ALMA Data Calibration

Violette Impellizzeri

ALMA Data Reduction Training Day

ALMA Local Expertise Group (Allegro)

Leiden Observatory - 27/11/2023

ALMA

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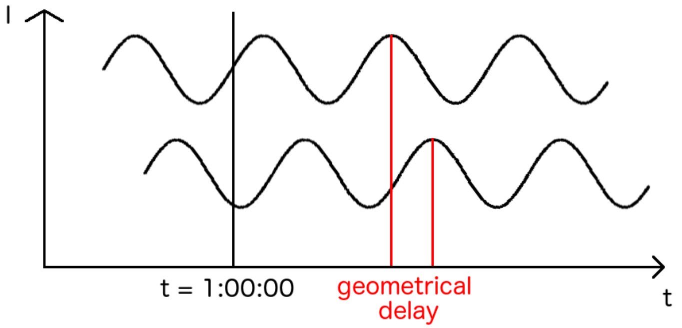
Calibration basics

Why do we need to calibrate our data?

What are the calibration steps?

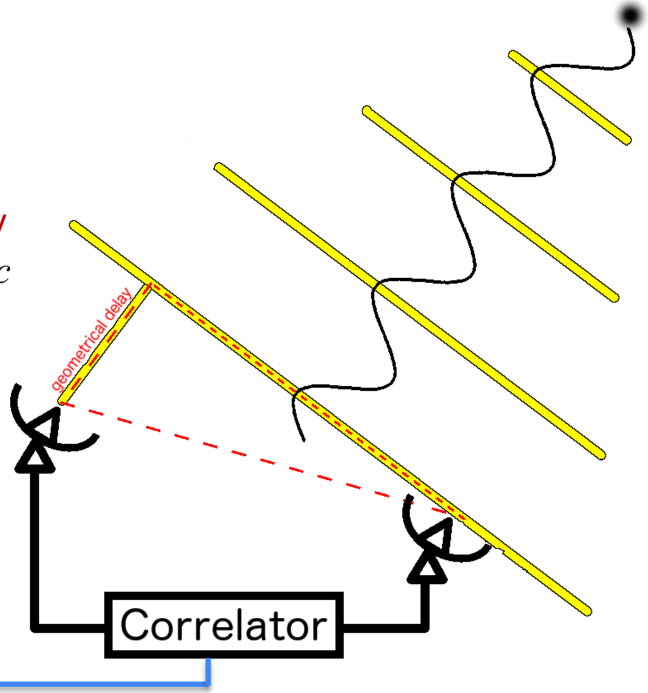
How do I know that the calibration was successful?

Ideal interferometer

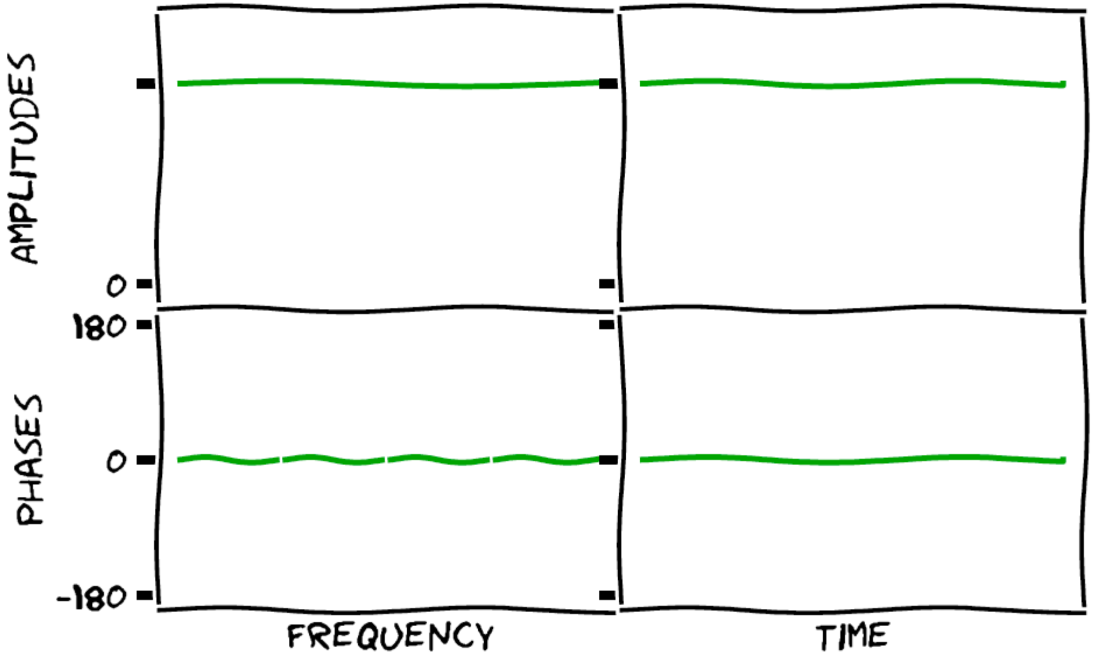


Geometric
Time Delay

$$\tau_g = \mathbf{b} \cdot \mathbf{s} / c$$

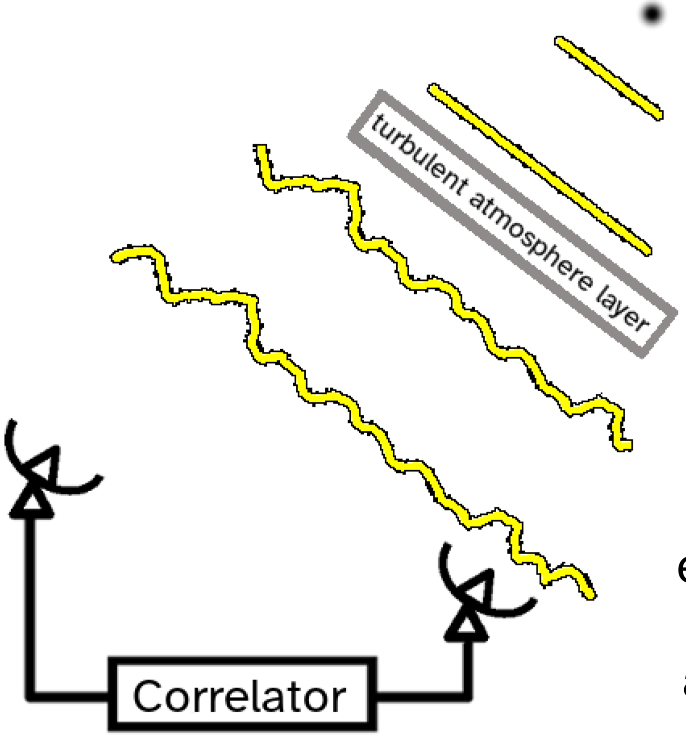


Ideal case



Real case: possible error sources

bad positions
(antennas and source)
⇩
delay errors



Perturbed wavefront due to atmosphere
⇩
phase errors

non-identical electronics/gains
⇩
amplitude errors

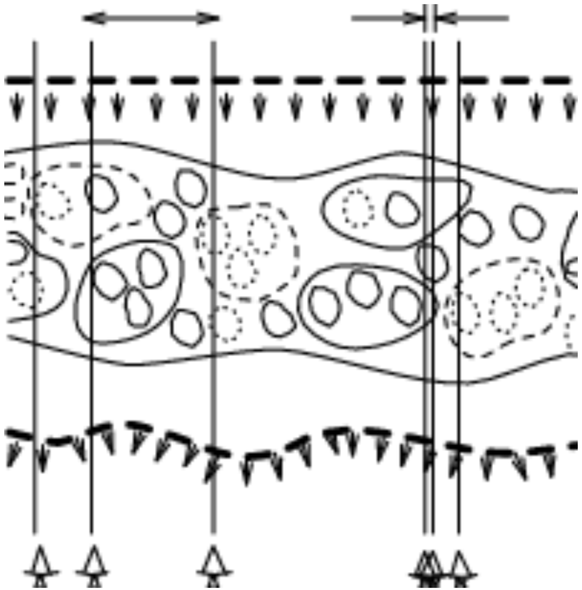
More sources of error

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

Antenna-based

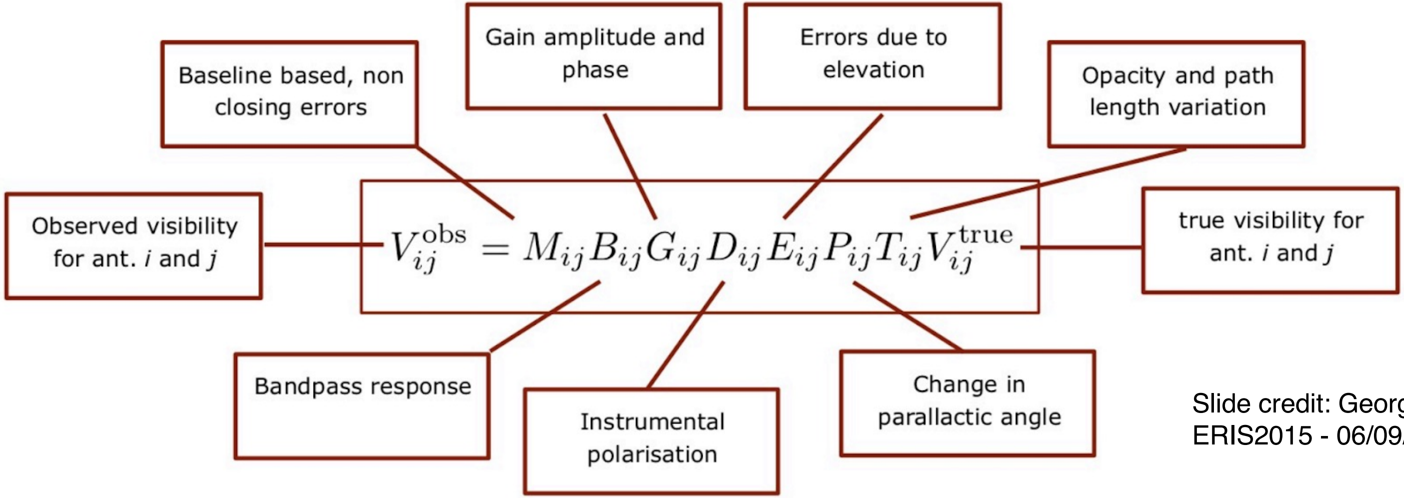
- Radiometer noise
- Correlator malfunctions
- Most Interference signals

baseline-based



ALMA EU ALI

Radio interferometry measurement equation



Slide credit: George Heald
ERIS2015 - 06/09/2015

Assumptions: Calibration parameters are antenna based.
Time and frequency effects are independent

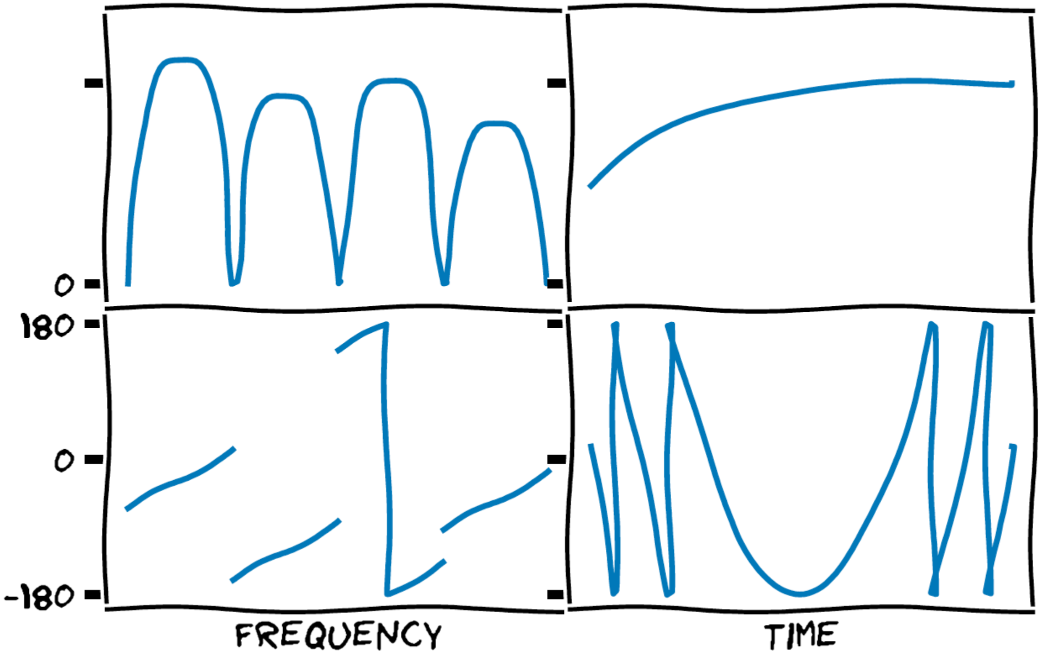
Calibration solves for each parameter (when required)

Real case

Bandpass shapes

Instrumental delay

Atmosphere



Source elevation

Intrinsic flux

variation

Atmosphere

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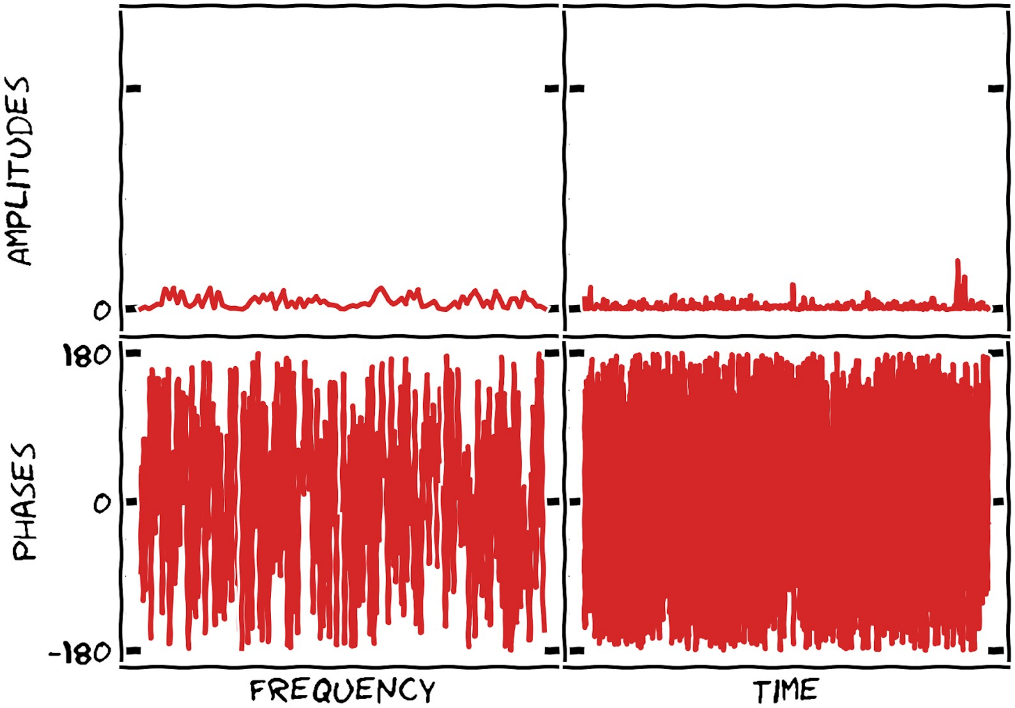
Target



Which sources do we observe?

- Bandpass calibrator (BC): Quasar (strong, point-like source)

  ⇕ can be the same

- Flux calibrator (FC): Quasar (needs flux density monitoring)

  OR

  Solar System Object (needs flux density model)

- Gain calibrator (GC): Point source close to target on sky

- Target (T)

BC FC GC T GC T GC T GC T GC T GC

→ time

Phase-referencing

Calibrator source close to target on sky (within a few degrees)

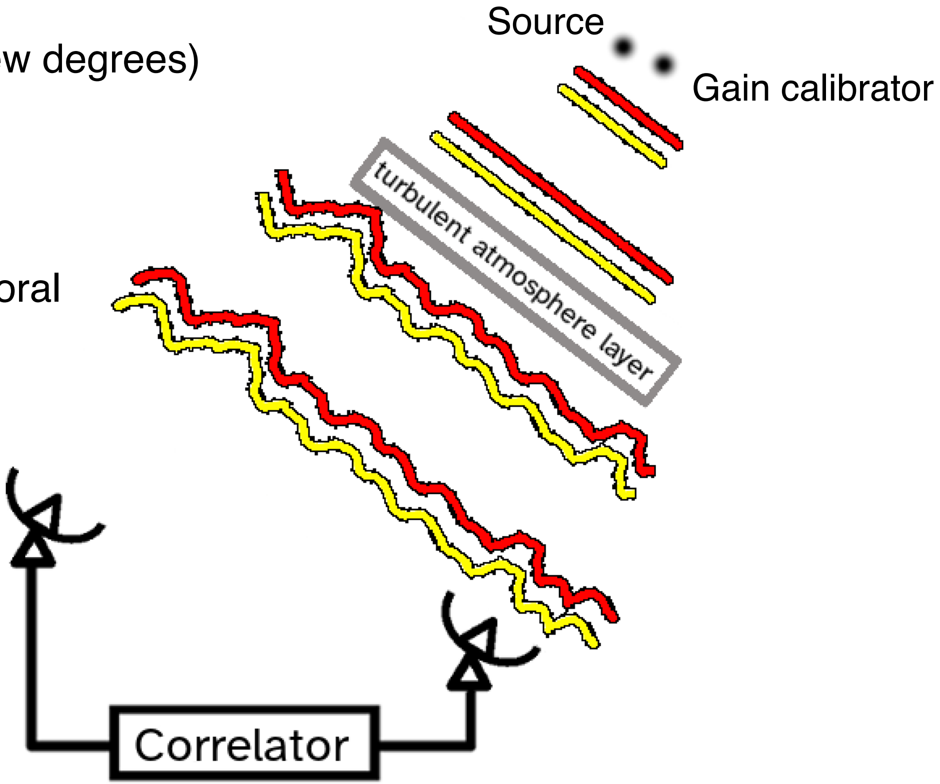
to be affected by the same part of the atmosphere

Phase-referencing cycle **fast** enough to trace temporal

changes in atmosphere

GC T GC T GC T GC T GC T GC

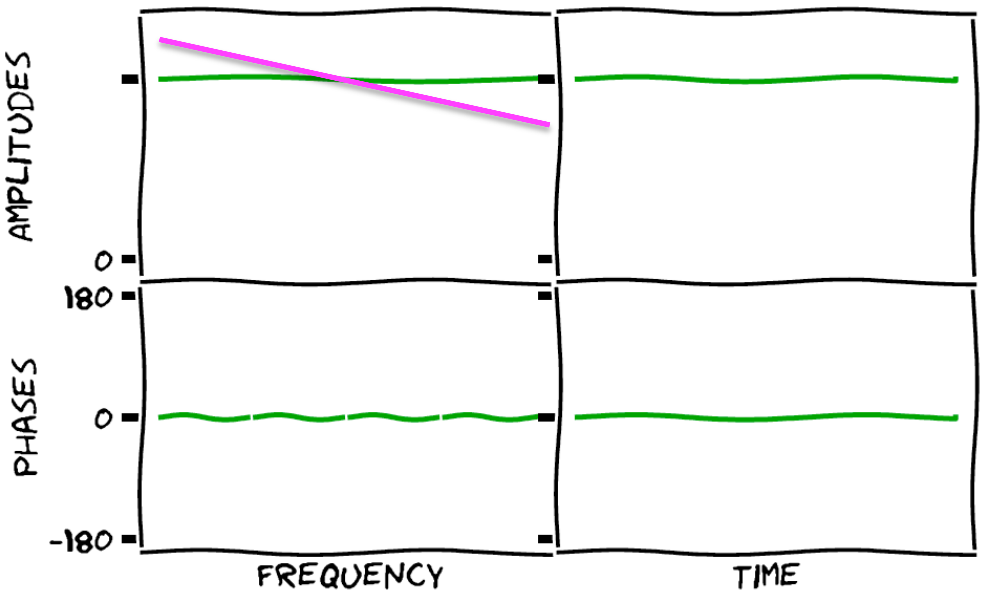
time



Calibrator properties (ideal case)

Point source:

- unresolved on all baselines → amplitude is the same on all baselines
- All sky brightness comes from single point → phases are flat/zero as function of baseline and time
- Quasars have flat spectra or known spectral indices



Bright sources to achieve high signal-to-noise ratios in small on-source time!

Three calibration steps

Primary calibration:

- Remove effects of the instrument
  - Bandpass; variation in receiver noise (Tsys); effects of shadowing; antenna positions

Secondary calibration:

- Remove effect of the atmosphere
  - Atmospheric variability (phase); atmospheric attenuation as function of time (Tsys)
- Scale to correct flux (flux calibrator)

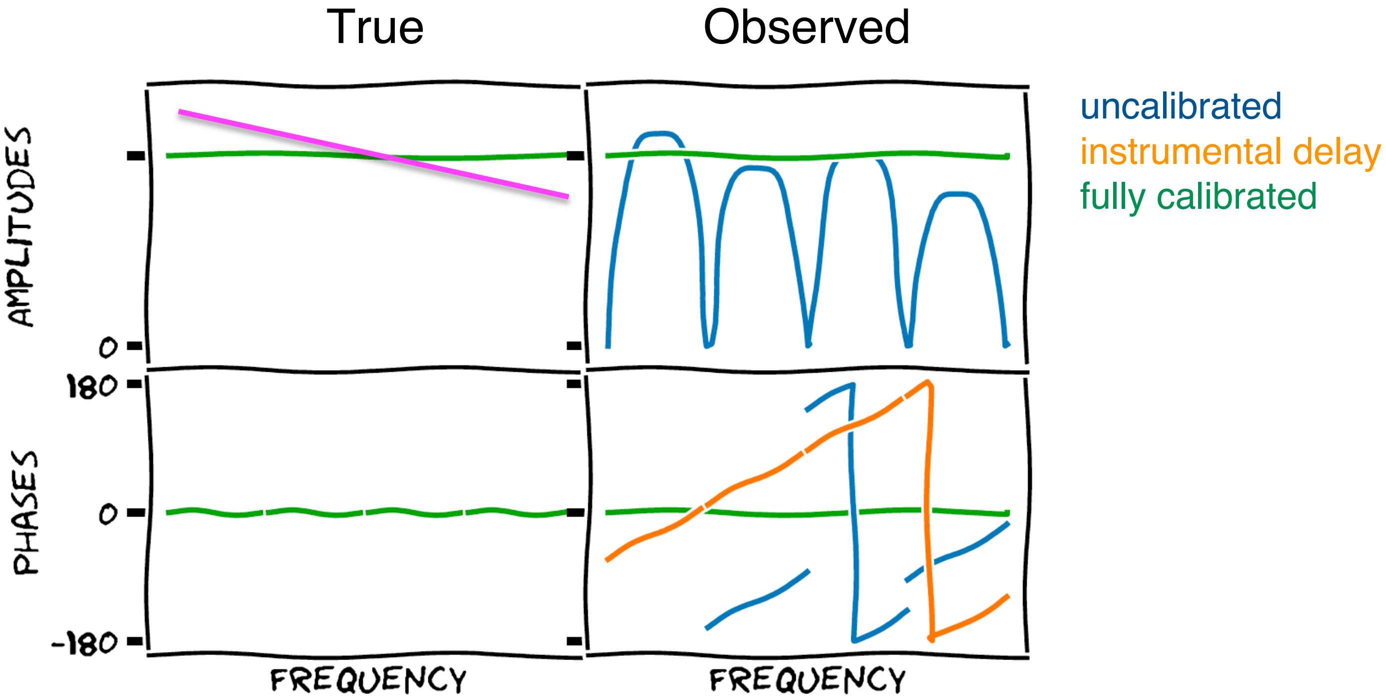
Self-calibration:

- Remove residual time dependent corrupting effects (target)

Primary calibration - bandpass calibrator

Bandpass

Instrumental delay
Atmosphere



Apply corrections to other calibrators and target

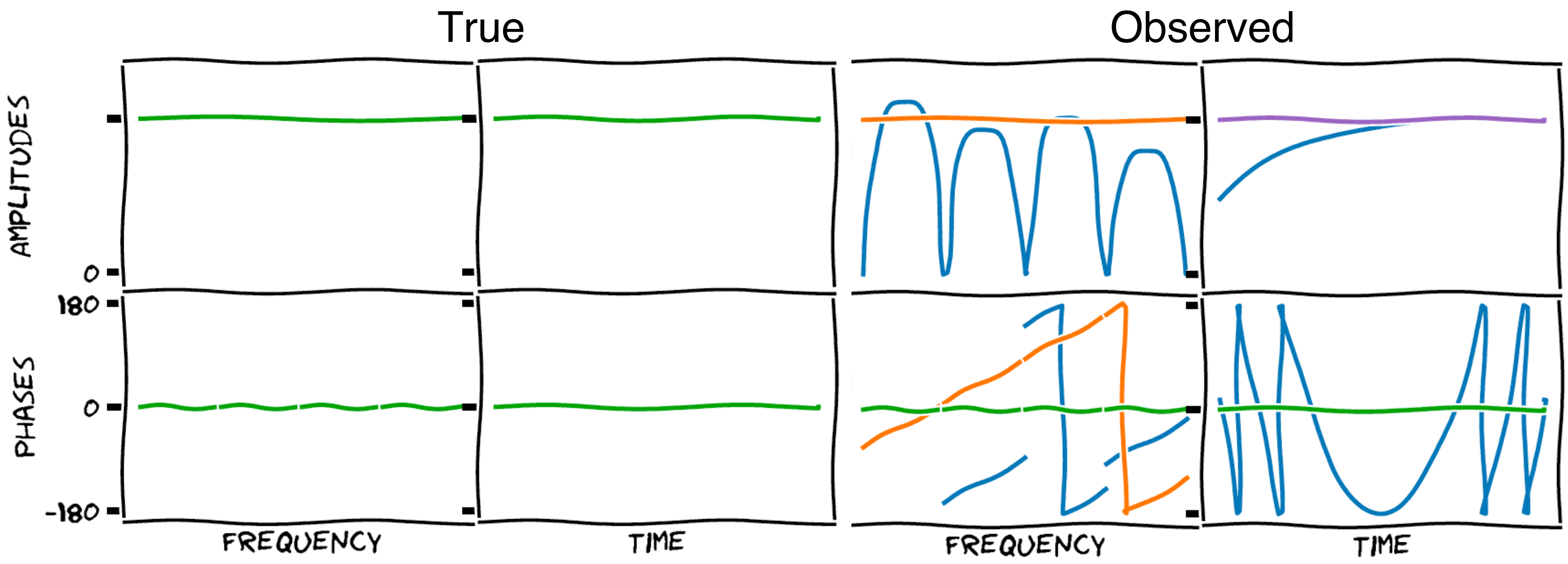
Secondary calibration - flux calibrator

Visibility amplitudes from correlator have arbitrary scaling.

Use strong, point-like source with known flux density or solar system object with well-known flux density model to convert these amplitudes into physically meaningful values

Apply scaling factors to other sources using, e.g. *setJy* and *fluxscale* in CASA

Secondary calibration - gain calibrator

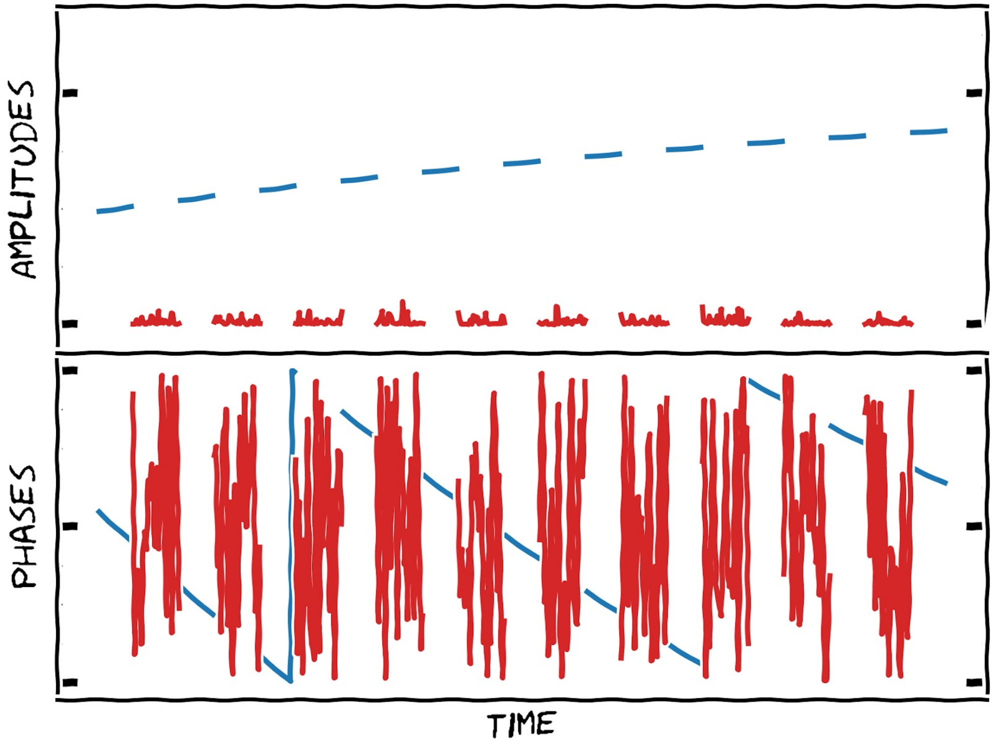


uncalibrated Bandpass Phase calibration Self-calibration

Secondary calibration - phase-referencing

GC T GC T GC T GC T GC T GC

time



Which source gets which calibration solution?

Calibration "Table" \ Calibrator	BP CAL	FLUX CAL	PHASE CAL	TARGET
FLUX SCALING	FLUX CAL (Scaled in fluxscale)	FLUX CAL (Model in setJy)	FLUX CAL (Scaled in fluxscale)	
BANDPASS	BP CAL	BP CAL	BP CAL	BP CAL
PHASE	BP CAL (short interval time solutions)	FLUX CAL (short time interval solutions)	PHASE CAL (long time interval solutions	PHASE CAL (long time interval solutions
AMPLITUDE	BP CAL (short interval time solutions)	FLUX CAL (short time interval solutions)	PHASE CAL (long time interval solutions	PHASE CAL (long time interval solutions

Manual vs pipeline calibration

Weblog review

Manual calibration

uid__XXXXX_scriptForCalibration.py

Diagnostic files under:

project_code/

science_goal.sous/

group.gous/

member.mous/

qa/

```
# ALMA Data Reduction Script

# Calibration

thesteps = []
step_title = {0: 'Import of the ASDM',
              1: 'Fix of SYSCAL table times',
              2: 'listobs',
              3: 'A priori flagging',
              4: 'Generation and time averaging of the WVR cal table',
              5: 'Generation of the Tsys cal table',
              6: 'Generation of the antenna position cal table',
              7: 'Application of the WVR, Tsys and antpos cal tables',
              8: 'Split out science SPWs and time average',
              9: 'Listobs, clear pointing table, and save original flags',
              10: 'Initial flagging',
              11: 'Putting a model for the flux calibrator(s)',
              12: 'Save flags before bandpass cal',
              13: 'Bandpass calibration',
              14: 'Save flags before gain cal',
              15: 'Gain calibration',
              16: 'Save flags before applycal',
              17: 'Application of the bandpass and gain cal tables',
              18: 'Split out corrected column'}

if 'applyonly' not in globals(): applyonly = False
try:
  print 'List of steps to be executed ...', mysteps
  thesteps = mysteps
except:
  print 'global variable mysteps not set.'
if (thesteps==[]):
  thesteps = range(0,len(step_title))
  print 'Executing all steps: ', thesteps
```

Pipeline calibration - Weblog

casa_pipescript.py

casa_piperestorescript.py

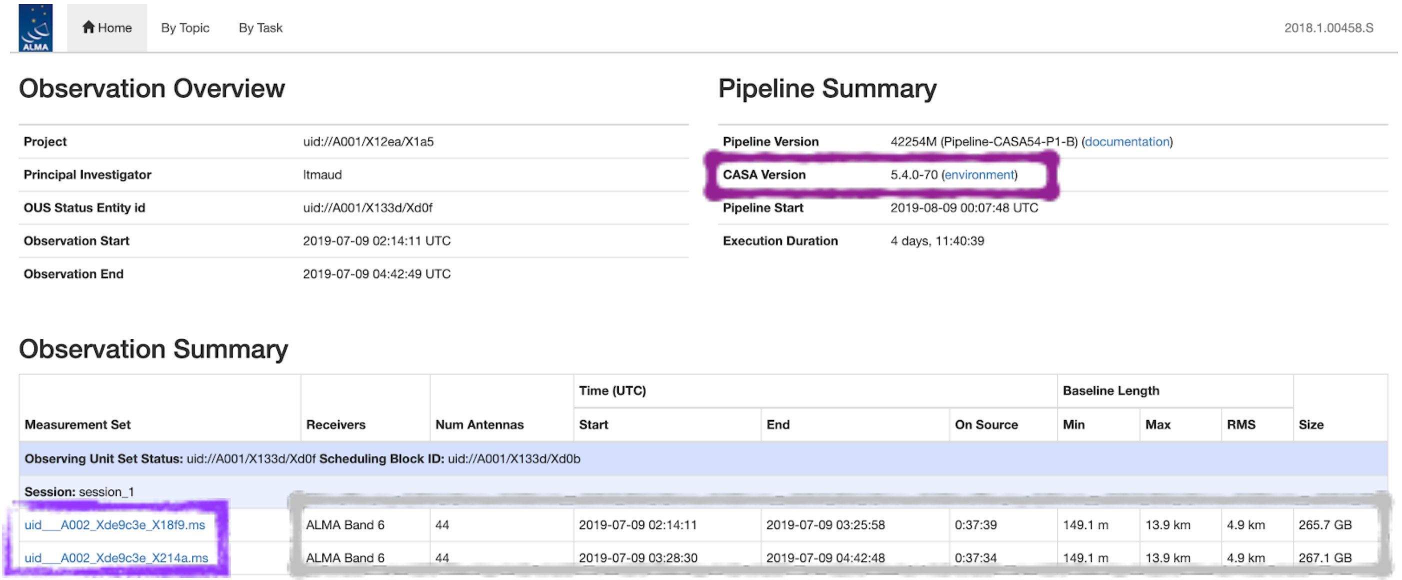
weblog :

gunzip and untar

weblog.tar.gz

cd weblog-date/html/

and open index.html



Home | By Topic | By Task | 2018.1.00458.S

Observation Overview

Project	uid://A001/X12ea/X1a5
Principal Investigator	ltmaud
OUS Status Entity id	uid://A001/X133d/Xd0f
Observation Start	2019-07-09 02:14:11 UTC
Observation End	2019-07-09 04:42:49 UTC

Pipeline Summary

Pipeline Version	42254M (Pipeline-CASA54-P1-B) (documentation)
CASA Version	5.4.0-70 (environment)
Pipeline Start	2019-08-09 00:07:48 UTC
Execution Duration	4 days, 11:40:39

Observation Summary

			Time (UTC)			Baseline Length			
Measurement Set	**Receivers**	**Num Antennas**	**Start**	**End**	**On Source**	**Min**	**Max**	**RMS**	**Size**
Observing Unit Set Status: uid://A001/X133d/Xd0f **Scheduling Block ID:** uid://A001/X133d/Xd0b									
Session: session_1									
uid___A002_Xde9c3e_X18f9.ms	ALMA Band 6	44	2019-07-09 02:14:11	2019-07-09 03:25:58	0:37:39	149.1 m	13.9 km	4.9 km	265.7 GB
uid___A002_Xde9c3e_X214a.ms	ALMA Band 6	44	2019-07-09 03:28:30	2019-07-09 04:42:48	0:37:34	149.1 m	13.9 km	4.9 km	267.1 GB

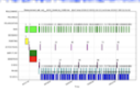
Measurement set overview

Overview of 'uid___A002_Xde9c3e_X18f9.ms'

Observation Execution Time

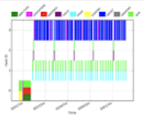
Start Time	2019-07-09 02:14:11
End Time	2019-07-09 03:25:58
Total Time on Source	1:01:44
Total Time on Science Target	0:37:39

LISTOBS OUTPUT



Intent vs Time

Track scan intent vs time



Field vs Time

Track observed field vs time

Spatial Setup

Science Targets	'W33A'
Calibrators	'J1825-1718', 'J1830-1606' and 'J1924-2914'

Spectral Setup

All Bands	'ALMA Band 6' and 'WVR'
Science Bands	'ALMA Band 6'

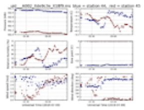
Antenna Setup

Min Baseline	149.1 m
Max Baseline	13.9 km
Number of Baselines	946
Number of Antennas	44

Sky Setup

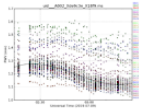
Min Elevation	55.24 degrees
Max Elevation	83.91 degrees

Weather



Weather plot

PWV



PWV plot

Scans

Intent vs time

Water vapour radiometer

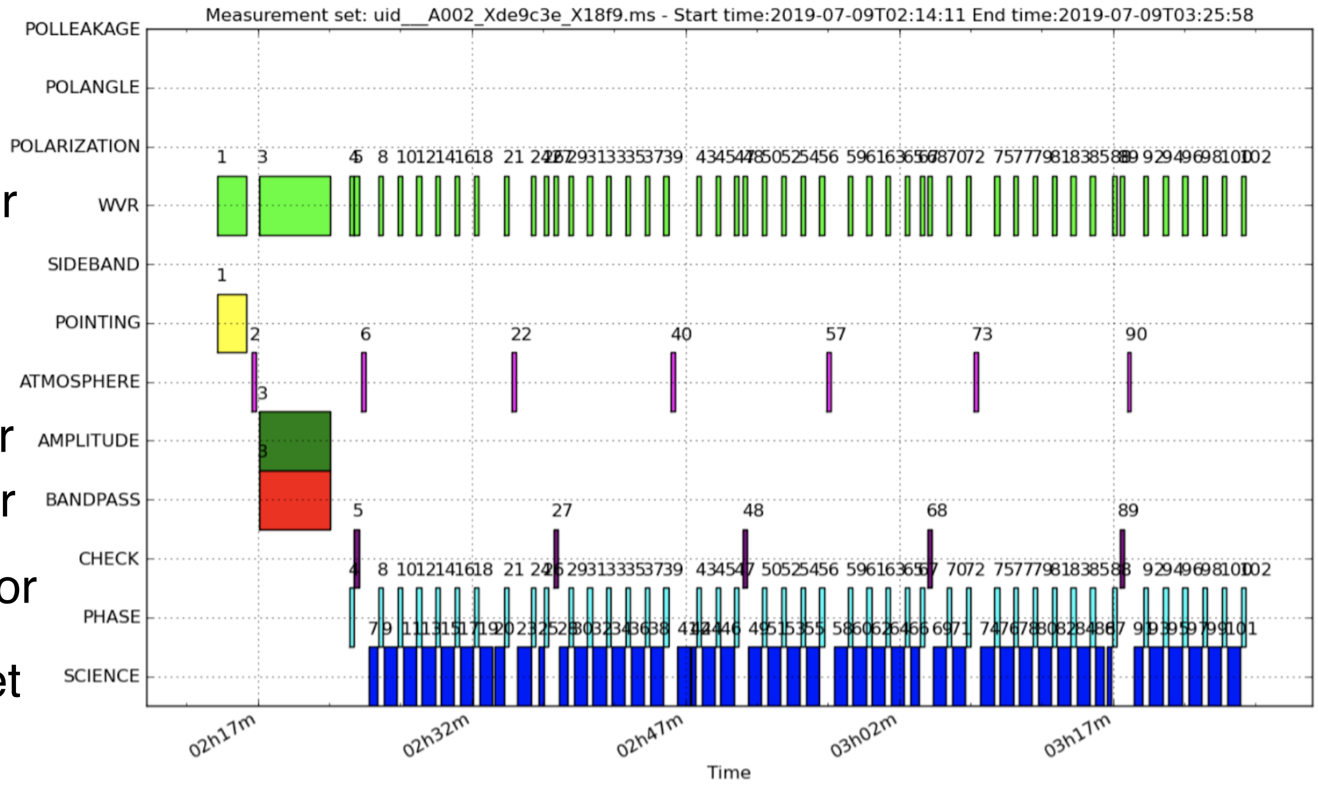
Pointing

Flux density calibrator

Bandpass calibrator

Gain calibrator

Target



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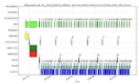

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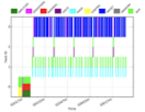

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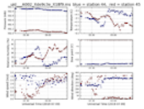
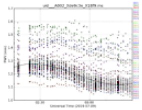


Weather plot

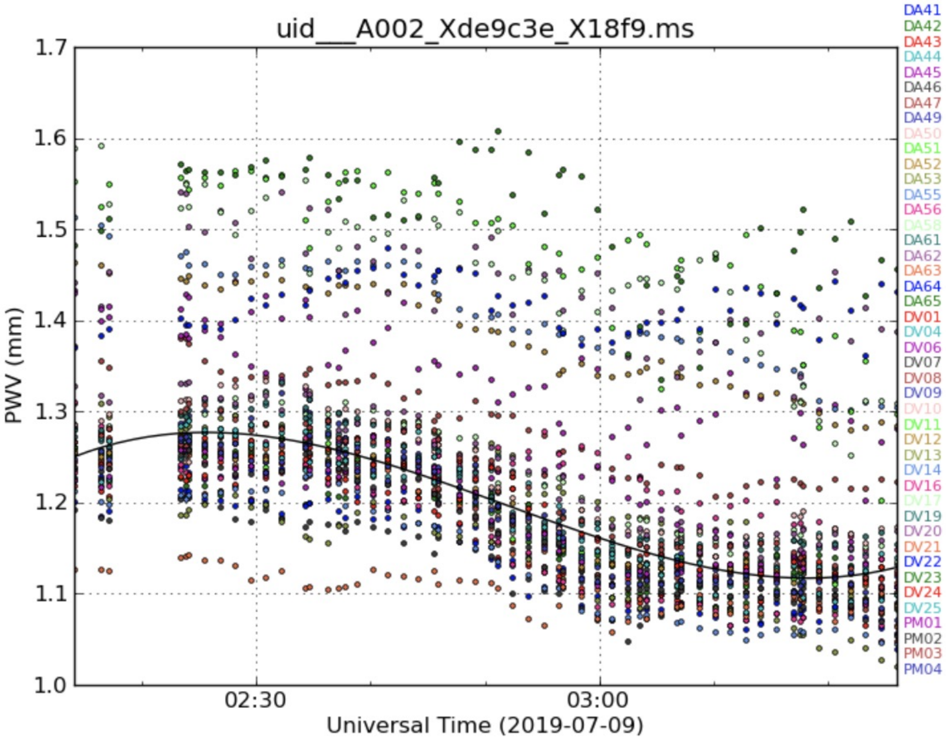
PWV



PWV plot

Scans

Precipitable water vapour



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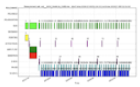

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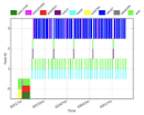

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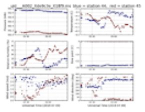
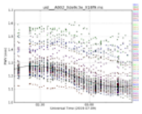


Weather plot

PWV



PWV plot

Scans

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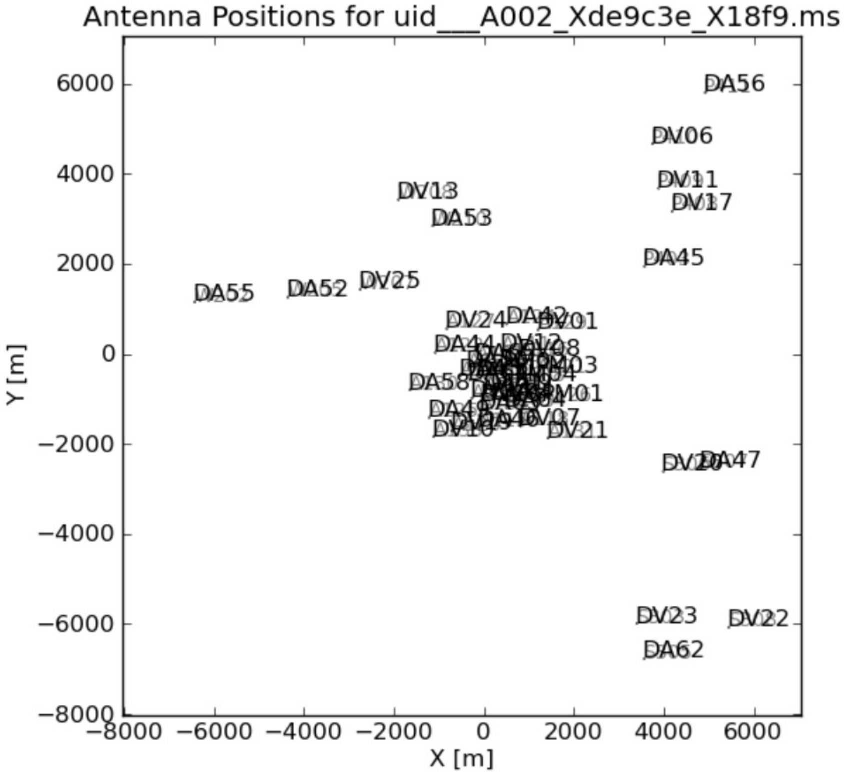
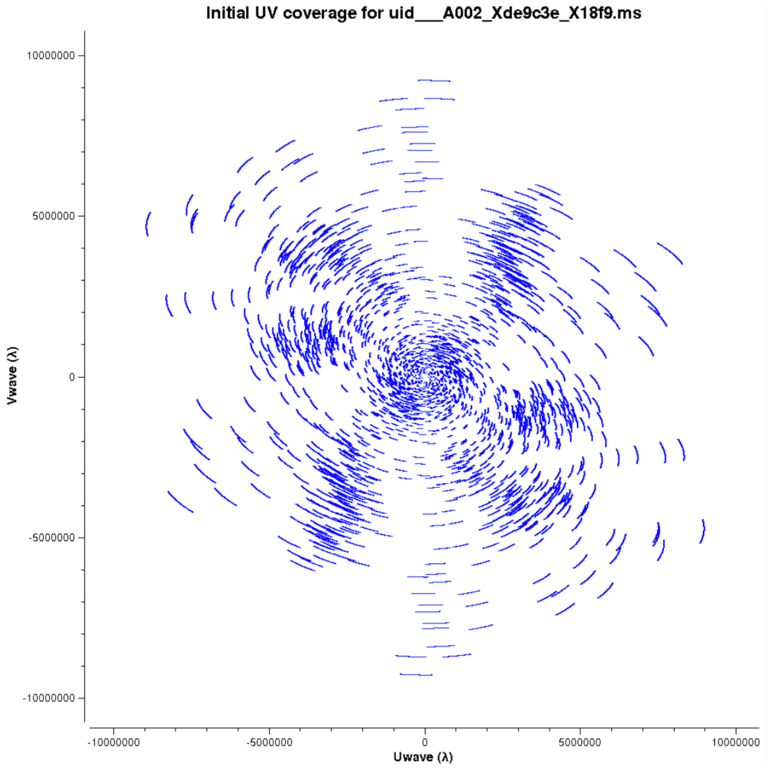
Antenna positions



UV coverage



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Pipeline calibration - Weblog

Warnings & Errors / Flagging Summary

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Observation Overview

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Principal Investigator	ltmaud
OUS Status Entity id	uid://A001/X133d/Xd0f
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Warnings and Errors

Warnings and Errors

Stage	Task	Type	Message
7	hifa_tsysflag	Warning	flag edgechans - uid___A002_Xde9c3e_X18f9.ms iteration 1 raised 12 flagging commands
7	hifa_tsysflag	Warning	flag birdies - uid___A002_Xde9c3e_X18f9.ms iteration 1 raised 4 flagging commands
7	hifa_tsysflag	Warning	flag edgechans - uid___A002_Xde9c3e_X214a.ms iteration 1 raised 12 flagging commands
7	hifa_tsysflag	Warning	flag birdies - uid___A002_Xde9c3e_X214a.ms iteration 1 raised 4 flagging commands
9	hifa_wvrgcalflag	QA Warning	RMS improvement was 1.24 for uid___A002_Xde9c3e_X18f9.ms
12	hifa_bandpassflag	Warning	Evaluation of flagging heuristics for uid___A002_Xde9c3e_X18f9.ms raised total of 5 flagging command(s)
12	hifa_bandpassflag	Warning	uid___A002_Xde9c3e_X18f9.ms - for intent BANDPASS (field J1924-2914) and spw 25, the following antennas are fully flagged: DA44
12	hifa_bandpassflag	Warning	uid___A002_Xde9c3e_X18f9.ms - for intent BANDPASS (field J1924-2914) and spw 27, the following antennas are fully flagged: DA44

Flagging summary

Flagging percentages for Source name: J1830-1606, Intents: WVR,CHECK

spw	DA41	DA42	DA43	DA44	DA45	DA46	DA47	DA49	DA50	DA51	DA52	DA53	DA55	DA56	DA58	DA61	DA62	DA63	DA64	DA65	DV01	DV04	DV06	DV
25	4.72	4.72	5.08	100.00	4.72	4.72	4.72	4.72	4.72	4.72	4.72	4.72	4.72	4.72	4.72	4.72	4.72	4.72	4.72	4.72	4.72	4.72	4.72	4.7
27	4.88	4.88	5.13	100.00	4.88	4.88	4.88	4.88	4.88	4.88	4.88	4.88	4.88	4.88	5.77	4.88	4.88	4.88	4.88	4.88	5.47	4.88	4.88	8.6
29	4.70	4.70	4.70	100.00	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.7
31	4.70	4.70	4.70	100.00	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.7

Flagging percentages for Source name: J1825-1718, Intents: WVR,PHASE

spw	DA41	DA42	DA43	DA44	DA45	DA46	DA47	DA49	DA50	DA51	DA52	DA53	DA55	DA56	DA58	DA61	DA62	DA63	DA64	DA65	DV01	DV04	DV06	DV
25	9.16	7.81	7.78	100.00	8.86	9.24	9.17	9.34	8.31	6.07	8.87	8.17	8.11	6.94	7.85	7.02	6.95	6.02	7.09	9.52	5.74	5.74	5.74	5.7
27	9.32	7.96	7.84	100.00	9.01	9.40	9.33	9.49	8.46	6.23	9.03	8.32	8.26	7.10	8.87	7.18	7.11	6.18	7.25	9.67	6.49	5.90	5.90	9.6
29	11.34	9.64	9.61	100.00	10.69	11.42	11.35	11.51	10.48	8.25	10.70	10.34	10.28	9.12	10.02	9.20	9.13	8.19	9.27	11.69	7.91	7.91	7.91	7.9
31	9.14	7.79	7.42	100.00	8.84	9.22	9.15	9.32	8.29	6.05	8.85	8.15	8.09	6.92	7.83	7.00	6.93	6.00	7.07	9.50	5.72	5.72	5.72	5.7

Pipeline calibration - Weblog

Warnings & Errors / Flagging Summary

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2018.1.00458.S

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Observation End	2019-07-09 04:42:49 UTC

Pipeline Summary

Pipeline Version	42254M (Pipeline-CASA54-P1-B) (documentation)
CASA Version	5.4.0-70 (environment)
Pipeline Start	2019-08-09 00:07:48 UTC
Execution Duration	4 days, 11:40:39

Observation Summary

			Time (UTC)			Baseline Length			
Measurement Set	**Receivers**	**Num Antennas**	**Start**	**End**	**On Source**	**Min**	**Max**	**RMS**	**Size**
Observing Unit Set Status: uid://A001/X133d/Xd0f **Scheduling Block ID:** uid://A001/X133d/Xd0b									
Session: session_1									
uid___A002_Xde9c3e_X18f9.ms	ALMA Band 6	44	2019-07-09 02:14:11	2019-07-09 03:25:58	0:37:39	149.1 m	13.9 km	4.9 km	265.7 GB
uid___A002_Xde9c3e_X214a.ms	ALMA Band 6	44	2019-07-09 03:28:30	2019-07-09 04:42:48	0:37:34	149.1 m	13.9 km	4.9 km	267.1 GB

Calibration tasks

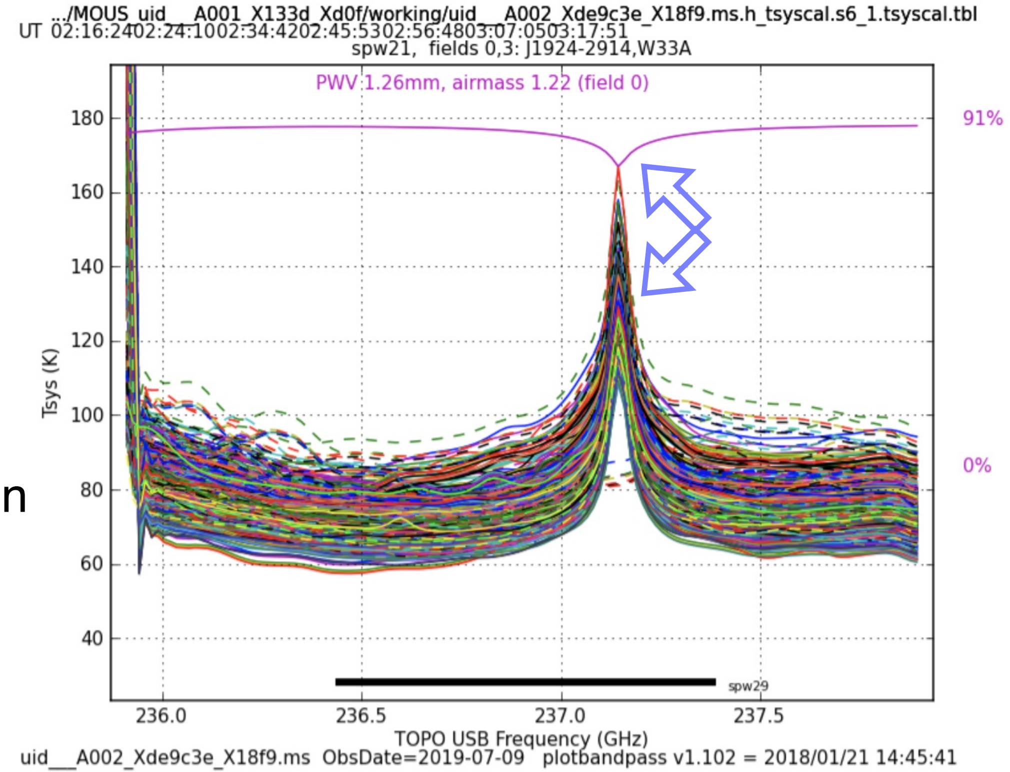
Task		QA Score	Duration
1. **hifa_importdata**: Register measurement sets with the pipeline		1.00	0:46:07
2. **hifa_flagdata**: ALMA deterministic flagging		1.00	3:18:59
3. **hifa_fluxcalflag**: Flag spectral features in solar system flux calibrators		1.00	0:00:05
4. **hif_rawflagchans**: Flag channels in raw data		1.00	0:49:25
5. **hif_refant**: Select reference antennas		1.00	0:04:13
6. **h_tsyscal**: Calculate Tsys calibration		1.00	0:13:06
7. **hifa_tsysflag**: Flag Tsys calibration		0.99	0:17:32
8. **hifa_antpos**: Correct for antenna position offsets	Nonzero antenna position offsets	0.90	0:00:12
9. **hifa_wvrgcalflag**: Calculate and flag WVR calibration	1.24x improvement	0.62	1:59:20
10. **hif_lowgainflag**: Flag antennas with low gain		1.00	1:27:05

Tsys

6. **h_tsyscal**: Calculate Tsys calibration

Tsys - sensitivity of each antenna with time (atmosphere & receivers)

Correct for sky and receiver noise/variation



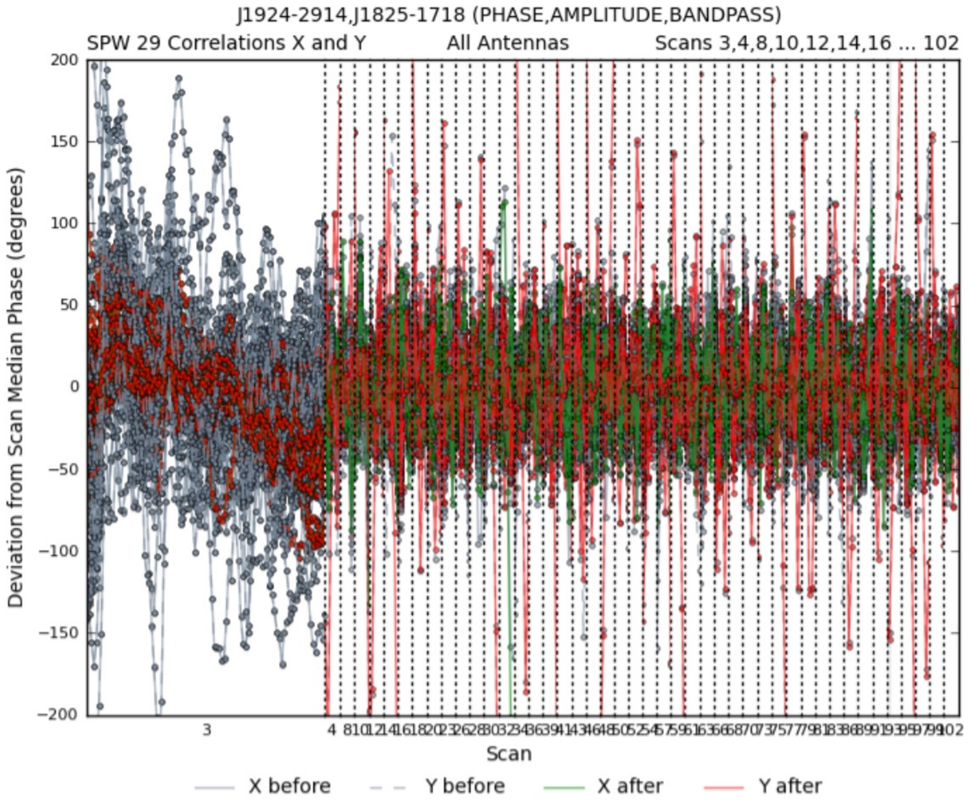
Water vapour radiometer correction

9. **hifa_wvrgcalflag:** Calculate and flag WVR calibration

Variations in the amount of water vapour lead to atmospheric phase fluctuations (very short timescales < 1 min)

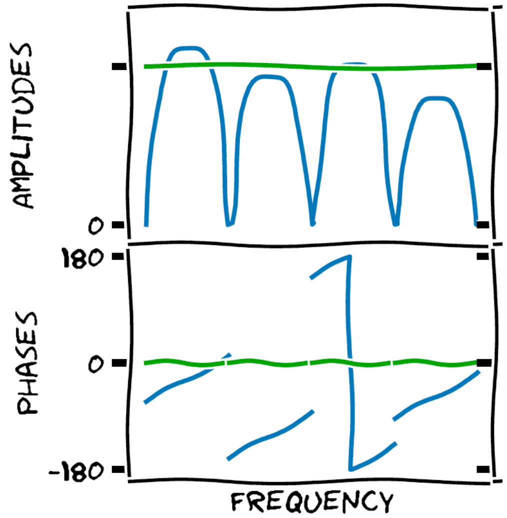
Phase noise should decrease

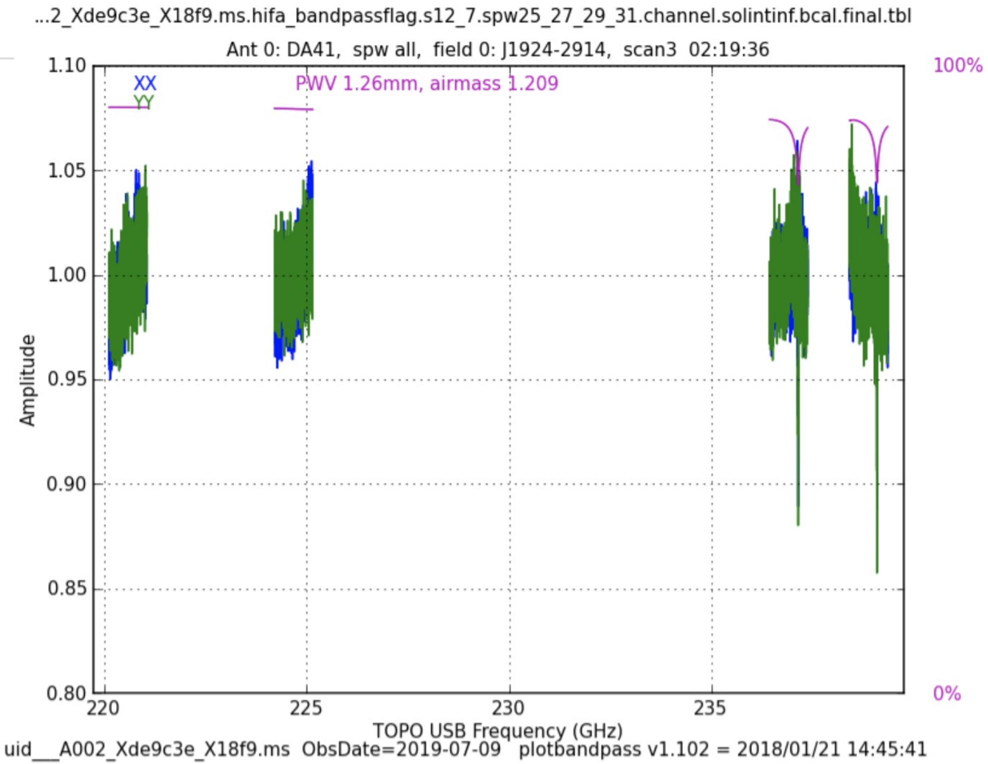
—> If not, pipeline will not apply the correction



Bandpass calibration

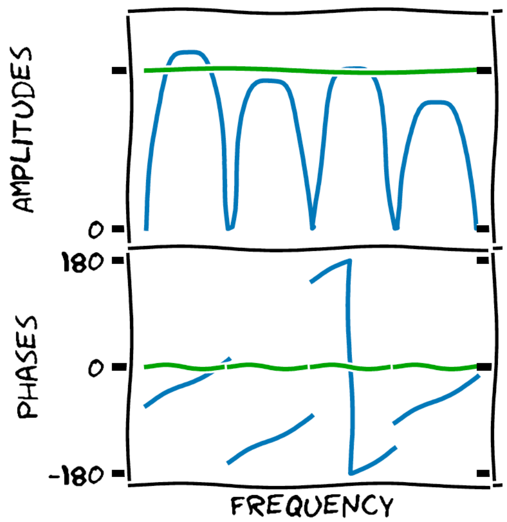
12. **hifa_bandpassflag**: Phase-up bandpass calibration and flagging

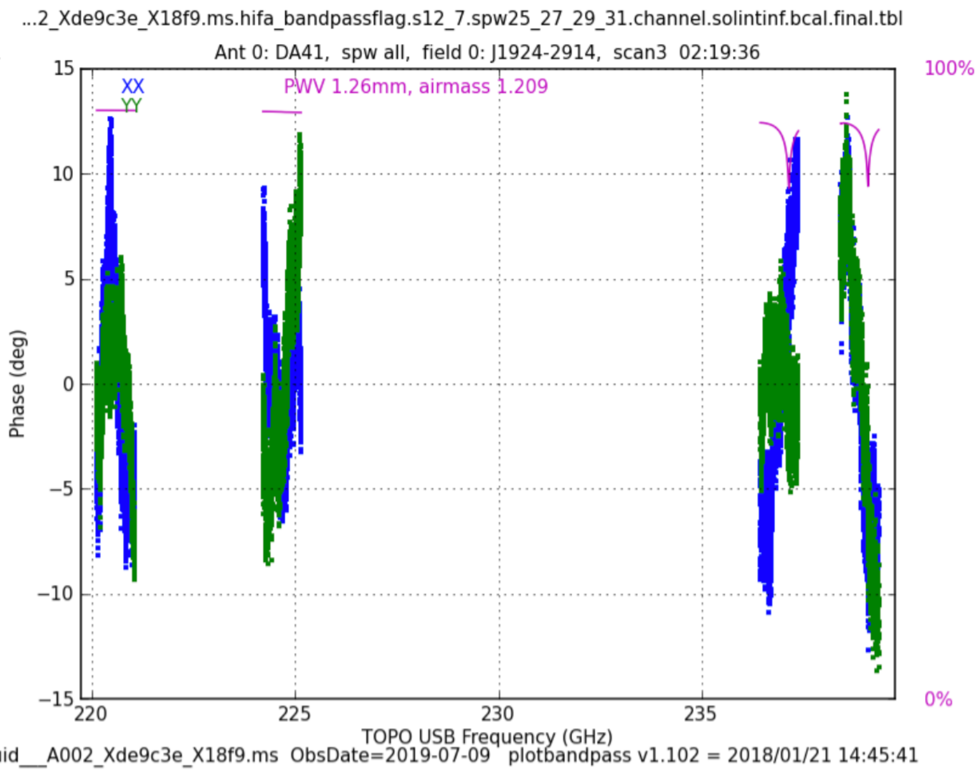




Bandpass calibration

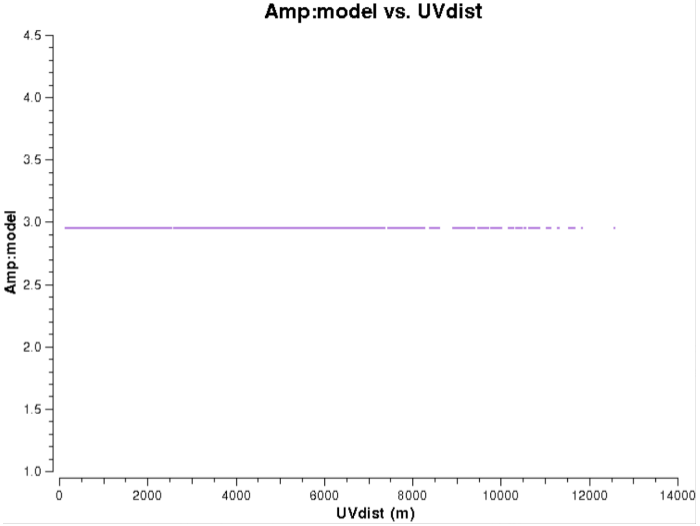
12. **hifa_bandpassflag**: Phase-up bandpass calibration and flagging

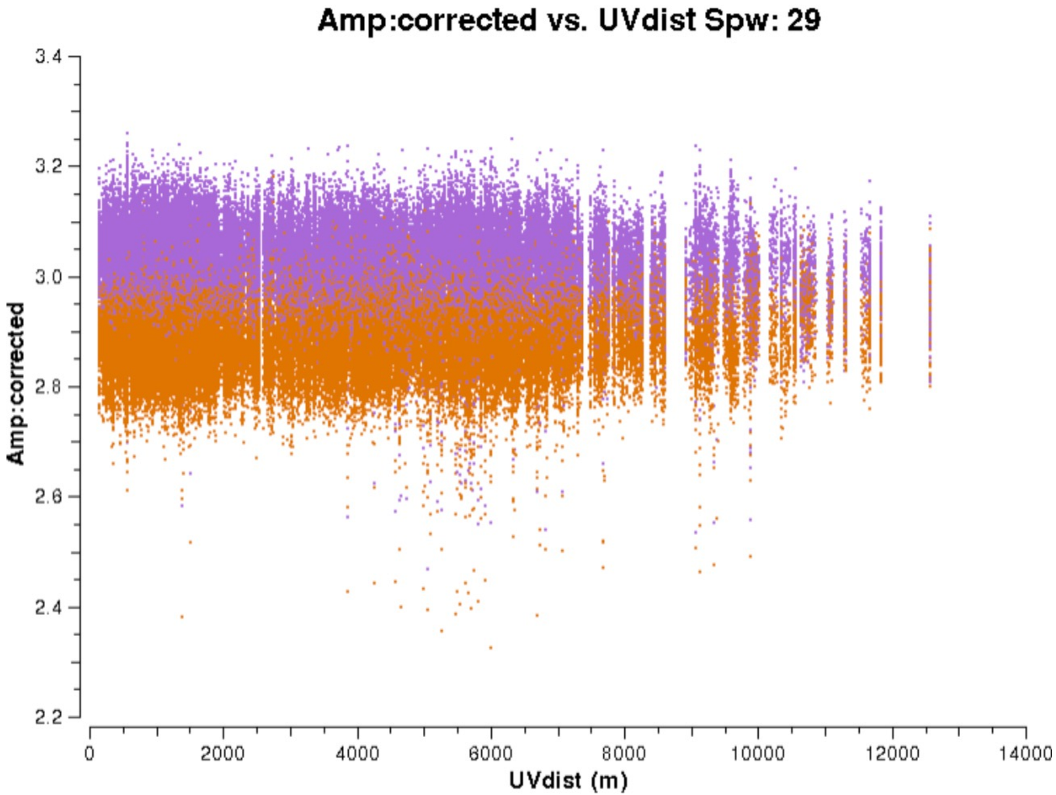




Flux calibration

11. hif_setmodels: Set calibrator model visibilities



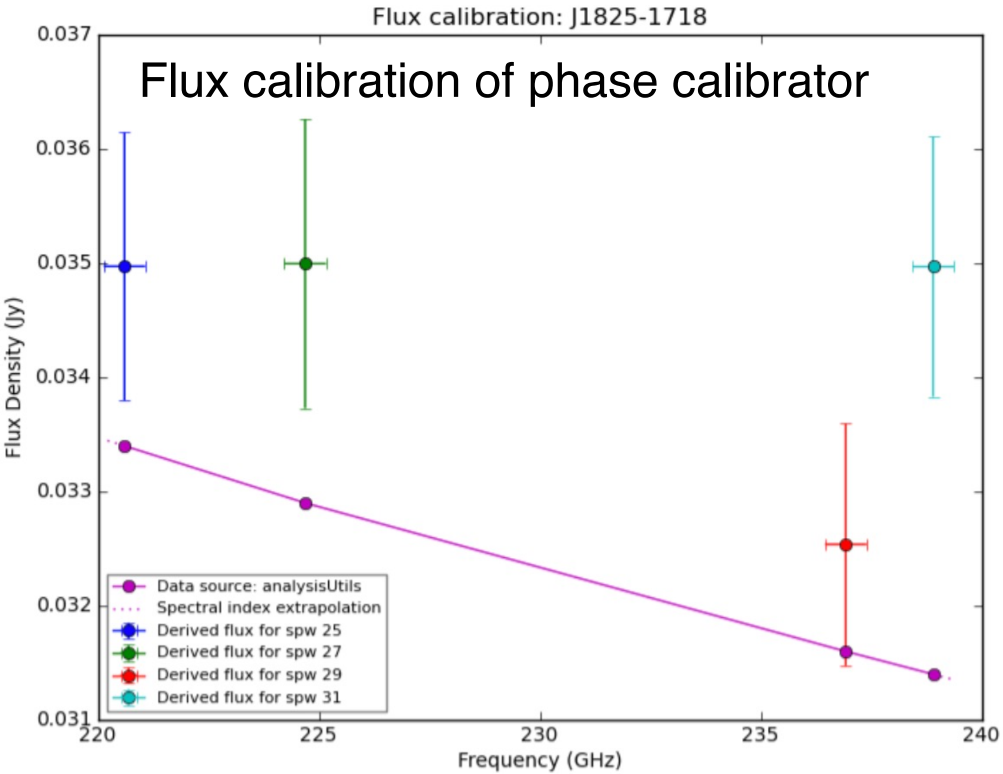


Flux consistency

15. **hifa_gfluxscale**: Transfer fluxscale from amplitude calibrator

Compare with
https://almascience.eso.org/sc/

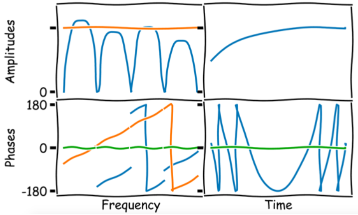
Absolute flux density error: ~10-15%

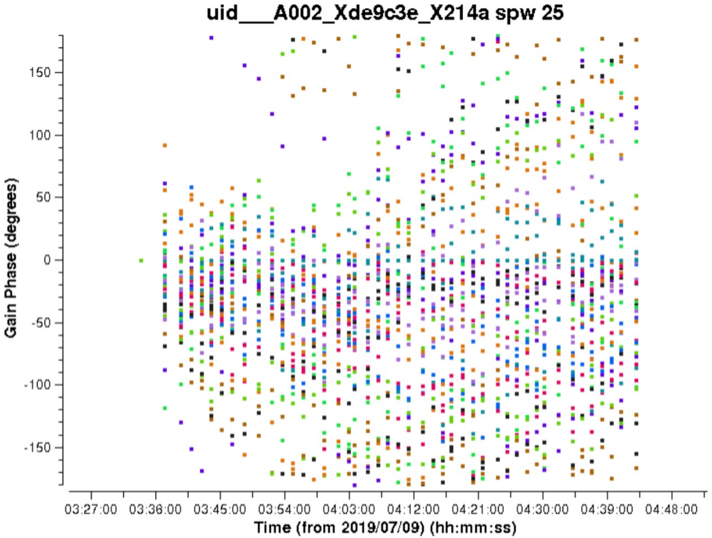


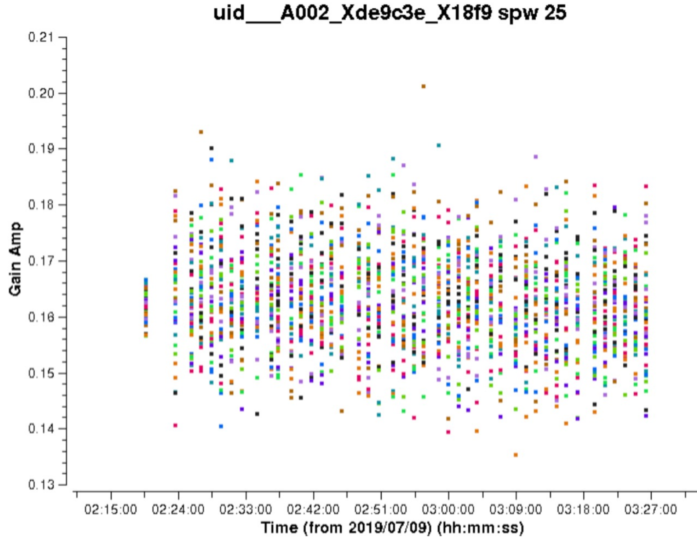
Phase calibration

16. **hifa_timegaincal**: Gain calibration

Phase and amplitude corrections to be applied to the target





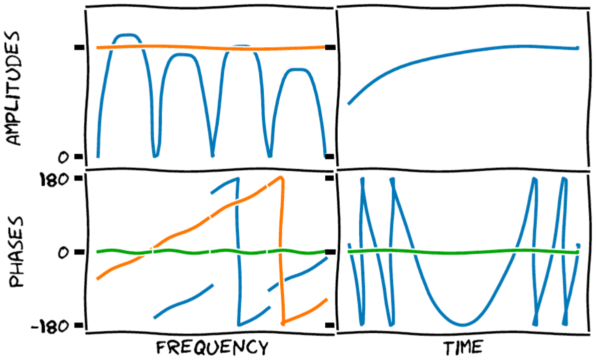


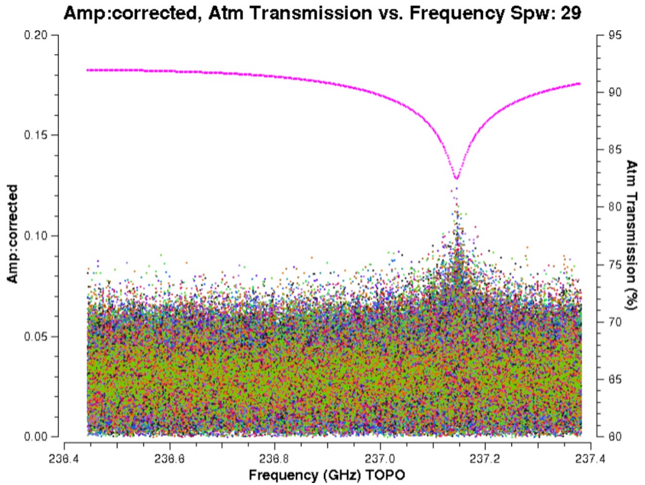
Applying all calibrations

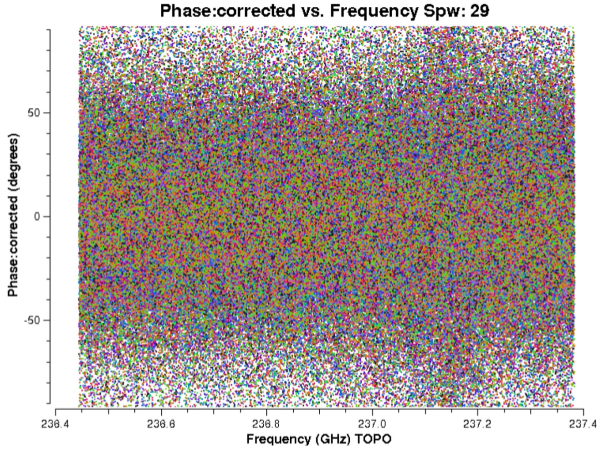
17. **hif_applycal**: Apply calibrations from context

Apply all corrections to:

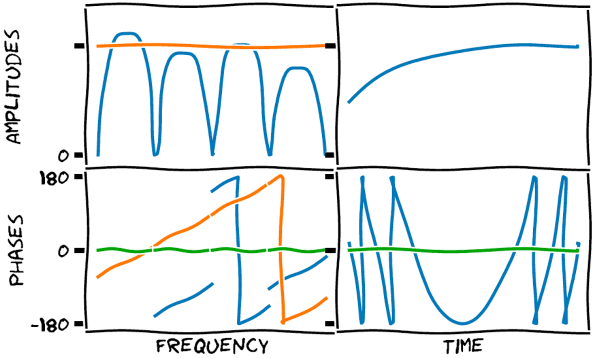
- calibrators themselves
- science target

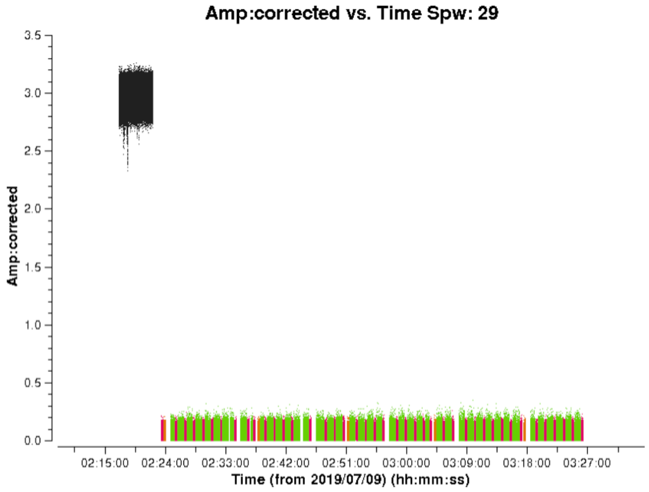


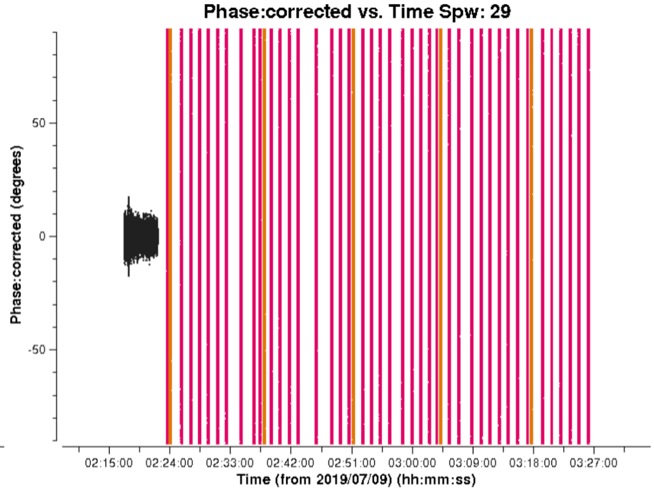




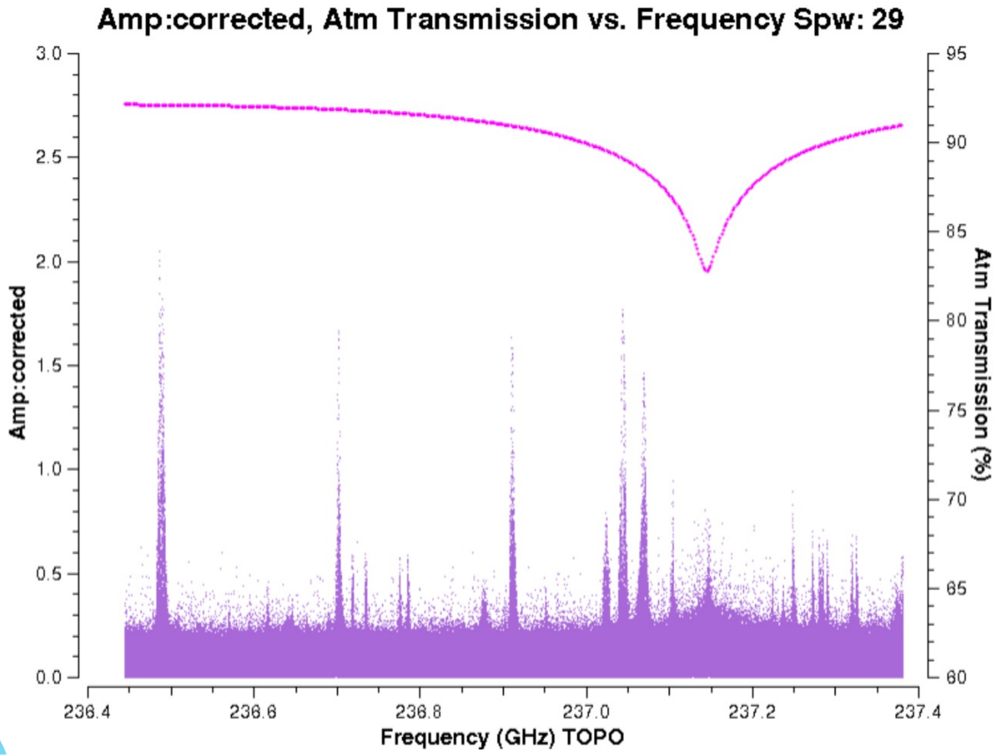
Phase calibration







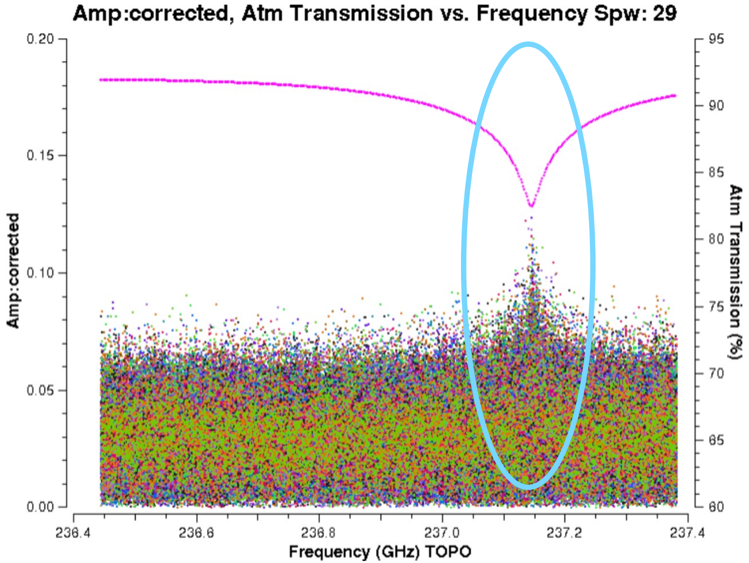
The target


Amp:corrected, Atm Transmission vs. Frequency Spw: 29
Amp:corrected
Atm Transmission (%)
Frequency (GHz) TOPO
3.0
2.5
2.0
1.5
1.0
0.5
0.0
95
90
85
80
75
70
65
60
236.4
236.6
236.8
237.0
237.2
237.4

Tweak the pipeline

Extra flagging needed for the atmospheric line

Add extra flagging in calibration/*flagtemplate.txt and re-run casapipescript.py



More details at:
"Tweaking the pipeline script" by R. Miura (NAOJ)
https://alma-intweb.mtk.nao.ac.jp/~saigo/EAARC_CASA/reference/TweakPipeline.pptx.pd

Need help?

If you have any questions or need help with your data, please contact us at

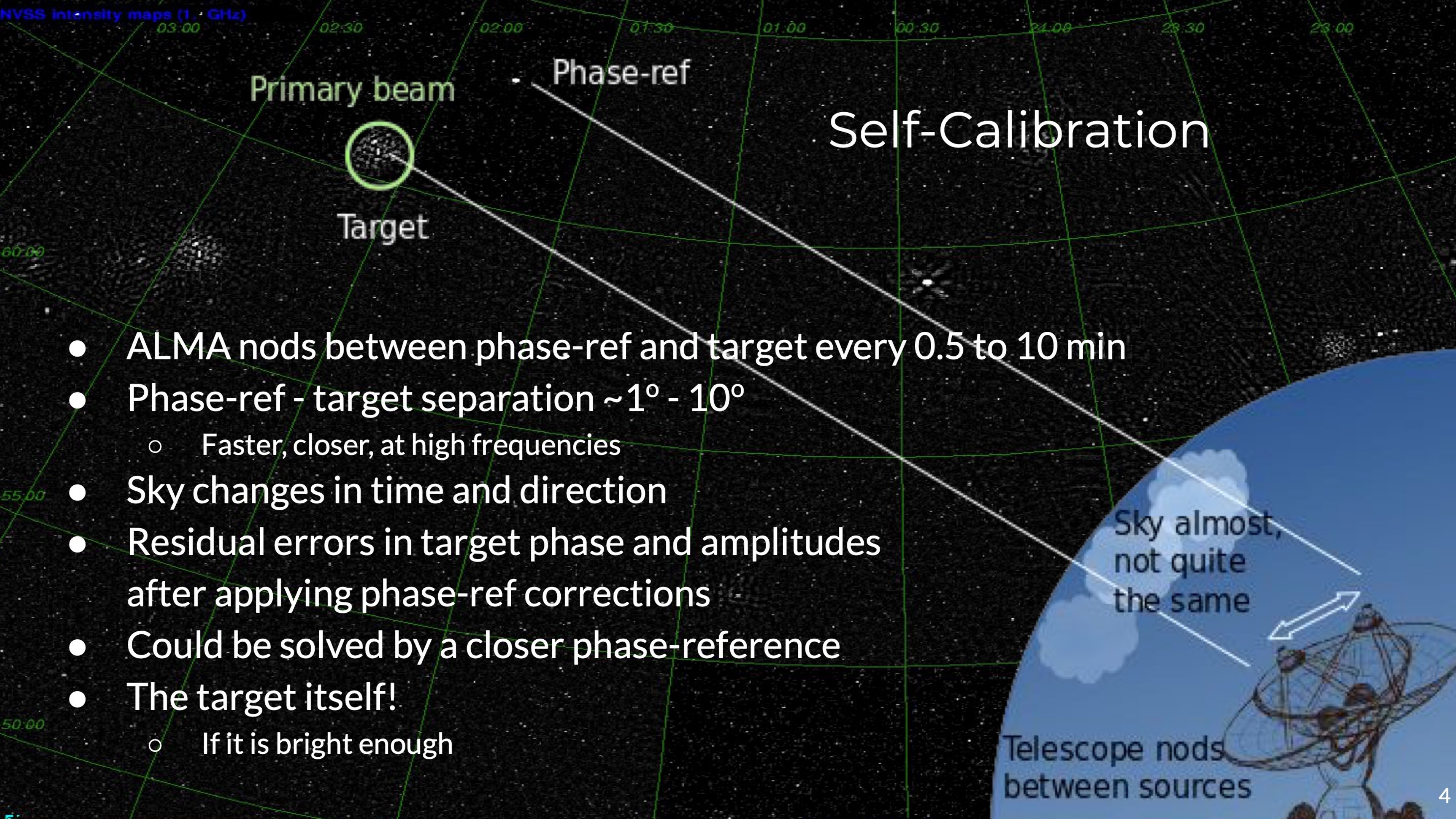
alma@strw.leidenuniv.nl

We are happy to help!

Self - calibration

A short intro!

Self-Calibration



- ALMA nods between phase-ref and target every 0.5 to 10 min
- Phase-ref - target separation ~1º - 10º
  - Faster, closer, at high frequencies
- Sky changes in time and direction
- Residual errors in target phase and amplitudes after applying phase-ref corrections
- Could be solved by a closer phase-reference
- The target itself!
  - If it is bright enough

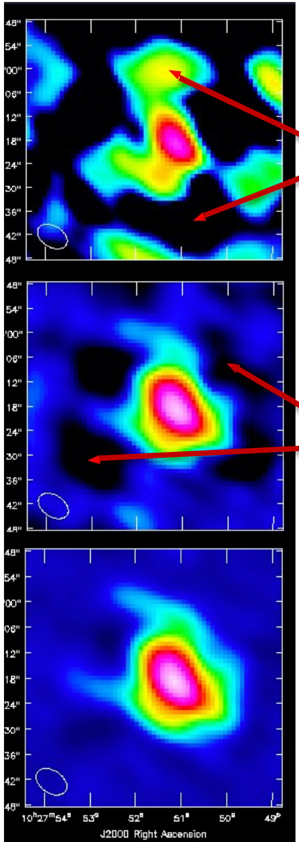
After self-cal images errors remain

Phase errors:

- emission is smeared – astrometry degraded
- visibility amplitudes are decorrelated → flux density reduced
- weak emission undetectable
- excess noise
- anti-symmetric artefacts

Amplitude errors:

- spotty of stripy emission
- flux density lower than expected
– symmetric artefacts
- noise increased



Phase-reference solutions
positive & negative artefacts
- **phase**-errors dominate

Self-calibration phase
only

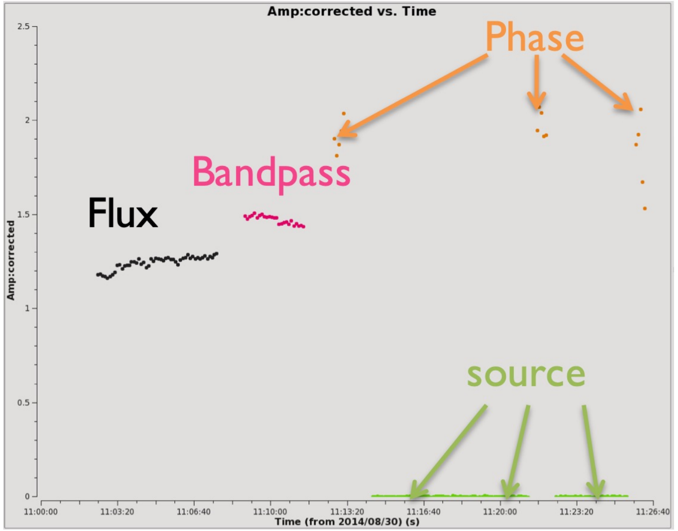
Symmetric artefacts
remain - amp. errors

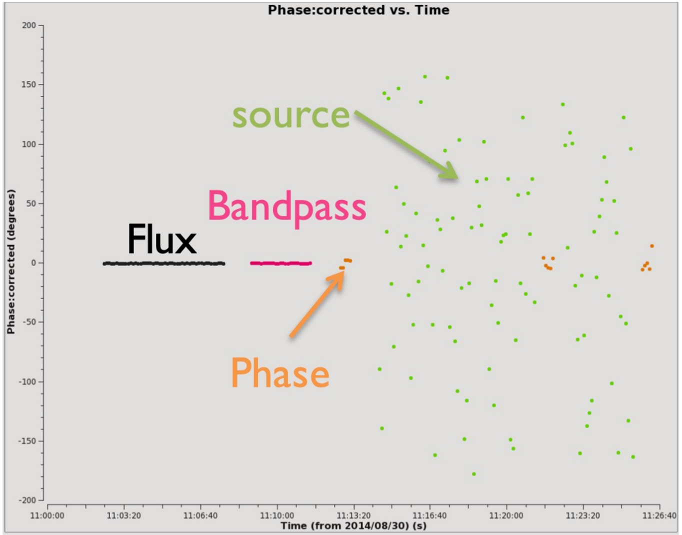
Self-calibration phase
followed by amplitude

From CASAGUIDE
On NGC3256

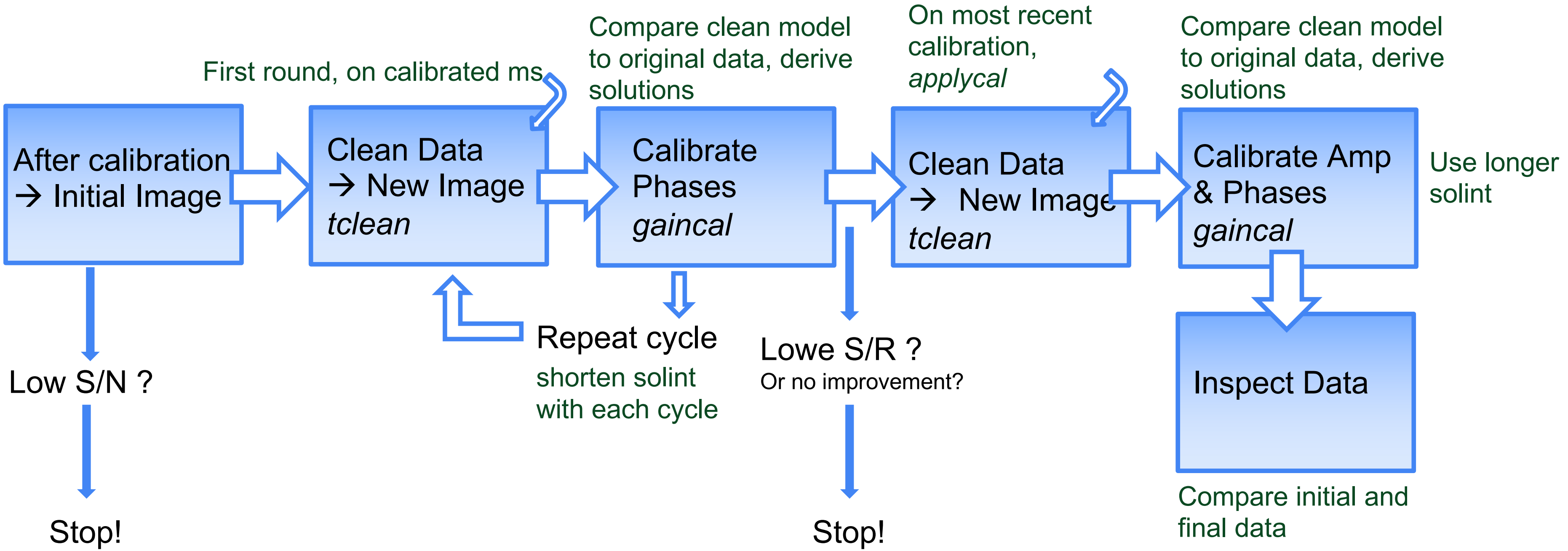
Self calibration – a short short summary

- Self-calibration the **target ITSELF** to better calibrate the antenna-based complex gains (i.e., amplitudes and phases) as a function of time.
- By creating a model of the target, you can calibrate the target itself. You can get a model of your source through an initial image of your source.
- There are two types of self-calibration: 1) Phase and 2) Amplitude & Phase





The "self-cal" cycle



Sensitivity considerations

For phase self-calibration:
Need to detect the target with a S/N > 40 in a solution time (**solint**) for 40 ALMA antennas

Solint's vary from scan length (~ mins), or integration time (~ secs), or longer

How to estimate your chances of success :
- measure rms in emission-free region of your map ; measure peak in the map → Peak/rms is your S/N

If dominated by extended emission, estimate the flux density on the longer baselines (by plotting the uv-data). If the majority of baselines cannot "see" the bulk of the emission (i.e. emission is resolved out) at a S/N of about 3, the self-cal will most likely fail.

For amplitude self-calibration:
Need to detect the target with a S/N > 100 in a solution time (**solint**)

Amplitude corrections are more subject to deficiencies in the model image.

For more details…

Please go to I-TRAIN….

https://almascience.nrao.edu/tools/eu-arc-network/i-train

https://home.strw.leidenuniv.nl/~alma/doc/allegroDRC/selfcal.html

Choosing the solution interval - phase

- Start cautiously, e.g. scan length, to avoid freezing-in imperfect model
  - See previous talks
  - Can compare S/N to optimise solint (also see VLA self-calibration CASA guide)
    - Maybe harder if sensitivity or signal changes a lot with frequency or baseline length
- Can estimate analytically integration time giving required S/N per antenna
  - S = peak flux in Jy/beam, ideal σ_{rms}, N antennas $\sigma_{\rm rms} \propto \frac{T_{\rm sys}}{\sqrt{N(N-1)/2 \times \Delta\nu \times \Delta t}}$
  - $\Delta\nu$ total bandwidth (used in image), Δt total time on target
    - Initial actual image σ_{rms} higher, atmospheric as well as thermal noise
      - Actual σ_{rms} should decrease as self-calibration progresses
- Each antenna has (N-1) baselines
  - Degrees of freedom also reduced by refant, arbitrary origin of phase
  - Noise per antenna $\sigma_{\rm rms,ant} = \sigma_{\rm rms} \times \sqrt{\frac{(N(N-1)/2)}{(N-3)}}$

I-TRAIN #6: Improving image fidelity through self-calibration
25 May 2021, 11:00 CEST

Materials:
- training video (YouTube)
- presentation Self-Calibration Basic
- presentation Self-Calibration Advanced
- Q&A session
- instructions
- dataset and script (size: 1.8 GB!)

Tutors: Emily Moravec, Anita Richards, Andrés Pérez-Sánchez, MCarmen Toribio

In this session you will learn how to self-calibrate your interferometric images to improve their image fidelity. In particular, you will learn criteria to decide whether to self-calibrate, how to choose parameter values - and when to stop - and thus, how to improve the image dynamic range and bring faint details out of the noise.

Before the session, attendees will be requested to do some preparations in order to be able to follow this tutorial in full. The preparations will consist of downloading a dataset and installing a compatible CASA version and instructions on how to do so will be made available on the Science Portal at least a week in advance. Presentation slides will be made available in the Science Portal the day before the session.

The duration of this training session will be about two hours and will include a live demo and an interactive Q&A. The first hour will be an interactive tutorial and demonstration. The second hour will be devoted to Q&A, advanced techniques and special cases. For questions do not hesitate to contact us at contact@nordic-alma.se.

Thank you for your attention !