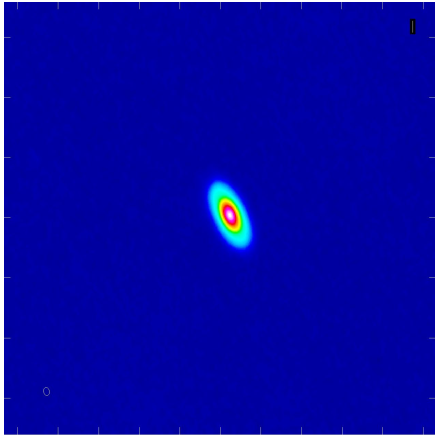
Initial
SNR = 285



inf_EB
SNR = 402



inf
SNR = 776



int
SNR = 1151

hif_selfcal output - weblog

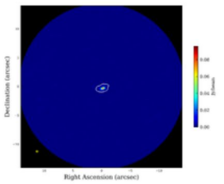
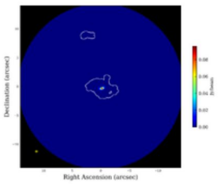
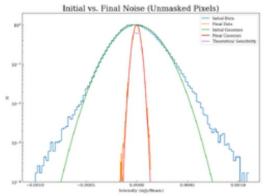
List of Self-cal Targets

Field	Band	spw	phasecenter	cell	imsize	Solints to Attempt	Success	Contline applied	Line applied
IRS48 (rep.source)	Band 7	25,27,29,31	ICRS 16:27:37.1797 -024.30.35.480	['0.052arcsec']	[540, 540]	inf_EB, inf, 151.20s, 48.38s, 12.10s, int	✔	✔	✔

Self-calibration Target(s) Summary

Self-cal Target Details

IRS48 Band 7 back to top SUMMARY PER-SOLINT DETAILS

Data Type	Initial	Final	Brightness Dist. / Ratio
Image			
Integrated Flux	193.219 ± 2.278 mJy	200.061 ± 2.276 mJy	1.035
SNR	482.931	3050.983	6.318
SNR (N.F.)	484.433	3053.878	6.304
RMS	0.172 mJy/bm	0.031 mJy/bm	0.182
RMS (N.F.)			0.183
Beam	0.330"x0.258" -84.362 deg	0.331"x0.258" -84.180 deg	1.002
Success / Final Solint	Yes / int		
Stop Reason	None		

Solint	inf_EB	inf	151.20s
Result	Pass QA Plots	Pass QA Plots	Pass QA Plots
Integrated Flux	194.114 ± 0.646 mJy	192.873 ± 0.252 mJy	191.989 ± 0.169 mJy
Integrated Flux Change	1.008	1.001	0.991
Dynamic Range	633.264	1661.764	2479.466
DR Improvement	1.327	2.442	1.292
Dynamic Range (N.F.)	633.755	1664.341	2484.522
DR Improvement (N.F.)	1.327	2.442	1.292
RMS	0.134 mJy/bm	0.054 mJy/bm	0.037 mJy/bm
RMS Improvement	1.304	2.331	1.262
RMS (N.F.)	0.134 mJy/bm	0.054 mJy/bm	0.037 mJy/bm
RMS Improvement (N.F.)	1.304	2.331	1.262
Beam Pre	0.330"x0.258" -84.362 deg	0.330"x0.258" -84.368 deg	0.330"x0.258" -84.354 deg
Beam post			
Ratio of Beam Area			1.000
Clean Threshold	4.278 mJy/bm	1.067 mJy/bm	0.457 mJy/bm

Features in current release vs future releases

In the recent Pipeline release:

- Self-calibration of single-pointing ALMA (and VLA) datasets
  - Multi-source EBs work
  - I.e. no mosaics

In the Standalone development branch:

- Near-field heuristics with improved near-field mask generation
- Improved heuristics for “long baseline” datasets
- Mosaics work
- Available here soon (when stable): https://github.com/jjtobin/auto_selfcal.git
- Or here now (development): https://github.com/psheehan/auto_selfcal.git

Summary

- Self-calibration is not magic, but rather a well-understood process to improve (sometimes drastically) the quality of data from interferometers
  - Care and caution is required, but is not tremendously difficult
  - Make sure your model is a good representation of the data
  - Make sure the data you put into solver, is a good match to the model
  - If you are lacking a little in S/N try one of the “S/N increase techniques”
  - If you really don’t have enough S/N don’t keep the dodgy results!

- For more examples, advice, and explanatory details see:
  - **Advanced Gain Calibration Techniques in Radio Interferometry** (https://arxiv.org/abs/1805.05266) **Crystal Brogan, Todd Hunter, Ed Fomalont**

- Automated self calibration is now a reality for continuum data
  - CASA-integrated pipeline version (based on stable version)
    - https://science.nrao.edu/srdp/self-calibration-preview
  - Also available via ALMA reimaging service within NRAO archive (https://data.nrao.edu)

Self-Cal Resources

- ALMA Self-cal Tutorial
  - https://casaguides.nrao.edu/index.php?title=First_Look_at_Self_Calibration_CASA_6
- VLA Self-cal Tutorial
  - https://casaguides.nrao.edu/index.php?title=VLA_Self-calibration_Tutorial-CASA6.4.1
- Self Calibration Pipeline Preview
  - https://science.nrao.edu/srdp/self-calibration-preview

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