

Jansky **E**VLA Data Reduction Path

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Jansky Very Large Array

- Major upgrade of the world's most flexible, sensitive, and capable synthesis array

Significant leveraging of an existing (a.k.a. “paid for”) and operating telescope

- **Top-level goal:** Order-of-magnitude improvements in all observational capabilities, except resolution

✧ Complete frequency coverage from 1 to 50 GHz (0.7 to 30 cm)

✧ 1-hour, rms continuum point-source sensitivity of $3 \mu\text{Jy}$

✧ New correlator of unprecedented flexibility to enable matching resources to scientific goals

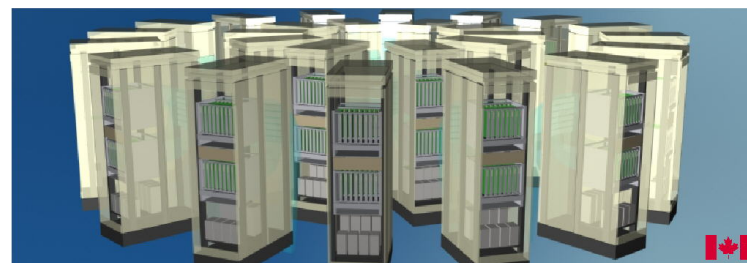
- **Status**

- All antennas modified
- Four receiver bands fully available: C, K, Ka, Q; remaining four bands (L, S, X, Ku) completed by late 2012
- Correlator fully installed, undergoing commissioning
- Science programs now well established

- **2011 September 20 ApJL Special Edition**

37 early science papers

Largest in ApJL history



Jansky VLA Science

THE ASTROPHYSICAL JOURNAL LETTERS

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The Astrophysical Journal Letters
Volume 739
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EARLY SCIENCE WITH THE EXPANDED VERY LARGE ARRAY

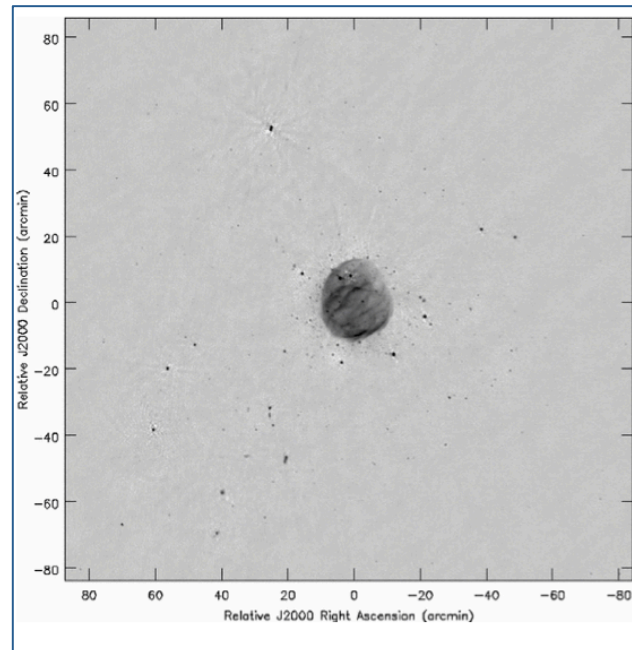
L1
The Expanded Very Large Array: A New Telescope for New Science
R. A. Perley, C. J. Chandler, B. J. Butler and J. M. Wrobel
doi:10.1088/2041-8205/739/1/L1

L2
Expanded Very Large Array Observations of the Barnard 5 Star-forming Core: Embedded Filaments Revealed
Jaime E. Pineda, Alyssa A. Goodman, Héctor G. Arce, Paola Caselli, Steven Longmore and Stuart Corder
doi:10.1088/2041-8205/739/1/L2

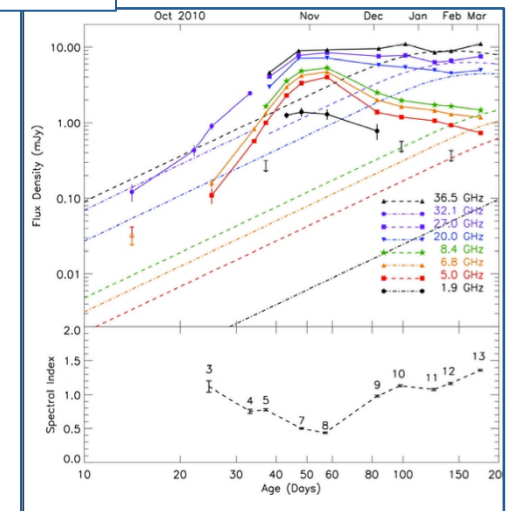
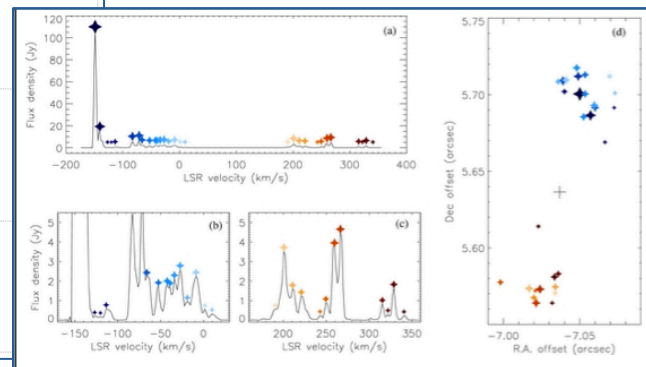
L3
An Expanded Very Large Array and CARMA Study of Dusty Disks and Torii with Large Grains in Dying Stars
R. Sahai, M. J. Claussen, S. Schnee, M. R. Morris and C. Sánchez Contreras
doi:10.1088/2041-8205/739/1/L3

L4
Imaging of the CCS 22.3 GHz Emission in the Taurus Molecular Cloud Complex
Nirupam Roy, Abhirup Datta, Emmanuel Momjian and Anuj P. Sarma
doi:10.1088/2041-8205/739/1/L4

L5
A Pilot Imaging Line Survey of RW LMi and IK Tau Using the Expanded Very Large Array
M. J. Claussen, L. O. Sjouwerman, M. P. Rupen, H. Olofsson, F. L. Schöier, P. Bergman and G. R. Knapp
doi:10.1088/2041-8205/739/1/L5



Supernova remnants (Bhatnagar et al.)
Water fountains in IRAS 18113–2503 (Gomez et al.)
Broadband radio light curves of novae (Krauss et al.)



VLA Data Reduction

Theoretical Background

- Interferometer measures product of electric fields from two receptors, **visibility**

$$V_{ij} = \langle E_i E_j^* \rangle$$

- Visibility has desirable property of being related to sky brightness distribution. Under ***certain*** assumptions, Fourier relation:

$$V_{ij} \Leftrightarrow I(\theta)$$

- Measured (V') vs. **True (V)** visibility

VLA Data Reduction Theoretical Background

- Consider

$$V_{ij}' \quad \leftarrow \quad ? \quad \rightarrow \quad V_{ij}$$

VLA Data Reduction

Theoretical Background

- Consider

$$V_{ij}' = b_{ij} B_i B_j^* G_i G_j^* V_{ij}$$

baseline-dependent effects

“gains” (amplitude & phase)

“bandpass” (frequency-dependent effects)

- Assumes *no direction dependent effects*
- Generally functions of time and/or frequency
- Special case of more general Hamaker-Sault-Bregman **measurement equation**

$$V_{ij}' = (\mathbf{J}_{\text{vis},i} \otimes \mathbf{J}_{\text{vis},j}) \Sigma (\mathbf{J}_{\text{sky},i}[\rho_k] \otimes \mathbf{J}_{\text{sky},j}^*[\rho_k]) \mathbf{S} \mathbf{V}_{S,ij,k}$$

(Hamaker, Bregman, & Sault 1996, *A&AS*, **117**, 137 and subsequent papers)

Measurement Set and the Data

```
listobs('mydata.ms')
```

```
#####  
#### Begin Task: listobs          #####
```

```
=====  
MeasurementSet Name: /scr2/casa/evla_6-cm_wideband/SN2010FZ_10s.ms      MS Version 2  
=====
```

```
Observer: Dr. Alicia M. Soderberg      Project: T.B.D.
```

```
Observation: EVLA
```

```
Data records: 1570726      Total integration time = 3359 seconds
```

```
Observed from 11-Jul-2010/21:30:44.0 to 11-Jul-2010/22:26:43.0 (UTC)
```

```
ObservationID = 0      ArrayID = 0
```

Date	Timerange (UTC)	Scan	FldId	FieldName	nRows	Int(s)	SpwIds	ScanIntent
11-Jul-2010/21:30:44.0	21:30:44.0 - 21:30:52.0	2	0	J0925+0019	404	6.43	[0, 1]	CALIBRATE_PHASE#UNSPECIFIED
	21:31:02.0 - 21:32:22.0	3	0	J0925+0019	5062	9.68	[0, 1]	CALIBRATE_PHASE#UNSPECIFIED
	...							
	21:35:02.0 - 21:35:51.5	6	0	J0925+0019	32640	9.44	[2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17]	CALIBRATE_PHASE#UNSPECIFIED
	21:36:01.0 - 21:38:20.5	7	0	J0925+0019	81600	9.93	[2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17]	CALIBRATE_PHASE#UNSPECIFIED
	21:38:44.0 - 21:39:51.0	9	1	SN2010FZ	43520	9.16	[2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17]	OBSERVE_TARGET#UNSPECIFIED
	21:40:01.0 - 21:41:20.5	10	1	SN2010FZ	48960	9.89	[2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17]	OBSERVE_TARGET#UNSPECIFIED
	21:41:30.0 - 21:42:50.0	11	1	SN2010FZ	48960	10	[2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17]	OBSERVE_TARGET#UNSPECIFIED
	21:43:00.0 - 21:44:20.0	12	1	SN2010FZ	48960	10	[2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17]	OBSERVE_TARGET#UNSPECIFIED
	21:44:30.0 - 21:45:50.0	13	1	SN2010FZ	48960	10	[2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17]	OBSERVE_TARGET#UNSPECIFIED
	21:46:00.0 - 21:47:19.5	14	1	SN2010FZ	48960	9.89	[2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17]	OBSERVE_TARGET#UNSPECIFIED
	21:47:29.0 - 21:47:49.0	15	1	SN2010FZ	16320	9.67	[2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17]	OBSERVE_TARGET#UNSPECIFIED
	[...]							
	22:25:13.0 - 22:25:13.0	42	2	3C286	1028	2.87	[2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17]	CALIBRATE_BANDPASS#UNSPECIFIED,CALIBRATE_AMPLI#UNSPECIFIED
	22:25:23.0 - 22:26:43.0	43	2	3C286	47757	9.6	[2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17]	CALIBRATE_BANDPASS#UNSPECIFIED,CALIBRATE_AMPLI#UNSPECIFIED

(nVis = Total number of time/baseline visibilities per scan)

Measurement Set and the Data

Fields: 3

ID	Code	Name	RA	Decl	Epoch	SrcId	nVis
0	D	J0925+0019	09:25:07.81503	+00.19.13.9334	J2000	0	303381
1	NONE	SN2010FZ	09:42:04.77000	+00.19.51.0000	J2000	1	1218560
2	K	3C286	13:31:08.28798	+30.30.32.9589	J2000	2	48785

(nVis = Total number of time/baseline visibilities per field)

Spectral Windows: (18 unique spectral windows and 1 unique polarization setups)

SpwID	#Chans	Frame	Ch1(MHz)	ChanWid(kHz)	TotBW(kHz)	Corrs
0	64	TOPO	7686	2000	128000	RR RL LR LL
1	64	TOPO	7836	2000	128000	RR RL LR LL
[...]						
16	64	TOPO	7256	2000	128000	RR RL LR LL
17	64	TOPO	7384	2000	128000	RR RL LR LL

Sources: 50

ID	Name	SpwId	RestFreq(MHz)	SysVel(km/s)
0	J0925+0019	0	-	-
[...]				
0	J0925+0019	17	-	-
1	SN2010FZ	2	-	-
[...]				
1	SN2010FZ	17	-	-
2	3C286	2	-	-
[...]				
2	3C286	17	-	-

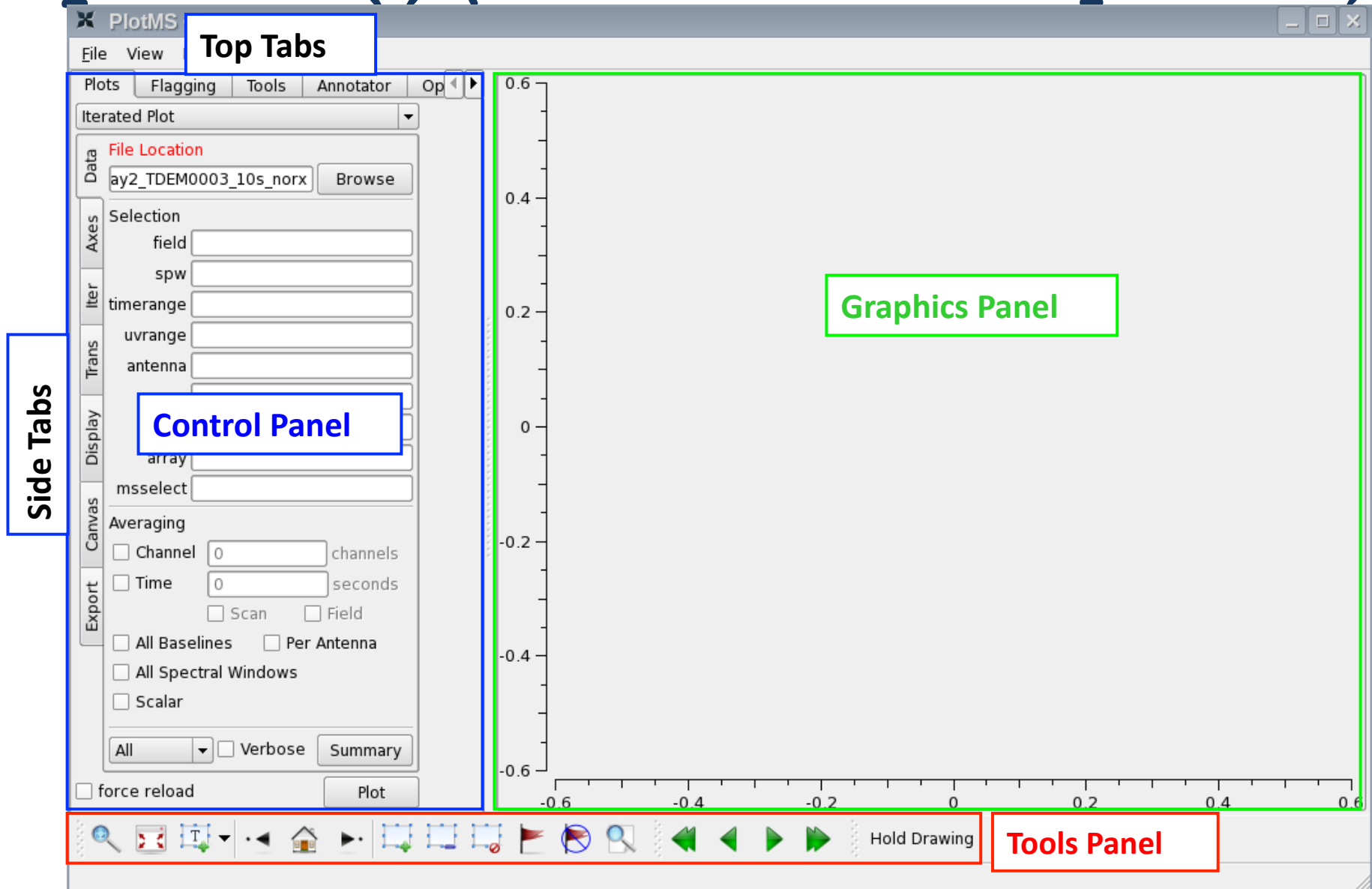
Antennas: 27:

ID	Name	Station	Diam.	Long.	Lat.
0	ea01	W09	25.0 m	-107.37.25.2	+33.53.51.0
1	ea02	E02	25.0 m	-107.37.04.4	+33.54.01.1
[...]					
25	ea27	E03	25.0 m	-107.37.02.8	+33.54.00.5
26	ea28	N08	25.0 m	-107.37.07.5	+33.54.15.8

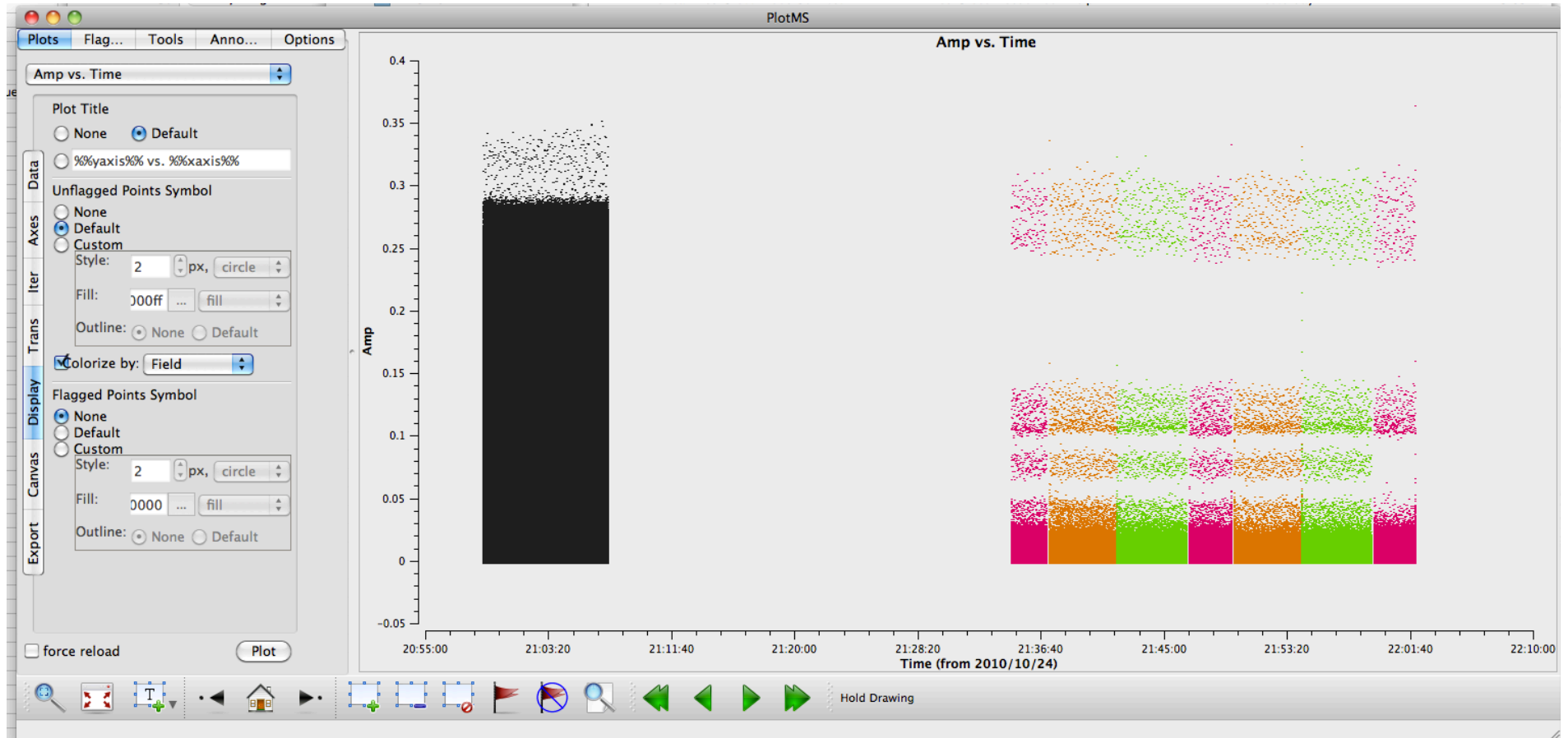
End Task: listobs #####
#####

Data Review

`plotms()` (command line `casaplotms`)



Data Review



$$V = V(u, v, w; t; v; i, j; p)$$

... per source

VLA Data Reduction Summary

$$V_{ij}' = b_{ij} B_i B_j^* G_i G_j^* V_{ij}$$

- Get data from the archive
- Examine data, remove bad data if necessary
 - Radio frequency interference (RFI), missing receivers, or other problems in the observing log
- Get information about the weather over the course of the observations
 - Typically for frequencies above 10 GHz
- Check if gain curves are needed (for G_i)
 - Generally useful for C-band and higher; don't exist (and probably aren't needed) for S-band; exist but not needed for L-band.
- Check for updated antenna positions, and apply corrections if needed (avoid b_{ij})
- Set flux density scale for amplitude calibrator (for $\text{amp}[G_i]$)
- Bandpass solution on the bandpass calibrator(s) (for B_i)
- Phase+amp gain solutions for the amplitude calibrator(s) (for $\text{amp}[G_i]$)
- Phase+amp solution on the calibrator(s) (for G_i)
- Apply the calibration to the science target (and calibrators)
- Imaging

Antenna Position Corrections I

for b_{ij}

- Visibility function $V_{ij}(u, v, w)$ is function of *baseline* or antenna separation
 $u = (b_{i,x} - b_{j,x})/\lambda$, $v = (b_{i,y} - b_{j,y})/\lambda$, $w = (b_{i,z} - b_{j,z})/\lambda$
- Consult VLA Baselines Correction site
 - <http://www.vla.nrao.edu/astro/archive/baselines/>
 - Corrections are **additive!**

```
;          2011 EVLA BASELINE CORRECTIONS IN METERS
;ANT
;MOVED OBSDATE   Put_In_ MC(IAT)  ANT  PAD   Bx      By      Bz
;
JAN18  JAN20     JAN22    01:05   6  N24  0.0223  0.0077  0.0077
JAN18  JAN20     JAN22    01:05   8  N28  0.0075  0.0064  0.0065
```

Diagram illustrating the data structure and highlighting key fields:

- window**: Points to the date range (JAN20) in the second row.
- correction**: Points to the correction value (By) in the second row.

Antenna Position Corrections II

`gencal()` for b_{ij}

```
gencal(vis='mydata.ms', caltable='mydata.pos',  
       caltype='antpos', antenna='ea07',  
       parameter=[0.0087, 0.0137, 0.0000])
```

- `vis` => name of measurement set
- `caltable` => where corrections are stored
Note this file, as you **need** to use it in all subsequent steps
- `caltype` => specify antenna position corrections
- `antenna` => name of antenna(s)
`antenna='ea09,ea10'`
- `parameter` => baseline corrections
 - `parameter=[0.01,0.02,0.03, -0.03,-0.01,-0.02]` for multiple antennas
 - Parameter list can include corrections for polarization and spectral window as well

VLA Data Calibration

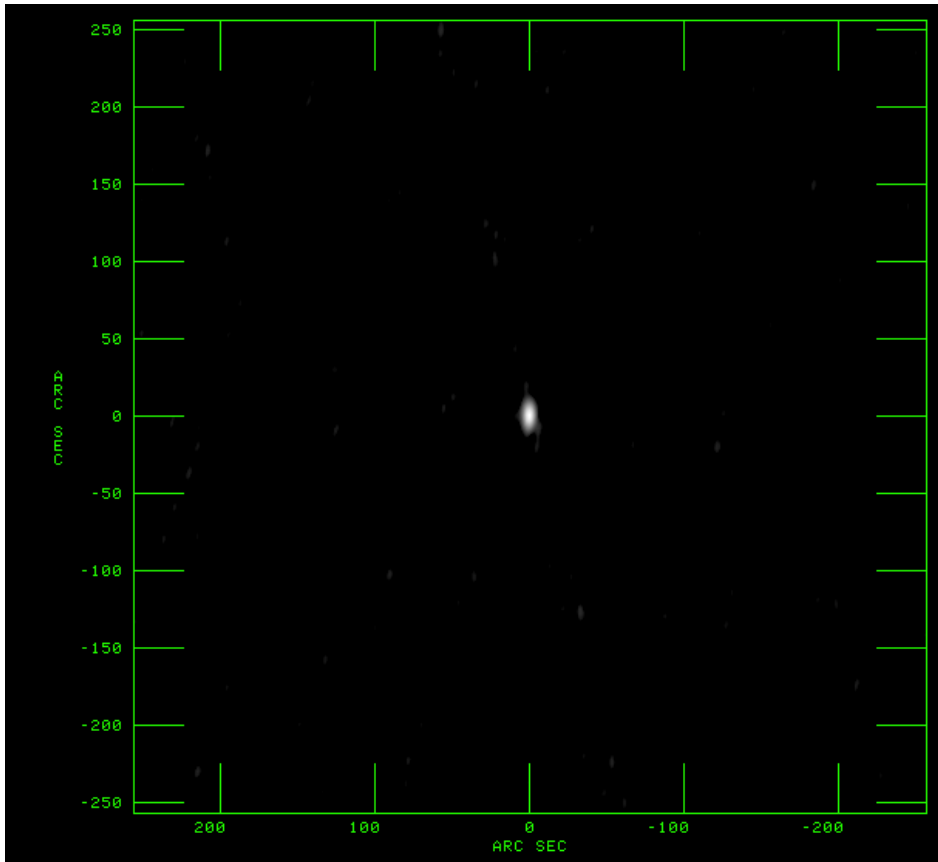
$$V_{ij}' = b_{ij} B_i B_j^* G_i G_j^* V_{ij}$$



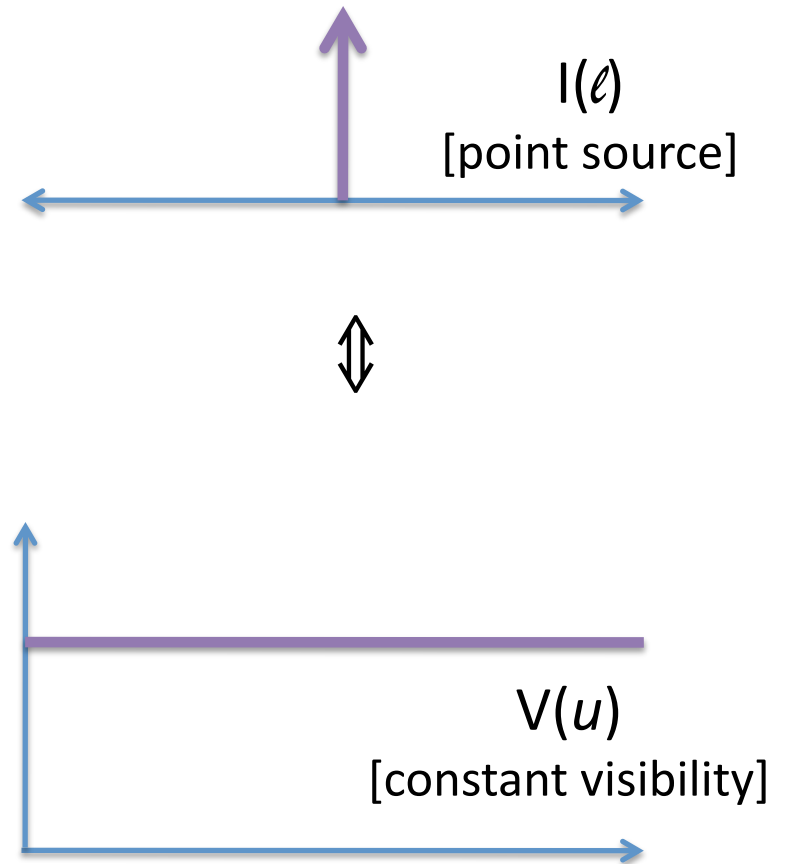
- Antenna-based
- How to get started?
 - V_{ij} is **True** visibility, but how do we know it?
- Calibrator sources of known properties
- Derive series of corrections, apply successively
 - Recall that b_{ij} corrections now applied to all subsequent steps



VLA Data Calibration II



Calibrator = source of known structure (spatial and/or frequency)



Flux Density Scale

`setjy()` for `amp[Gi]`

```
setjy(vis='mydata.ms', listmodimages=True)
setjy(vis='mydata.ms', field='2', scalebychan=True,
      modimage='/path/to/images/3C286_C.im')
```

- Select set of sources serve as defining flux density scale
3C 286, 3C 48, 3C 147, 3C 138
- Model images typically in a directory
`/Applications/CASA.app/Contents/Resources/casa-data/nrao/VLA/CalModels`
- After `setjy()` concludes, `mydata.ms` contains
 - Original measured visibility data (DATA)
 - Model visibility of effective point source (MODEL)

Bandpass Calibration for B_i

Bandpass describes variations as a function of frequency

- Often the result of electronics in system (e.g., filters)
- In general, $B_i = B_i(t, \nu)$
- For many cases, use $B_i = B_i(\nu)G_i'(t)$
 - Three-step procedure to remove time variations, then determine frequency-dependent variations
 - Time-dependent bandpass may be necessary for highest dynamic range spectral-line observations

Bandpass Calibration

1. Solve for phase as a function of time, over limited range of frequency channels

```
gaincal(vis='mydata.ms', caltable='mydata.G0', field='2', spw='0~13:23~28',  
        gaintype='G', refant='ea02', calmode='p', solint='int', minsnr=3,  
        gaintable='mydata.pos')
```

2. Solve for delays (derivative of phase with respect to time)

```
gaincal(vis='mydata.ms', caltable='mydata.K0', gaintable=  
        ['mydata.pos', 'mydata.G0'],  
        field='2', spw='0:8~59,1~13:4~59', gaintype='K',  
        refant='ea02', combine='scan', solint='inf', minsnr=3)
```

3. Solve for bandpass itself

```
bandpass(vis='mydata.ms', caltable='mydata.B0',  
         gaintable=['mydata.pos', 'mydata.G0', 'mydata.K0'],  
         field='2', refant='ea02', solnorm=False,  
         bandtype='B', combine='scan', solint='inf', gaincurve=True)
```

Bandpass Calibration 1

1. Solve for phase as a function of time, over limited range of frequency channels

```
gaincal
```

```
(vis='mydata.ms', caltable='mydata.G0', field='2', spw='0~13:23~28',  
gaintype='G', refant='ea02', calmode='p', solint='int', minsnr=3,  
gaintable='mydata.pos')
```

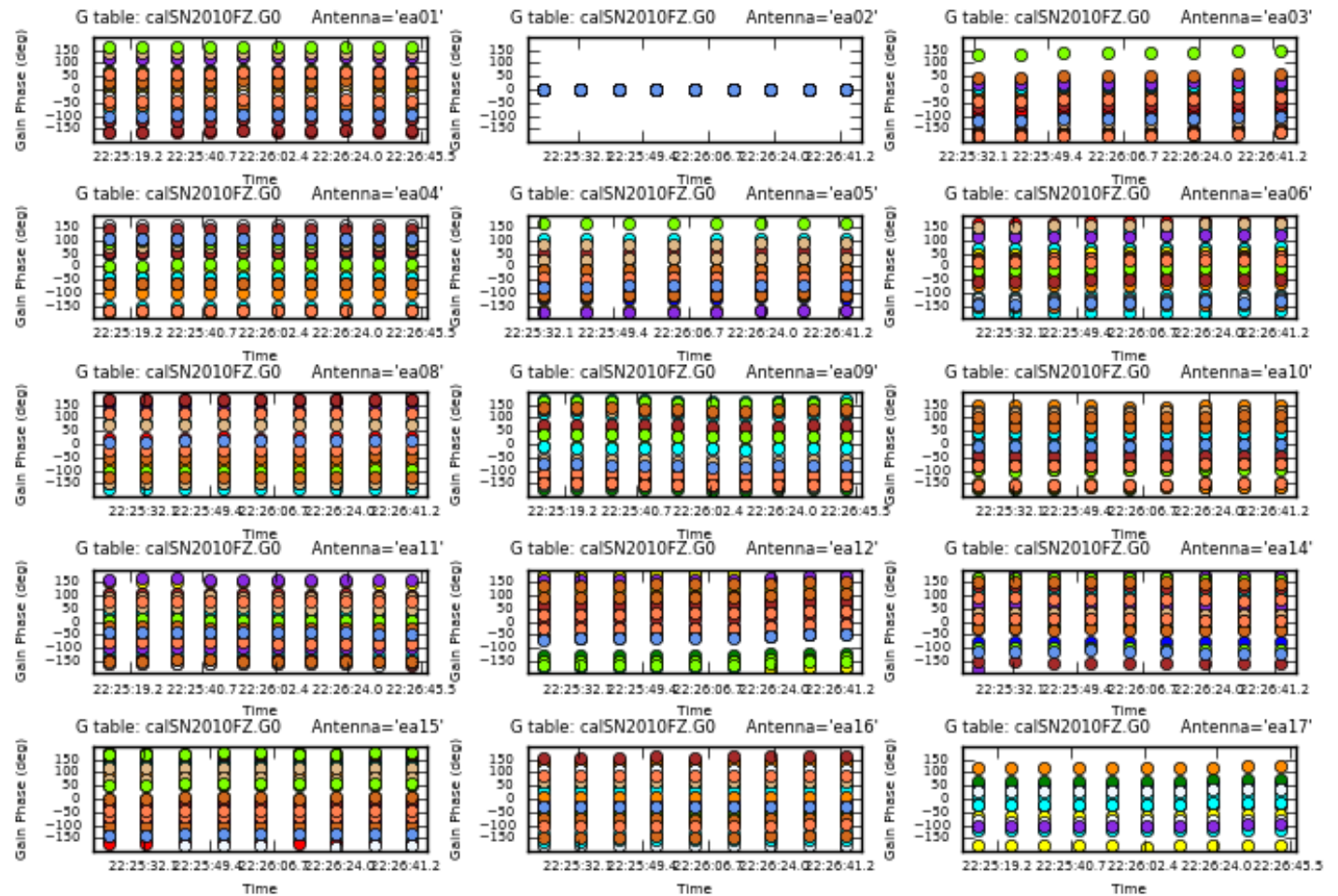
- `spw` => Restrict to limited range of frequency channels
- `calmode` => phase-only
- `solint` => individual integration
- `minsnr` => modest signal-to-noise ratios
- `gaintable` => apply any previously developed corrections
- `refant` => always relative to a reference antenna

Bandpass Calibration 1

gain phases

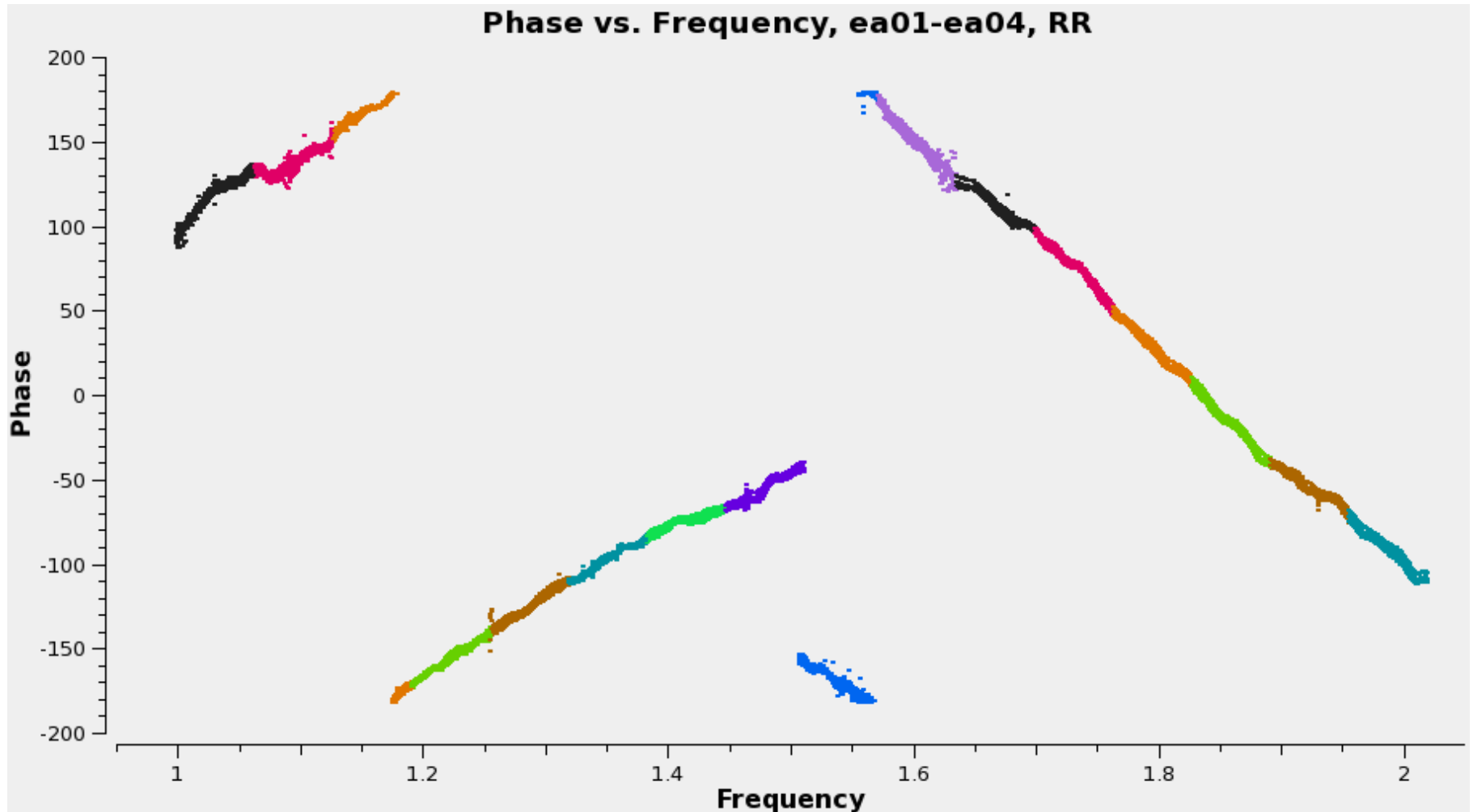
```

plotcal
(caltable='mydata
.G0',xaxis='time',
yaxis='phase',
antenna='0~10,12~
15',subplot=531,i
teration='antenna
',
plotrange=
[-1,-1,-180,180])
    
```



Bandpass Calibration 2

Delays



Bandpass Calibration 2

2. Solve for delays (derivative of phase with respect to time)

```
gaincal(vis='mydata.ms', caltable='mydata.K0', gaintable=  
    ['mydata.pos', 'mydata.G0'],  
        field='2', spw='0:8~59,1~13:4~59', gaintype='K',  
        refant='ea02', combine='scan', solint='inf', minsnr=3)
```

- `solint` => solve only for a delay integrated over the entire observation
- `combine` => combine scans in order to obtain integration over entire observation
- `spw` => large range of frequency channels
- `gaintype` => antenna based delays, but on a per spectral window basis

Bandpass Calibration 3

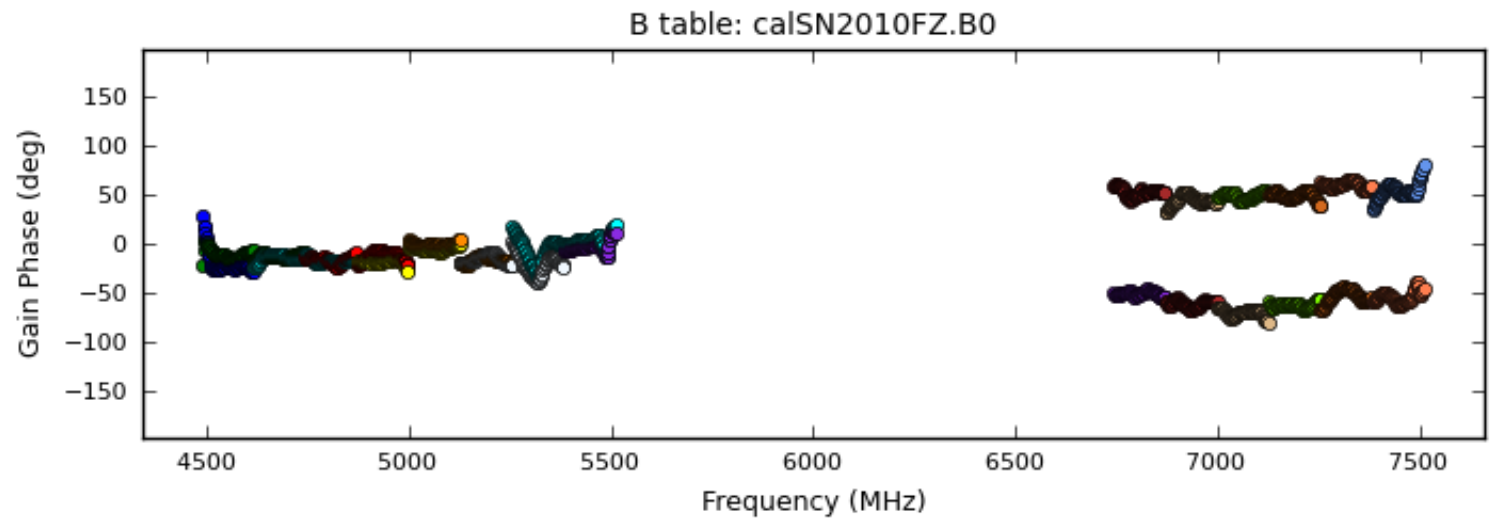
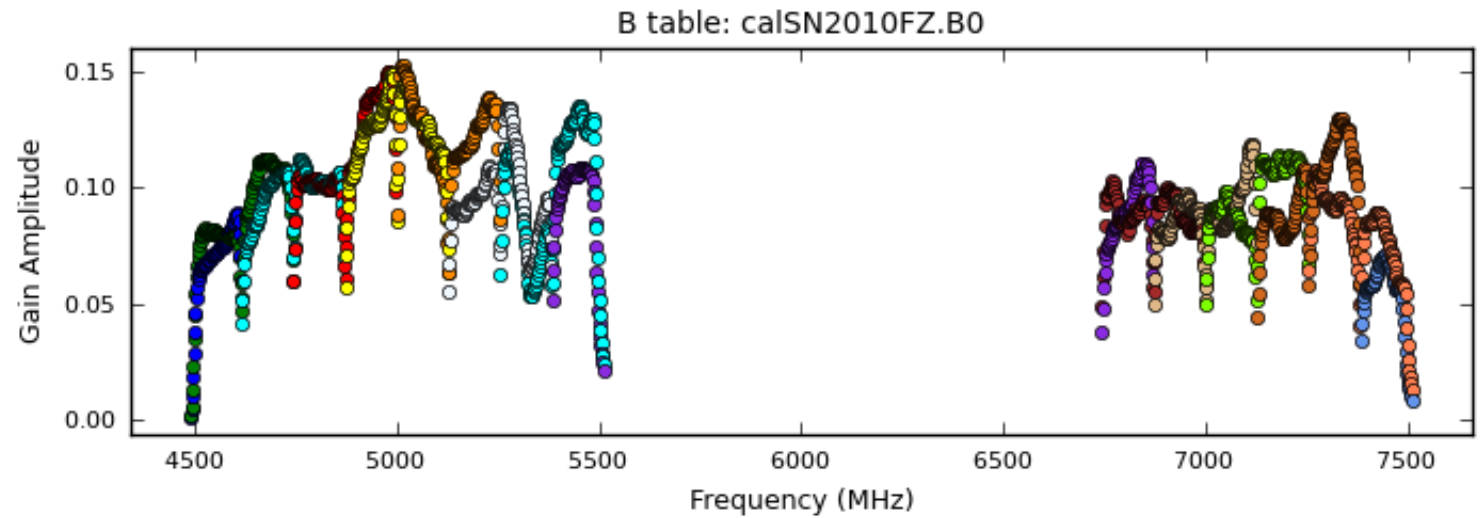
3. Solve for bandpass itself

```
bandpass(vis='mydata.ms', caltable='mydata.B0',  
         gaintable=['mydata.pos',  
                   'mydata.G0', 'mydata.K0'],  
         field='2', refant='ea02', solnorm=False,  
         bandtype='B', combine='scan', solint='inf',  
         gaincurve=True)
```

- `bandtype` => default, only other mode is experimental for now
- `solnorm` => False, else one will find some offsets between spw due to how amplitude scaling adjusts weights internally
- `gaincurve` => use, if necessary; typically at frequency ~ 5 GHz and higher
- `combine` & `solint` => integrate over entire observation

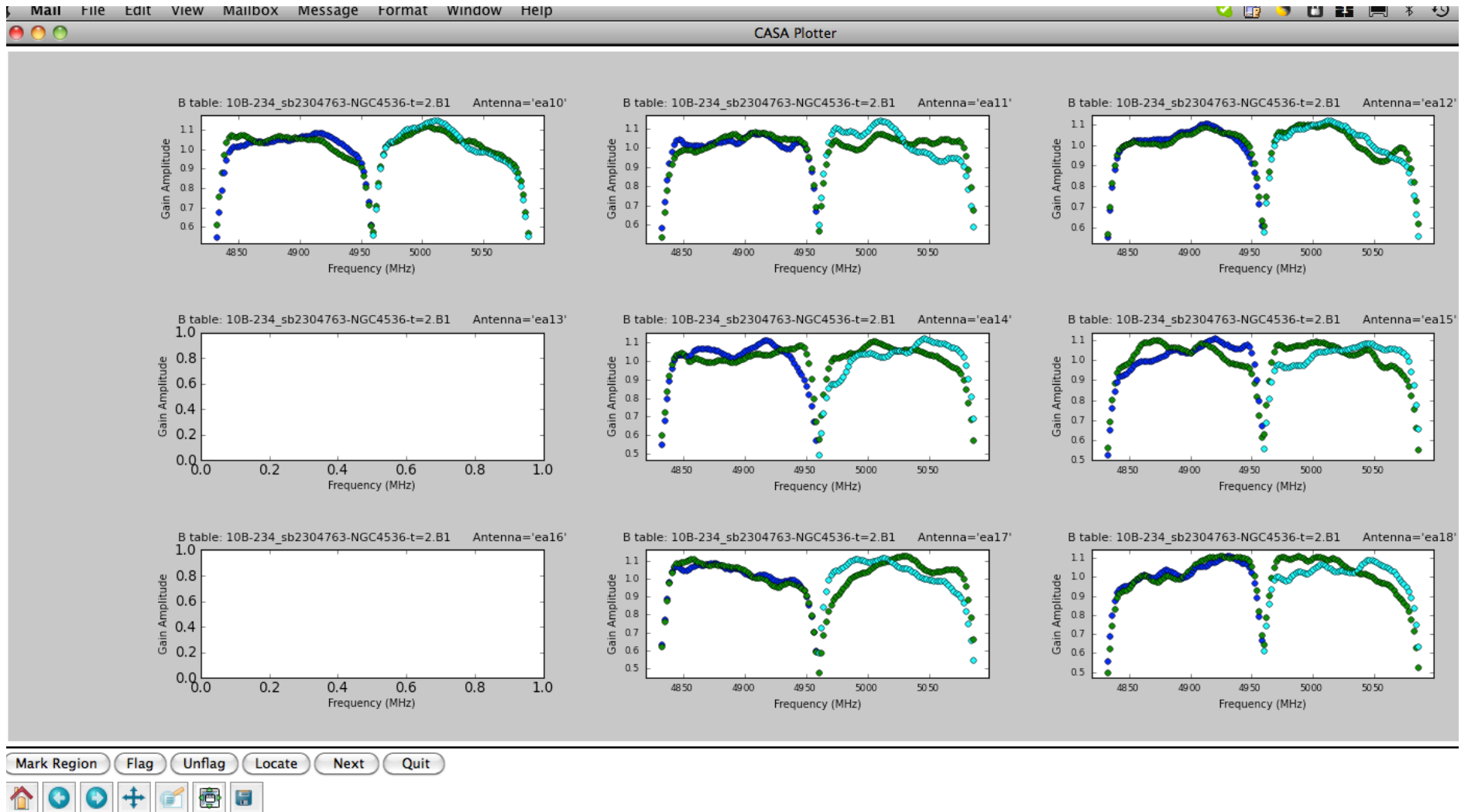
Bandpass Calibration 3

From plotcal()



Bandpass Calibration 3

From plotcal()



Gain Calibration for G_i

1. Determine amplitude scaling factors and phases for amplitude calibrator
 - `gaincal()`
 - Uses results from `setjy()` in which flux density of amplitude calibrator was specified
2. Determine amplitude scaling factors and phases for visibility phase calibrator
 - `gaincal()`
 - Assumes visibility phase calibrator has a flux density of 1 Jy
3. Scale the flux density of the visibility phase calibrator correctly
 - `fluxscale()`
4. Interpolate the amplitude and phase corrections from the visibility phase calibrator to the science target source(s)
 - `applycal()`

Gain Calibration on amplitude calibrator

```
gaincal(vis='mydata.ms', caltable='mydata.G1',  
        gaintable=['mydata.pos', 'mydata.K0', 'mydata.B0'],  
        field='2', refant='ea02', solnorm=F,  
        spw='0~13:4~59',  
        solint='int', gaintype='G', calmode='p')
```

```
gaincal(vis='mydata.ms', caltable='mydata.G2',  
        gaintable=['mydata.pos', 'mydata.K0', 'mydata.B0', 'mydata.G1'],  
        gainfield=['', '2', '2', '2'], field='0', refant='ea02', solnorm=F,  
        spw='0:10~59,...,13:4~8;15~36;42~59',  
        solint='inf', gaintype='G', calmode='a', gaincurve=True)
```

- `caltable + calmode` => specifies what kind of correction and where it is stored
- `gaintable + gainfield` => ensure that corrections derived from corrections from various sources not intermixed
- `solint` => per-interval vs. per-scan

Gain Calibration on visibility phase calibrator

```
gaincal(vis='mydata.ms', caltable='mydata.G1',
        gaintable=['mydata.pos', 'mydata.K0', 'mydata.B0'],
        field='0', refant='ea02', solnorm=F,
        spw='0:10~59,1~7:4~59,8:4~13;18~59,9~11:4~59,12:4~13;18~29;
31~33;46~51;53~59,13:4~8;15~36;42~59',
        solint='inf', gaintype='G', calmode='p', append=True)
gaincal(vis='mydata.ms', caltable='mydata.G2',
        gaintable=
        ['mydata.pos', 'mydata.K0', 'mydata.B0', 'mydata.G1'],
        gainfield=['2', '2', '2', '0'],
        field='0', refant='ea02', solnorm=F,
        spw='0:10~59,1~7:4~59,8:4~13;18~59,9~11:4~59,12:4~13;18~29;
31~33;46~51;53~59,13:4~8;15~36;42~59',
        solint='inf', gaintype='G', calmode='a', gaincurve=True, append
        =True)
```

- `gaintable + gainfield =>` ensure that solutions are not intermixed
- `append =>` iterative solutions, but need amplitude and visibility phase calibrator solutions together

Flux Density Scale

```
fluxscale
```

```
(vis='mydata.ms', caltable='mydata.G2',  
fluxtable='mydata.F2', reference='2',  
transfer='0')
```

- `reference + transfer` => from the amplitude calibrator (reference) to the visibility phase calibrator (transfer)
- `fluxtable + caltable` => from combined amplitude solutions in `caltable`, produce new scalings in `fluxtable`

Interpolation to Science Target (whew!)

```
applycal(vis='mydata.ms', field='1', gaintable=  
  ['mydata.K0', 'mydata.B0', 'mydata.G1', 'mydata.F2'],  
  gainfield=['', '', '0', '0'],  
  interp=['nearest', 'nearest', 'linear', 'linear'],  
  parang=False, calwt=F, gaincurve=T)
```

- `field` vs. `gainfield` => calibrator vs. target source(s)
- `interp` => interpolation method

Science Target Data

```
split(vis='mydata.ms',outputvis='target.ms',  
      datacolumn='corrected',field='1',spw='0~11')
```

- `outputvis` => new measurement set
- `datacolumn` => corrected, so that calibrated data extracted
CORRECTED_DATA becomes DATA
- `field` => only interested in science target

Further Topics

- Bookkeeping, bookkeeping, bookkeeping!
- Opacity, WVR, self-calibration ...
Next talk
- Advanced topics
Polarization, spectral line aspects (e.g., continuum subtraction), baseline-based calibration, ...
- Imaging, self-calibration, and hybrid mapping
 - Tune in tomorrow
 - Self-calibration similar to calibration