

NRAO



National Radio Astronomy Observatory



Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array



Self-Calibration



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Motivation

ALMA has impressive sensitivity when compared with other mm-wave interferometers!

Many objects will be sufficiently **strong** so they can be used to better calibrate **themselves** to obtain a more accurate image. This is called self-calibration and it really works, if you are careful! 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.

Self-cal may not be included in the data shipped to PI's. **SO, YOU SHOULD LEARN HOW TO DO IT.** It is just a minor change to the ordinary gaincal calibration, but generally with lower signal-to-noise.



Outline

- Calibration: Determining antenna complex gains
- Minor adjustment for self-calibration
- Why self-cal works
- Sensitivity and noise considerations
- Examples here and in working area

Strong point source

ngc3256 Continuum and line



The Visibilities

Amplitudes and Phases

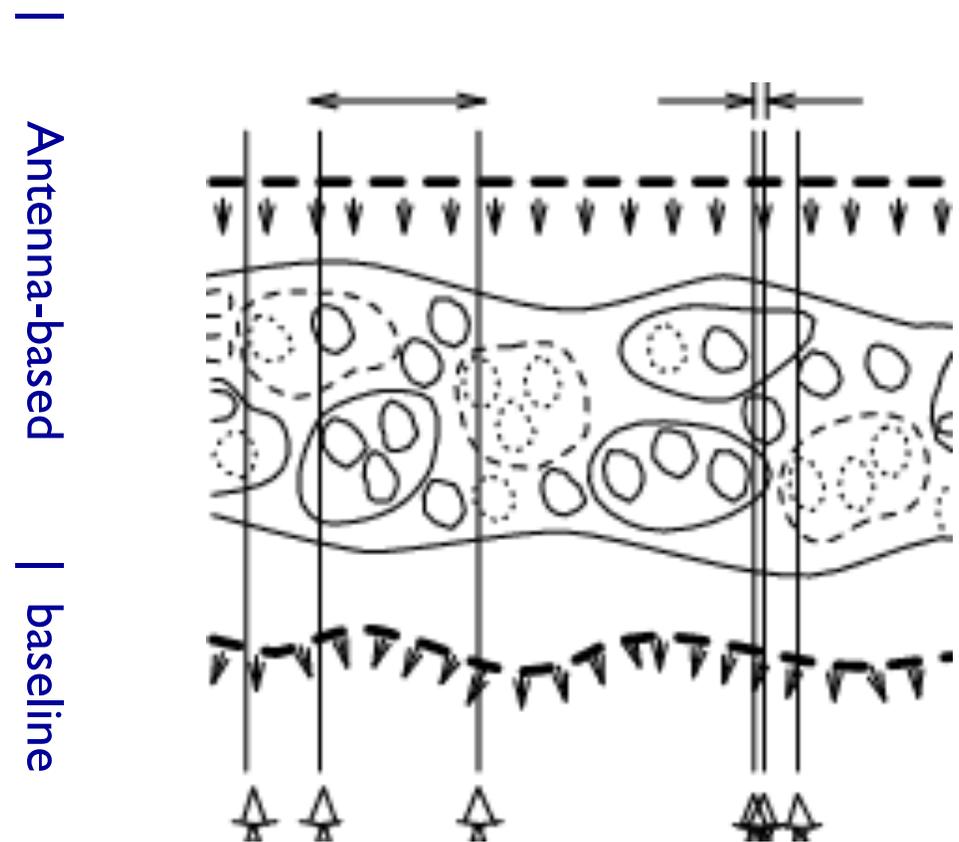
- Each pair of antennas (i, j) will generate a visibility (amplitude and phase), $V(i, j; t, \nu)$, the 2D Fourier transform of the brightness on the sky, $T(x, y; \nu)$.
- Every integration: time interval, Δt , about 5 sec
 - Every channel: frequency interval, $\Delta \nu$, 10 MHz
 - u, v for a visibility are determined from ($i, j; t, \nu$)



Data Corruption Types

The true visibility is corrupted by many effects:

- Atmosphere absorption
- Radio “seeing”
- Variable pointing offsets
- Variable delay offsets
- Electronic gain changes
- Electronic delay changes
- Electronic phase changes
- Radiometer noise
- Correlator mal-functions
- Most Interference signals



Antenna-based Calibrations

- The most important corruptions as associated with an antenna
- Basic Calibration Equation

$$V_{i,j}^{\circ}(t,\nu) = g_i(t)g_j^*(t) \cdot b_i(\nu)b_j^*(\nu) \cdot V_{i,j}(t,\nu) + e_{i,j}(t,\nu)$$

Where

$V_{i,j}^{\circ}(t,\nu)$ = Observed visibility on baseline (i,j) at time t, and frequency ν

$V_{i,j}(t,\nu)$ = True visibility on baseline (i,j) at time t, and frequency ν

$g_i(t)$ = Complex temporal gain for antenna i (* means complex conjugate)

$b_i(\nu)$ = Complex frequency bandpass for antenna i

$e_{i,j}(t,\nu)$ = Noise and other small baseline-based contaminations.

NOTE: The bandpass is generally stable with time and is assumed to be determined independently and the correction applied to the observed visibility. So, all data will be collapsed in frequency space.
CASA does have a blcal, but not need except in exceptional circumstances.

GAIN SOLUTIONS ARE THE REASON SELF-CAL WORKS



Antenna-based Calibrations

Bottom line:

1. For N antennas, $(N-1)*N/2$ visibilities are measured.
2. After internal calibrations to remove 'baseline-based anomalies, only N amplitude gains and $(N-1)$ phase gains will describe the complete calibration of the data.
3. This redundancy can be used in several ways:
 - Decrease antenna gain calibration noise
 - Simultaneously improve source structure (self-cal)



Antenna Calibration Equation

- Basic calibration involves observing “calibrators” of known brightness, position and morphology. Usually they are quasars, bright point sources, or solar system objects with accurately known models with visibility is $M_{i,j}(t_k, \nu)$
- Determine gain corrections, g_i , that minimizes S_k for each time stamp t_k where

$$S_k = \sum_k \sum_{i,j}^{i \neq j} w_{i,j} |g_i(t_k) g_j^*(t_k) V_{i,j}^o(t_k) - M_{i,j}(t_k)|^2$$

- The solution interval, T_m , is the data averaging time used to obtain the values of g_i , typically [solint='int' or 'inf'] The a priori weight of each data point is $w_{i,j}$. The interval should be as short as possible, as long as there is sufficient SNR for a robust solution.



Self-Calibration Equation

- The normal calibrations determine $g_i(t_k)$ from the calibrator observations and applied to data using applycal.
- An image, $T(x,y)$, can then be made for each target.
- Additional calibrations can then be determined to improve BOTH the differential gains at the target $\Delta g_i(t_k)$ and an improved image.

$$S_k = \sum_k \sum_{i,j}^{i \neq j} w_{i,j} |M_{i,j}^2(t_k)| |\Delta g_i(t_k) \Delta g_j^*(t_k) \frac{V_{i,j}^c(t_k)}{M_{i,j}(t_k)} + \frac{\Delta M_{i,j}}{M_{i,j}}|^2$$

- $V_{i,j}^c(t_k)$ is the corrected visibility data after normal gain calibration
- Note: M and ΔM are the visibilities associated with $T(x,y)$ and $\Delta T(x,y)$, which is unknown.
- The effective weight of a point varies as M^2 , so extended sources that have low visibilities at long spacings will have less weight.



To a first approximation, the complex gain for antenna i , Δg_i , can be obtained by combining the ratio of the observed visibility with the model for each of the baselines associated with antenna i . If the model is in error, then another term equal to the fraction of the model error is also added to the estimate of Δg_i .

$$\Delta g_i \approx \frac{1}{N-1} \sum_{j \neq i}^j \left[\frac{V_{i,j}^c}{M_{i,j}} + \frac{\Delta M_{i,j}}{M_{i,j}} \right] \quad (1)$$

Since all instrumental/tropospheric errors are assumed to be antenna-based, these gain terms are correlated for each j^{th} antenna to the i^{th} antenna and will produce a significant effect on Δg_i . On the otherhand, the model error term,

$$\frac{\Delta M_{i,j}}{M_{i,j}} \quad (2)$$

produce baseline-based quantities (as are all structure visibilities), and the sum of these terms tends to decrease (remember, these are all complex quantities) approximately by $\sqrt{N-1}$, where N is the number of antennas. Large-scale model errors produce more random visibility errors than small-scale model errors. Thus, the effect of a model error on the antenna gain estimate is significantly reduced.

BOTTOM LINE: As long as the initial model is reasonably well-known, then the gain-solver will obtain the antenna-based calibrations with minimal effect from the baseline-based contributions of the source model error. The image then made will be significantly improved, because of the correction of antenna-based errors (mostly the phase), and a better image $T(x, y) + \Delta T(x, y)$ will be obtained. However, this process must be done iteratively in order to converge on a good approximation of the structure.

PROBLEMS: Problems occur when the apriori model is in error, especially for extended sources, and when the solution signal to noise is low (see tables) in which case bogus structures can and will be produced.



Different Sensitivities

- ALMA properties used for these Sensitivity Calculations:
 - N = 25 antennas of 12-m diameter
 - 10-sec integration time; 2 GHz bandwidth, One polarization

Several ALMA Sensitivities (units=mJy)

Date specification		Band 3	Band 6	Band 7	Band 9
Image rms	σ_i	0.93	1.50	3.21	25.6
Baseline rms	σ_b	16.1	26.0	55.6	443.0
Antenna rms	σ_g	3.4	5.54	11.8	95.0

$\sigma_i = \sigma_b / \text{sqrt}[(N*N-1)/2]$: i.e number of baselines

$\sigma_g = \sigma_b / \text{sqrt}(N-3)$: antenna gain error from calibration

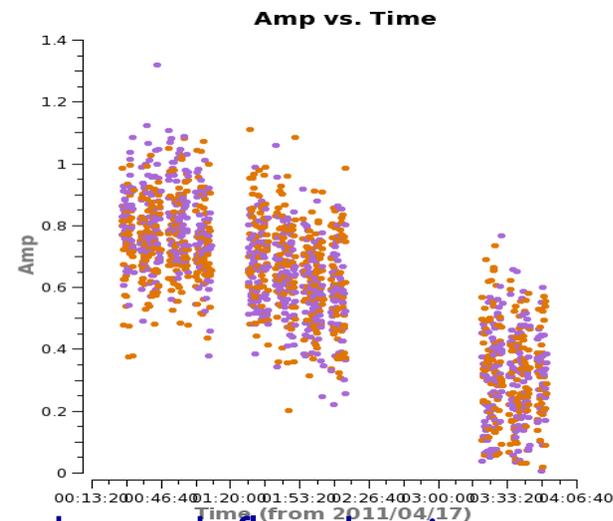
- Scale sensitivities to solution interval T_m , and frequency width.



Antenna Calibration Sensitivities

For calibration and self-calibration, the critical factor is the antenna gain dynamic range, d_g . The best method to determine this quantity is as follows:

- (1) Find the rms noise for a typical baseline for each sampled point, σ_b . The best method is to use plotms on data with little structure. Determine σ_g for a sample interval by scaling by $1/\sqrt{N-3}$.
- (2) Make an image after normal calibration and determine the peak flux density, P . This peak is a lower limit. The rms on the image may be large because of dynamic range limits, and should not be used to estimate $d_g = P/\sigma_g$.
- (3) Choose the solution interval so that d_g is at least 25 (table next page)
- (4) Additional SNR can be obtained by:
 - gaintype= 'T' in gaincal to average X and Y
 - combine = 'spw' in gaincal to average spw's**WHY? Because after initial calibration, these should have almost the same phase errors with time.**



Calibration Sensitivities Effects (N=25)

d_g	Amp error	Phase error	d_b	d_i
0	100%	180 d	0	0
3	33%	15.0 d	0.6	11.0
5	20%	9.7 d	1.1	18.4
10	10%	5.7 d	2.1	36.9
25	4%	2.3 d	5.3	92.3
100	1%	0.6 d	21.3	370

d_g phase error must be smaller than expected instrumental and tropospheric phase error which is often 10-20 deg

d_g amp error must be smaller than expected instrumental and absorption amplitude errors, usually $< 5\%$



Self-cal Example (in tutorial)

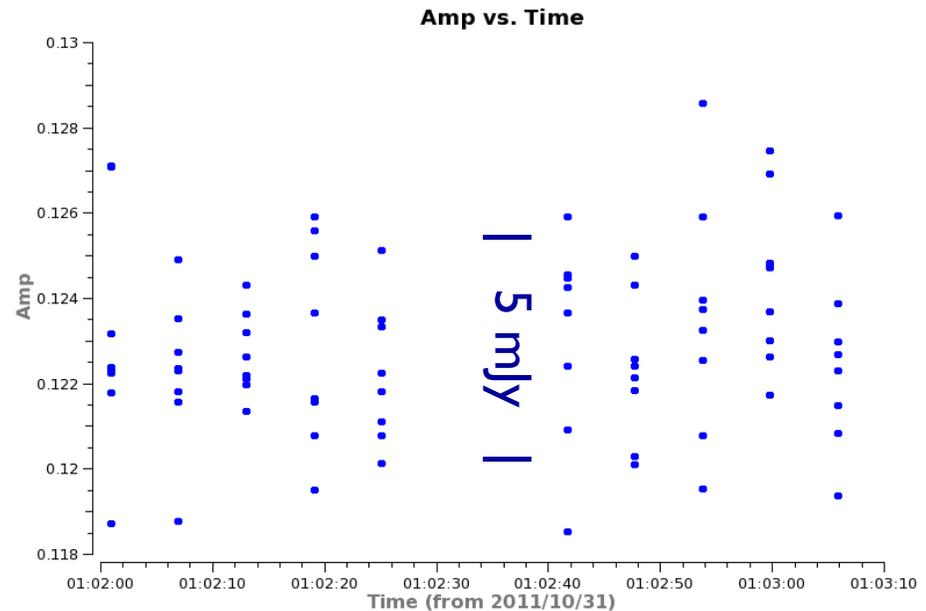
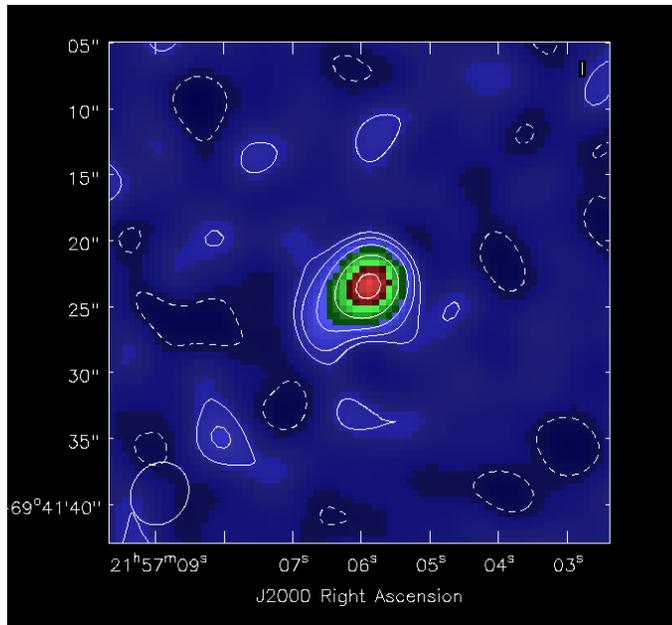


Image of 2157-694 after normal cal
 $P_k = 95$ mJy, $\text{contlev} = 5$ mJy; $d_i \sim 40$
 Noise = **1.5 mJy**: Dyn Range Limited!!

Expected image noise = **0.05** mJy =
 $5 \text{ mJy} / \sqrt{10 * 15 * 7 * 8}$

Data for typical baseline, using plotms.
 Noise is about 5 mJy per point.

6-sec samples, 10 samples in scan

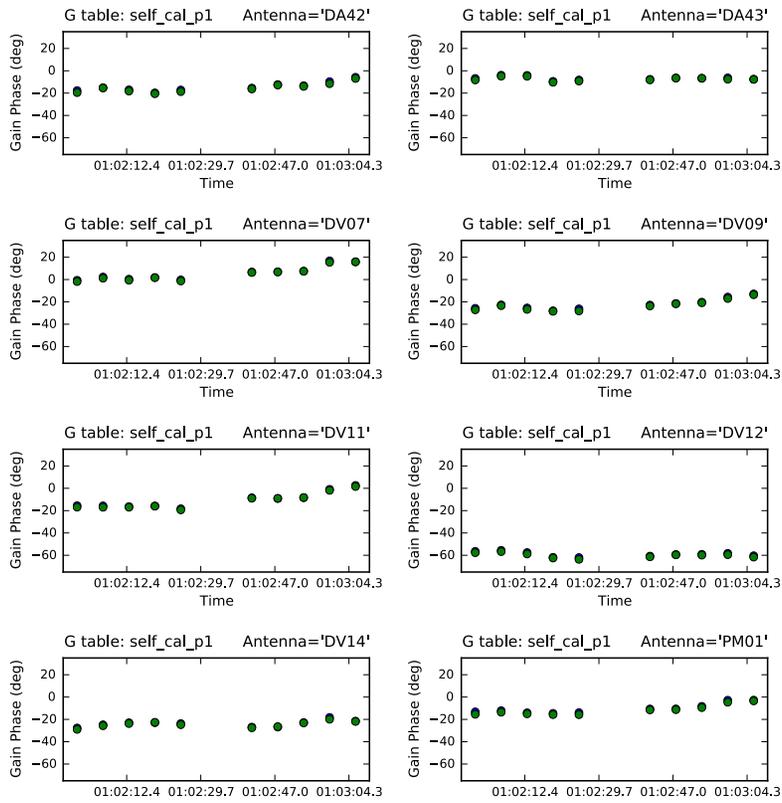
Baseline dyn rng: $d_b = 124 \text{ mJy} / 5 \text{ mJy} = 25$

$N = 15$ antennas, $d_g = 25 * \sqrt{12} = 87$

Expect 1.2%, 0.7 deg gain accuracy.



Selfcal Example (cont)



Phase solutions for some antennas
One pol, one spw
Solution per 6sec data sample

General Comments for ALMA selfcal
Phase offsets biggest problems, not
short-term phase noise (WVR)

Hence, solution intervals of many min or
more can remove phase offsets.

Amplitude self-cal is only effective if >90%
of the flux density is in the image after
phase self-cals, i.e. beware of extended
sources.

Solutions must be continuous in time!! This
is the ultimate test of success. If there
are large phase changes, then plot
difference of X-Y solution. This is the true
indication of solution noise.



Selfcal Example (cont)

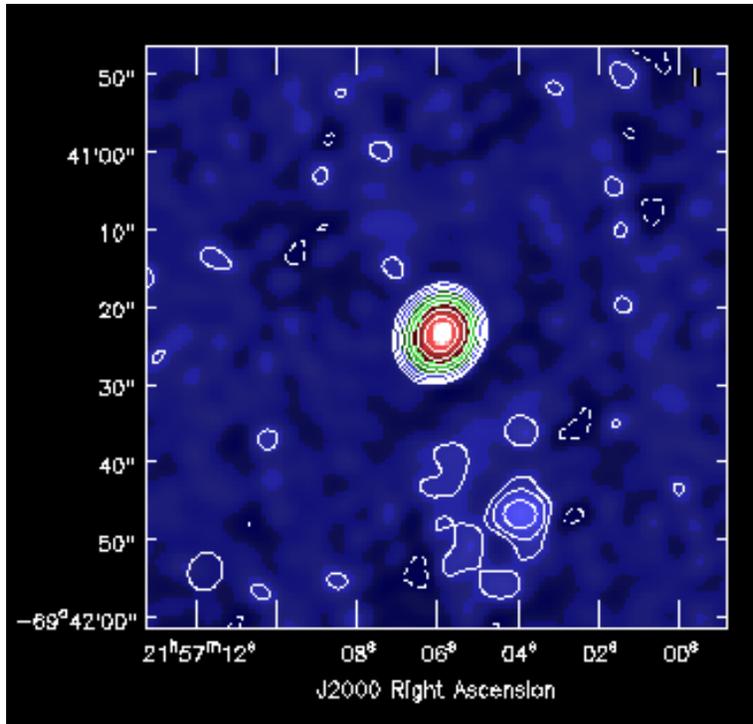


Image of 2157-694 after phasecal 1
Pk = 120 mJy Jy, clev=0.5 mJy; $d_i \sim 240$
Image noise = **0.22 mJy**
Expected noise = 0.05 mJy

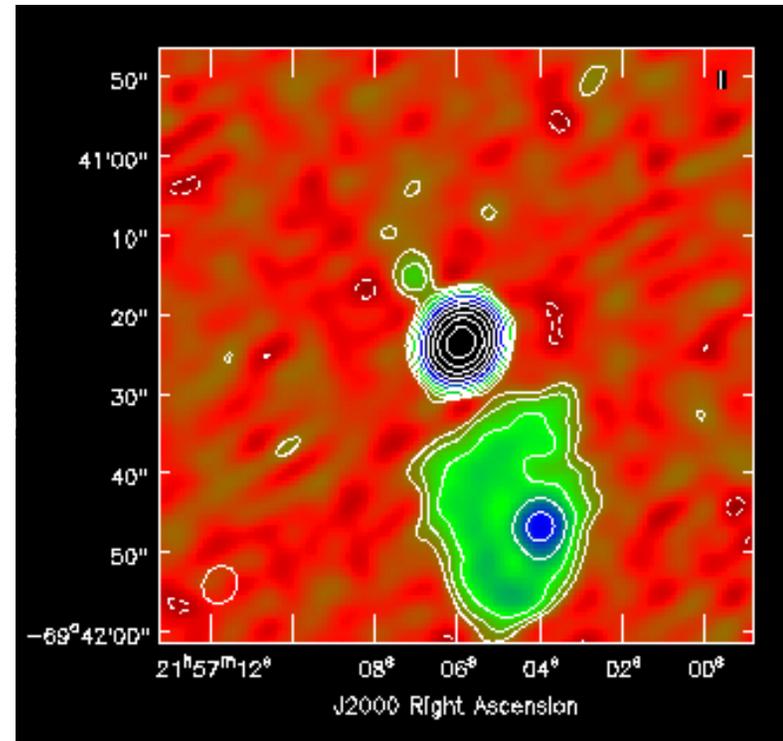
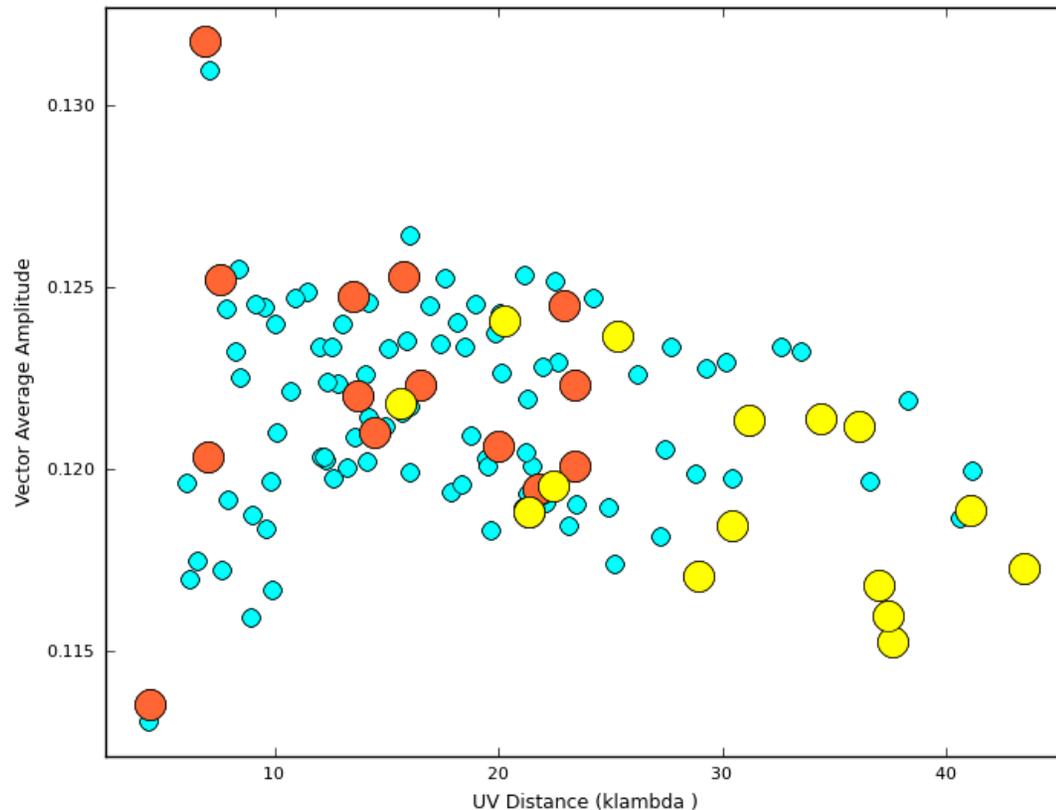


Image of 2157-694 after phasecal 2 and
amplitude selfcal, over entire scan
Pk = 122 mJy Jy, clev=0.15 mJy; $d_i \sim 2000$
Image noise = **0.06 mJy**
Expected noise = 0.05 mJy



Antenna Gain Averaging over Baseline



PLOT: MODEL VISIBILITY AMPLITUDE
VS UV-DIST FOR 2157-694

Small blue dots: The amplitudes for all
105 baselines (N=15).

Big red dots: Visibility amplitudes for an
antenna near the array center

Big yellow dots: visibility amplitudes for
an antenna at the end of the array.

The large-scale and small-scale structure in the source produce the variations in amplitude with uv-distance. The average of these visibilities associated with one antenna averages out most of the structure variation to give a good approximation of that antenna gain.



NGC3256 Self-cal Example (in tutorial)

Selfcal Line or Continuum? (N=8)

1. Look at calibrated data to determine baseline rms over relevant frequency. If source is strong, look at XX-YY in order to remove structure and estimate noise.
2. Look at initial image to determine peak flux density and approximate structure:

FROM NGC3256:

Cont: Peak = 11 mJy; $\sigma_b = \text{rms noise}/\text{baseline}/6s = 30 \text{ mJy}$
in 1.6 GHz, one spw, one pol.

Line: Peak = 1200 mJy; $\sigma_b = \text{rms noise}/\text{baseline}/6s = 150 \text{ mJy}$
in 0.078 GHz in six summed channels, one pol

CONCLUSION:

Self-cal on Line will have MUCH better antenna SNR than continuum.



NGC3256 Self-cal Example (in tutorial)

Script in tutorial will do the following:

Make continuum image using all data

Selfcal phase using solution interval of 25 min

Plot phase solutions, apply and reimage --- Better image by factor 3

Try selfcal amplitude --- woops, new component to north?????
sidelobe aliasing!!

Make image of strongest spectral line.

Selfcal phase using solution interval of 12 min, could go shorter

More often phase solutions than continuum; apply and reimage

Wow: Much better. Even component to north may be there.

Did not try amplitude cal. You should try!



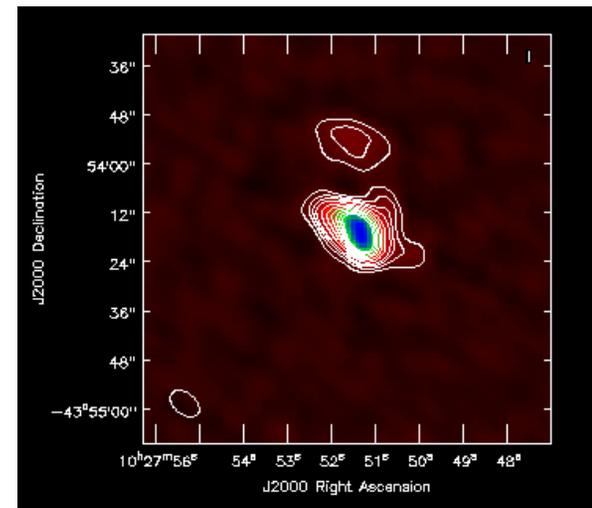
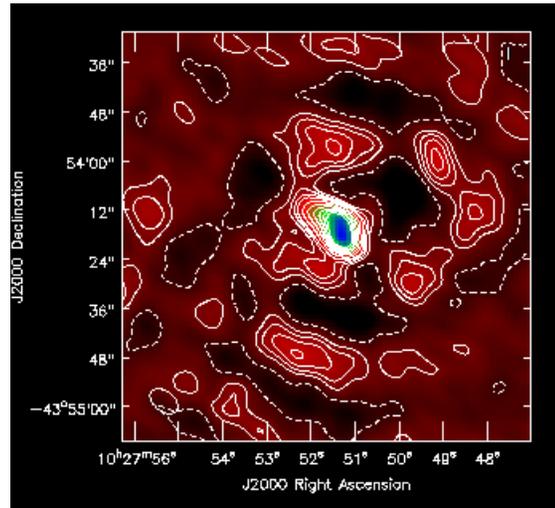
NGC3256 Self-cal Example (in tutorial)

Before Self-cal

After Self-cal

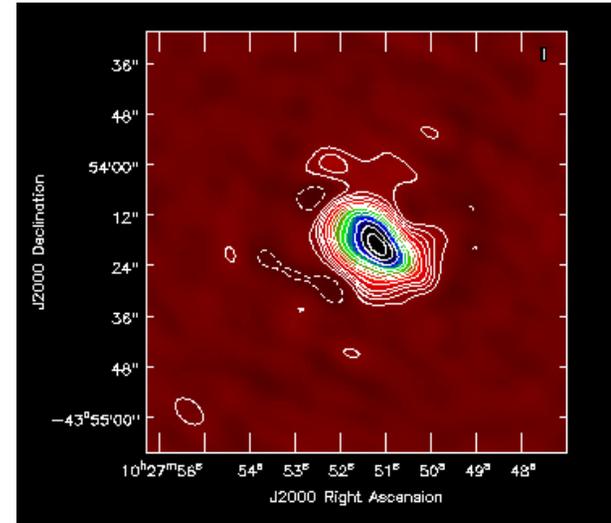
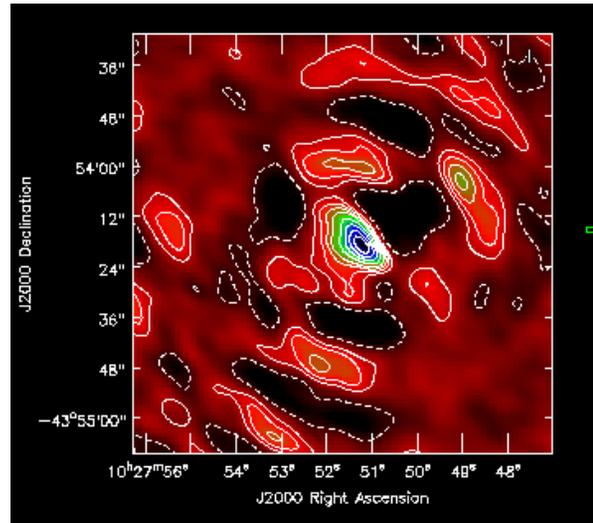
Continuum

phase and amp sc
contlev=0.3 mJy
peaks, 7.0, 9.0



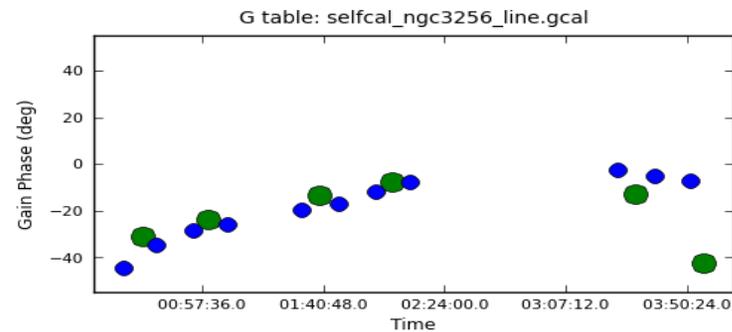
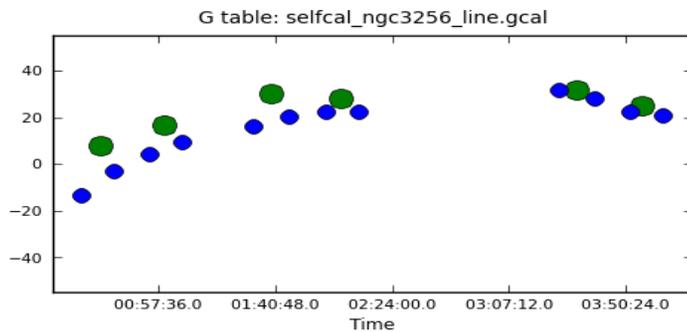
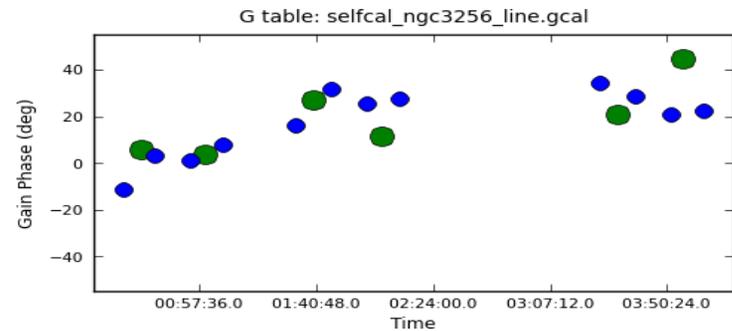
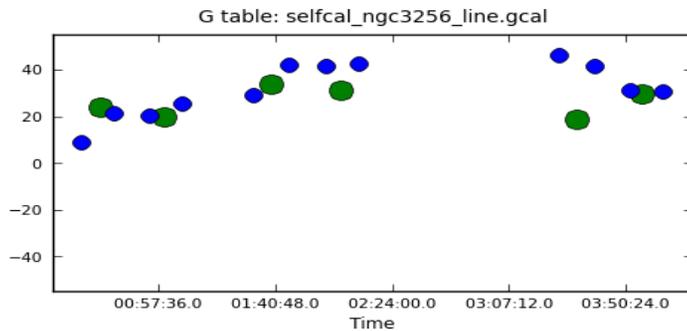
Line emission

Just phase sc
contlev=0.05 mJy,
0.02 mJy
peaks 0.68, 1.15 Jy



NGC3256 Self-cal Example

Comparison of continuum selfcal (green) with line selfcal (blue)
for four antennas



- Line self-cal more frequent with better SNR, but agreement is good.



Mosaic self-cal

- Self-cal on mosaic images similar to single field self-cal
because you pick the strongest mosaic field and self-cal on this alone.
Could use the brightest two or three fields if about the same strength.
- Choose continuum or line emission, whichever give better SNR
- Image the field(s) on its own, and proceed with normal self-cal as before
probably easiest to split out the source(s) in a separate ms.
- Self-cal solutions spotty, only occur when bright field(s) were observed,
but long term phase errors will be followed.
- Use this self-cal gain table and apply to entire data set with all fields.
- Good luck with new mosaic image.



Future ALMA Self-cal Problems

- When ALMA gets going, many of the sources will be strong, but also very extended. This make self-cal much more difficult since initial model may have missing flux density, and the antenna gain signal to noise may be much less at longer baselines than shorter baseline (should have mentioned earlier)
- The 'simplistic' approach here may need a lot of sophistication.



Self-cal for Dummies

Okay, forget all of the complicated stuff in the previous slides. Here is what the experts really do.

- (1) Calibrate and image the target as well as possible. If image is possibly distorted because of errors, clean conservatively---only emission you believe in.
- (2) Don't fool around with sensitivity calculations. If the peak of the source is greater than about 20 times noise, self-cal might work!
- (3) For ALMA, pick a solution interval equal to about one half of a target scan – about 2 to 10 min.
- (3) Selfcal phase only. Make sure model column has the source image visibility.
- (4) Note number of solutions thrown out. If more than 30%, then source is probably too weak. Try averaging polarizations and spw's to gain SNR.
- (5) Analyze resultant phases for reasonable continuity with time, especially the two or three solutions from one scan. X-Y phase should be smaller than about 10 deg for reasonable SNR result.



Self-cal for Dummies (cont)

- (6) Depending on phase quality, shorten solution interval if you can.
- (7) Reimage the source after applying self-cal. If phase corrections were typically larger than about 10 deg, significant improvement should occur.
- (8) Clean again somewhat conservatively, but image quality should improve.
- (9) If the new image has noise lowered to >50%, do another phase self-cal.
- (10) Amplitude self-calibrations are more 'dangerous'. Usually, a priori amplitude correction is good to a few percent. If source is extended, the model might be missing some flux density (this doesn't bother the phase solution much).
- (11) BUT, amplitude self-cal is useful as an editing tool. Even if you don't believe the amplitude corrections, sudden drop-outs in the target data can be seen by any significant drop in the self-cal amplitude. This data should then be flagged.
- (12-200) **GOOD LUCK**

