

Principles of data-reduction



I – Single-Dish Data



Single-dish Data Reduction

Modes of observing

- Position switching
- Frequency switching
- Grid mapping
- On-the-fly (OTF) scan mapping

- All techniques require measurements of the pass-band shape, which for 3-mm observations changes on timescales of minutes.
 - Instrumental (constant) & atmospheric (dynamic) components

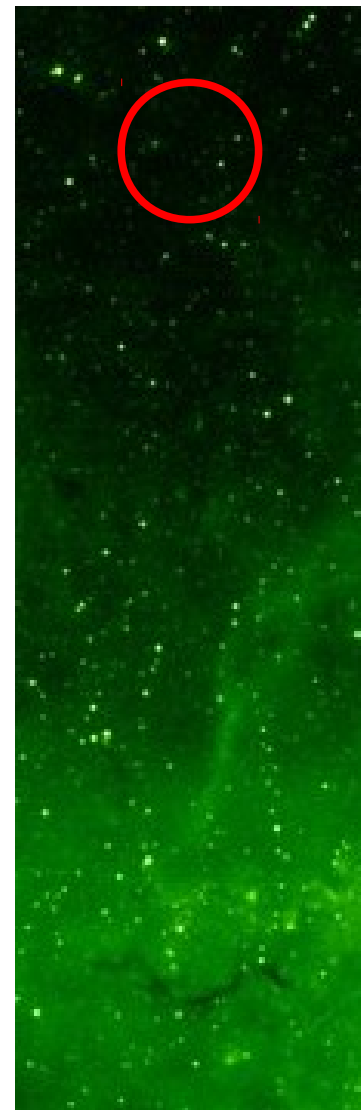
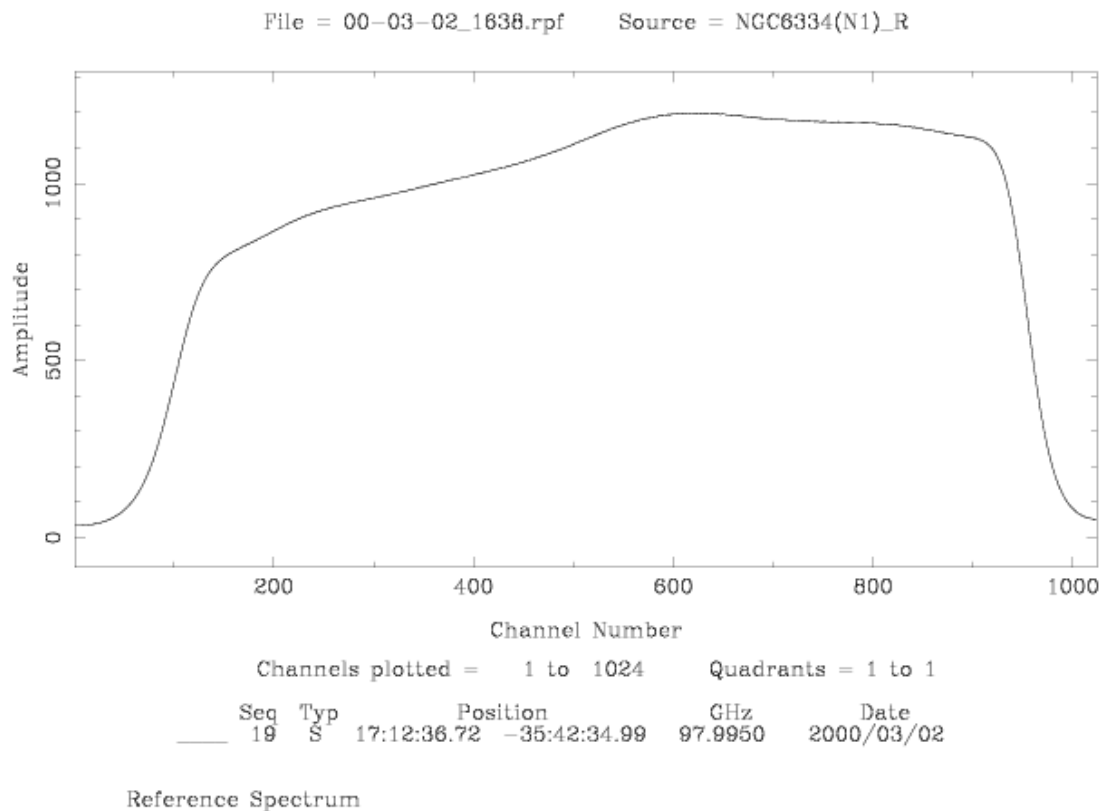


Single-dish Data Reduction

Modes of observing

THE UNIVERSITY OF
SYDNEY

- Position switching



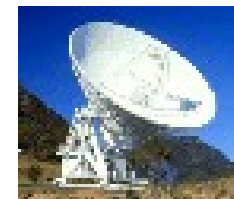
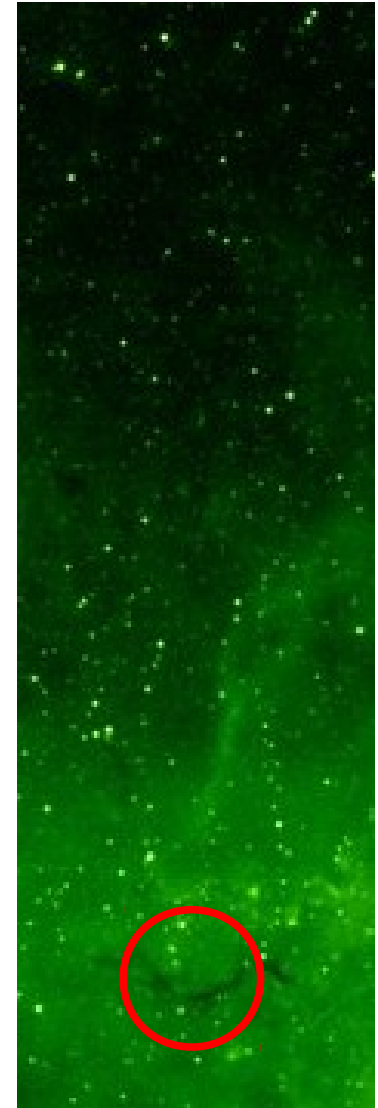
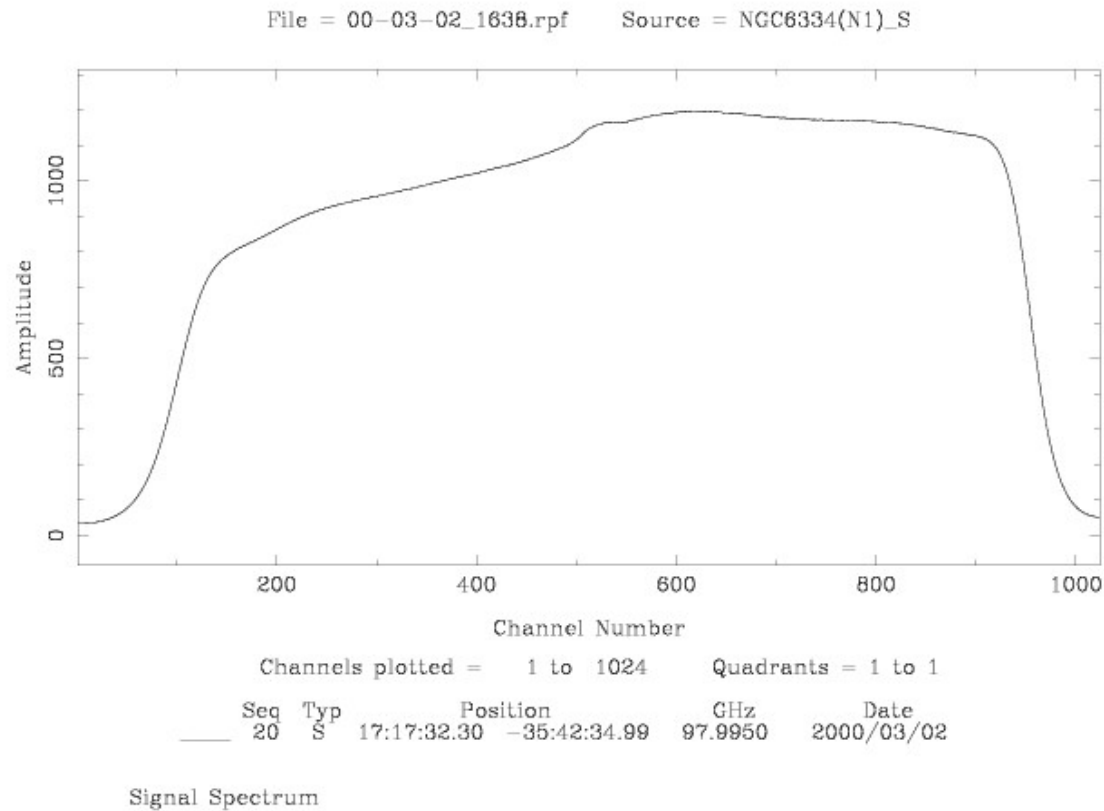


Single-dish Data Reduction

Modes of observing

THE UNIVERSITY OF
SYDNEY

- Position switching

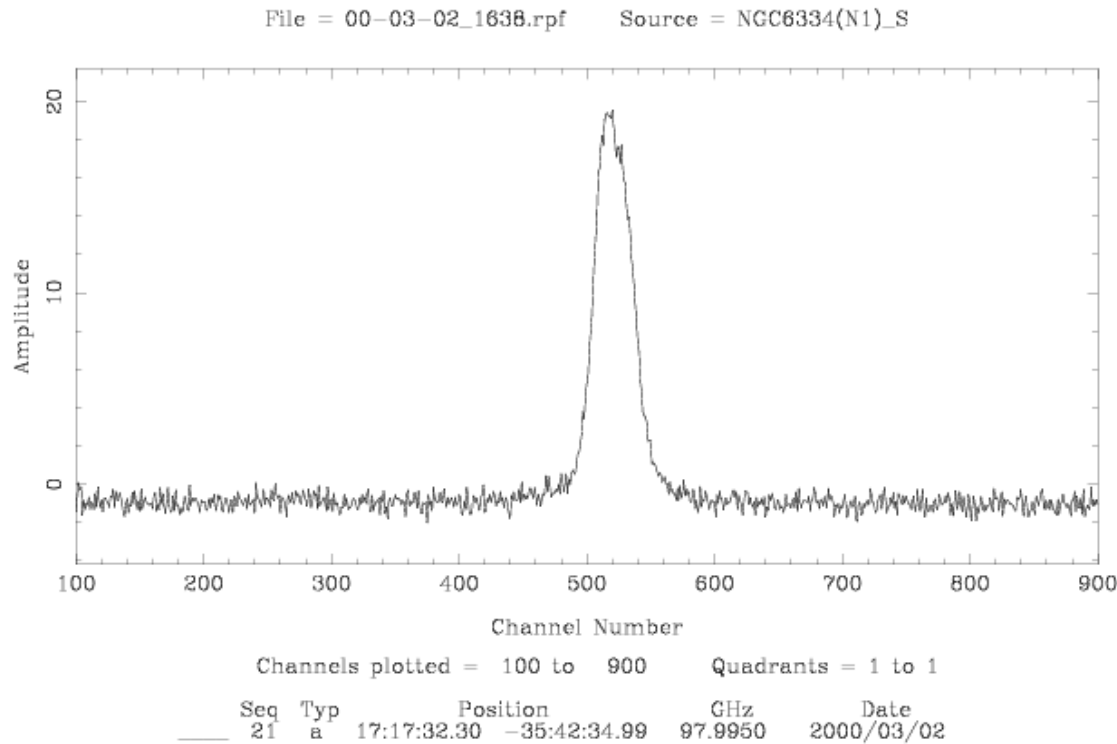




Single-dish Data Reduction

Modes of observing

- Position switching

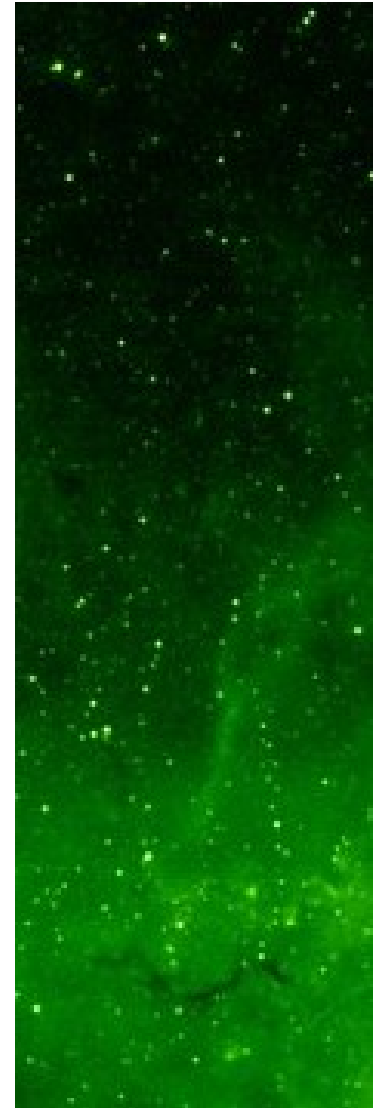


Quotient

$$T_A^* = \frac{(P_{\text{on-source}} - P_{\text{off-source}})}{P_{\text{off-source}}}$$

T_{sys}

Calibrated using a BB 'paddle' @3mm

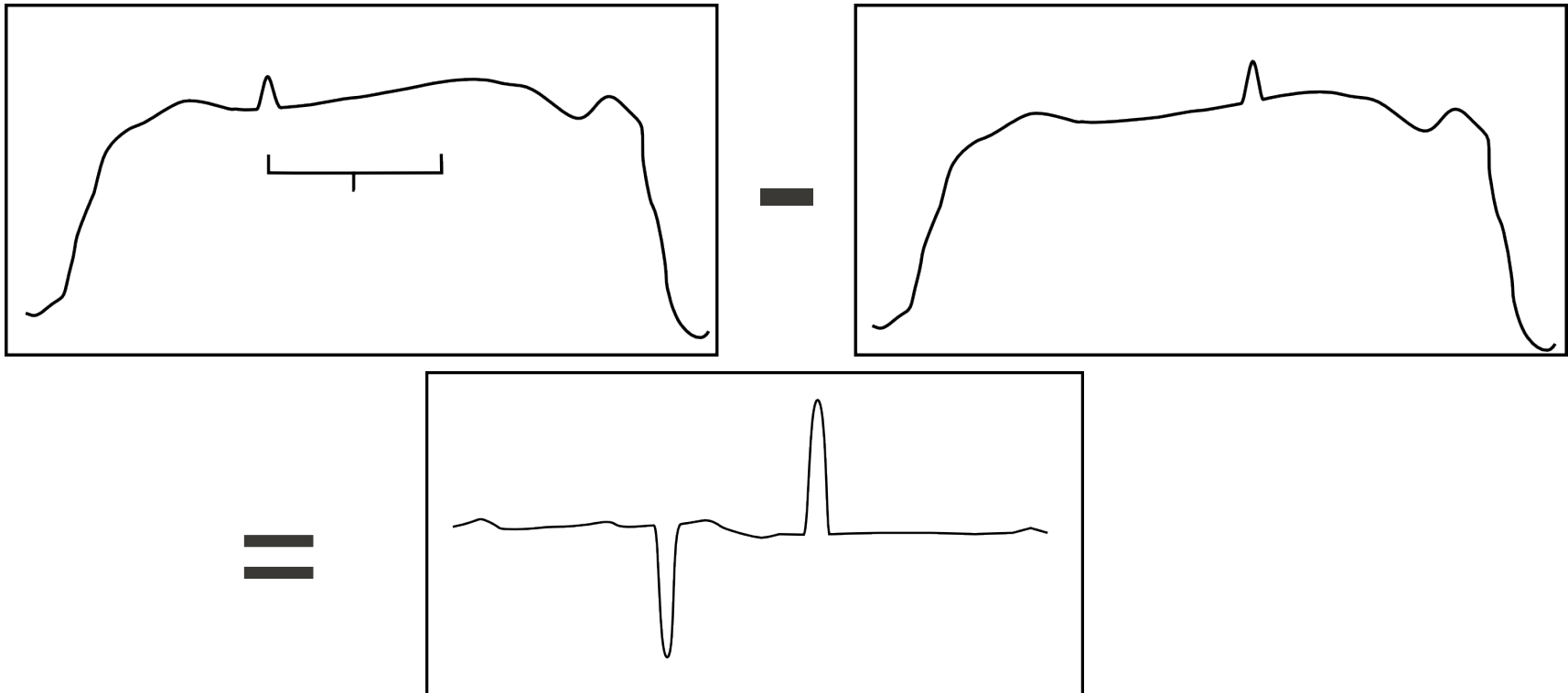




Single-dish Data Reduction

Modes of observing

- Frequency switching used for strong emission lines in quiet parts of the spectrum.
- Telescope remains on-source at all times, but shifts the sky frequency a fraction of the bandpass.
 - Sensitivity better by $\sqrt{2}$ over position switching

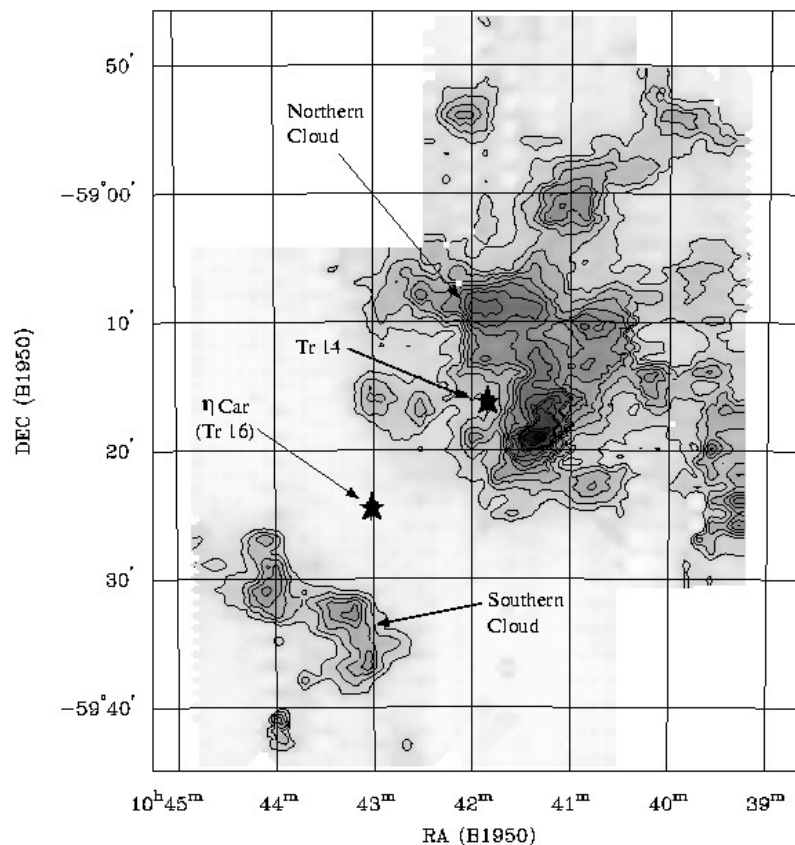
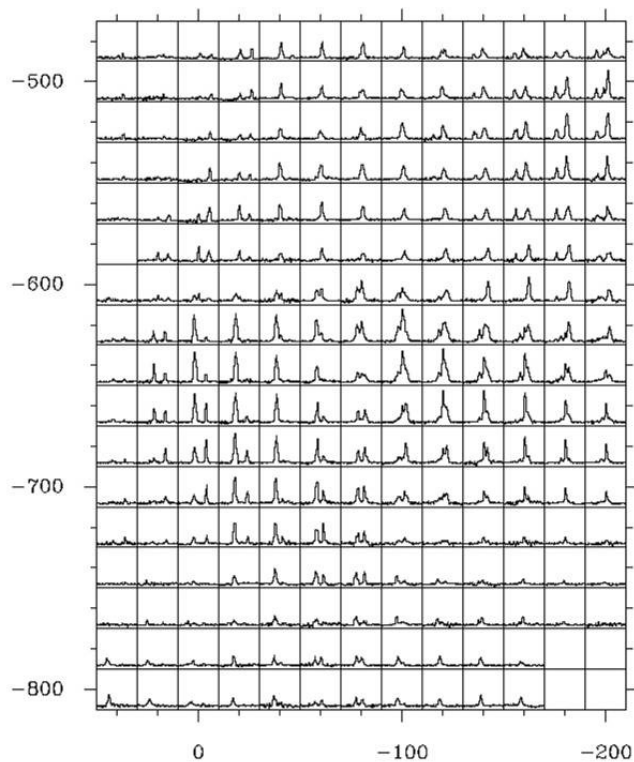




Single-dish Data Reduction

Modes of observing

- Grid mapping is a variant of position-switching.
- A grid of pointing positions are observed in succession.
- For fully sampled maps the on-source positions must be separated by $\leq \frac{1}{2}$ a beam FWHM.

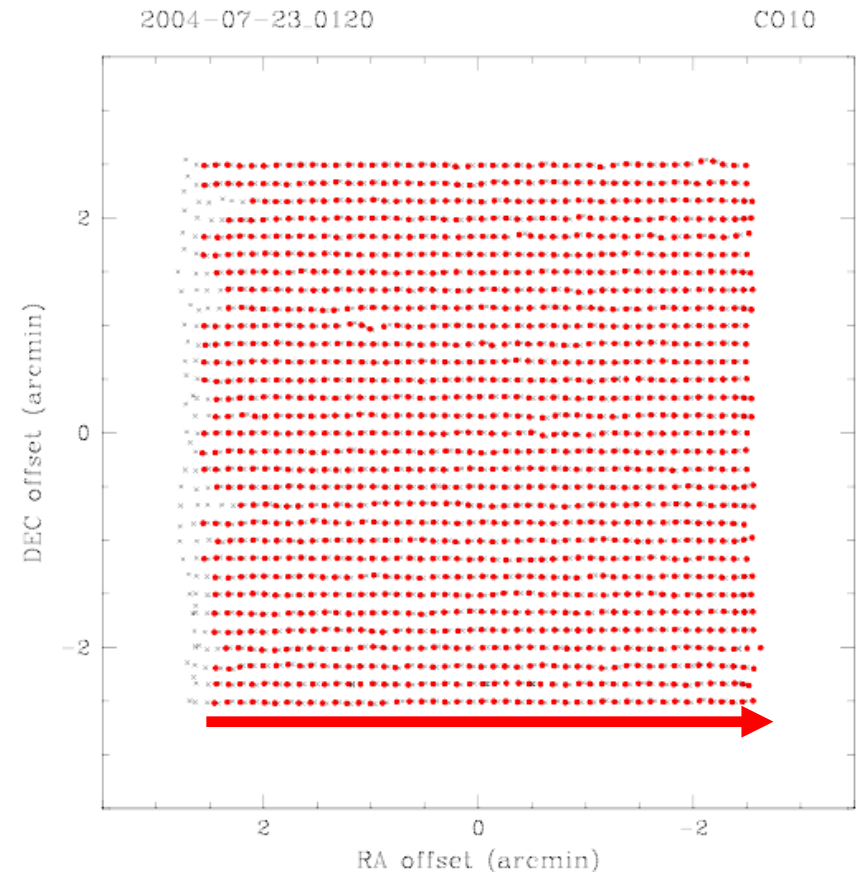
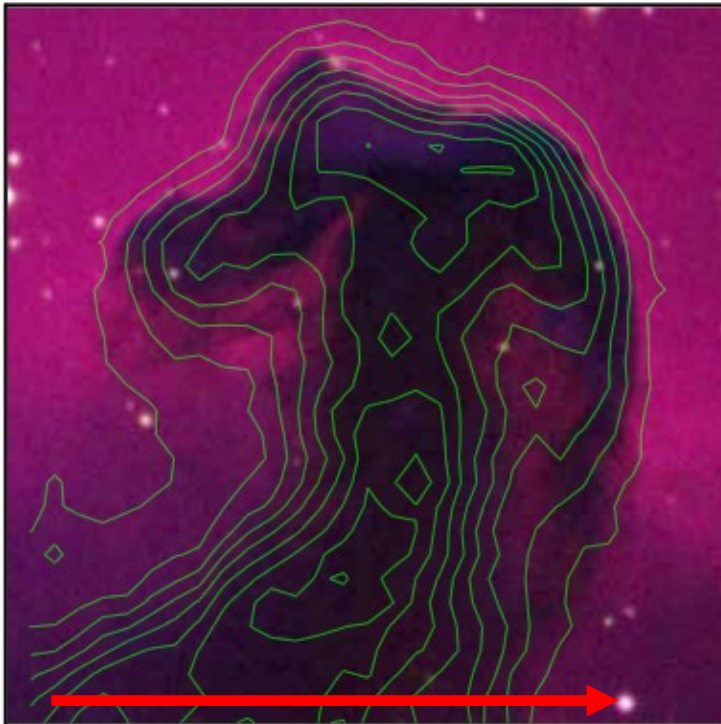




Single-dish Data Reduction

Modes of observing

- In on-the-fly (OTF) mapping the telescope is continually scanned along rows or columns.
- Spectra are written to disk every cycle and the scan rate is set so that smearing is negligible compared to the beam FWHM.





Single-dish Data Reduction

Note on sensitivity & temperature scales

- Radiometer equation:

$$\sigma_{\text{rms}} = \frac{T_{\text{sys}}}{\sqrt{\Delta\nu t_{\text{on}}}} \left[1 + \frac{t_{\text{on}}}{t_{\text{off}}} \right]^{1/2}$$

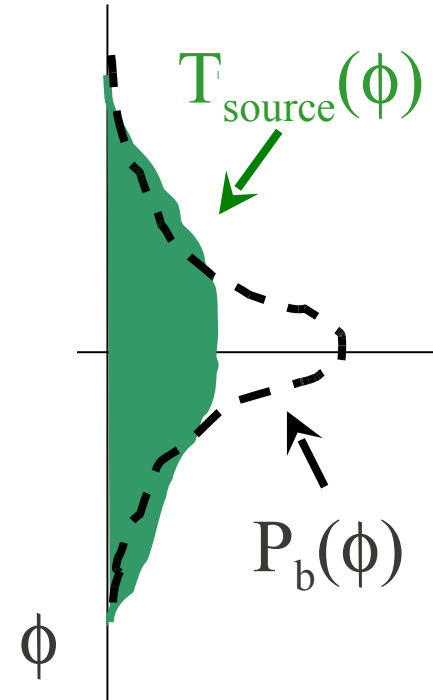
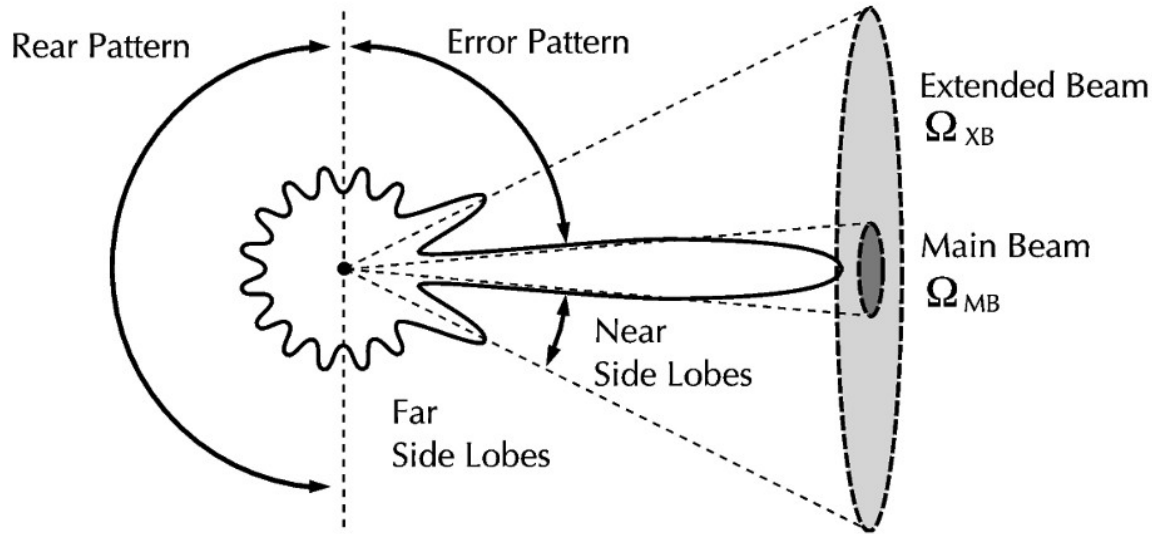
- Averaging 2 polarisations gives additional $\sqrt{2}$ improvement, as does frequency switching.
- For rapidly sampled data (OTF mode) can use the same off-source spectrum for several on.
 - Optimal $t_{\text{on}}/t_{\text{off}} = 1/\sqrt{N}$
- Not the whole story however ...



Single-dish Data Reduction

Note on sensitivity & temperature scales

- T_A^* scale assumes source emission fills the forward hemisphere of the telescope beam



- Fraction of power received in the main beam given by η_{mb}

$$T_{mb} = T_A^* / \eta_{mb}$$



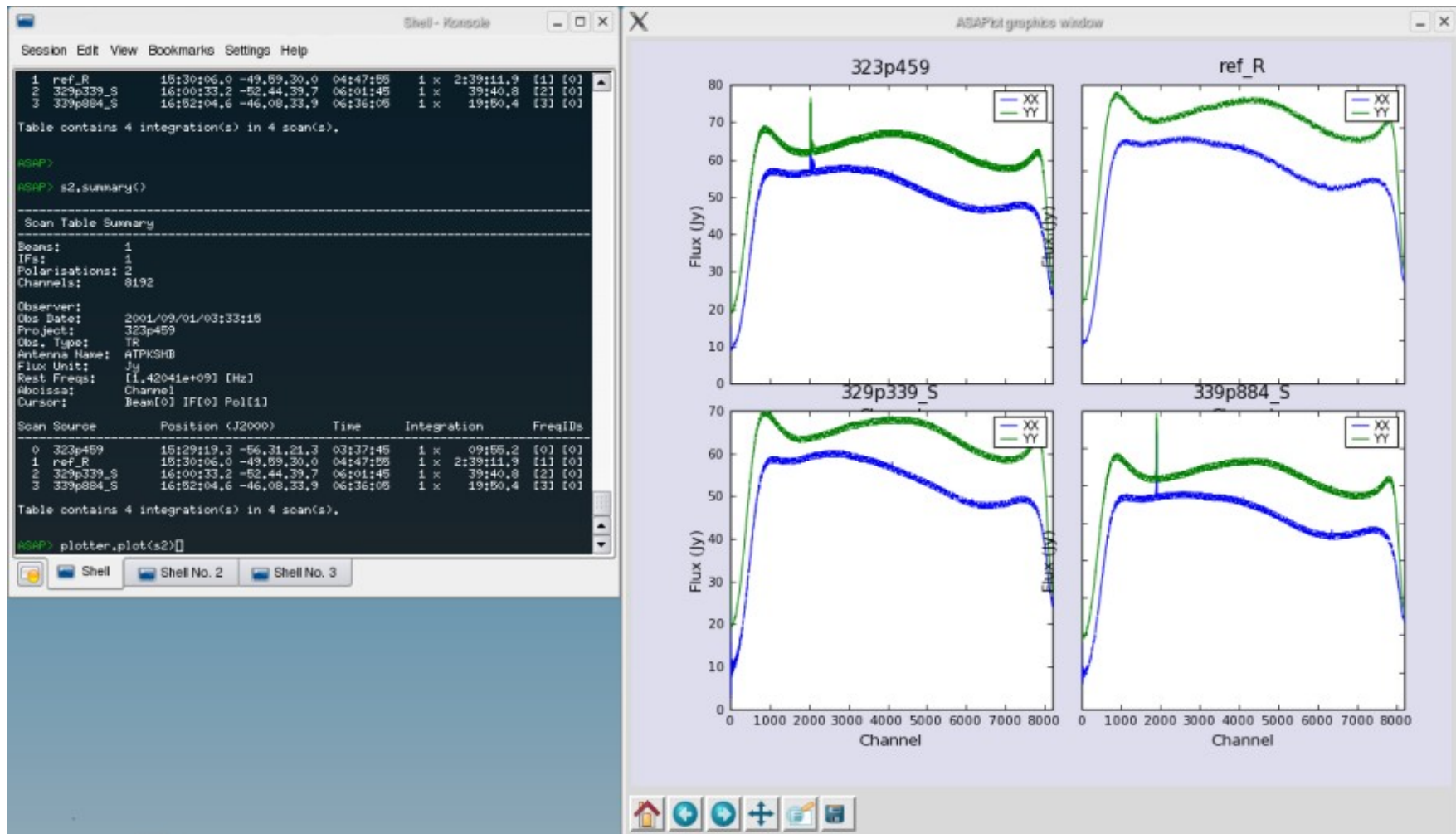
Basic data-reduction steps

- Perform quotient to remove bandpass shape
- Flag out any noisy channels (typically at edges)
- Flag out any bad scans (weather, RFI etc.)
- Fit & subtract a baseline polynomial to remove any residual differences between on- and off-spectra
- Single pointing:
 - Average all scans together weighted by $t_{\text{int}}/T_{\text{sys}}^2$
- Mapping:
 - Resample the spectra onto a regular pixel grid using a smoothing kernel



ASAP

- Very powerful spectral-line reduction package
 - See Malte's talk





Livedata & Gridzilla

- Livedata:

The screenshot displays three overlapping windows from the Livedata software suite:

- Multibeam data processing:** Features a 'DATA REDUCTION CONTROL' section with a 'Reader' status of 'IDLE'. It includes checkboxes for 'Bandpass calibration', 'Monitor output', 'Statistics', and 'Write data', all currently unchecked. Below this is the 'MULTIBEAM READER' section with 'Max retries: 0' and an 'Input data selection' grid of 13 numbered beam positions (1-13) arranged in a cross pattern. Further down are controls for 'IFs' (a 4x4 grid), 'Channel range' (set to 1 - end), 'Read X-pol' (unchecked), frequency offsets (Δ), 'Interpolate' (checked), and 'Calibrate...' (unchecked).
- LiveData - Parkes Multibeam Data Reduction:** A 'SCHEDULER' window with tabs for 'Configuration', 'GENERAL', 'START', 'Pause', 'Stop after this', 'STOP NOW', 'HELP', and 'EXIT'. It contains fields for 'Read directory', 'Write directory', and 'File wildcard(s)' (set to *.hpf *.mbf *.rpf *.sdfits). It also features three lists: 'Raw files', 'Queued files', and 'Processed files', each with 'Update', 'Enqueue', 'Dequeue', and 'Clear' buttons.
- Livedata logger:** A log window showing the timestamp '20:36:50: 2011/09/25 EST (Sun) Livedata logger'.

- Automatically quotient & baseline OTF map spectra



Livedata & Gridzilla

- Gridzilla:

- Resample spectra into a regular data-cube



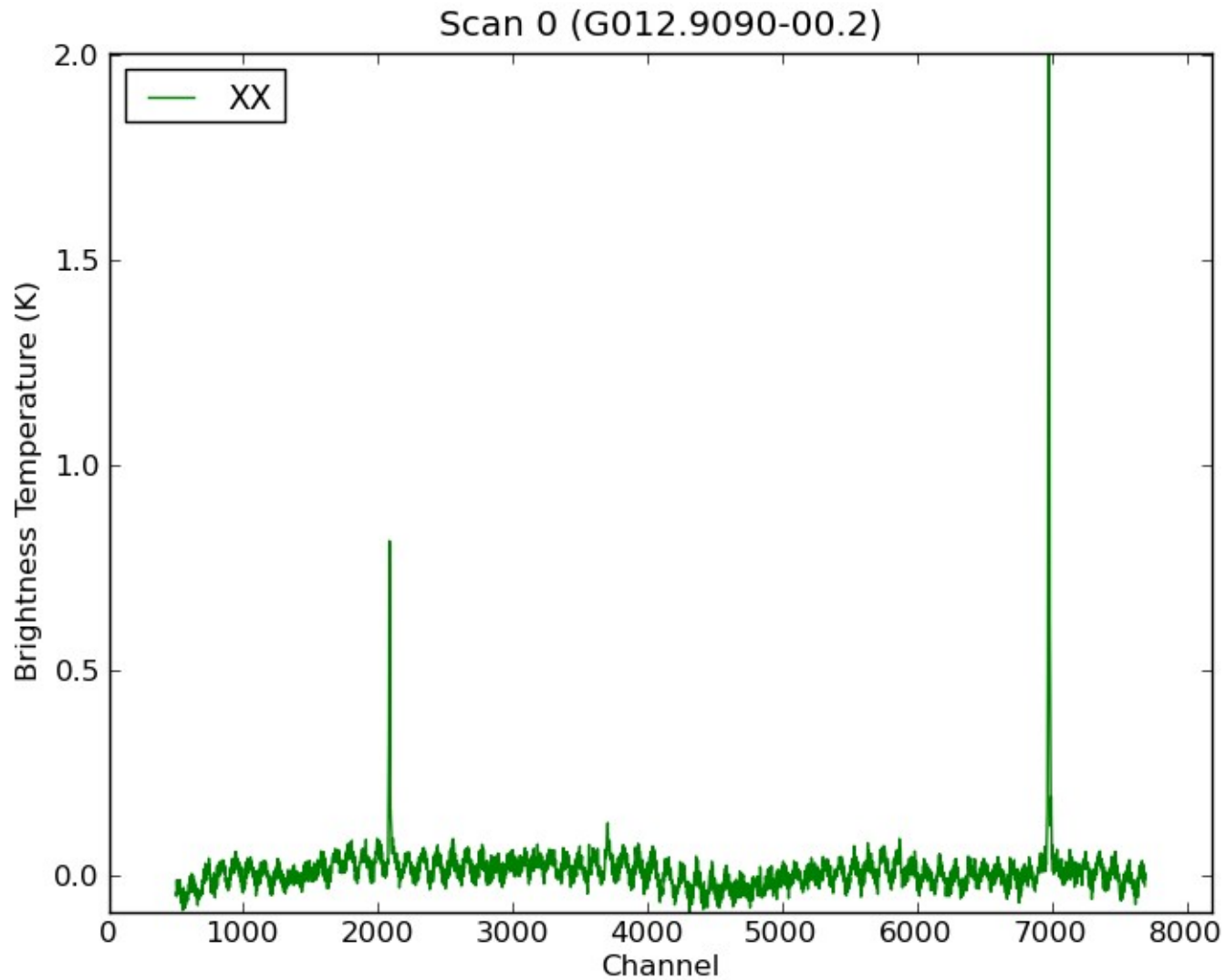
Additional techniques

- SD data sometimes affected by a semi-regular ripple
- Over a small enough window can be well fitted by a sine-wave
- One alternative is to flag the data in the fourier domain
- Cosine-edge filter mitigates some 'ringing', but still need to remove bright lines first



Additional techniques

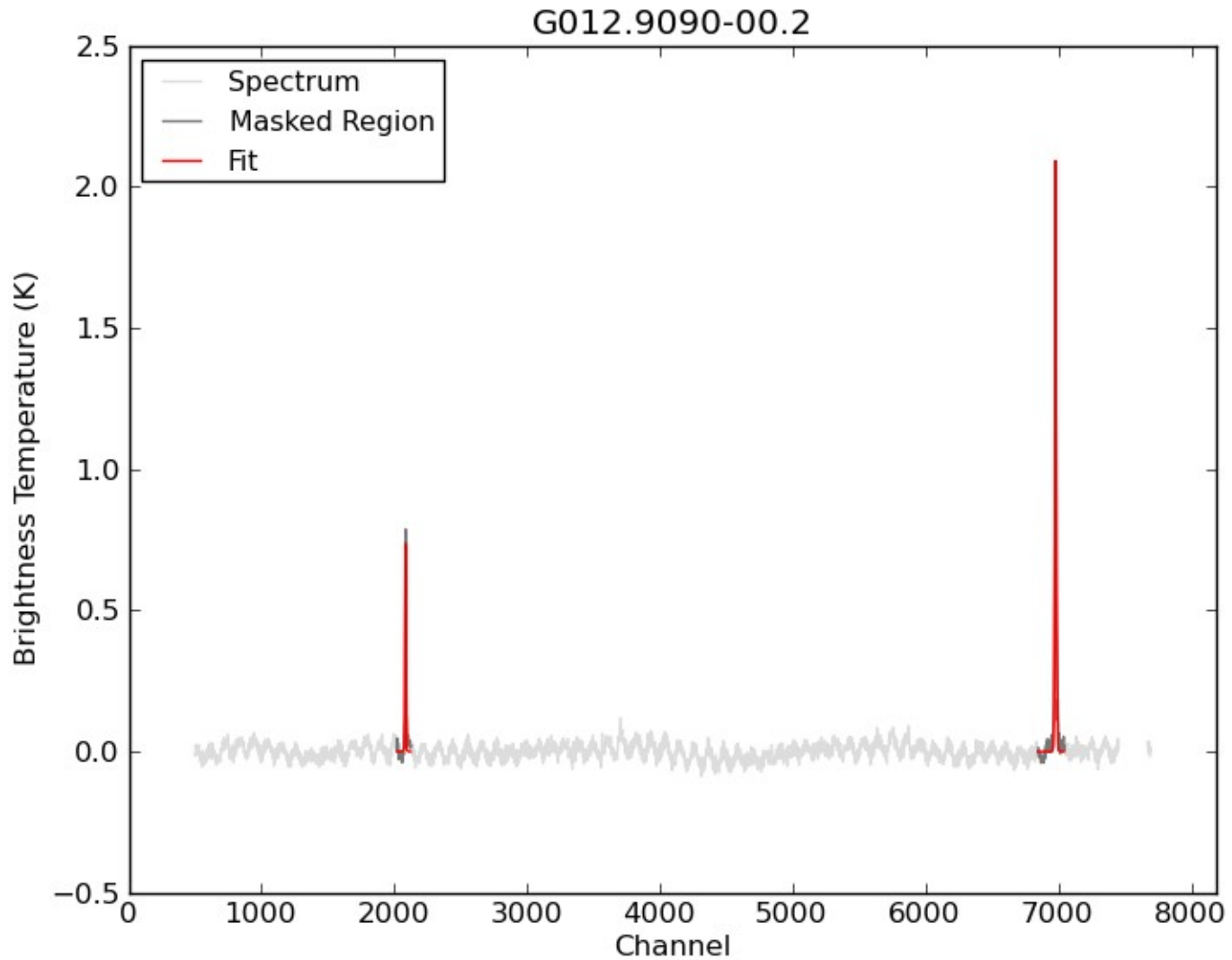
- Ripple caused by a standing wave in the telescope





Additional techniques

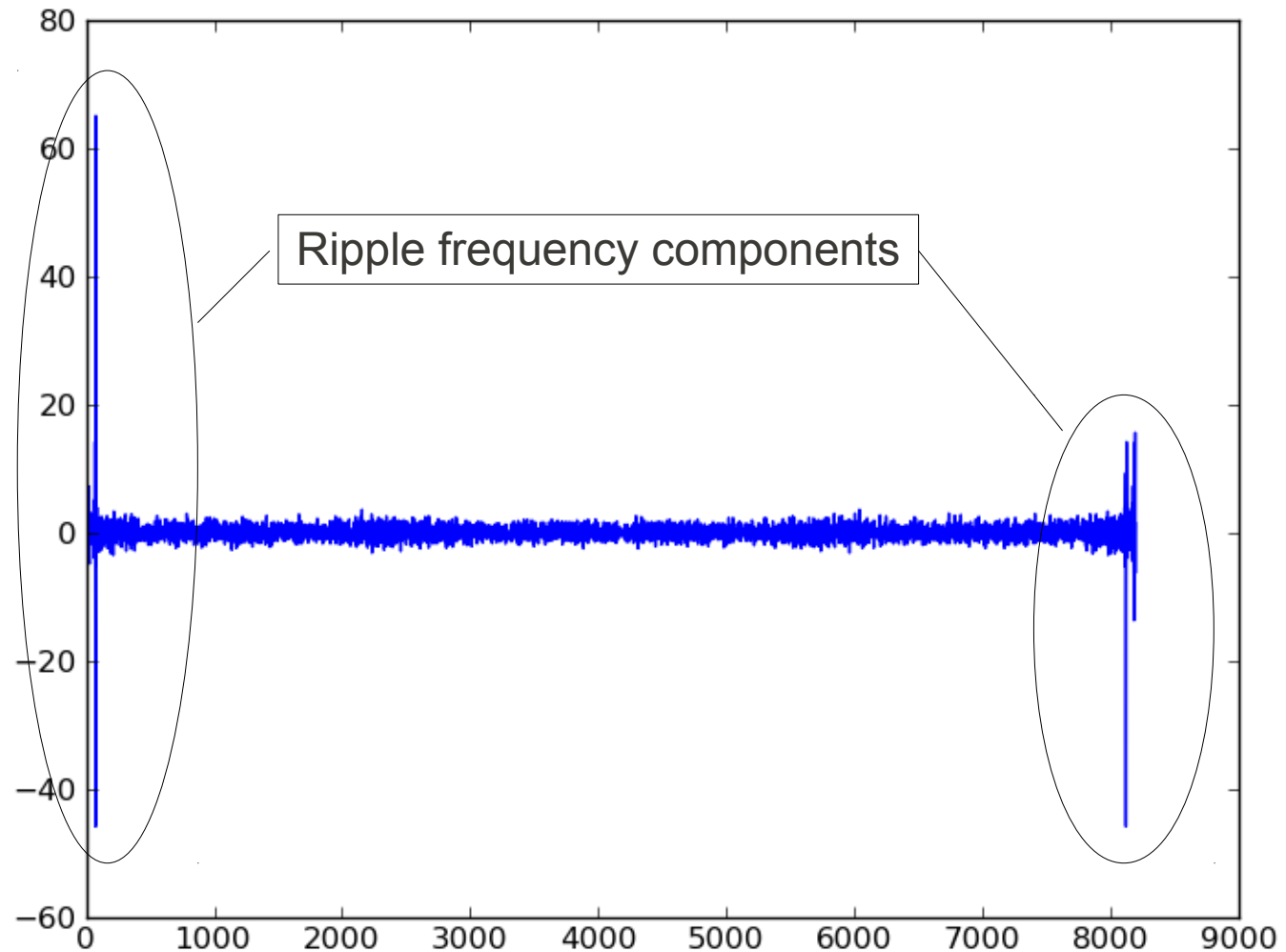
- First fit & remove any bright lines





Additional techniques

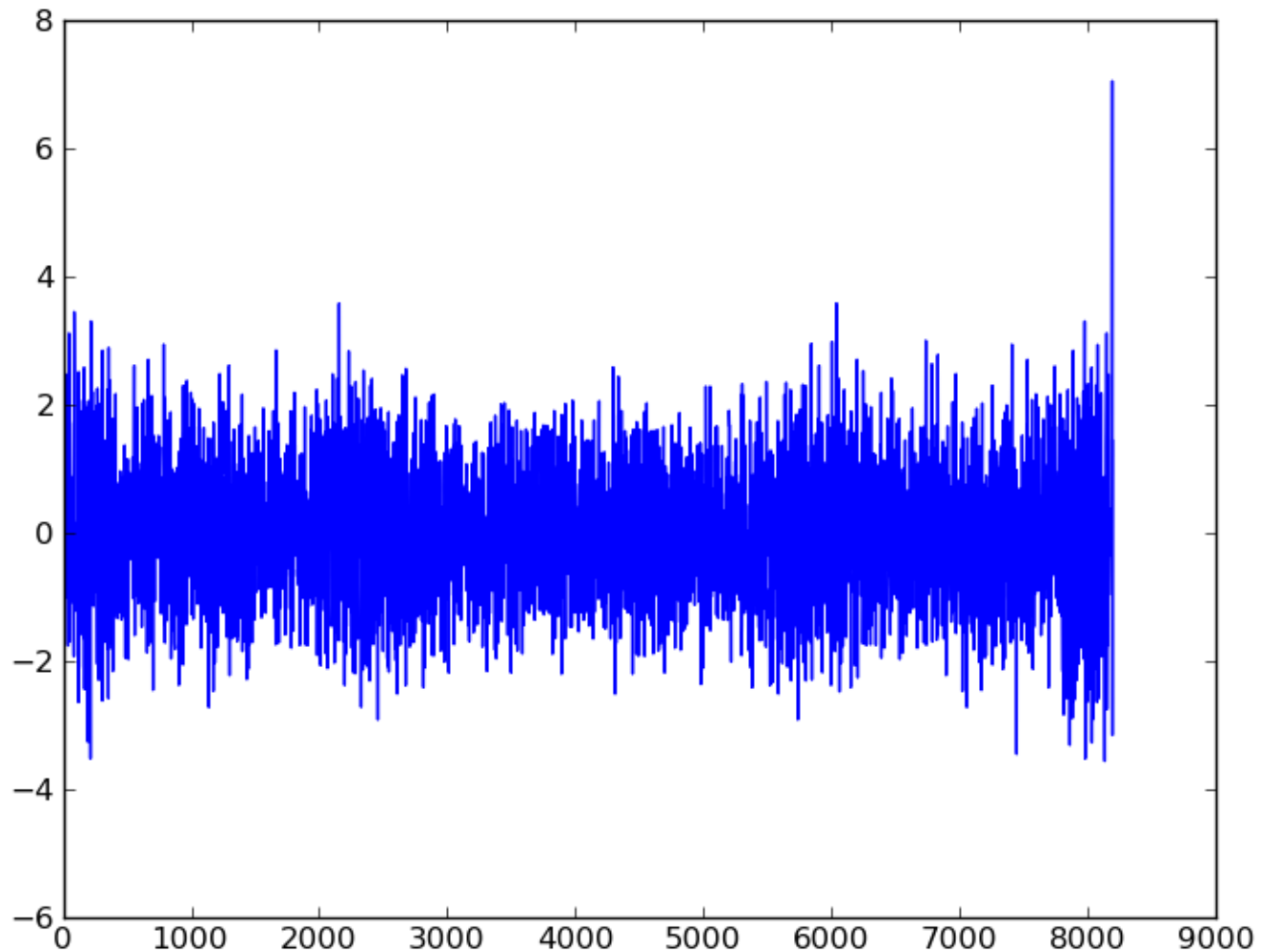
- Then take the FT of the spectrum
 - Flag off the spikes @ 30 MHz





Additional techniques

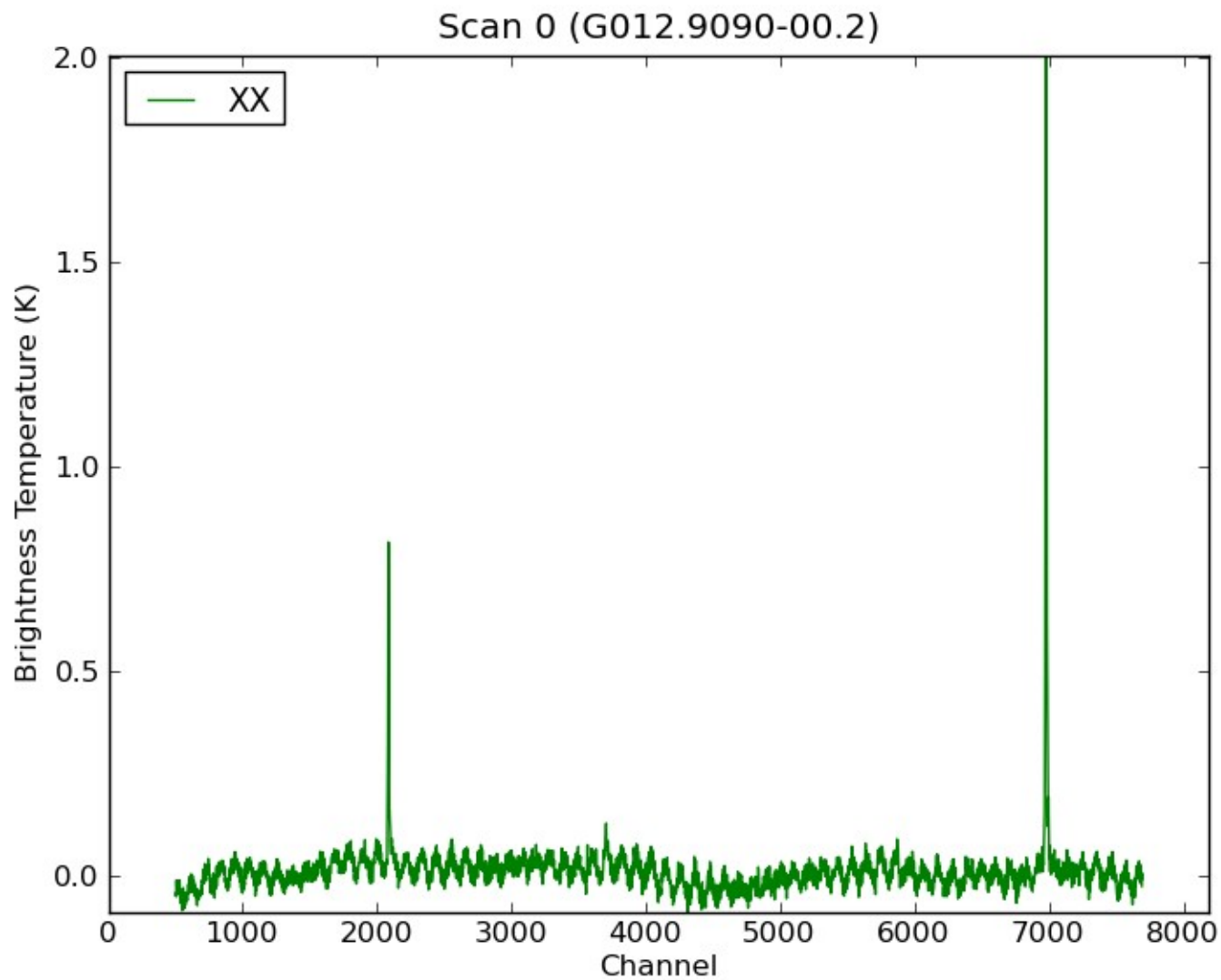
- Then take the FT of the spectrum
 - Flag off the spikes @ 30 MHz





Additional techniques

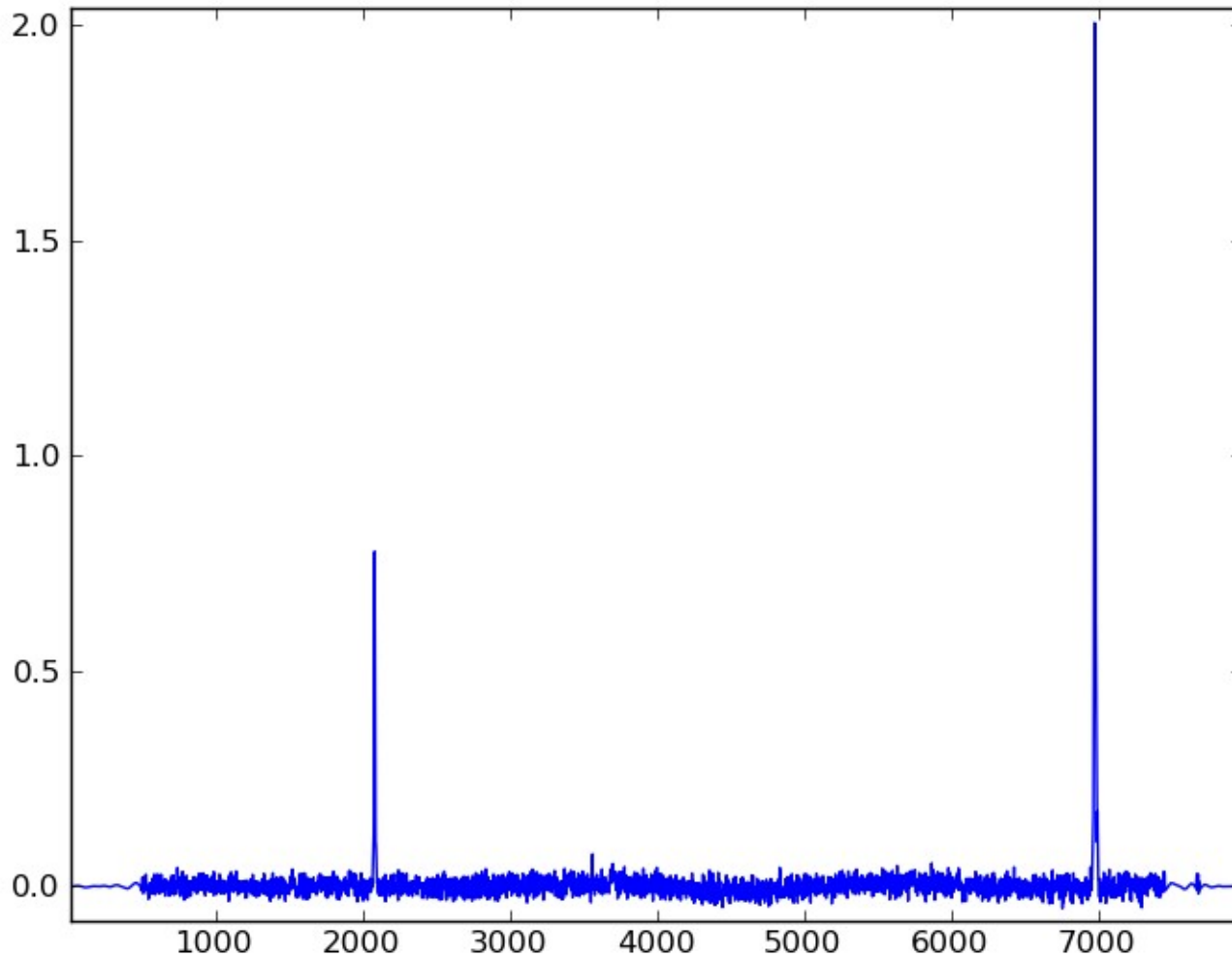
- Original spectrum ...





Additional techniques

- Inverse FT & restore bright lines to spectrum



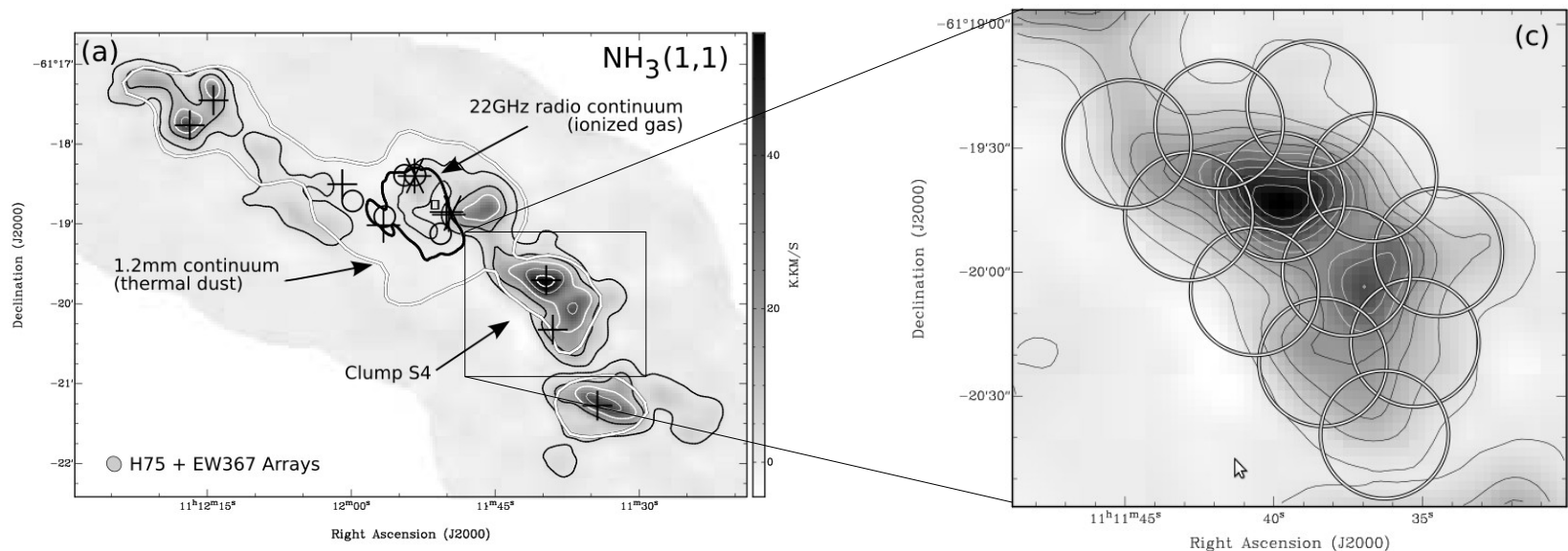
II – Interferometric Data



Reducing data from interferometers

Observing modes

- Two traditional observing modes on ATCA:
 - Single fields & pointed mosaics
- Single fields:
 - Image out to the primary beam FWHM
- Mosaicing
 - Combine multiple single fields into a large map





Reducing data from interferometers

Observing modes

- Two traditional observing modes on ATCA:
 - Single fields & pointed mosaics
- Single fields:
 - Image out to the primary beam FWHM
- Mosaicing
 - Combine multiple single fields into a large map
- Same observing schedule for both in principle
 - Sandwich observations of the science targets between 'secondary' calibrators
 - Track the changes phase and amplitude attenuation due to the atmosphere



Reducing data from interferometers

Observing modes

- Example schedule file
 - 9 science sources, observed in groups of 3

#	Source	Cal	RA	Dec	Epoch	Time(LST)	ScanLength	Az	El	Drive	ScanType	Aver	Freq-1	Freq-2	Pointing
1	pointing		18:33:39.915	-21:03:40.050	J2000	00:00:00	00:05:00	255:26:25.1	17:33:40.7	00:04:30	Point	1	93504	95552	Update
2	paddle		17:50:14.500	-28:54:31.000	J2000	00:05:01	00:02:00	243:02:37.5	11:24:41.2	00:00:00	Paddle	1	91978	92500	Offset
3	1830-210	C	18:33:39.915	-21:03:40.050	J2000	00:05:01	00:02:00	254:53:33.2	16:30:55.1	00:00:27	Dwell	1	91978	92500	Offset
4	G0.55-0.85		17:50:14.500	-28:54:31.000	J2000	00:07:28	00:05:00	242:46:51.6	10:56:18.8	00:00:00	Dwell	1	91978	92500	Offset
5	G5.89-0.39		18:00:31.000	-24:03:59.000	J2000	00:07:28	00:05:00	248:13:42.8	10:37:39.4	00:00:00	Dwell	1	91978	92500	Offset
6	G8.67-0.36		18:06:19.000	-21:37:32.000	J2000	00:07:28	00:05:00	251:03:36.0	10:37:48.9	00:00:00	Dwell	1	91978	92500	Offset
7	paddle		18:06:14.800	-20:31:37.000	J2000	00:07:28	00:02:00	252:01:53.6	10:05:16.7	00:00:00	Paddle	1	91978	92500	Offset
8	1830-210	C	18:33:39.915	-21:03:40.050	J2000	00:07:28	00:02:00	254:37:21.9	16:00:10.3	00:00:17	Dwell	1	91978	92500	Offset
9	G9.62+0.19		18:06:14.800	-20:31:37.000	J2000	00:09:46	00:05:00	251:46:10.2	9:37:06.9	00:00:00	Dwell	1	91978	92500	Offset
10	G10.30-0.15		18:08:55.500	-20:05:58.000	J2000	00:09:46	00:05:00	252:27:26.4	9:57:42.0	00:00:00	Dwell	1	91978	92500	Offset
11	G10.63-0.38		18:10:29.200	-19:55:41.000	J2000	00:09:46	00:05:00	252:47:22.1	10:12:01.9	00:00:00	Dwell	1	91978	92500	Offset
12	1830-210	C	18:33:39.915	-21:03:40.050	J2000	00:09:46	00:02:00	254:22:16.6	15:31:37.2	00:00:15	Dwell	1	91978	92500	Offset
13	paddle		18:08:38.200	-19:51:50.000	J2000	00:12:02	00:05:00	252:22:21.7	9:19:21.9	00:00:00	Paddle	1	91958	92500	Offset
14	1830-210	C	18:33:39.915	-21:03:40.050	J2000	00:12:02	00:02:00	254:07:19.1	15:03:24.9	00:00:14	Dwell	1	91958	92500	Offset
15	G10.47+0.03		18:08:38.200	-19:51:50.000	J2000	00:14:16	00:05:00	252:06:49.8	8:51:45.8	00:00:00	Dwell	1	91958	92500	Offset
16	1830-210	C	18:33:39.915	-21:03:40.050	J2000	00:14:16	00:02:00	253:52:29.3	14:35:33.3	00:00:12	Dwell	1	91958	92500	Offset
17	pointing		17:43:58.856	-3:50:04.617	J2000	00:16:29	00:05:00	262:38:39.7	-4:54:36.4	00:00:00	Point	1	93504	95552	Update
18	paddle		18:42:58.100	-4:13:56.000	J2000	00:16:29	00:05:00	269:45:58.8	7:58:42.2	00:00:00	Paddle	1	91958	92500	Offset
19	1741-038	C	17:43:58.856	-3:50:04.617	J2000	00:16:29	00:02:00	262:38:39.7	-4:54:36.4	00:00:00	Dwell	1	91958	92500	Offset
20	G28.20-0.05		18:42:58.100	-4:13:56.000	J2000	00:16:29	00:05:00	269:45:58.8	7:58:42.2	00:00:00	Dwell	1	91958	92500	Offset
21	G29.96-0.02		18:46:04.800	-2:39:20.000	J2000	00:16:29	00:05:00	271:32:11.8	7:51:21.9	00:00:00	Dwell	1	91958	92500	Offset
22	G30.71-0.06		18:47:36.500	-2:00:31.000	J2000	00:16:29	00:05:00	272:17:42.0	7:51:30.9	00:00:00	Dwell	1	91958	92500	Offset
23	G31.41+0.31		18:47:34.300	-1:12:47.000	J2000	00:16:29	00:05:00	272:58:56.7	7:26:51.2	00:00:00	Dwell	1	91958	92500	Offset
24	1741-038	C	17:43:58.856	-3:50:04.617	J2000	00:16:29	00:02:00	262:38:39.7	-4:54:36.4	00:00:00	Dwell	1	91958	92500	Offset



Reducing data from interferometers

Observing modes

- Example schedule file
 - 9 science sources, observed in groups of 3

#	Source	Cal	RA	Dec	Epoch	Time(LST)	ScanLength	Az	El	Drive	ScanType	Aver	Freq-1	Freq-2	Pointing
1	pointing		18:33:39.915	-21:03:40.050	J2000	00:00:00	00:05:00	255:26:25.1	17:33:40.7	00:04:30	Point	1	93504	95552	Update
2	paddle		17:50:14.000	-19:51:50.000	J2000	00:07:28	00:02:00	252:22:21.7	9:19:21.9	00:00:00	Paddle	1	91978	92500	Offset
3	1830-210	C	18:33:39.915	-21:03:40.050	J2000	00:07:28	00:02:00	254:37:21.9	16:00:10.3	00:00:17	Dwell	1	91978	92500	Offset
4	G0.55-0.85		17:50:14.000	-19:51:50.000	J2000	00:09:46	00:05:00	251:46:10.2	9:37:06.9	00:00:00	Dwell	1	91978	92500	Offset
5	G5.89-0.39		18:00:33.000	-21:03:36.000	J2000	00:07:28	00:02:00	251:03:36.0	10:37:48.9	00:00:00	Dwell	1	91978	92500	Offset
6	G8.67-0.36		18:06:14.800	-20:31:37.000	J2000	00:07:28	00:02:00	252:01:53.6	10:05:16.7	00:00:00	Paddle	1	91978	92500	Offset
7	paddle		18:06:14.800	-20:31:37.000	J2000	00:07:28	00:02:00	254:37:21.9	16:00:10.3	00:00:17	Dwell	1	91978	92500	Offset
8	1830-210	C	18:33:39.915	-21:03:40.050	J2000	00:07:28	00:02:00	254:37:21.9	16:00:10.3	00:00:17	Dwell	1	91978	92500	Offset
9	G9.62+0.19		18:06:14.800	-20:31:37.000	J2000	00:09:46	00:05:00	251:46:10.2	9:37:06.9	00:00:00	Dwell	1	91978	92500	Offset
10	G10.30-0.15		18:08:55.500	-20:05:58.000	J2000	00:09:46	00:05:00	252:27:26.4	9:57:42.0	00:00:00	Dwell	1	91978	92500	Offset
11	G10.63-0.38		18:10:29.200	-19:55:41.000	J2000	00:09:46	00:05:00	252:47:22.1	10:12:01.9	00:00:00	Dwell	1	91978	92500	Offset
12	1830-210	C	18:33:39.915	-21:03:40.050	J2000	00:09:46	00:02:00	254:22:16.6	15:31:37.2	00:00:15	Dwell	1	91978	92500	Offset
13	paddle		18:08:38.200	-19:51:50.000	J2000	00:12:02	00:05:00	252:22:21.7	9:19:21.9	00:00:00	Paddle	1	91958	92500	Offset
14	1830-210	C	18:33:39.915	-21:03:40.050	J2000	00:12:02	00:02:00	254:07:19.1	15:03:24.9	00:00:14	Dwell	1	91958	92500	Offset
15	G10.47+0.03		18:08:38.200	-19:51:50.000	J2000	00:14:16	00:05:00	252:06:49.8	8:51:45.8	00:00:00	Dwell	1	91958	92500	Offset
16	1830-210	C	18:33:39.915	-21:03:40.050	J2000	00:14:16	00:02:00	253:52:29.3	14:35:33.3	00:00:12	Dwell	1	91958	92500	Offset
17	pointing		17:43:58.856	-3:50:04.617	J2000	00:16:29	00:05:00	262:38:39.7	-4:54:36.4	00:00:00	Point	1	93504	95552	Update
18	paddle		18:42:58.100	-4:13:56.000	J2000	00:16:29	00:05:00	269:45:58.8	7:58:42.2	00:00:00	Paddle	1	91958	92500	Offset
19	1741-038	C	17:43:58.856	-3:50:04.617	J2000	00:16:29	00:02:00	262:38:39.7	-4:54:36.4	00:00:00	Dwell	1	91958	92500	Offset
20	G28.20-0.05		18:42:58.100	-4:13:56.000	J2000	00:16:29	00:05:00	269:45:58.8	7:58:42.2	00:00:00	Dwell	1	91958	92500	Offset
21	G29.96-0.02		18:46:04.800	-2:39:20.000	J2000	00:16:29	00:05:00	271:32:11.8	7:51:21.9	00:00:00	Dwell	1	91958	92500	Offset
22	G30.71-0.06		18:47:36.500	-2:00:31.000	J2000	00:16:29	00:05:00	272:17:42.0	7:51:30.9	00:00:00	Dwell	1	91958	92500	Offset
23	G31.41+0.31		18:47:34.300	-1:12:47.000	J2000	00:16:29	00:05:00	272:58:56.7	7:26:51.2	00:00:00	Dwell	1	91958	92500	Offset
24	1741-038	C	17:43:58.856	-3:50:04.617	J2000	00:16:29	00:02:00	262:38:39.7	-4:54:36.4	00:00:00	Dwell	1	91958	92500	Offset

Initial pointing on a strong calibrator



Reducing data from interferometers

Observing modes

- Example schedule file
 - 9 science sources, observed in groups of 3

#	Source	Cal	RA	Dec	Epoch	Time(LST)	ScanLength	Az	El	Drive	ScanType	Aver	Freq-1	Freq-2	Pointing
1	pointing		18:33:39.915	-21:03:40.050	J2000	00:00:00	00:05:00	255:26:25.1	17:33:40.7	00:04:30	Point	1	93504	95552	Update
2	paddle		17:50:14.500	-28:54:31.000	J2000	00:05:01	00:02:00	243:02:37.5	11:24:41.2	00:00:00	Paddle	1	91978	92500	Offset
3	1830-210	C	18:33:39.915	-21:03:40.050	J2000	00:09:46	00:02:00	254:22:16.6	15:31:37.2	00:00:15	Dwell	1	91978	92500	Offset
4	G0.55-0.85		17:50:14.500	-28:54:31.000	J2000	00:12:02	00:05:00	252:22:21.7	9:19:21.9	00:00:00	Paddle	1	91978	92500	Offset
5	G5.89-0.39		18:00:38.200	-19:51:50.000	J2000	00:14:16	00:05:00	252:06:49.8	8:51:45.8	00:00:00	Dwell	1	91978	92500	Offset
6	G8.67-0.36		18:06:04.800	-2:39:20.000	J2000	00:16:29	00:05:00	271:32:11.8	7:51:21.9	00:00:00	Dwell	1	91978	92500	Offset
7	paddle		18:06:04.800	-2:39:20.000	J2000	00:16:29	00:05:00	272:17:42.0	7:51:30.9	00:00:00	Dwell	1	91978	92500	Offset
8	1830-210	C	18:33:39.915	-21:03:40.050	J2000	00:14:16	00:02:00	253:52:29.3	14:35:33.3	00:00:12	Dwell	1	91978	92500	Offset
9	G9.62+0.19		18:06:04.800	-2:39:20.000	J2000	00:16:29	00:05:00	272:58:56.7	7:26:51.2	00:00:00	Dwell	1	91978	92500	Offset
10	G10.30-0.15		18:08:56.100	-4:13:56.000	J2000	00:16:29	00:05:00	269:45:58.8	7:58:42.2	00:00:00	Dwell	1	91978	92500	Offset
11	G10.63-0.38		18:10:20.000	-3:50:04.617	J2000	00:16:29	00:05:00	262:38:39.7	-4:54:36.4	00:00:00	Point	1	91978	92500	Offset
12	1830-210	C	18:33:39.915	-21:03:40.050	J2000	00:09:46	00:02:00	254:22:16.6	15:31:37.2	00:00:15	Dwell	1	91978	92500	Offset
13	paddle		18:08:38.200	-19:51:50.000	J2000	00:12:02	00:05:00	252:22:21.7	9:19:21.9	00:00:00	Paddle	1	91958	92500	Offset
14	1830-210	C	18:33:39.915	-21:03:40.050	J2000	00:12:02	00:02:00	254:07:19.1	15:03:24.9	00:00:14	Dwell	1	91958	92500	Offset
15	G10.47+0.03		18:08:38.200	-19:51:50.000	J2000	00:14:16	00:05:00	252:06:49.8	8:51:45.8	00:00:00	Dwell	1	91958	92500	Offset
16	1830-210	C	18:33:39.915	-21:03:40.050	J2000	00:14:16	00:02:00	253:52:29.3	14:35:33.3	00:00:12	Dwell	1	91958	92500	Offset
17	pointing		17:43:58.856	-3:50:04.617	J2000	00:16:29	00:05:00	262:38:39.7	-4:54:36.4	00:00:00	Point	1	93504	95552	Update
18	paddle		18:42:58.100	-4:13:56.000	J2000	00:16:29	00:05:00	269:45:58.8	7:58:42.2	00:00:00	Paddle	1	91958	92500	Offset
19	1741-038	C	17:43:58.856	-3:50:04.617	J2000	00:16:29	00:02:00	262:38:39.7	-4:54:36.4	00:00:00	Dwell	1	91958	92500	Offset
20	G28.20-0.05		18:42:58.100	-4:13:56.000	J2000	00:16:29	00:05:00	269:45:58.8	7:58:42.2	00:00:00	Dwell	1	91958	92500	Offset
21	G29.96-0.02		18:46:04.800	-2:39:20.000	J2000	00:16:29	00:05:00	271:32:11.8	7:51:21.9	00:00:00	Dwell	1	91958	92500	Offset
22	G30.71-0.06		18:47:36.500	-2:00:31.000	J2000	00:16:29	00:05:00	272:17:42.0	7:51:30.9	00:00:00	Dwell	1	91958	92500	Offset
23	G31.41+0.31		18:47:34.300	-1:12:47.000	J2000	00:16:29	00:05:00	272:58:56.7	7:26:51.2	00:00:00	Dwell	1	91958	92500	Offset
24	1741-038	C	17:43:58.856	-3:50:04.617	J2000	00:16:29	00:02:00	262:38:39.7	-4:54:36.4	00:00:00	Dwell	1	91958	92500	Offset

Paddle: observations of a blackbody with known temperature to determine T_{sys}
Required only at 3mm wavelengths



Reducing data from interferometers

Observing modes

- Example schedule file
 - 9 science sources, observed in groups of 3

#	Source	Cal	RA	Dec	Epoch	Time(LST)	ScanLength	Az	EI	Drive	ScanType	Aver	Freq-1	Freq-2	Pointing
1	pointing		18:33:39.915	-21:03:40.050	J2000	00:00:00	00:05:00	255:26:25.1	17:33:40.7	00:04:30	Point	1	93504	95552	Update
2	paddle		17:50:14.500	-28:54:31.000	J2000	00:05:01	00:02:00	243:02:37.5	11:24:41.2	00:00:00	Paddle	1	91978	92500	Offset
3	1830-210	C	18:33:39.915	-21:03:40.050	J2000	00:05:01	00:02:00	254:53:33.2	16:30:55.1	00:00:27	Dwell	1	91978	92500	Offset
4	G0.55-0.85		17:50:14.500	-28:54:31.000	J2000	00:07:28	00:05:00	242:46:51.6	10:56:18.8	00:00:00	Dwell	1	91978	92500	Offset
5	G5.89-0.39		18:00:31.000	-24:03:59.000	J2000	00:07:28	00:05:00	248:13:42.8	10:37:39.4	00:00:00	Dwell	1	91978	92500	Offset
6	G8.67-0.36		18:06:19.000	-21:27:22.000	J2000	00:07:28	00:05:00	251:02:26.0	10:37:48.9	00:00:00	Dwell	1	91978	92500	Offset
7	paddle		18:06:19.000	-21:27:22.000	J2000	00:07:28	00:05:00	251:02:26.0	10:05:16.7	00:00:00	Paddle	1	91978	92500	Offset
8	1830-210	C	18:33:39.915	-21:03:40.050	J2000	00:07:28	00:02:00	254:53:33.2	16:00:10.3	00:00:17	Dwell	1	91978	92500	Offset
9	G9.62+0.19		18:06:19.000	-21:27:22.000	J2000	00:07:28	00:05:00	251:02:26.0	9:37:06.9	00:00:00	Dwell	1	91978	92500	Offset
10	G10.30-0.15		18:08:38.200	-19:51:50.000	J2000	00:07:28	00:05:00	252:22:21.7	9:57:42.0	00:00:00	Dwell	1	91978	92500	Offset
11	G10.63-0.38		18:10:21.000	-19:51:50.000	J2000	00:07:28	00:05:00	253:02:21.7	10:12:01.9	00:00:00	Dwell	1	91978	92500	Offset
12	1830-210	C	18:33:39.915	-21:03:40.050	J2000	00:07:28	00:02:00	254:53:33.2	15:31:37.2	00:00:15	Dwell	1	91978	92500	Offset
13	paddle		18:08:38.200	-19:51:50.000	J2000	00:12:02	00:05:00	252:22:21.7	9:19:21.9	00:00:00	Paddle	1	91958	92500	Offset
14	1830-210	C	18:33:39.915	-21:03:40.050	J2000	00:12:02	00:02:00	254:07:19.1	15:03:24.9	00:00:14	Dwell	1	91958	92500	Offset
15	G10.47+0.03		18:08:38.200	-19:51:50.000	J2000	00:14:16	00:05:00	252:06:49.8	8:51:45.8	00:00:00	Dwell	1	91958	92500	Offset
16	1830-210	C	18:33:39.915	-21:03:40.050	J2000	00:14:16	00:02:00	253:52:29.3	14:35:33.3	00:00:12	Dwell	1	91958	92500	Offset
17	pointing		17:43:58.856	-3:50:04.617	J2000	00:16:29	00:05:00	262:38:39.7	-4:54:36.4	00:00:00	Point	1	93504	95552	Update
18	paddle		18:42:58.100	-4:13:56.000	J2000	00:16:29	00:05:00	269:45:58.8	7:58:42.2	00:00:00	Paddle	1	91958	92500	Offset
19	1741-038	C	17:43:58.856	-3:50:04.617	J2000	00:16:29	00:02:00	262:38:39.7	-4:54:36.4	00:00:00	Dwell	1	91958	92500	Offset
20	G28.20-0.05		18:42:58.100	-4:13:56.000	J2000	00:16:29	00:05:00	269:45:58.8	7:58:42.2	00:00:00	Dwell	1	91958	92500	Offset
21	G29.96-0.02		18:46:04.800	-2:39:20.000	J2000	00:16:29	00:05:00	271:32:11.8	7:51:21.9	00:00:00	Dwell	1	91958	92500	Offset
22	G30.71-0.06		18:47:36.500	-2:00:31.000	J2000	00:16:29	00:05:00	272:17:42.0	7:51:30.9	00:00:00	Dwell	1	91958	92500	Offset
23	G31.41+0.31		18:47:34.300	-1:12:47.000	J2000	00:16:29	00:05:00	272:58:56.7	7:26:51.2	00:00:00	Dwell	1	91958	92500	Offset
24	1741-038	C	17:43:58.856	-3:50:04.617	J2000	00:16:29	00:02:00	262:38:39.7	-4:54:36.4	00:00:00	Dwell	1	91958	92500	Offset

3 science targets
between 2 calibrator
scans



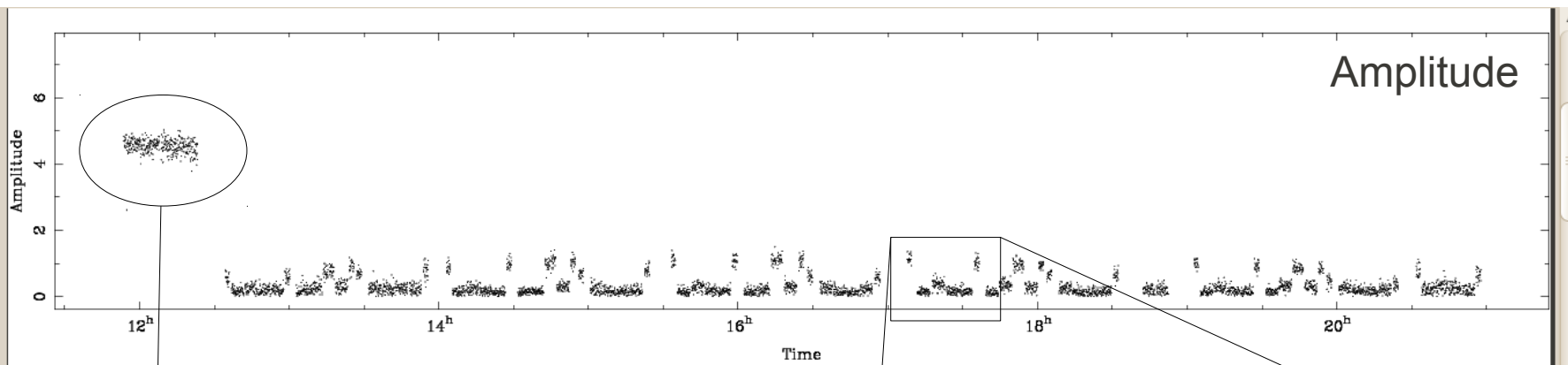
Reducing data from interferometers

Observing modes

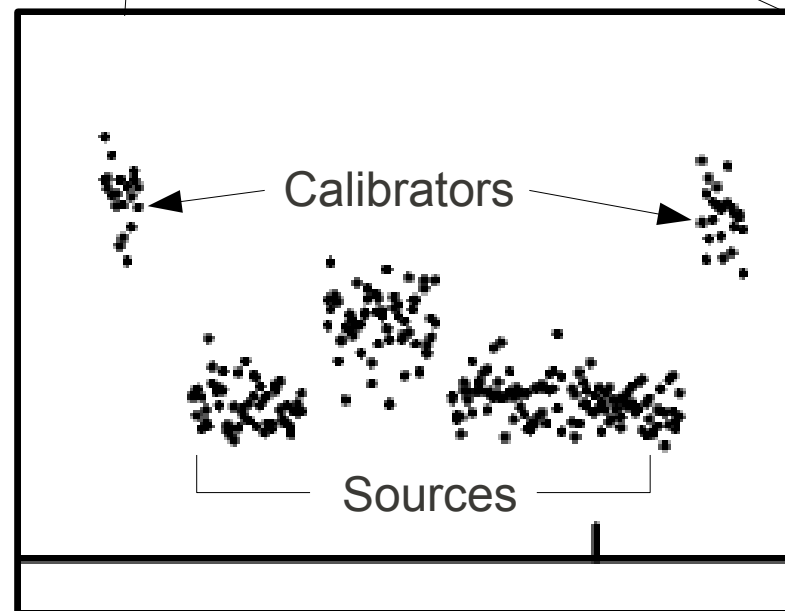
- Also require:
 - 15 minute observation of a strong pass-band calibrator
 - 5-15 minute observation of a primary flux calibrator (planet @ 3mm, otherwise quasar)
 - AIPS & MIRIAD have in-built models
- Above 10 GHz pointing observations should be conducted over 30-60 minutes
- Secondary calibrator should be < 1 degree away from science targets



Reducing data from interferometers



Primary flux calibrator
& bandpass calibrator





Reducing data from interferometers

Data reduction recipe - loading

- Load & inspect data (*atlod in miriad*)
 - Correct for 'birdies'
- Manually flag gross errors from uncalibrated data
 - (*uvflg* using the '*select=*' keyword)
 - Tracking errors, shadowed data
 - Concentrate on calibrators initially
 - Bad antennas or baselines, major weather-related phase excursions – check the observing log
- Split out individual frequency bands
 - Insert rest-frequency information (*puthd*)



Reducing data from interferometers

Data reduction recipe – bandpass calibration

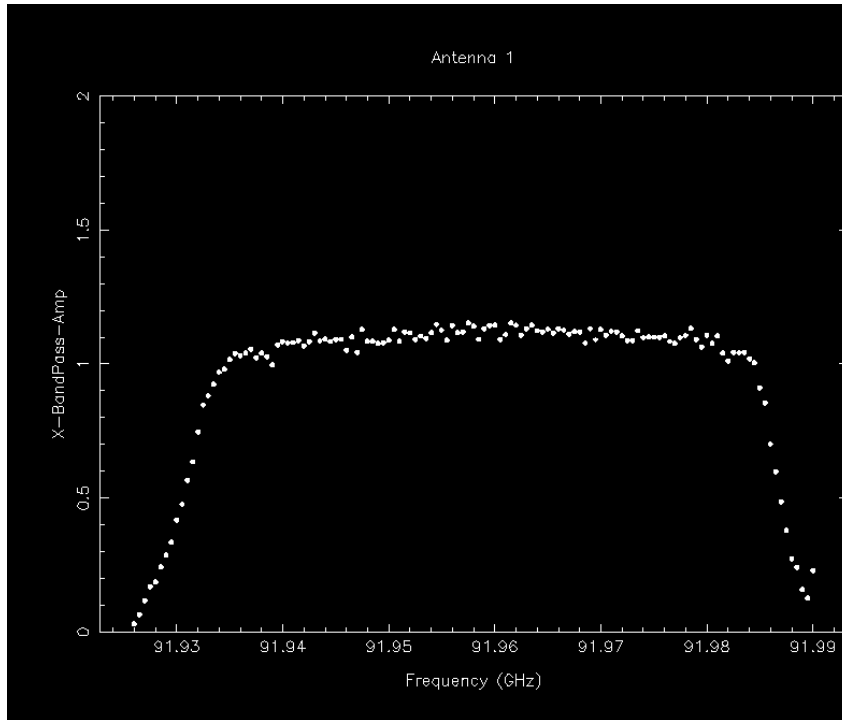
- Bandpass calibration
 - Need to solve for the antenna-based bandpass shapes, both amplitude and phase
 - Approximately constant with time, (but for high-dynamic range imaging can use multiple bandpass-calibrators in run)
 - Strong point-source for high signal-to noise on all observations



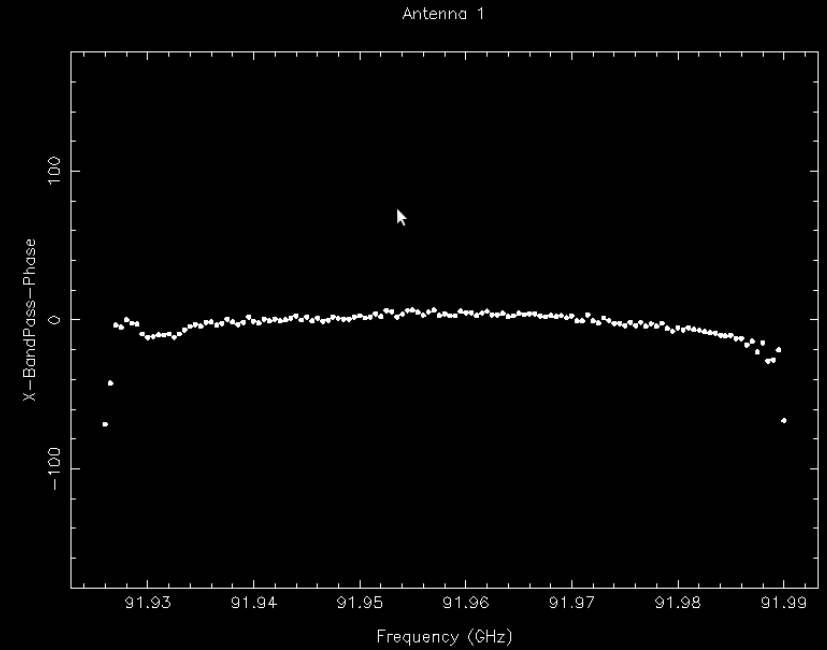
Reducing data from interferometers

Data reduction recipe – bandpass calibration

Amplitude solution



Phase solution

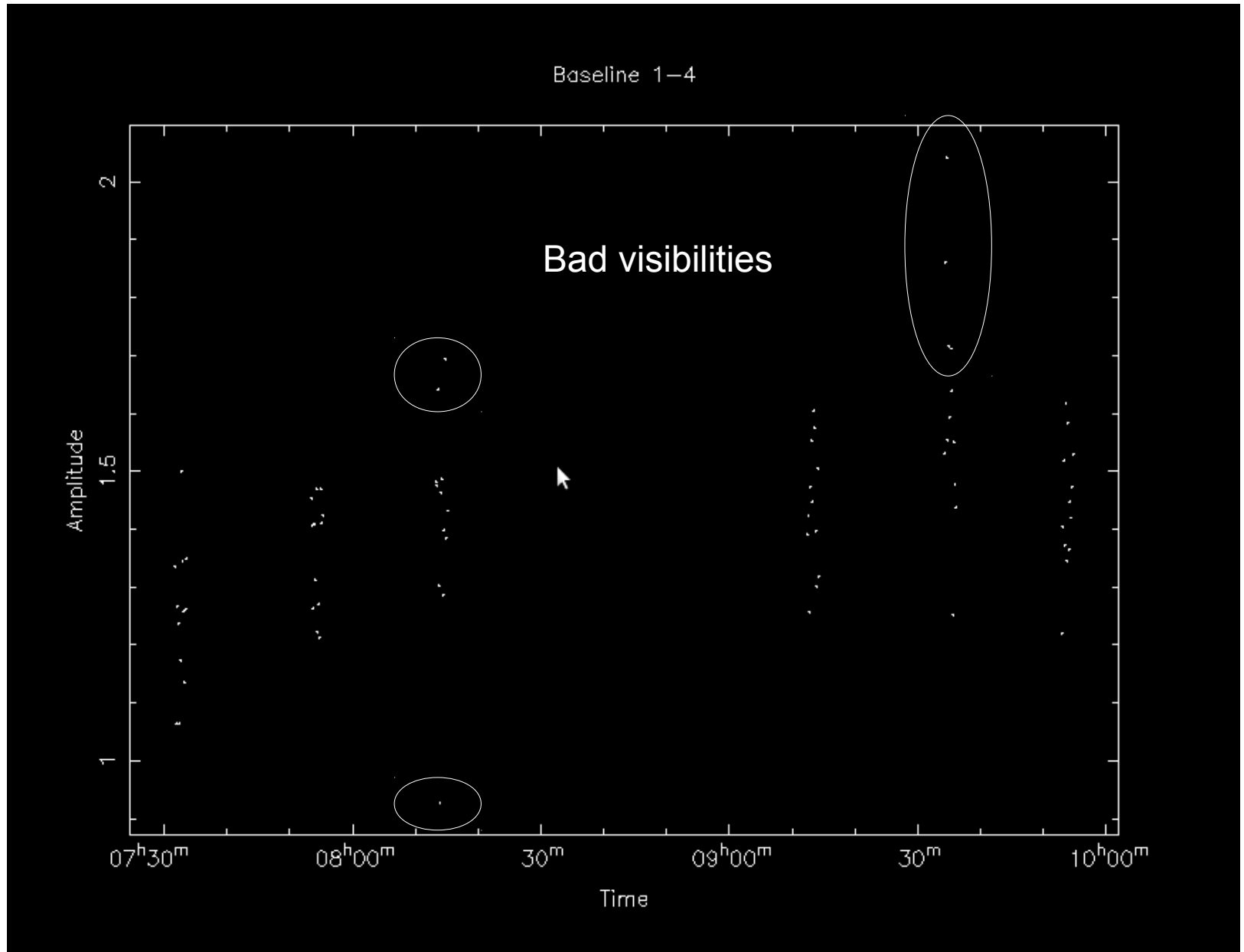


- Bandpass solutions are applied to the data before any further calibration is performed
 - MIRIAD & AIPS use tables to separate out calibration solutions from data



Reducing data from interferometers

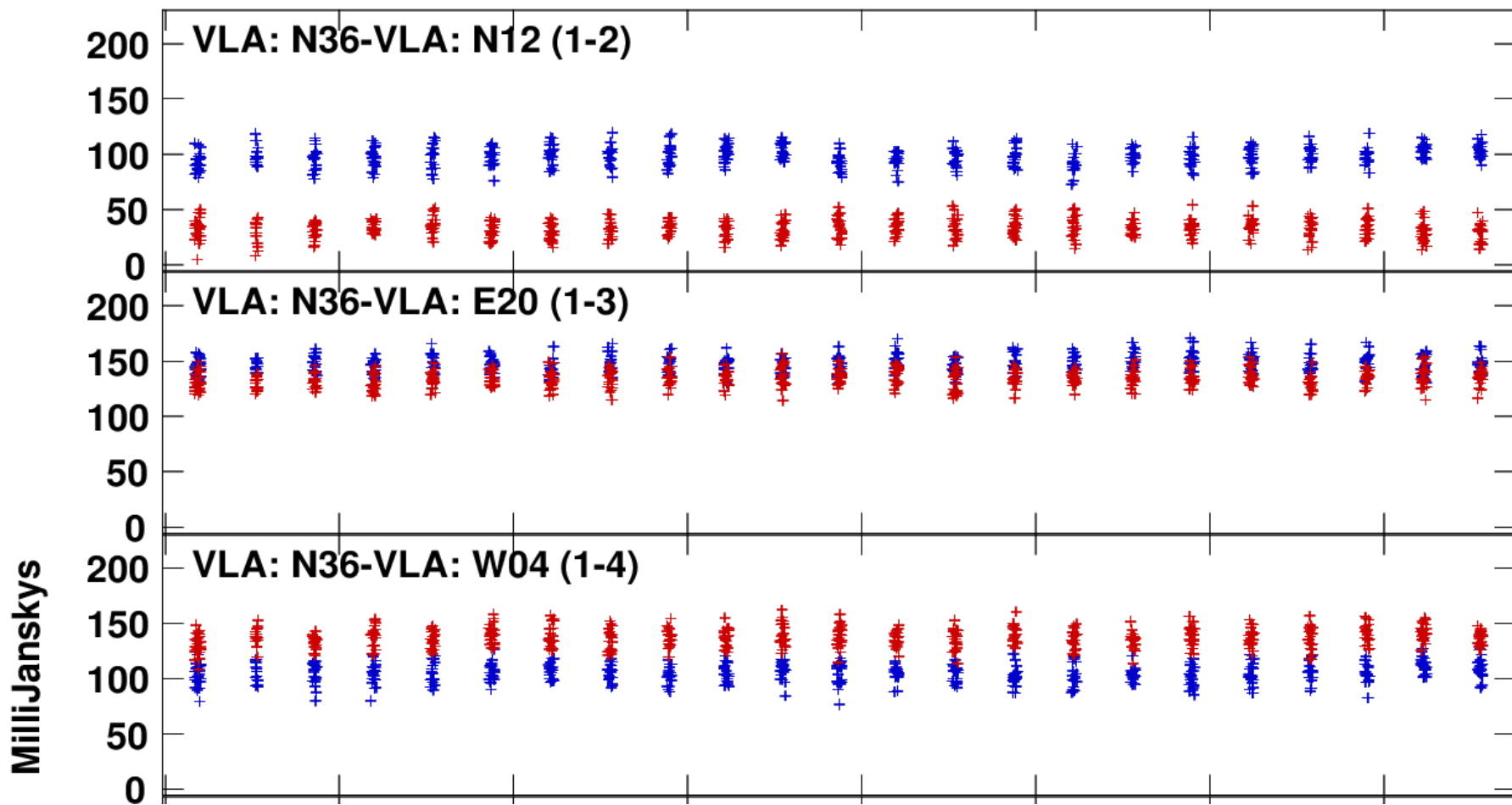
Data reduction recipe – basic flagging





Reducing data from interferometers

Data reduction recipe – gains vs time calibration



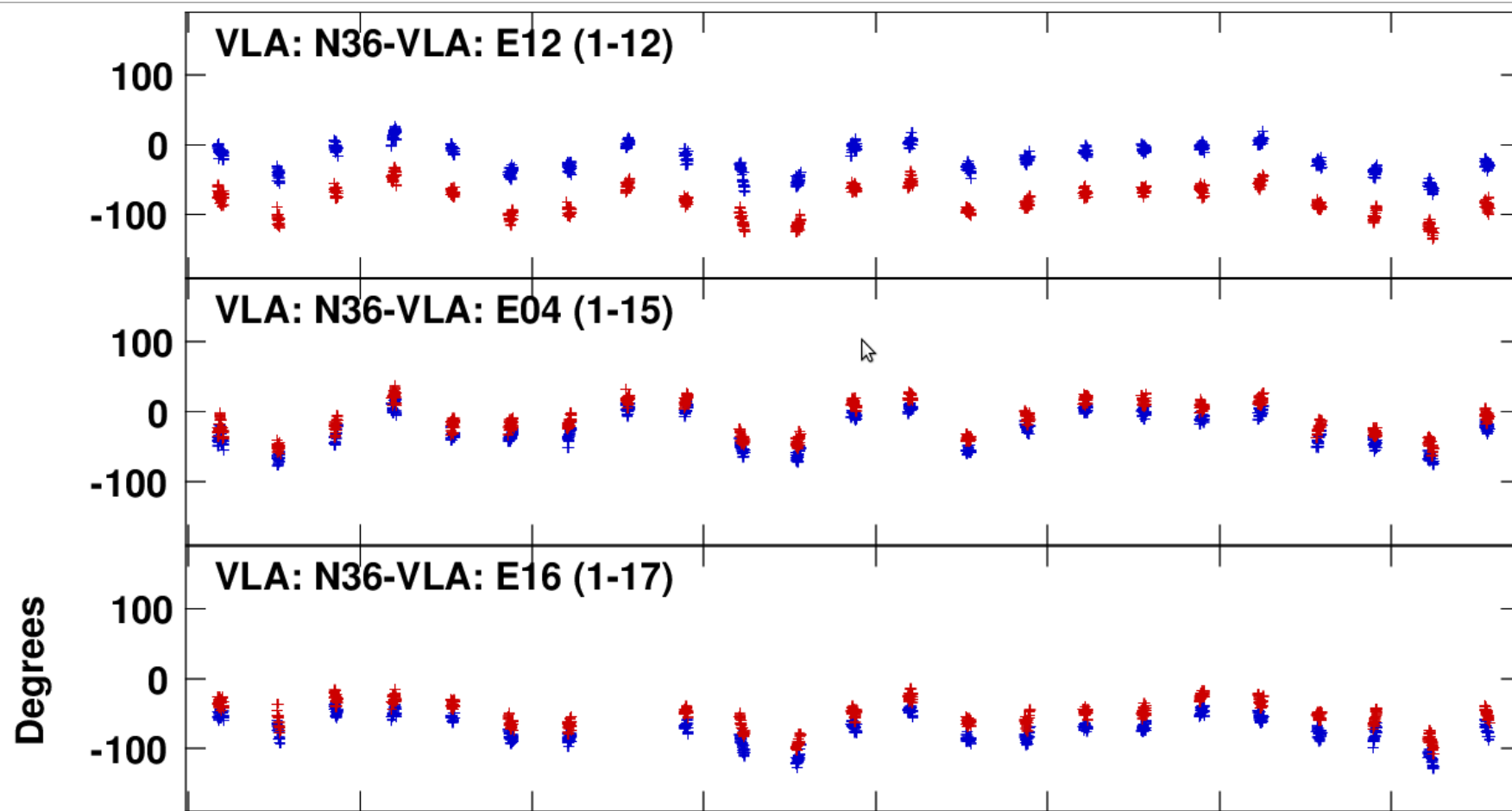
- Raw amplitudes vs time
 - Red = polarisation I
 - Blue = polarisation II

This is actually very good data taken during good weather on the VLA @ 5 GHz. High-frequency ATCA data is more challenging!



Reducing data from interferometers

Data reduction recipe – gains vs time calibration

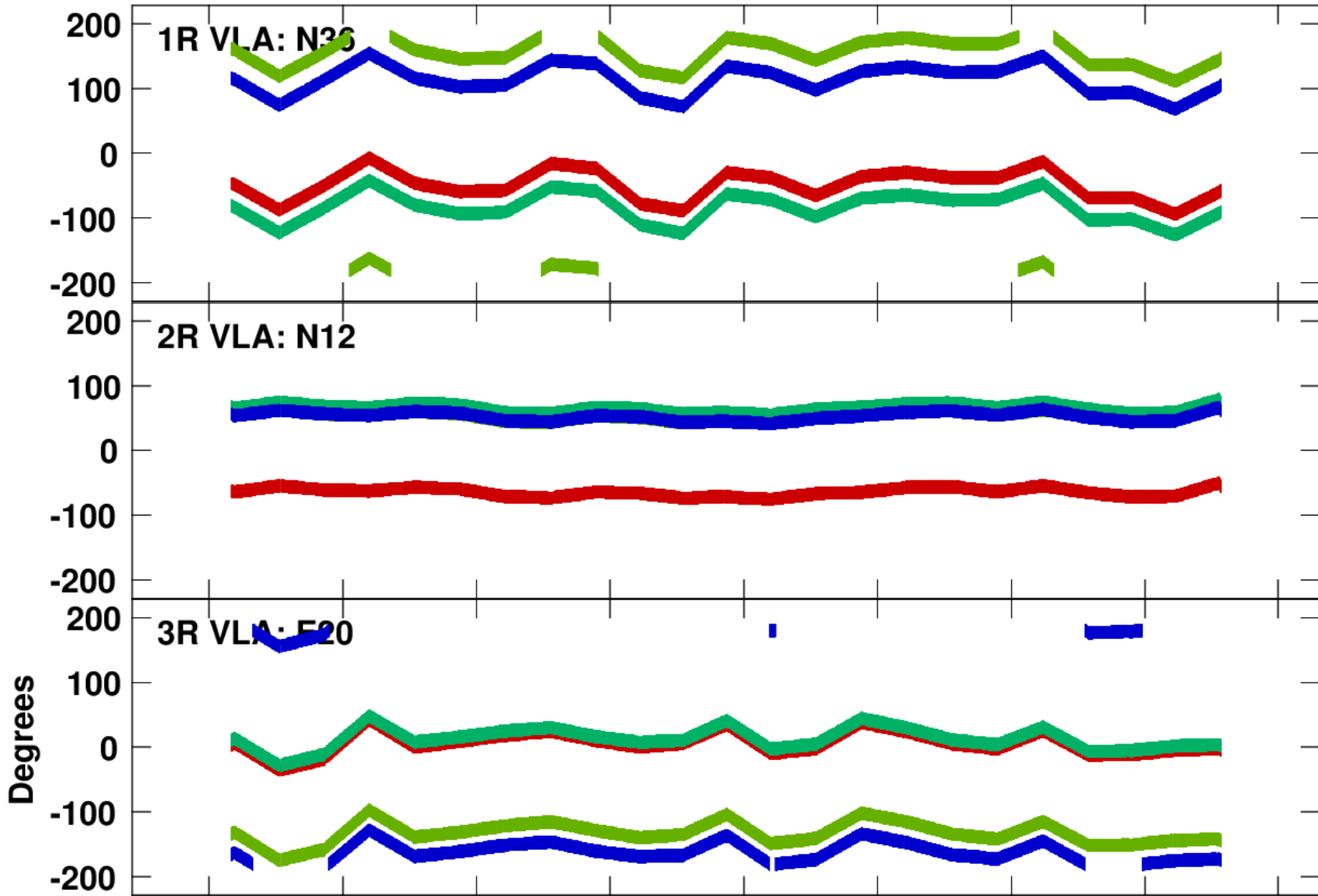


- Raw phases vs time
 - Multiple baselines
- Solve for *antenna* based terms ...



Reducing data from interferometers

Data reduction recipe – gains vs time calibration

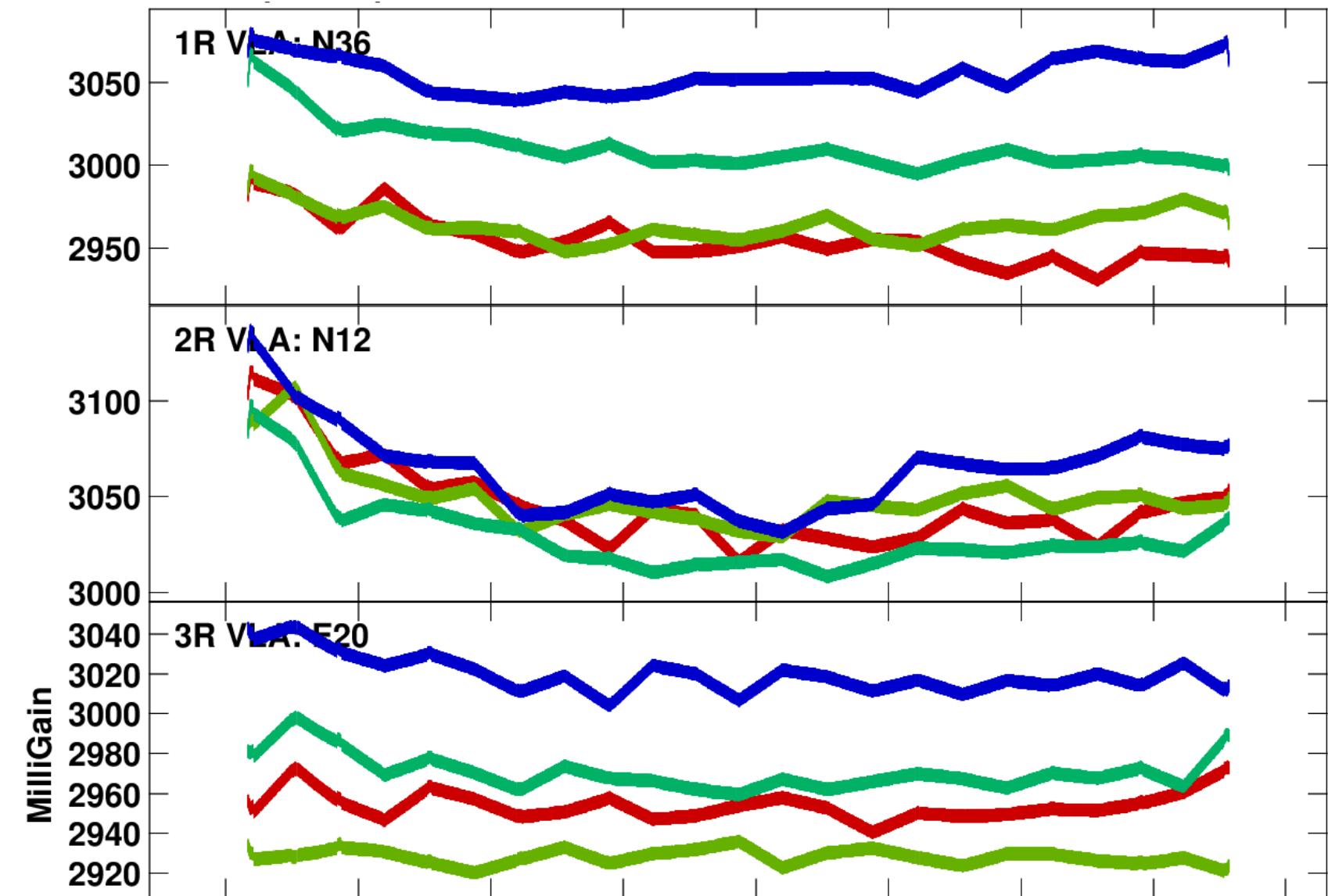


- Phase solutions (2 freq & 2 Polarisation @VLA)



Reducing data from interferometers

Data reduction recipe – gains vs time calibration

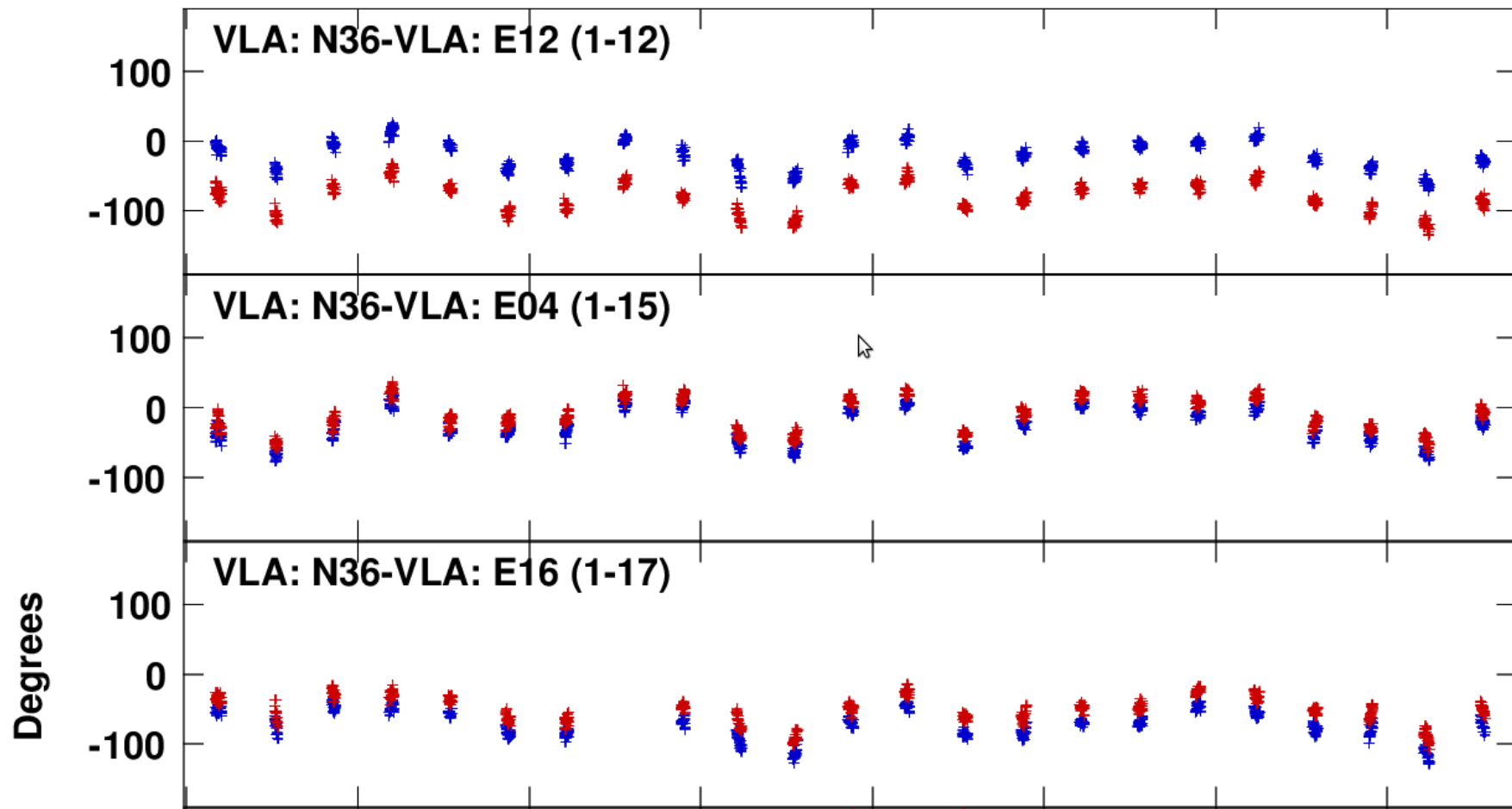


- o Amplitude solutions



Reducing data from interferometers

Data reduction recipe – gains vs time calibration

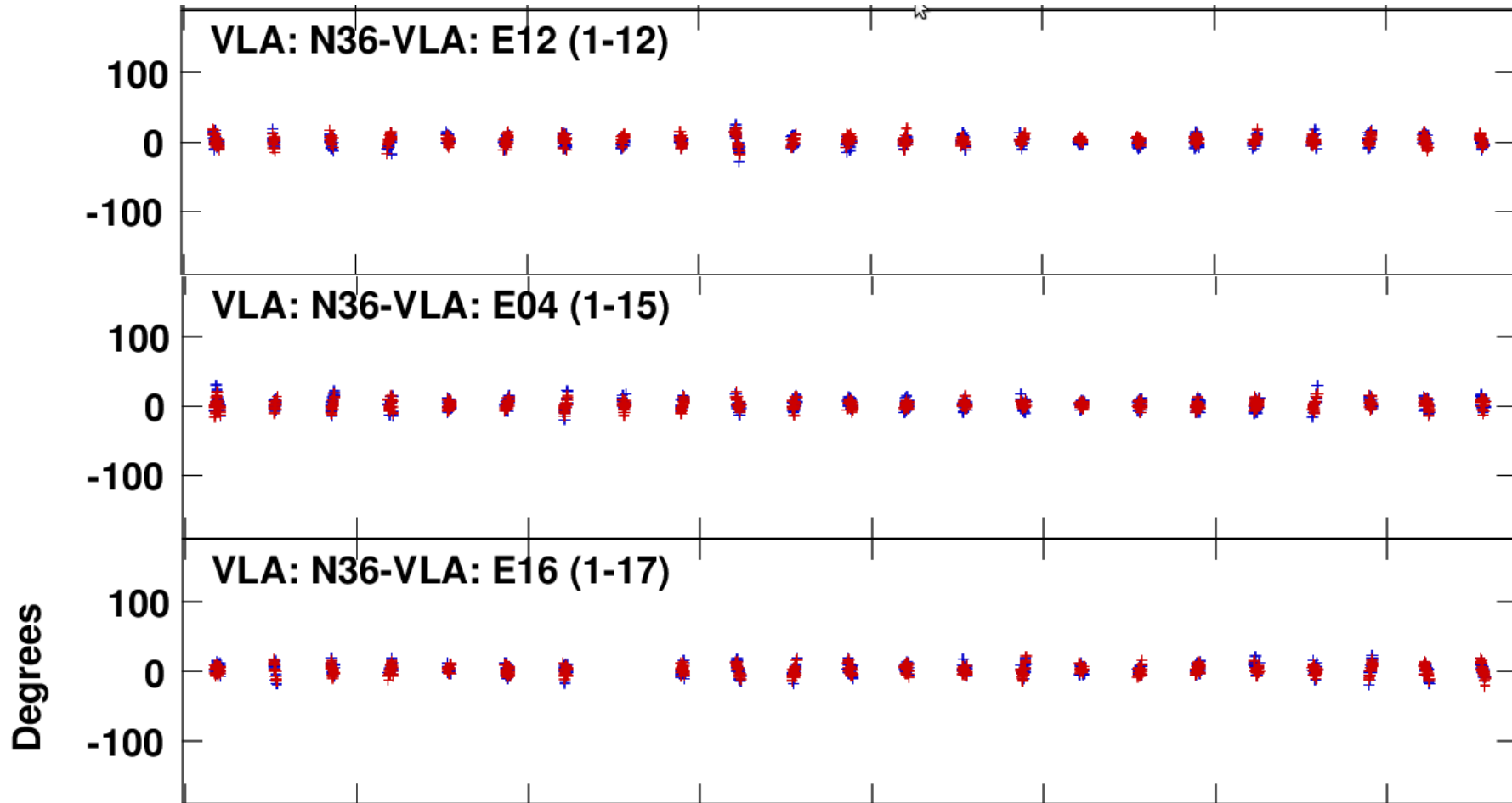


- Raw phases vs time
- Applying the solutions we get ...



Reducing data from interferometers

Data reduction recipe – gains vs time calibration

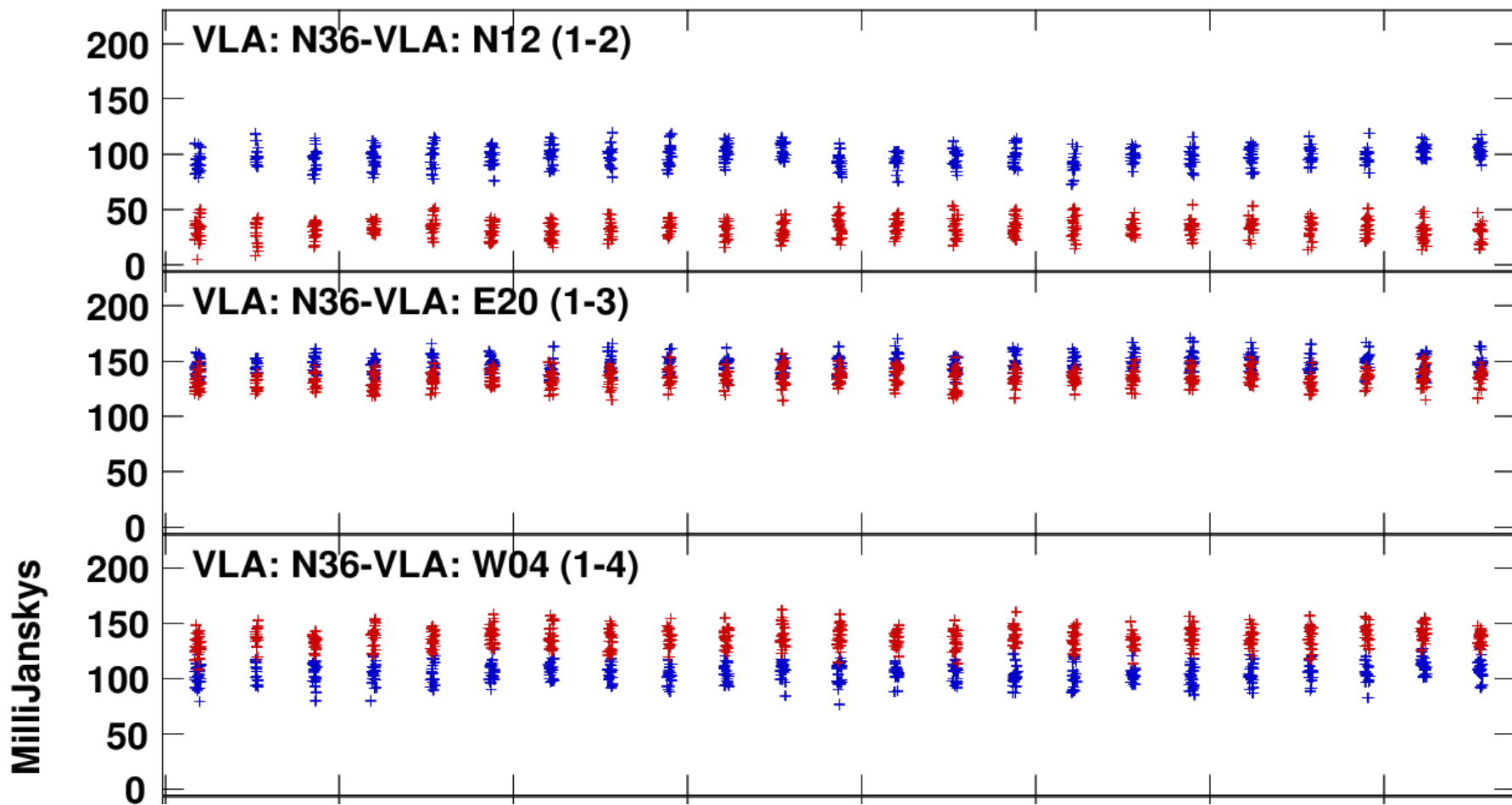


- Raw phases vs time
- Applying the solutions we get ...



Reducing data from interferometers

Data reduction recipe – gains vs time calibration

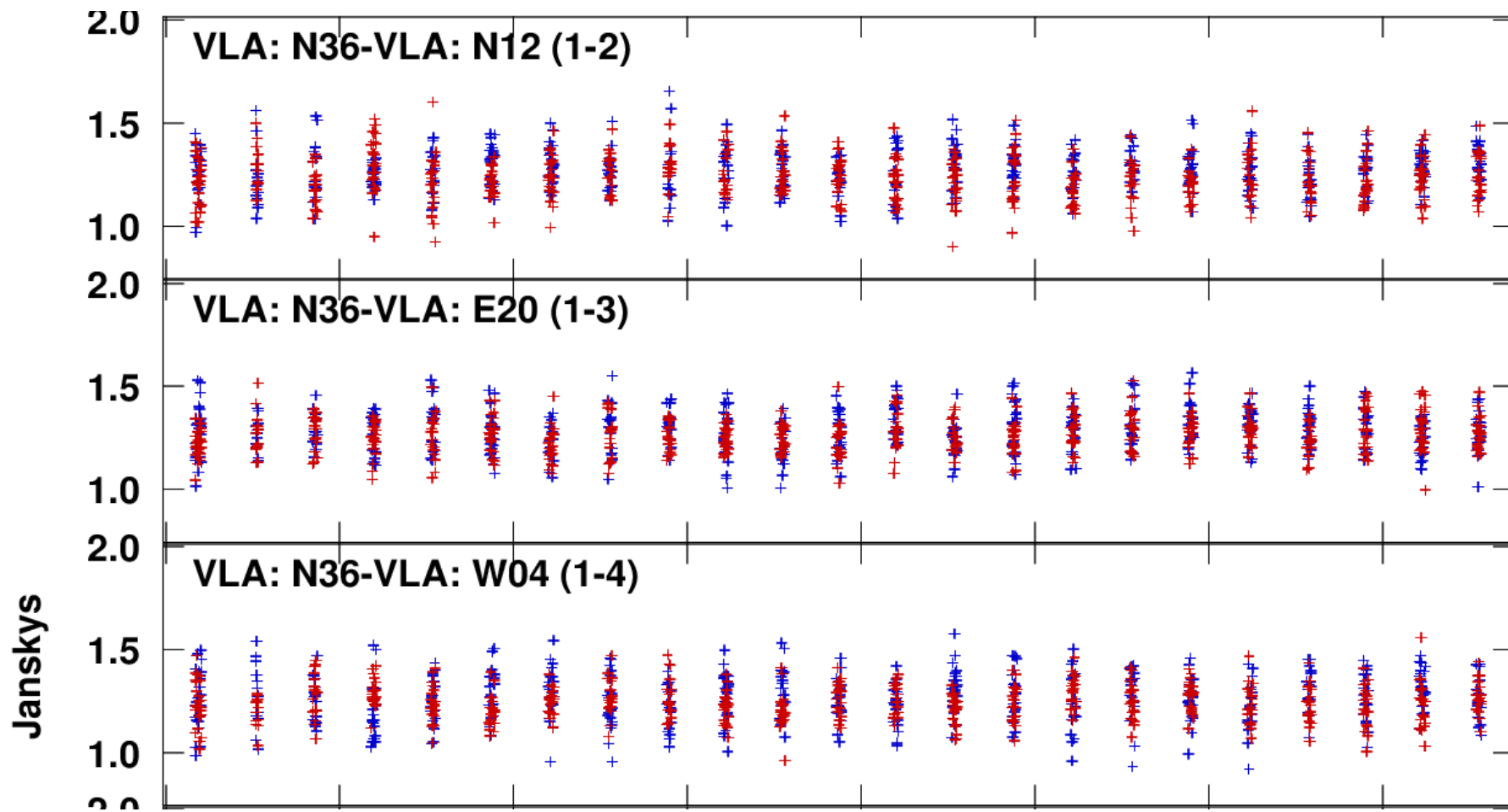


- Raw amplitudes vs time
- Applying the solutions we get ...



Reducing data from interferometers

Data reduction recipe – gains vs time calibration



- Raw amplitudes vs time
- Applying the solutions we get ...



Reducing data from interferometers

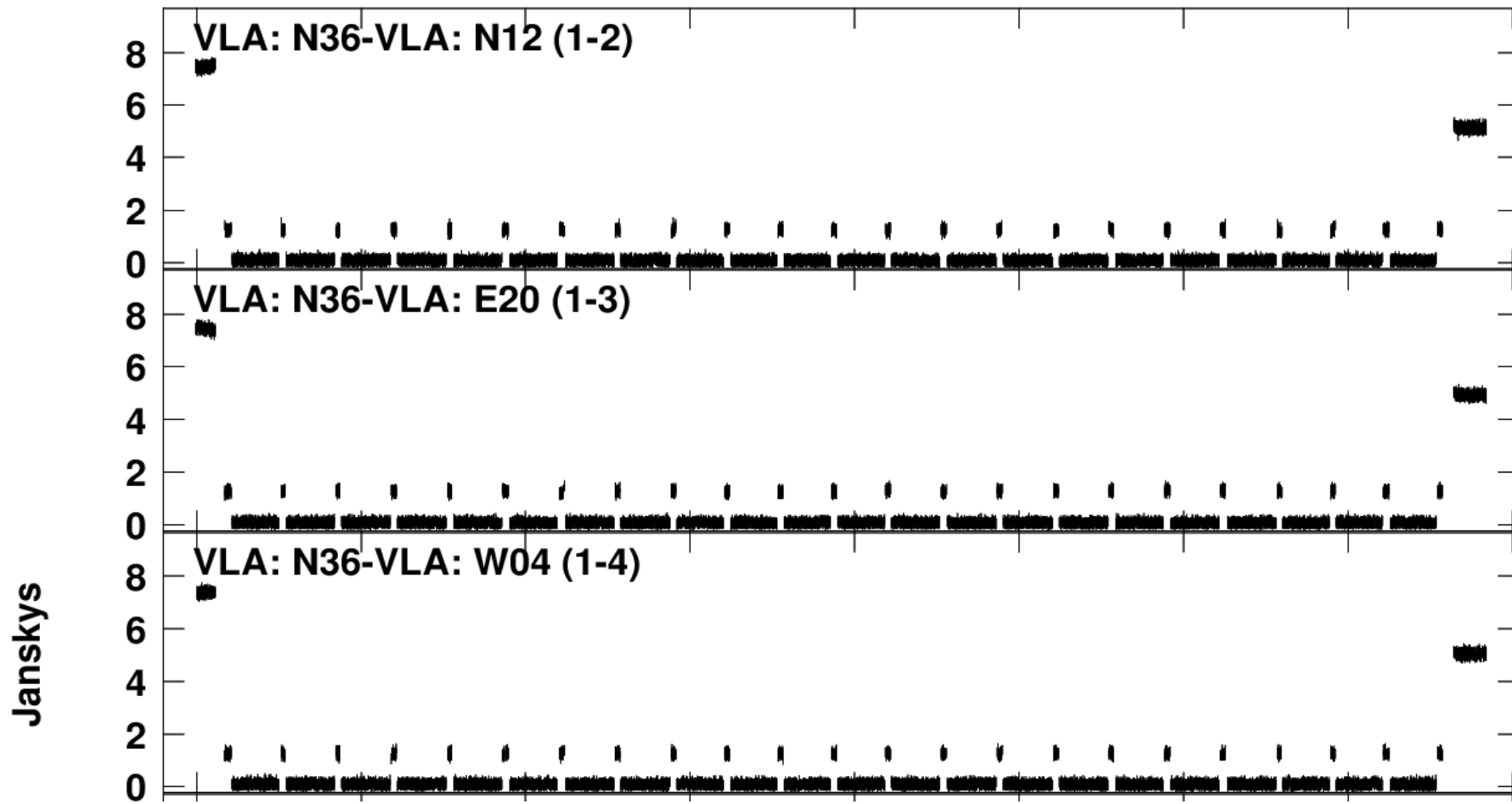
Data reduction recipe – gains vs time calibration

- Dataset is now calibrated enough to image, but does not have accurate *absolute* flux scale
 - Bootstrap from observation of primary flux calibrator via comparison to a known model
 - Scale secondary calibrator solutions by a simple factor
- MIRIAD & AIPS have inbuilt tasks which make this very easy:
 - Gpboot, gpcal & plboot



Reducing data from interferometers

Data reduction recipe – gains vs time calibration



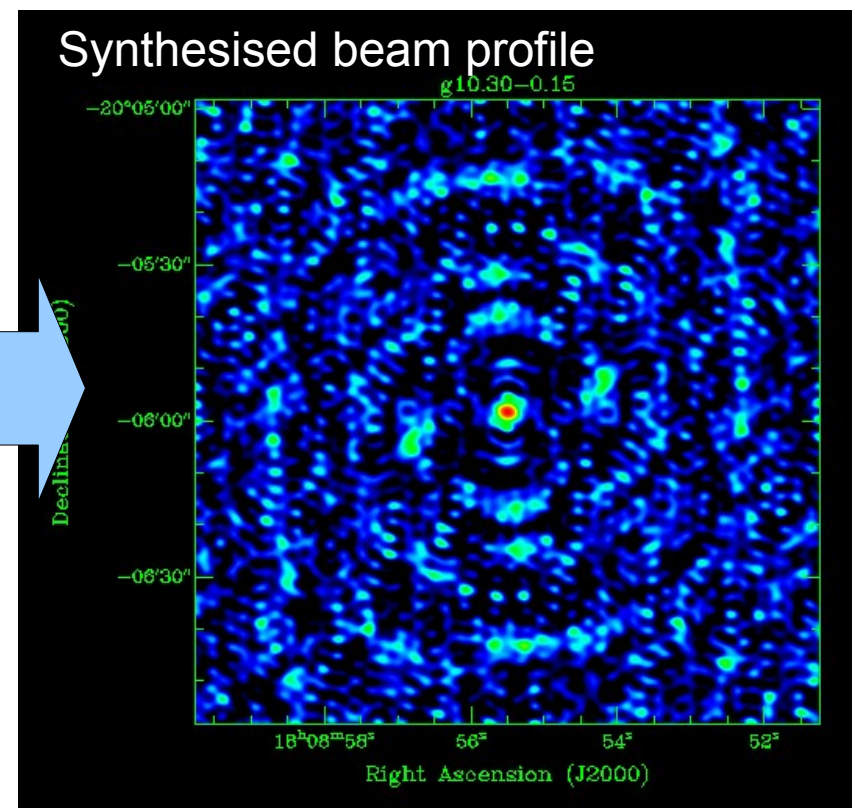
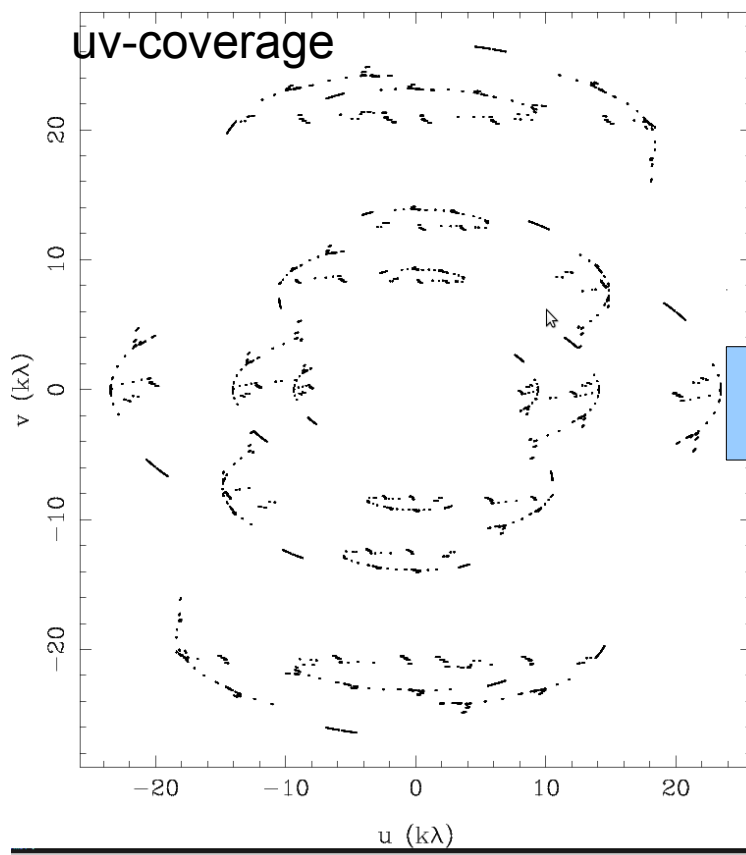
- Final calibrated uv -dataset
- Now split out science sources and image!



Reducing data from interferometers

Data reduction recipe – Imaging

- Run *Invert* (MIRIAD) or *Imagr* (AIPS) to Fourier-transform the uv -data onto the image plane
- Dataset is undersampled in the uv -plane, so need to use a deconvolution algorithm to fill in the gaps

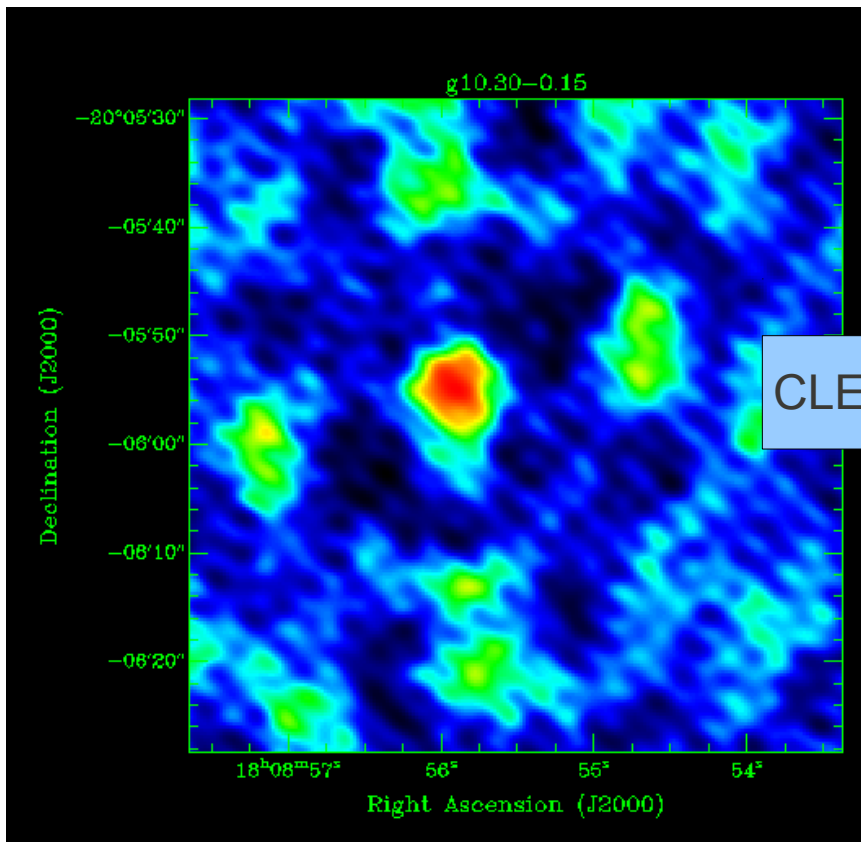




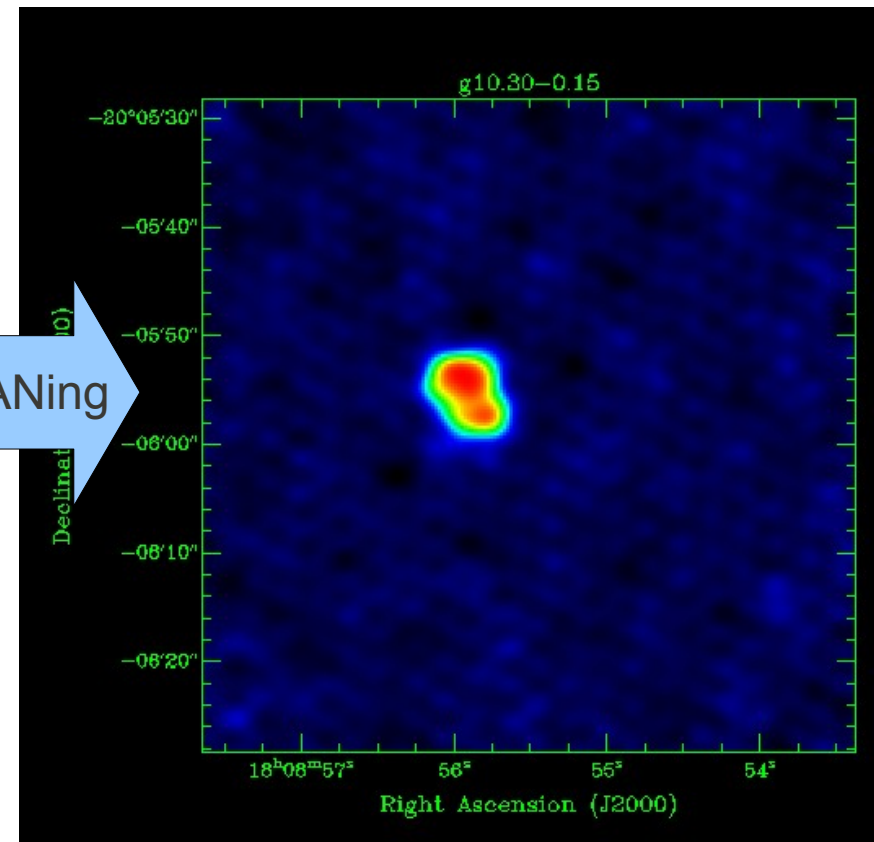
Reducing data from interferometers

Data reduction recipe – Imaging

- Run *Invert* (MIRIAD) or *Imagr* (AIPS) to Fourier-transform the uv -data onto the image plane
- Dataset is undersampled in the uv -plane, so need to use a deconvolution algorithm to fill in the gaps



CLEANing



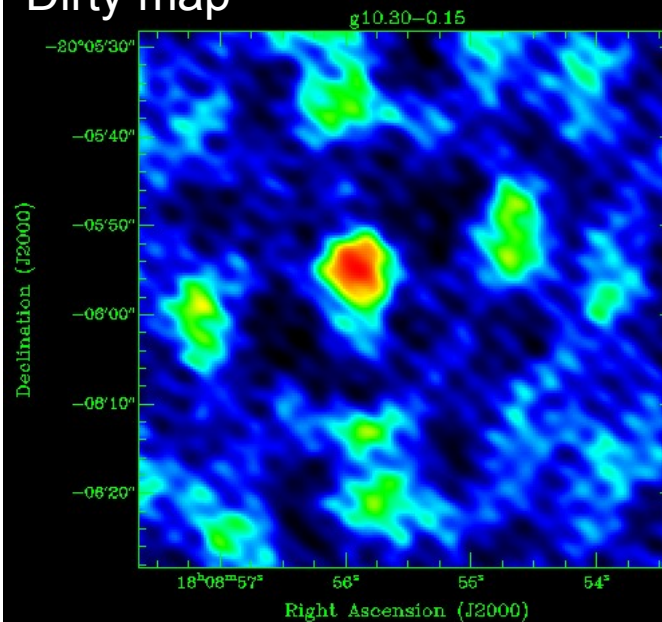


Reducing data from interferometers

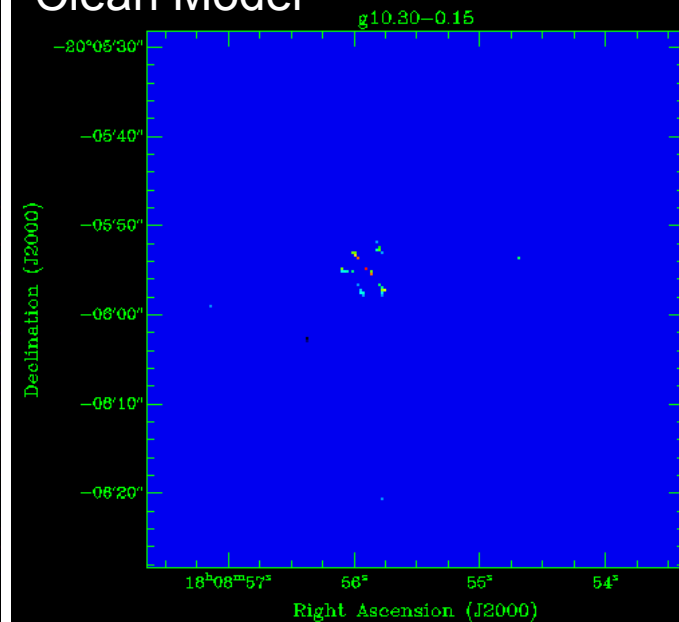
Data reduction recipe – Imaging

Niter=50

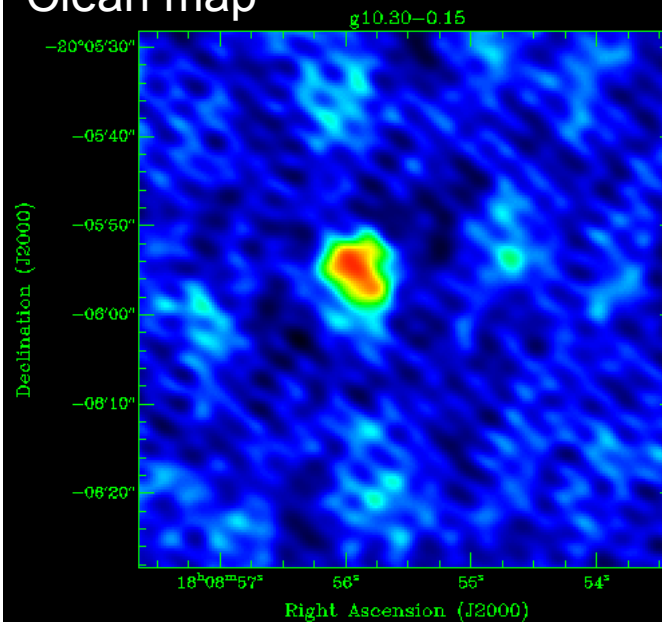
Dirty map



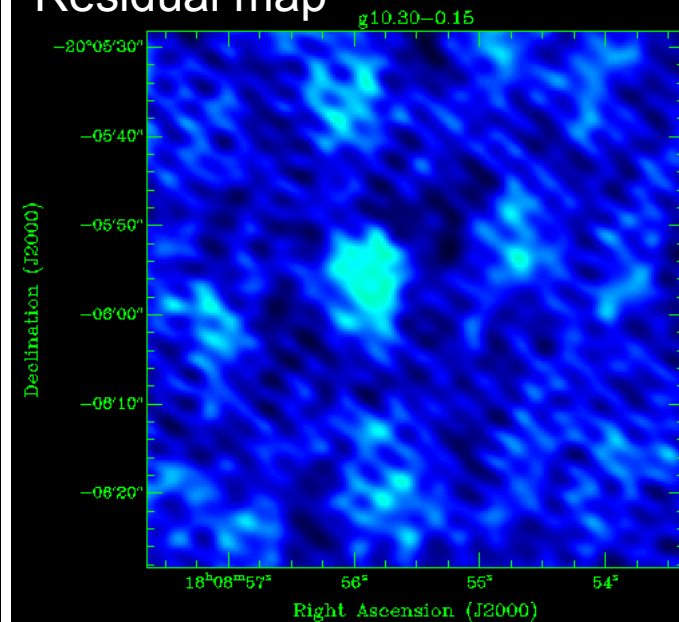
Clean Model



Clean map



Residual map

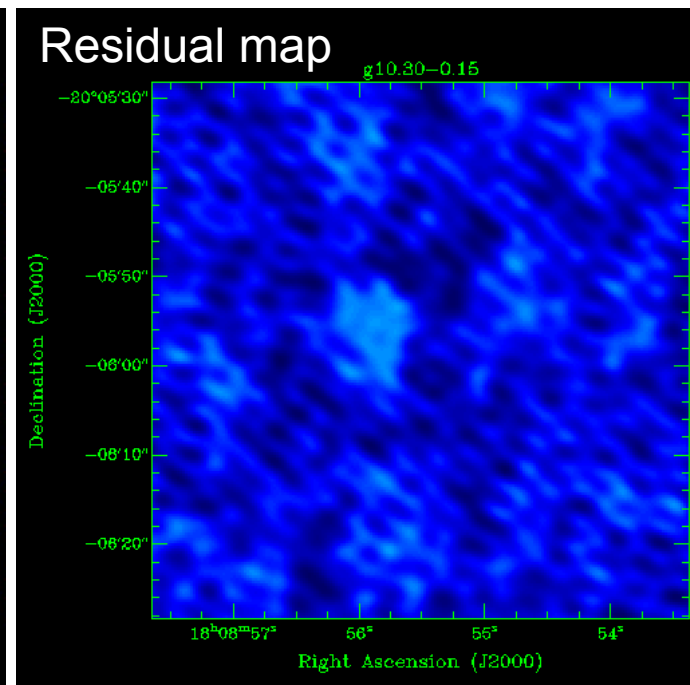
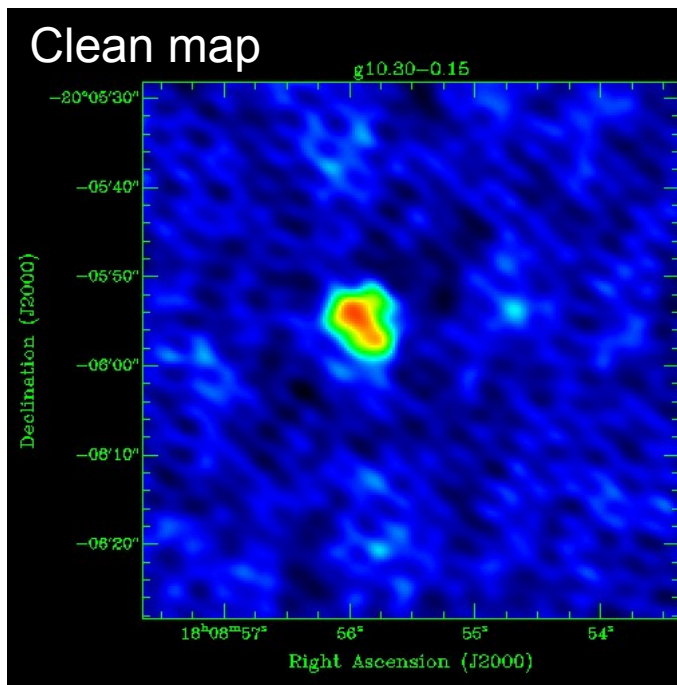
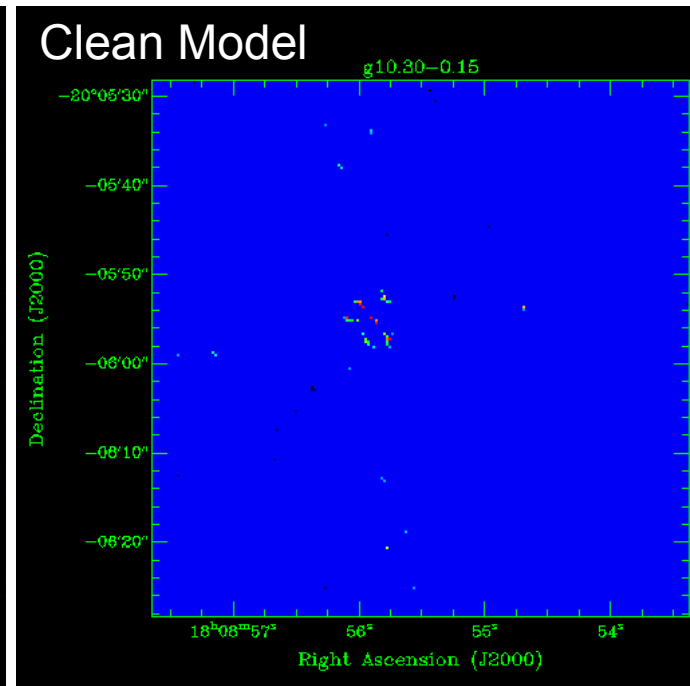
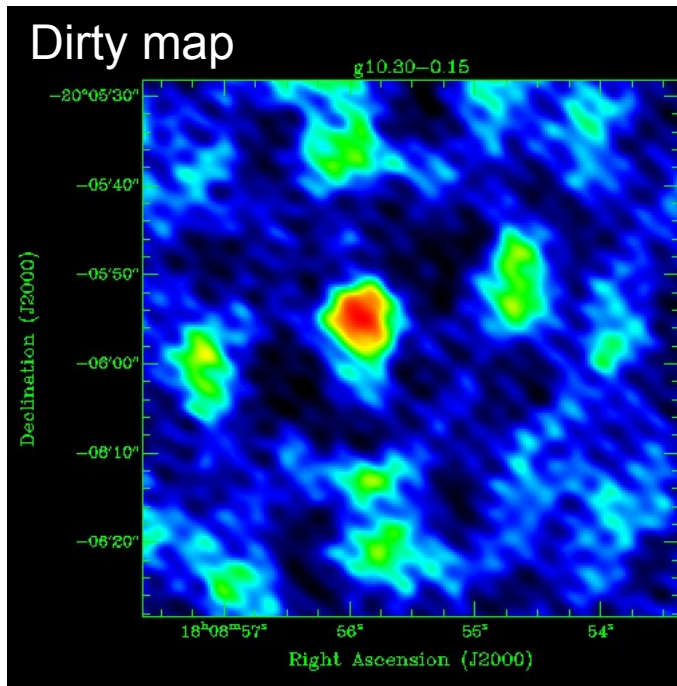




Reducing data from interferometers

Data reduction recipe – Imaging

Niter=100





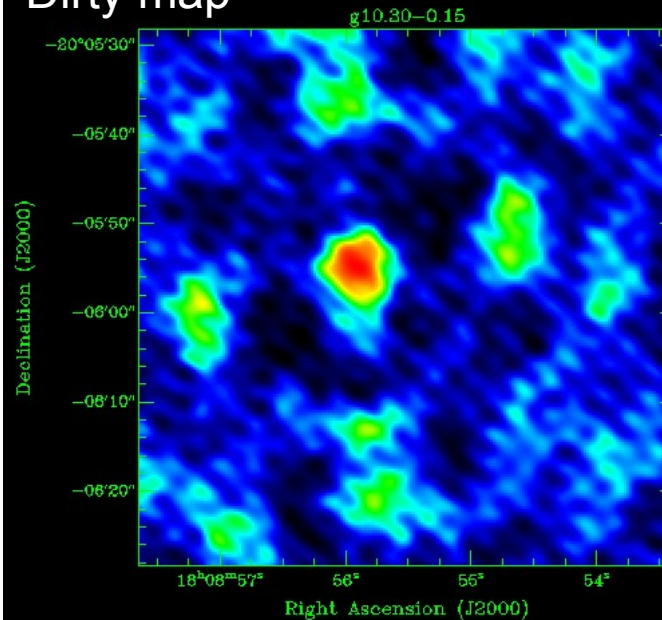
THE UNIVERSITY OF SYDNEY

Reducing data from interferometers

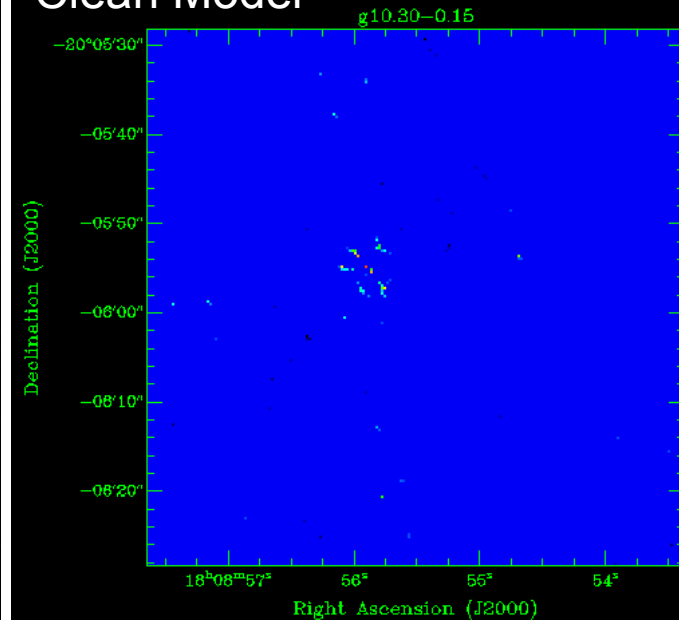
Data reduction recipe – Imaging

Niter=150

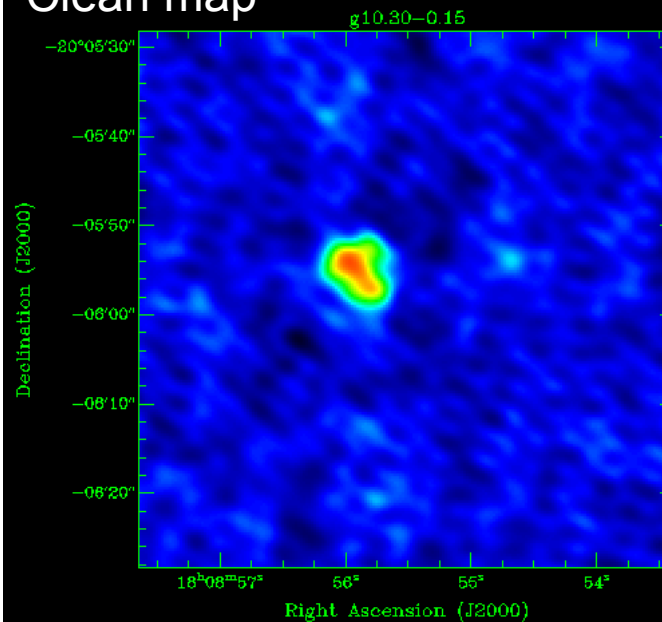
Dirty map



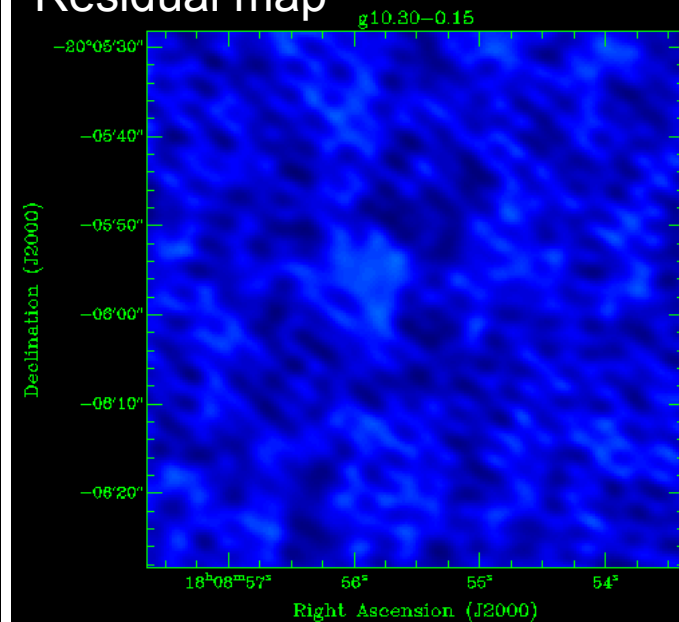
Clean Model



Clean map



Residual map





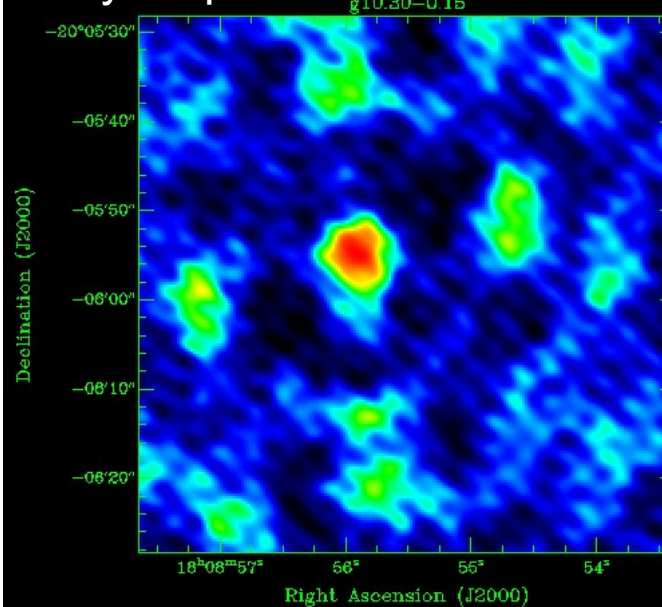
THE UNIVERSITY OF SYDNEY

Reducing data from interferometers

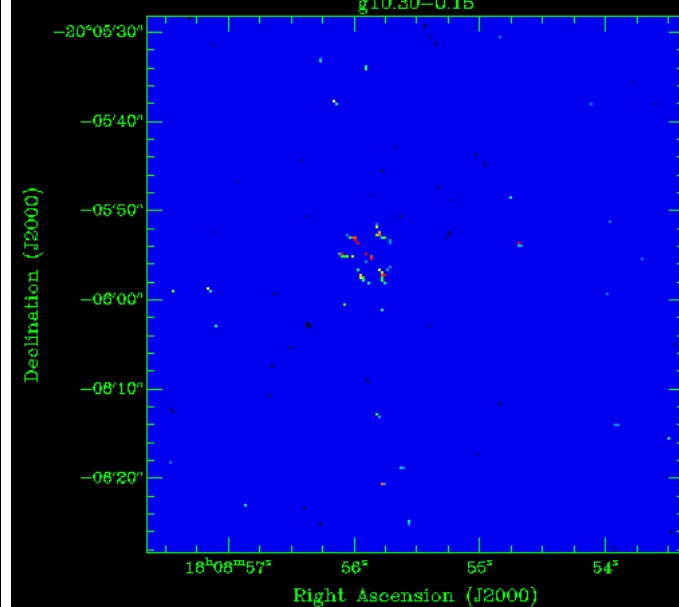
Data reduction recipe – Imaging

Niter=200

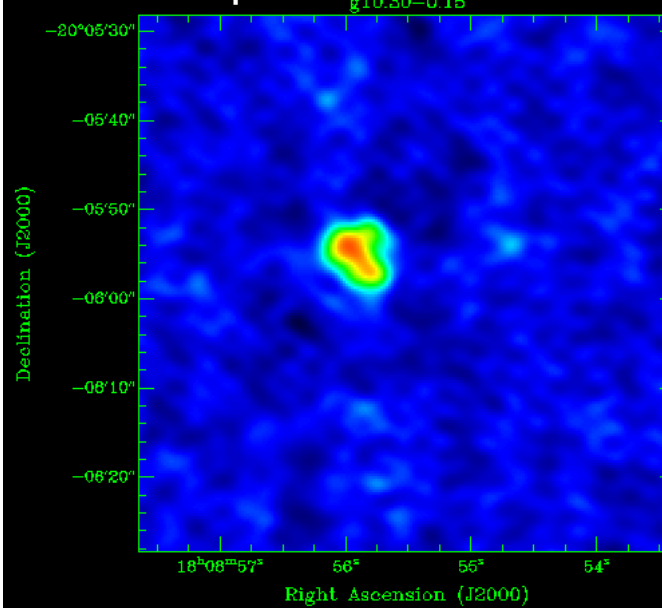
Dirty map



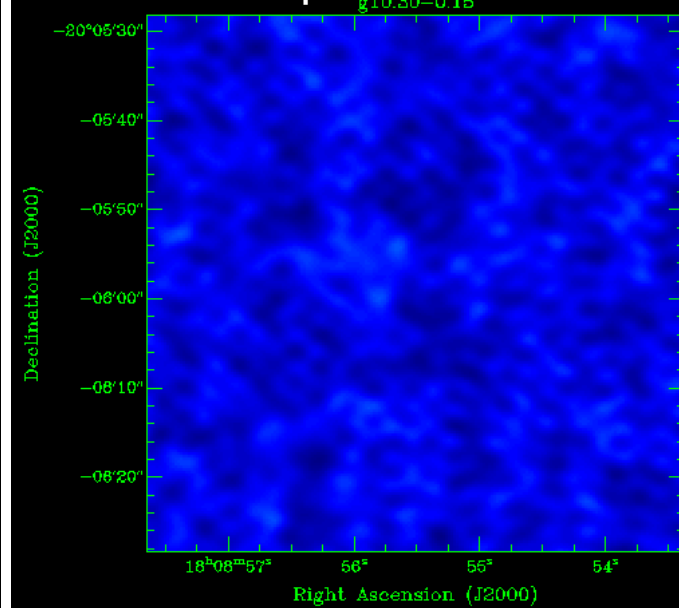
Clean Model



Clean map



Residual map





THE UNIVERSITY OF
SYDNEY

Reducing data from interferometers

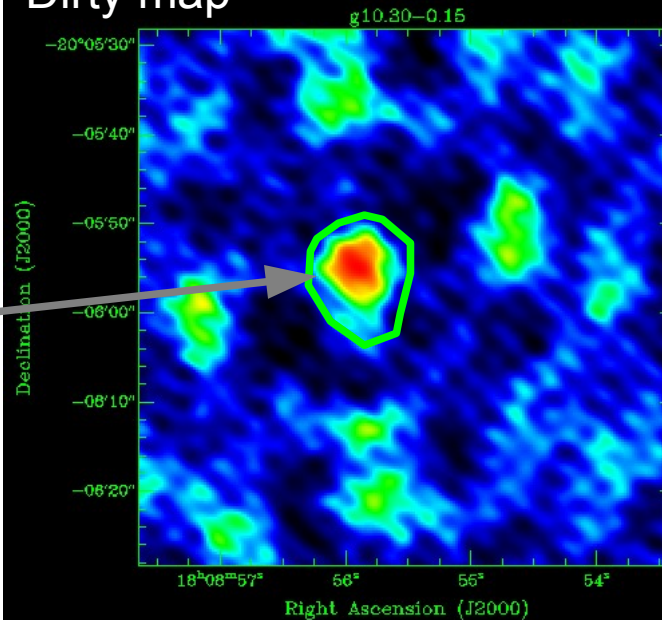
Data reduction recipe – Imaging

Niter=200

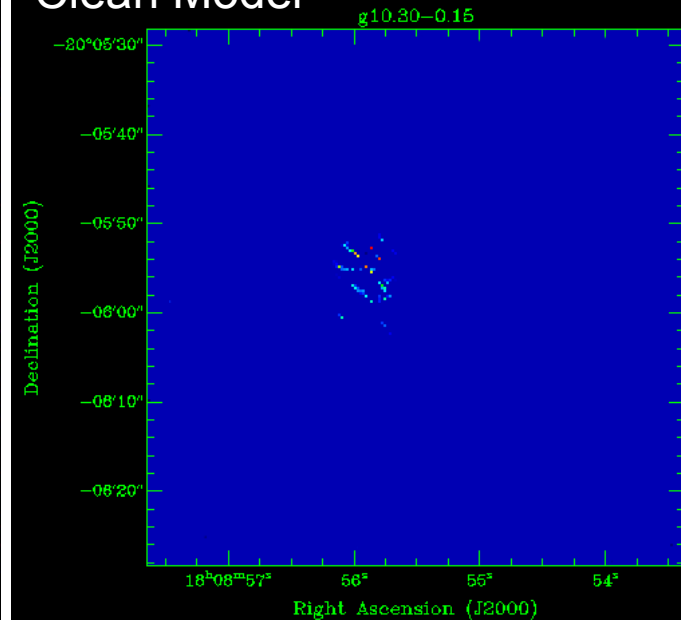
+

clean-box

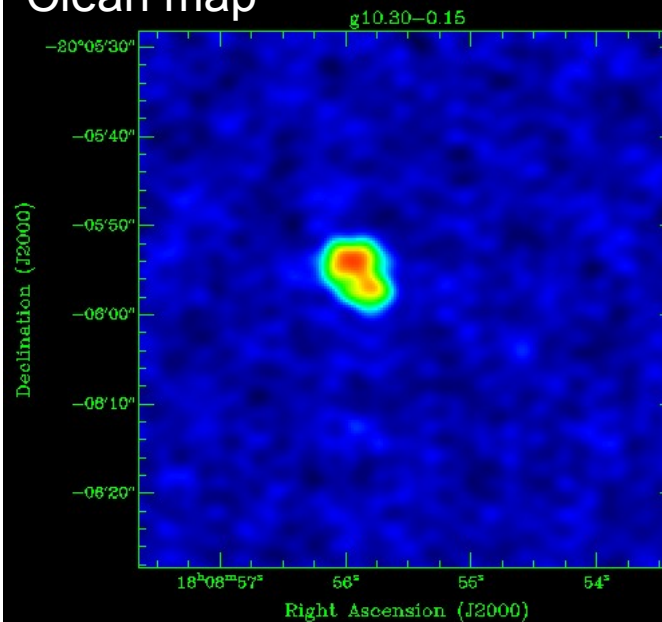
Dirty map



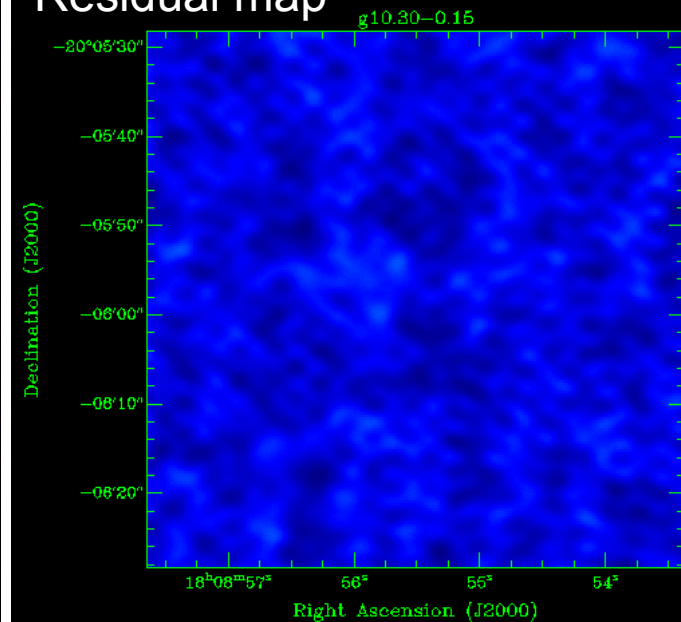
Clean Model



Clean map



Residual map





Aside: Interferometric vs single-dish units

- Interferometric data calibrated in Janskys
- Flux-density: *power received per unit collecting area, per unit frequency interval* $\text{W m}^{-2} \text{Hz}^{-1} = 10^{26} \text{ Jy}$

$$F_\nu = \frac{L_\nu \leftarrow \text{Luminosity}}{4\pi d^2 \leftarrow \text{Distance}}$$

- Single-dish data calibrated in Kelvin
- Brightness: flux-density per solid angle

$$I_\nu = \frac{F_\nu}{\Omega} = \frac{2k_B T_{\text{mb}}}{\lambda^2}$$

Beam solid angle \rightarrow



Aside: Interferometric vs single-dish units

- Example: Mopra @ 3mm wavelengths

$$T_{\text{mb}} = \frac{\lambda^2 F_\nu}{2k_B \Omega} = 13.6 \text{ K} \left(\frac{\lambda_{\text{mm}}}{\theta''} \right)^2 \left(\frac{F_\nu}{\text{Jy}} \right)$$

- A source of 1 Jy will produce a T_{mb} of 0.1 K in the $\theta=35''$ Mopra beam
- Applying a beam efficiency of $\eta_b=0.4$ results in $T_A^* = \eta_b T_{\text{mb}} = 40 \text{ mK}$ if the source fills the beam



Pandora's box

- Expert users should know about:
 - Self-calibration
 - Weighting schemes
 - Polarisation
 - Wide-field imaging
 - Correcting for phase gradients across the field of view
 - Sidelobes from strong sources in the outer beam