Calibration and Editing

Greg Taylor

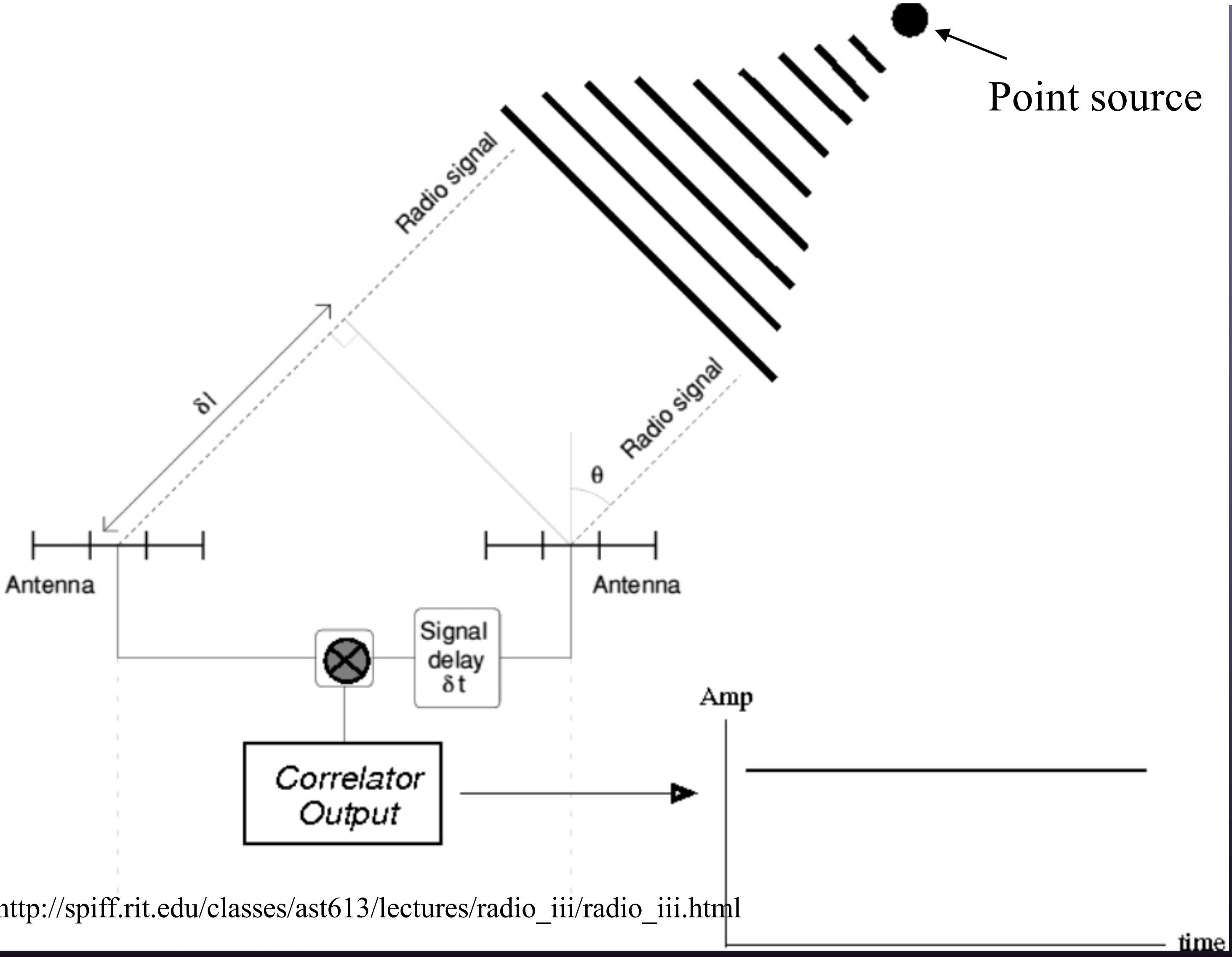
University of New Mexico

Spring 2017

Astronomy 423 at UNM

Radio Astronomy

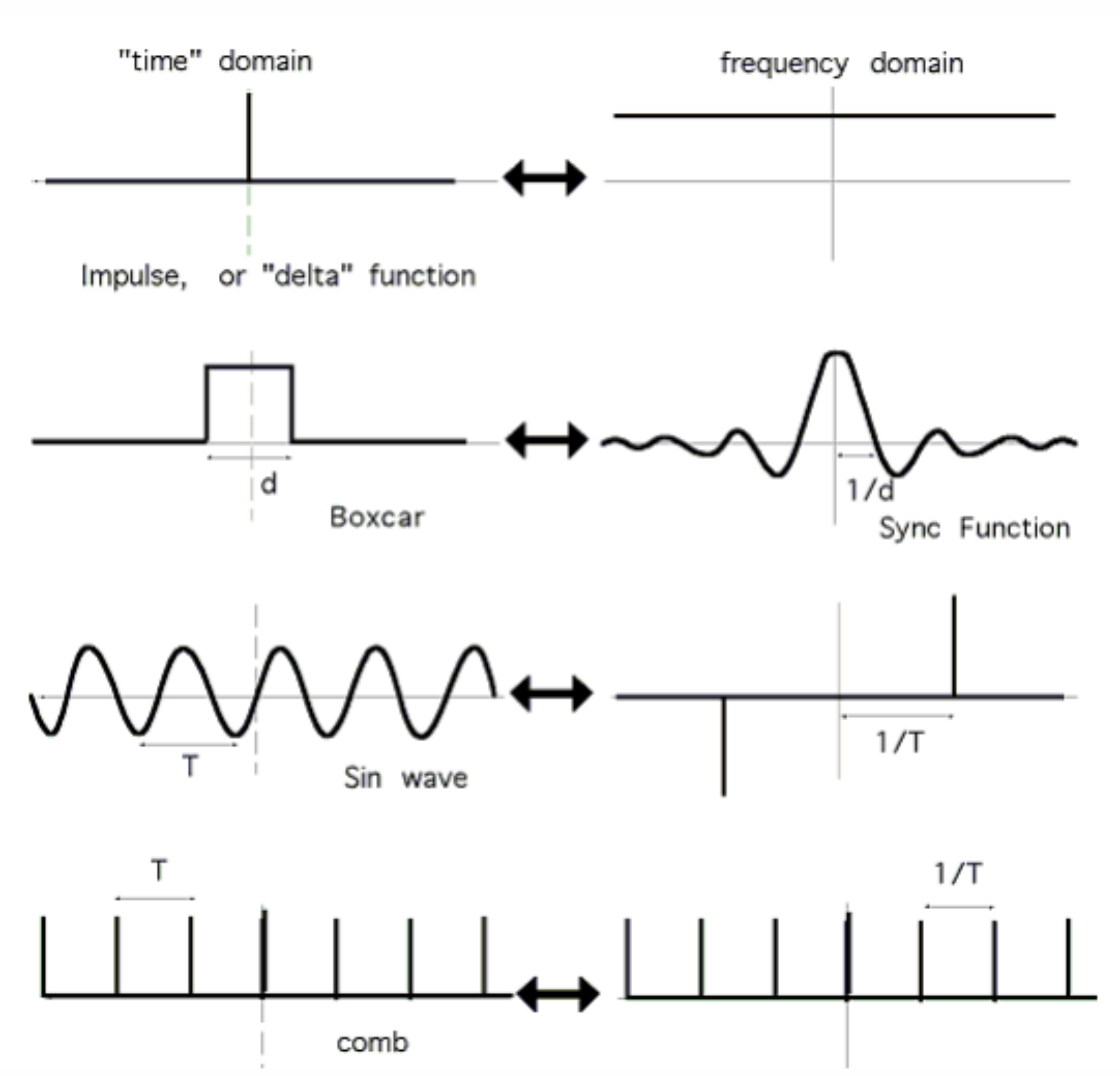
Interferometry Basics



http://spiff.rit.edu/classes/ast613/lectures/radio_iii/radio_iii.html

Fourier Transform Pairs

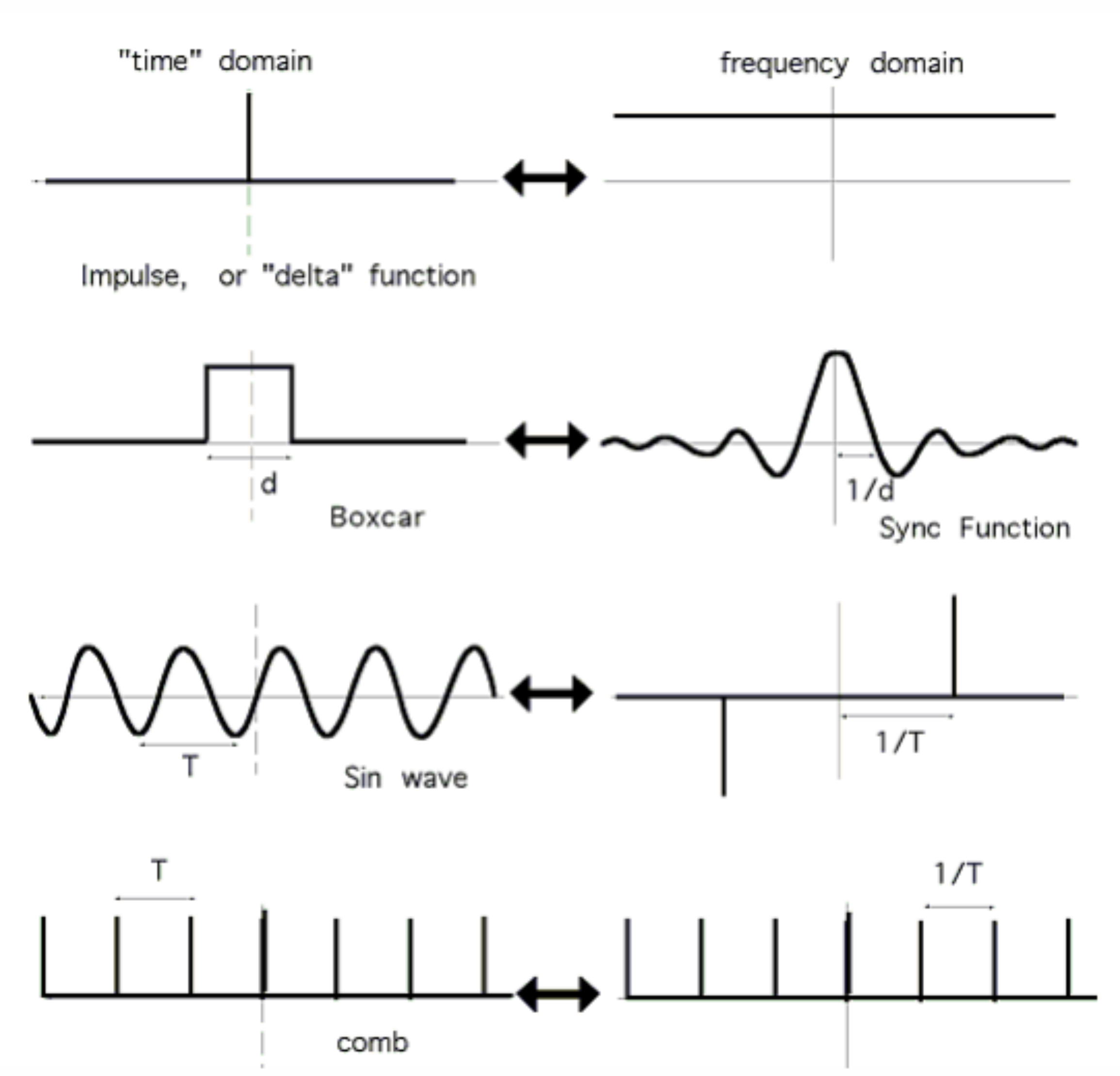
Name 3
FT relations:
1)AntennaAperture
2)
3)



Name 3
FT relations:
1) Power pattern
2)
3)

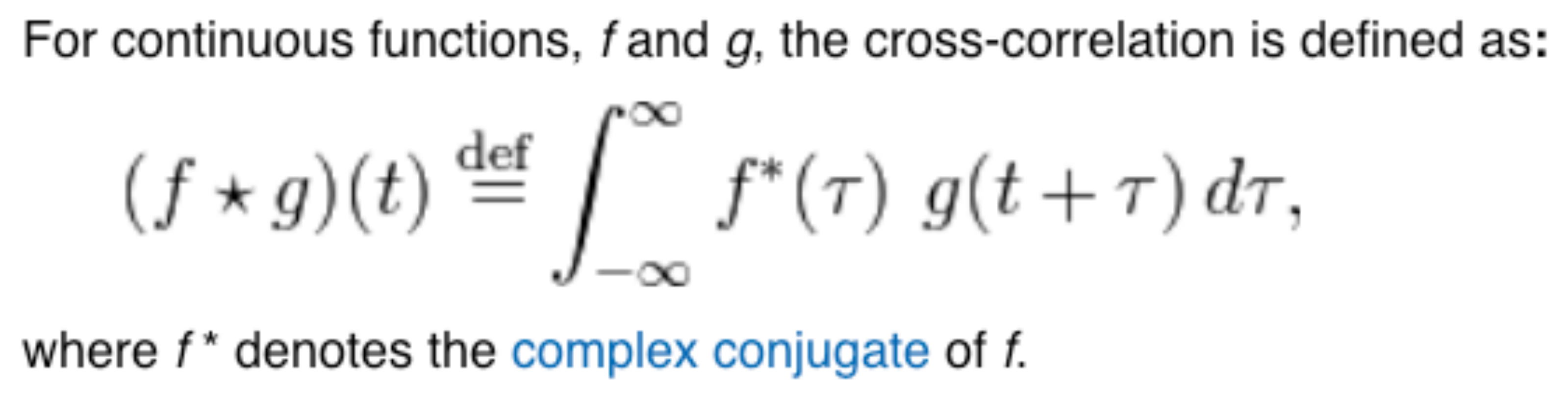
Fourier Transform Pairs

Name 3
FT relations:
1)AntennaAperture
2) Time series
3) Sky brightness



Name 3
FT relations:
1) Power pattern
2) Power spectrum
3) Visibility

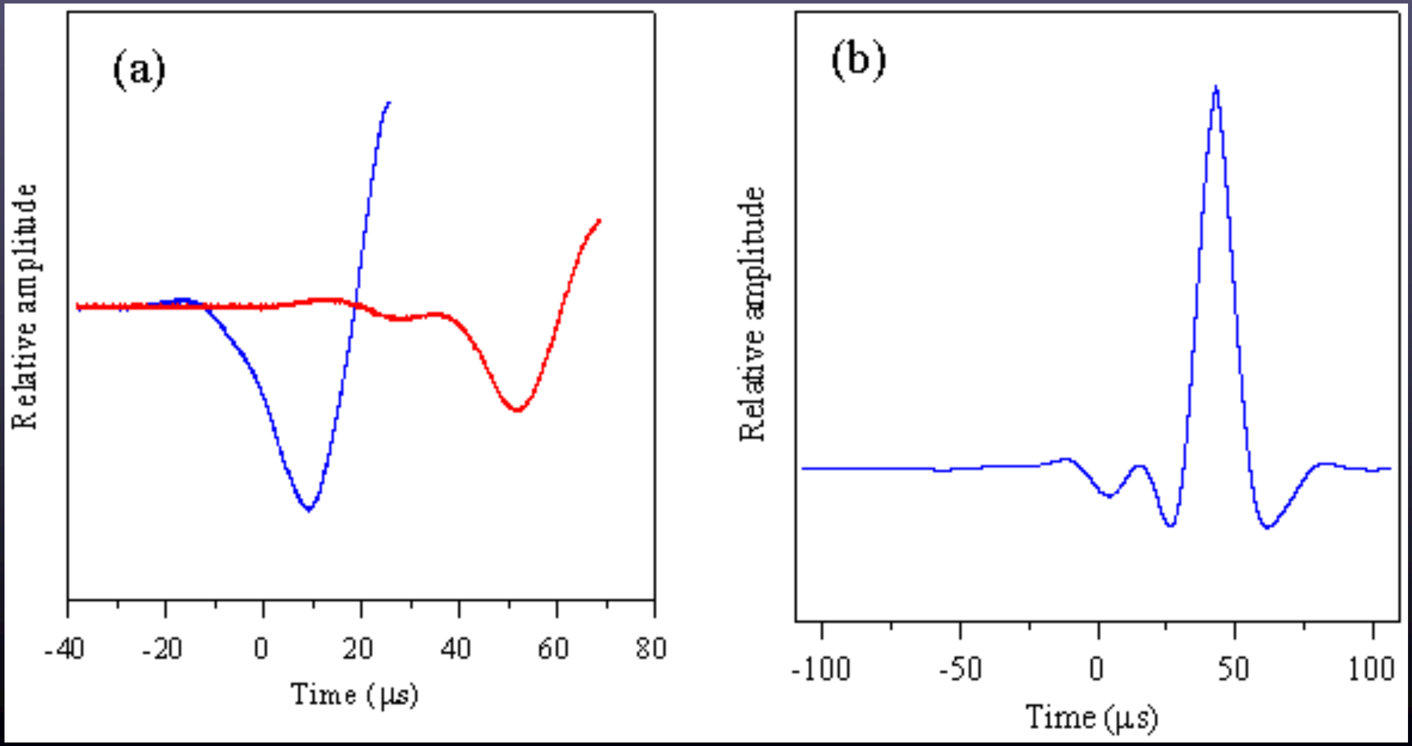
The Correlation Function



For continuous functions, *f* and *g*, the cross-correlation is defined as:

$$(f \star g)(t) \overset{\mathrm{def}}{=} \int_{-\infty}^{\infty} f^*(\tau)\ g(t+\tau)\,d\tau,$$

where f^* denotes the complex conjugate of *f*.



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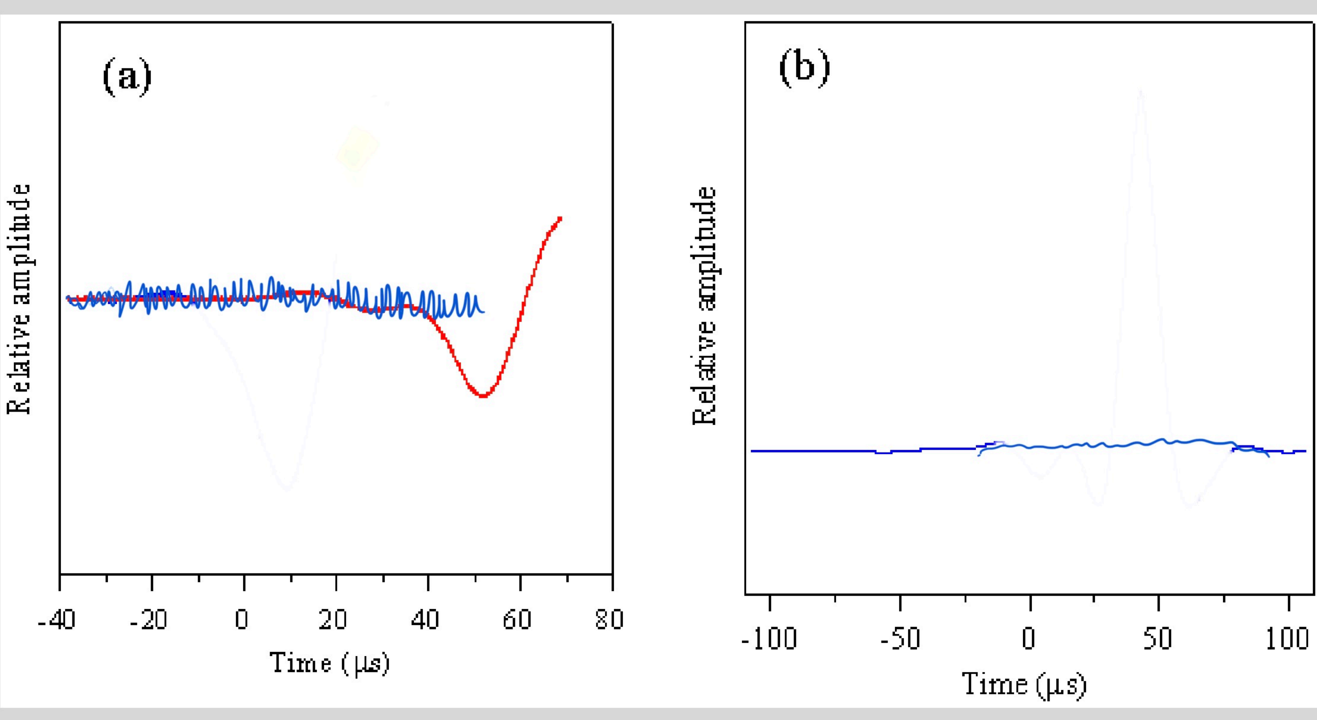
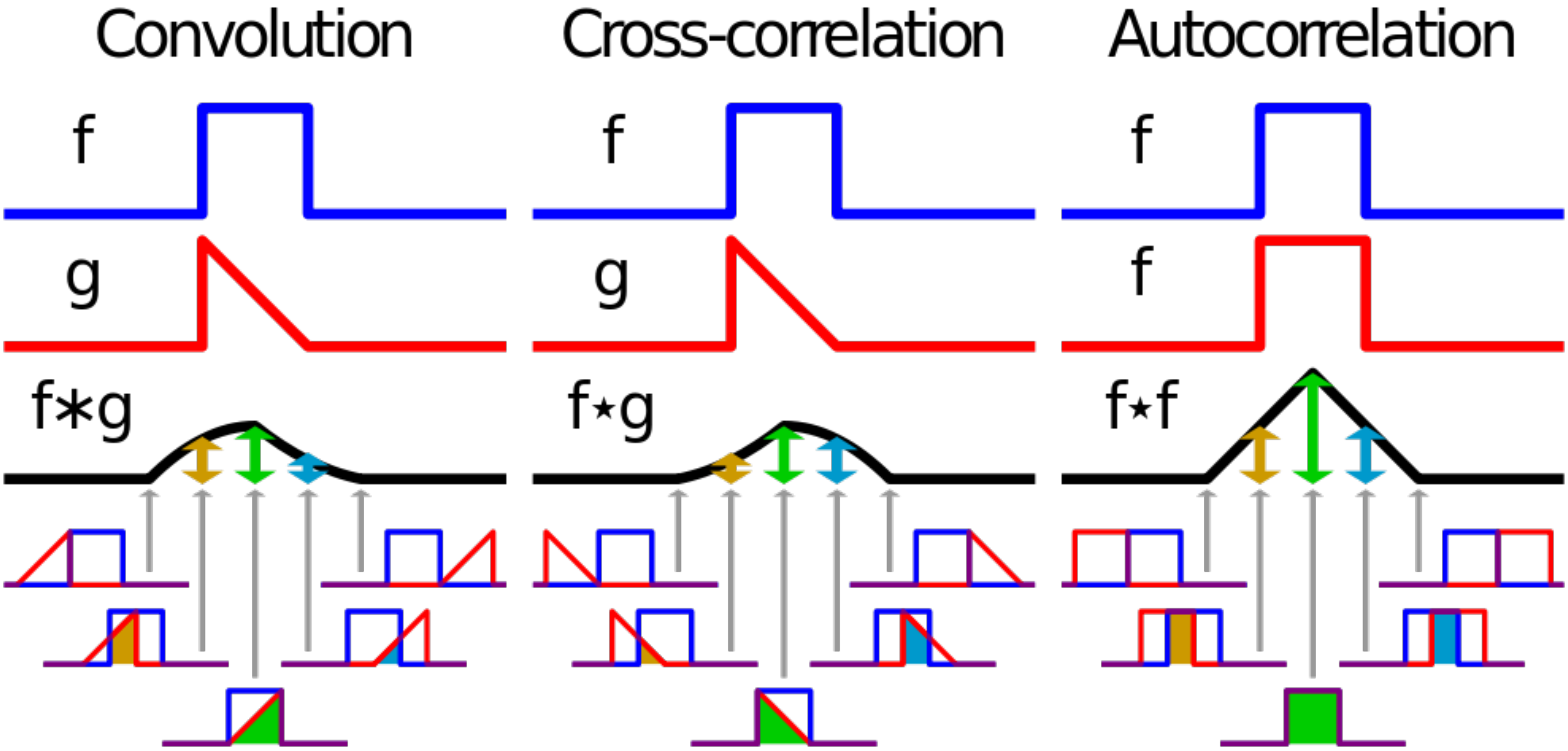
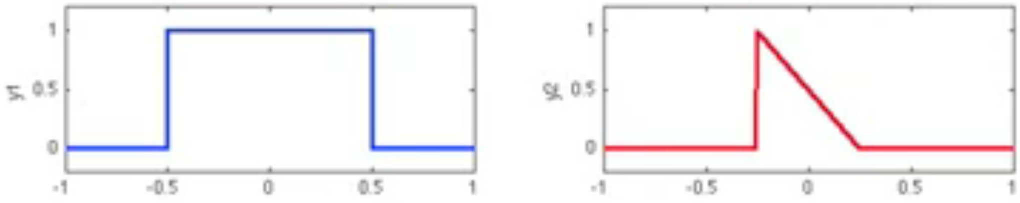


Auto-Correlation and Convolution Functions

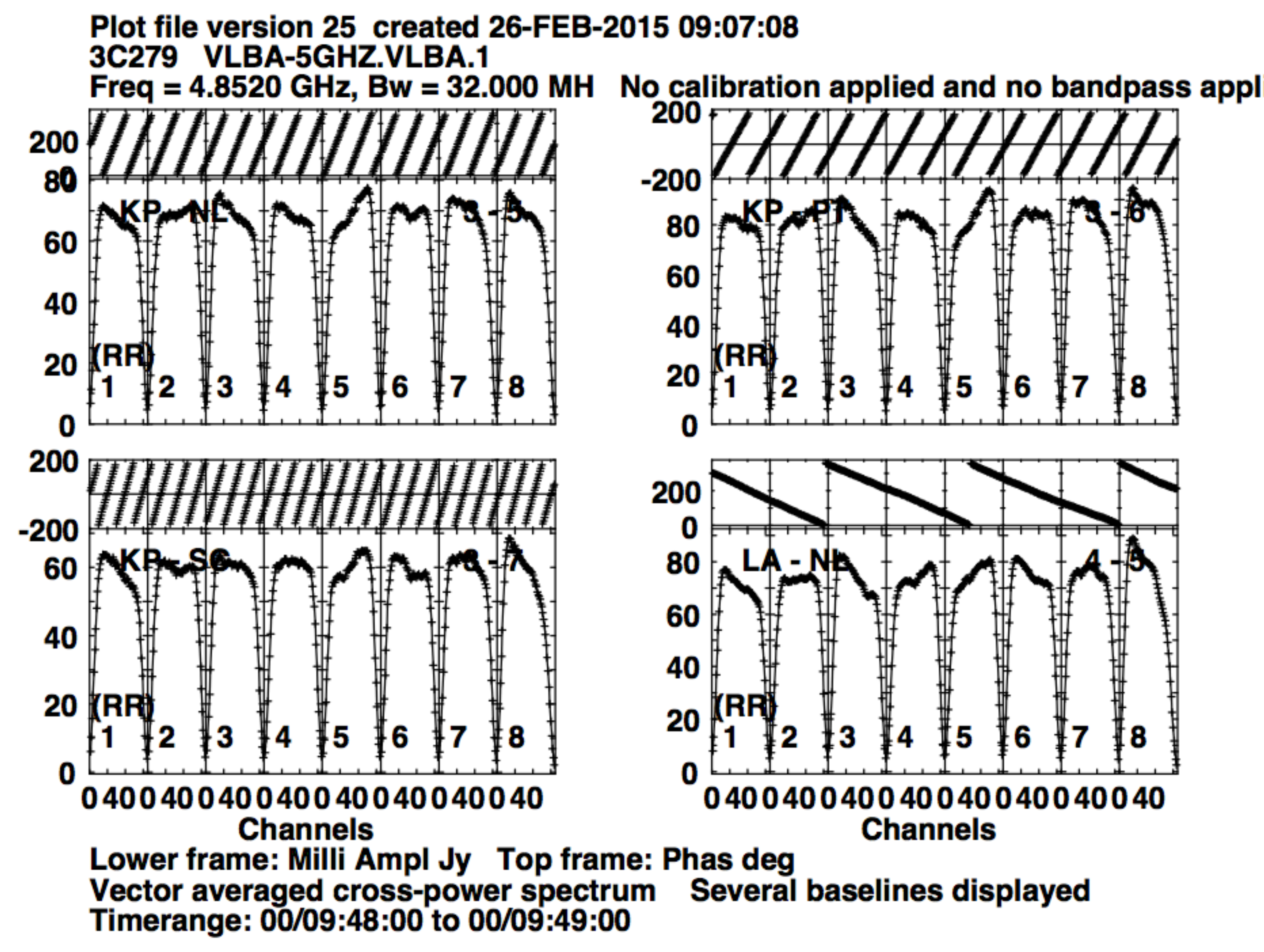


Auto-Correlation and Convolution Functions



Fringe Fitting

2015
ASTR423
VLBA
obs
3C279



Plot file version 25 created 26-FEB-2015 09:07:08
3C279   VLBA-5GHZ.VLBA.1
Freq = 4.8520 GHz, Bw = 32.000 MH   No calibration applied and no bandpass appl

Lower frame: Milli Ampl Jy   Top frame: Phas deg
Vector averaged cross-power spectrum   Several baselines displayed
Timerange: 00/09:48:00 to 00/09:49:00

Announcements

- HW4 – 12 received, 1 MIA
- VLA observing done!
- LWA observing ?
- Exam 1 on Wednesday, March 3
- Constants posted
- Review problem 3-1
- Send me your choices

G. Taylor, Astr 423 at UNM

Outline

- Why calibrate and edit?
- How to calibrate
- What to Edit
- Practical Calibration Planning
- Calibration Evaluation
- A Dictionary of Calibration Components
- More on editing and RFI
- Summary

This lecture is complementary to Chapter 5 of ASP 180 and is based on a lecture by George Moellenbrock

Why Calibration and Editing?

- Synthesis radio telescopes, though well-designed, are not perfect (e.g., surface accuracy, receiver noise, polarization purity, stability, etc.)
- Need to accommodate engineering (e.g., frequency conversion, digital electronics, etc.)
- Hardware or control software occasionally fails or behaves unpredictably
- Scheduling/observation errors sometimes occur (e.g., wrong source positions)
- Atmospheric conditions not ideal (not limited to “bad” weather)
- Radio Frequency Interference (RFI)

Determining *instrumental properties* (calibration)
is as important as
determining *radio source properties*

From Idealistic to Realistic

- Formally, we wish to obtain the visibility function, which we intend to invert to obtain an image of the sky:

$$V(u,v) = \int_{sky} I(l,m) e^{-i2\pi(ul+vm)} dl\ dm$$

- In practice, we correlate (multiply & average) the electric field (voltage) samples, x_i & x_j, received at pairs of telescopes (i,j)
  - Averaging duration is set by the expected timescales for variation of the correlation result (typically 10s or less for the VLA)
- Single radio telescopes are devices for collecting the signal $x_i(t)$ and providing it to the correlator.

What signal is really collected?

- The net signal delivered by antenna *i*, $x_i(t)$, is a combination of the desired signal, $s_i(t,l,m)$, corrupted by a factor $J_i(t,l,m)$ and integrated over the sky, and noise, $n_i(t)$:

$$x_i(t) = \int_{sky} J_i(t,l,m) s_i(t,l,m)\ dldm + n_i(t)$$

$$= s_i'(t) + n_i(t)$$

- $J_i(t,l,m)$ is the product of a host of effects which we must *calibrate*
- In some cases, effects implicit in the $J_i(t,l,m)$ term corrupt the signal irreversibly and the resulting data must be *edited*
- $J_i(t,l,m)$ is a complex number
- $J_i(t,l,m)$ is *antenna-based*
- Usually, $|n_i| >> |s_i|$

The Measurement Equation

- We can now write down the calibration situation in a general way - the Measurement Equation:

$$\vec{V}_{ij}^{obs} = \int_{sky} \left(\overleftrightarrow{J}_i \otimes \overleftrightarrow{J}_j^{*}\right) \vec{I}\left(l,m\right) e^{-i2\pi\left(u_{ij}l+v_{ij}m\right)} dldm$$

- …and consider how to solve it!

The Measurement Equation - Simplified

$$\vec{V}_{ij}^{obs} = \int_{sky} \left(\overleftrightarrow{J}_i \otimes \overleftrightarrow{J}_j^{*}\right) \vec{I}\left(l,m\right) e^{-i2\pi\left(u_{ij}l+v_{ij}m\right)} dldm$$

- First, isolate non-direction-dependent effects, and factor them from the integral:

$$= \left(\overleftrightarrow{J}_i^{vis} \otimes \overleftrightarrow{J}_j^{vis*}\right) \int_{sky} \left(\overleftrightarrow{J}_i^{sky} \otimes \overleftrightarrow{J}_j^{sky*}\right) \vec{I}\left(l,m\right) e^{-i2\pi\left(u_{ij}l+v_{ij}m\right)} dldm$$

- Next, we recognize that it is often possible to assume $J^{sky}=1$, and we have a relationship between ideal and observed Visibilities:

$$= \left(\overleftrightarrow{J}_i^{vis} \otimes \overleftrightarrow{J}_j^{vis*}\right) \int_{sky} \vec{I}\left(l,m\right) e^{-i2\pi\left(u_{ij}l+v_{ij}m\right)} dldm$$

$$\vec{V}_{ij}^{obs} = \left(\overleftrightarrow{J}_i^{vis} \otimes \overleftrightarrow{J}_j^{vis*}\right) \vec{V}_{ij}^{ideal}$$

Solving the Measurement Equation

- The *J* terms can be factored into a series of components representing physical elements along the signal path:

$$\vec{V}_{ij}^{obs} = \left(\overleftrightarrow{J}_i^{1} \otimes \overleftrightarrow{J}_j^{1*}\right)\left(\overleftrightarrow{J}_i^{2} \otimes \overleftrightarrow{J}_j^{2*}\right)\left(\overleftrightarrow{J}_i^{3} \otimes \overleftrightarrow{J}_j^{3*}\right)\left(\overleftrightarrow{J}_i^{\dots} \otimes \overleftrightarrow{J}_j^{\dots *}\right)\vec{V}_{ij}^{ideal}$$

- Depending upon availability of estimates for various *J* terms, we can re-arrange the equation and solve for any single term, if we know V^{ideal}:

$$\left[\left(\overleftrightarrow{J}_i^{2} \otimes \overleftrightarrow{J}_j^{2*}\right)^{-1}\left(\overleftrightarrow{J}_i^{1} \otimes \overleftrightarrow{J}_j^{1*}\right)^{-1}\vec{V}_{ij}^{obs}\right] = \left(\overleftrightarrow{J}_i^{solve} \otimes \overleftrightarrow{J}_j^{solve*}\right)\left[\left(\overleftrightarrow{J}_i^{4} \otimes \overleftrightarrow{J}_j^{4*}\right)\left(\overleftrightarrow{J}_i^{\dots} \otimes \overleftrightarrow{J}_j^{\dots *}\right)\vec{V}_{ij}^{ideal}\right]$$

- After obtaining estimates for all relevant *J,* data can be corrected:

$$\vec{V}_{ij}^{corrected} = \left(\overleftrightarrow{J}_i^{\dots} \otimes \overleftrightarrow{J}_j^{\dots *}\right)^{-1}\left(\overleftrightarrow{J}_i^{3} \otimes \overleftrightarrow{J}_j^{3*}\right)^{-1}\left(\overleftrightarrow{J}_i^{2} \otimes \overleftrightarrow{J}_j^{2*}\right)^{-1}\left(\overleftrightarrow{J}_i^{1} \otimes \overleftrightarrow{J}_j^{1*}\right)^{-1}\vec{V}_{ij}^{obs}$$

Solving the Measurement Equation

- Formally, solving for any calibration component is always the same non-linear fitting problem:

$$\vec{V}_{ij}^{\,corrected\cdot obs} = \left(\overleftrightarrow{J}_i^{\,solve} \otimes \overleftrightarrow{J}_j^{\,solve*}\right)\vec{V}_{ij}^{\,corrupted\cdot ideal}$$

  - Algebraic particulars are stored safely and conveniently inside the matrix formalism (out of sight, out of mind!)
  - Viability of the solution depends on the underlying algebra (hardwired in calibration applications) and relies on *proper calibration observations*

Antenna-based Calibration

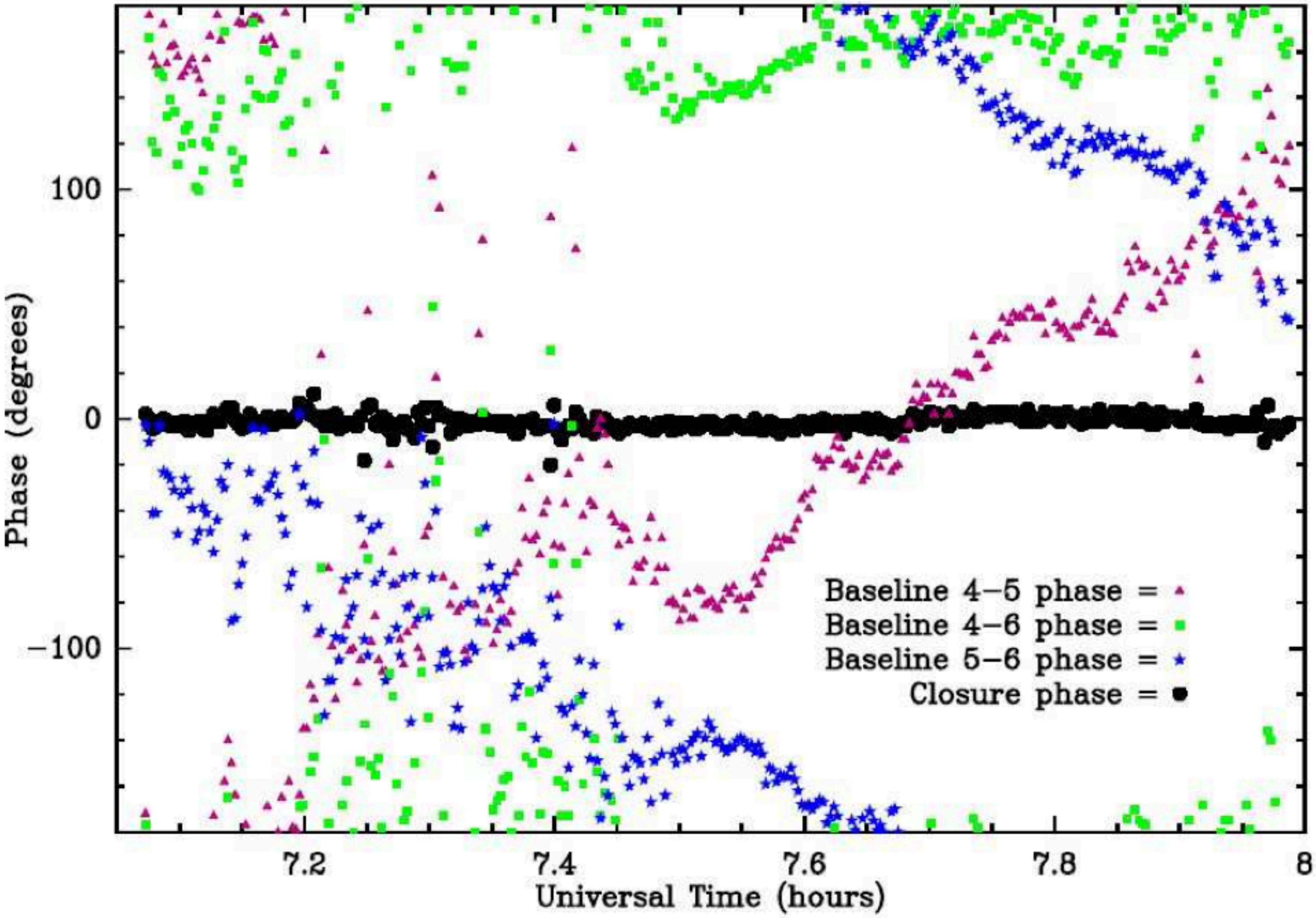
- Success of synthesis telescopes relies on antenna-based calibration
  - N antenna-based factors, N(N-1) visibility measurements
  - Fundamentally, only information that cannot be factored into antenna-based terms is believable as being of astronomical origin
- Closure: calibration-independent observables:
  - Closure phase (3 baselines):

$$\phi_{ij}^{obs} + \phi_{jk}^{obs} + \phi_{ki}^{obs} = \phi_{ij}^{real} + \left(\theta_i - \theta_j\right) + \phi_{jk}^{real} + \left(\theta_j - \theta_k\right) + \phi_{ki}^{real} + \left(\theta_k - \theta_i\right)$$
$$= \phi_{ij}^{real} + \phi_{jk}^{real} + \phi_{ki}^{real}$$

  - Closure amplitude (4 baselines):

$$\left|\frac{V_{ij}^{obs} V_{kl}^{obs}}{V_{ik}^{obs} V_{jl}^{obs}}\right| = \left|\frac{J_i J_j V_{ij}^{real} J_k J_l V_{kl}^{real}}{J_i J_k V_{ik}^{real} J_j J_l V_{jl}^{real}}\right|$$
$$= \left|\frac{V_{ij}^{real} V_{kl}^{real}}{V_{ik}^{real} V_{jl}^{real}}\right|$$

Antenna-based Calibration



Planning for Good Calibration

- A priori calibrations (provided by the observatory)
    - Antenna positions, earth orientation and rate
    - Clocks
    - Antenna pointing, gain, voltage pattern
    - Calibrator coordinates, flux densities, polarization properties
- Absolute flux calibration
    - True calibration very difficult, requires great effort
    - Substitute is to reference to a source of known flux (e.g., 3C286)
- Cross-calibration
    - Observe nearby point sources against which calibration components can be solved, and transfer solutions to target observations
    - Choose appropriate calibrators for different components; usually strong point sources because we can predict their visibilities
    - Choose appropriate timescales for each component
- Simple (common) example, Gain and Bandpass:

$$\begin{aligned}\vec{V}_{ij}^{obs} &= \left(\overleftrightarrow{B}_i \otimes \overleftrightarrow{B}_j^{*}\right)\left(\overleftrightarrow{G}_i \otimes \overleftrightarrow{G}_j^{*}\right)\vec{V}_{ij}^{ideal} \\ &= \overleftrightarrow{B}_{ij}\overleftrightarrow{G}_{ij}\vec{V}_{ij}^{ideal}\end{aligned}$$

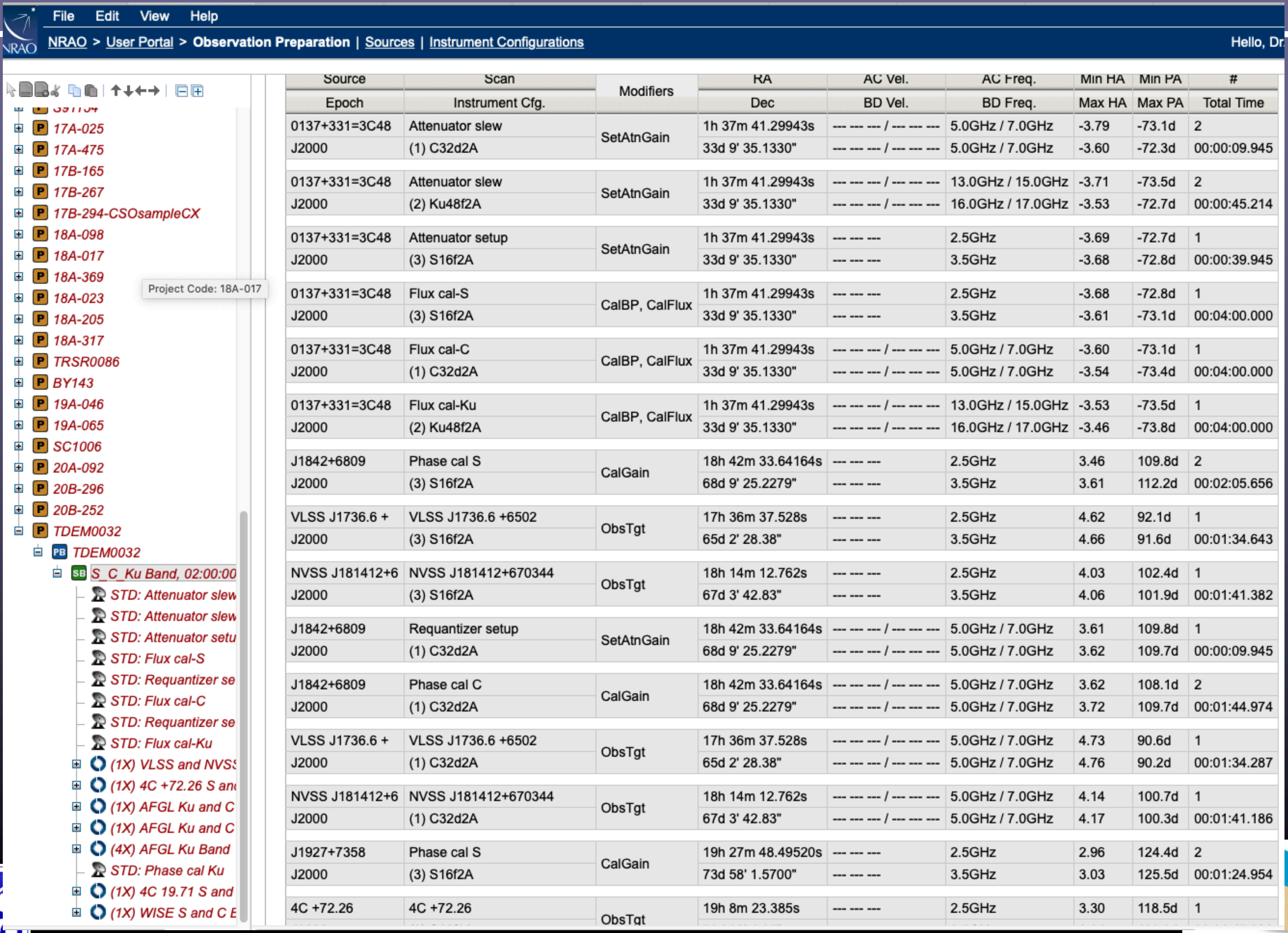
"Electronic" Gain, *G*

- Catch-all for most amplitude and phase effects introduced by antenna electronics (amplifiers, mixers, quantizers, digitizers)
    - Most commonly treated calibration component
    - Dominates other effects for standard VLA observations
    - Includes scaling from engineering (correlation coefficient) to radio astronomy units (Jy), by scaling solution amplitudes according to observations of a flux density calibrator
    - Often also includes ionospheric and tropospheric effects which are typically difficult to separate unto themselves

Bandpass Response, *B*

- *G*-like component describing frequency-dependence of antenna electronics, etc.
  - Filters used to select frequency passband not square
  - Optical and electronic reflections introduce ripples across band
  - Often assumed time-independent, but not necessarily so
  - Typically (but not necessarily) normalized

Typical VLA observation



NRAO > User Portal > **Observation Preparation** | Sources | Instrument Configurations

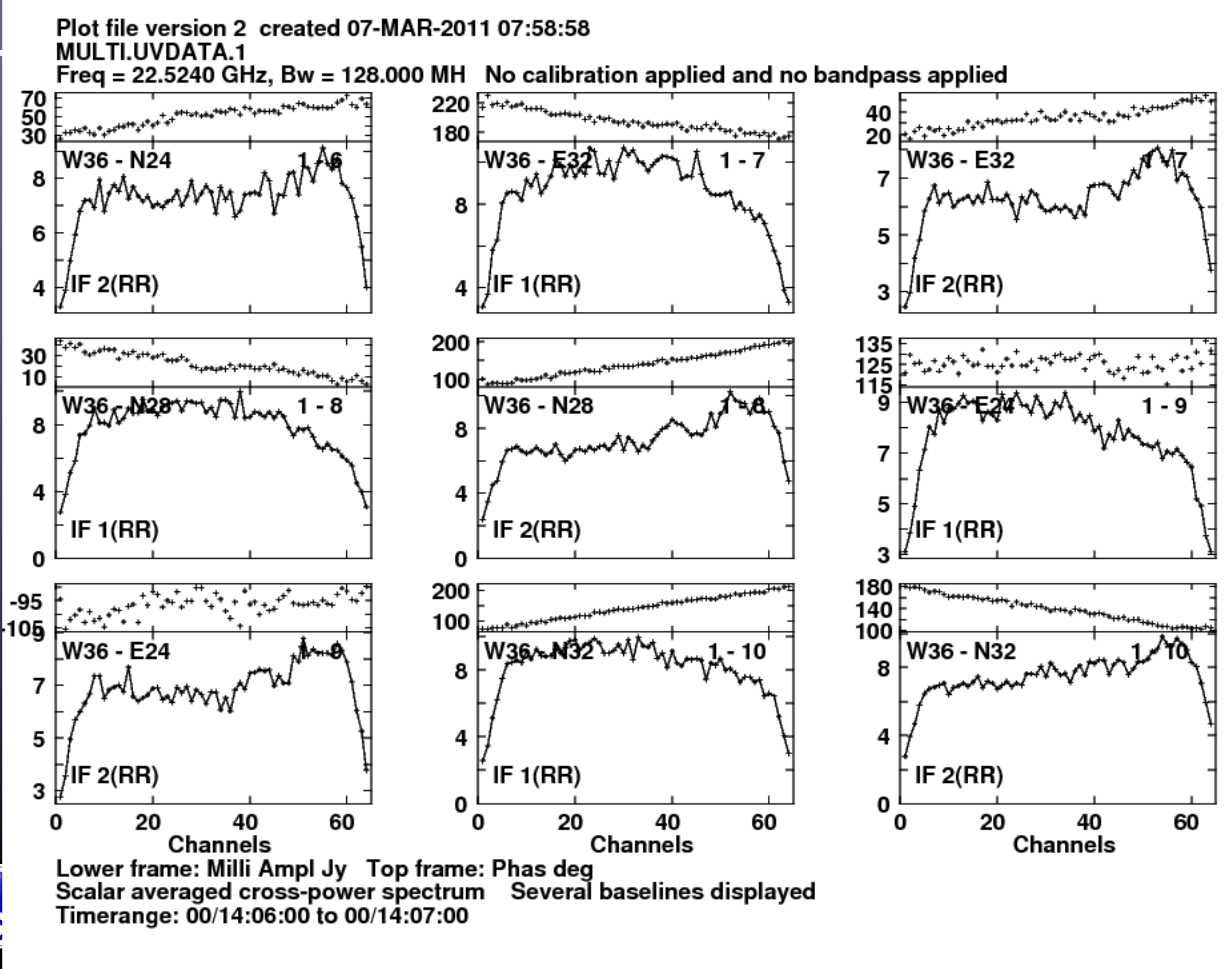
Hello, Dr

- 17A-025
- 17A-475
- 17B-165
- 17B-267
- 17B-294-CSOsampleCX
- 18A-098
- 18A-017
- 18A-369
- 18A-023
- 18A-205
- 18A-317
- TRSR0086
- BY143
- 19A-046
- 19A-065
- SC1006
- 20A-092
- 20B-296
- 20B-252
- TDEM0032
  - TDEM0032
    - S_C_Ku Band, 02:00:00
      - STD: Attenuator slew
      - STD: Attenuator slew
      - STD: Attenuator setu
      - STD: Flux cal-S
      - STD: Requantizer se
      - STD: Flux cal-C
      - STD: Requantizer se
      - STD: Flux cal-Ku
      - (1X) VLSS and NVS
      - (1X) 4C +72.26 S an
      - (1X) AFGL Ku and C
      - (1X) AFGL Ku and C
      - (4X) AFGL Ku Band
      - STD: Phase cal Ku
      - (1X) 4C 19.71 S and
      - (1X) WISE S and C E

Project Code: 18A-017

Source	Scan	Modifiers	RA	AC Vel.	AC Freq.	Min HA	Min PA	#
Epoch	Instrument Cfg.		Dec	BD Vel.	BD Freq.	Max HA	Max PA	Total Time
0137+331=3C48	Attenuator slew	SetAtnGain	1h 37m 41.29943s	--- --- --- / --- --- ---	5.0GHz / 7.0GHz	-3.79	-73.1d	2
J2000	(1) C32d2A		33d 9' 35.1330"	--- --- --- / --- --- ---	5.0GHz / 7.0GHz	-3.60	-72.3d	00:00:09.945
0137+331=3C48	Attenuator slew	SetAtnGain	1h 37m 41.29943s	--- --- --- / --- --- ---	13.0GHz / 15.0GHz	-3.71	-73.5d	2
J2000	(2) Ku48f2A		33d 9' 35.1330"	--- --- --- / --- --- ---	16.0GHz / 17.0GHz	-3.53	-72.7d	00:00:45.214
0137+331=3C48	Attenuator setup	SetAtnGain	1h 37m 41.29943s	--- --- ---	2.5GHz	-3.69	-72.7d	1
J2000	(3) S16f2A		33d 9' 35.1330"	--- --- ---	3.5GHz	-3.68	-72.8d	00:00:39.945
0137+331=3C48	Flux cal-S	CalBP, CalFlux	1h 37m 41.29943s	--- --- ---	2.5GHz	-3.68	-72.8d	1
J2000	(3) S16f2A		33d 9' 35.1330"	--- --- ---	3.5GHz	-3.61	-73.1d	00:04:00.000
0137+331=3C48	Flux cal-C	CalBP, CalFlux	1h 37m 41.29943s	--- --- --- / --- --- ---	5.0GHz / 7.0GHz	-3.60	-73.1d	1
J2000	(1) C32d2A		33d 9' 35.1330"	--- --- --- / --- --- ---	5.0GHz / 7.0GHz	-3.54	-73.4d	00:04:00.000
0137+331=3C48	Flux cal-Ku	CalBP, CalFlux	1h 37m 41.29943s	--- --- --- / --- --- ---	13.0GHz / 15.0GHz	-3.53	-73.5d	1
J2000	(2) Ku48f2A		33d 9' 35.1330"	--- --- --- / --- --- ---	16.0GHz / 17.0GHz	-3.46	-73.8d	00:04:00.000
J1842+6809	Phase cal S	CalGain	18h 42m 33.64164s	--- --- ---	2.5GHz	3.46	109.8d	2
J2000	(3) S16f2A		68d 9' 25.2279"	--- --- ---	3.5GHz	3.61	112.2d	00:02:05.656
VLSS J1736.6 +	VLSS J1736.6 +6502	ObsTgt	17h 36m 37.528s	--- --- ---	2.5GHz	4.62	92.1d	1
J2000	(3) S16f2A		65d 2' 28.38"	--- --- ---	3.5GHz	4.66	91.6d	00:01:34.643
NVSS J181412+6	NVSS J181412+670344	ObsTgt	18h 14m 12.762s	--- --- ---	2.5GHz	4.03	102.4d	1
J2000	(3) S16f2A		67d 3' 42.83"	--- --- ---	3.5GHz	4.06	101.9d	00:01:41.382
J1842+6809	Requantizer setup	SetAtnGain	18h 42m 33.64164s	--- --- --- / --- --- ---	5.0GHz / 7.0GHz	3.61	109.8d	1
J2000	(1) C32d2A		68d 9' 25.2279"	--- --- --- / --- --- ---	5.0GHz / 7.0GHz	3.62	109.7d	00:00:09.945
J1842+6809	Phase cal C	CalGain	18h 42m 33.64164s	--- --- --- / --- --- ---	5.0GHz / 7.0GHz	3.62	108.1d	2
J2000	(1) C32d2A		68d 9' 25.2279"	--- --- --- / --- --- ---	5.0GHz / 7.0GHz	3.72	109.7d	00:01:44.974
VLSS J1736.6 +	VLSS J1736.6 +6502	ObsTgt	17h 36m 37.528s	--- --- --- / --- --- ---	5.0GHz / 7.0GHz	4.73	90.6d	1
J2000	(1) C32d2A		65d 2' 28.38"	--- --- --- / --- --- ---	5.0GHz / 7.0GHz	4.76	90.2d	00:01:34.287
NVSS J181412+6	NVSS J181412+670344	ObsTgt	18h 14m 12.762s	--- --- --- / --- --- ---	5.0GHz / 7.0GHz	4.14	100.7d	1
J2000	(1) C32d2A		67d 3' 42.83"	--- --- --- / --- --- ---	5.0GHz / 7.0GHz	4.17	100.3d	00:01:41.186
J1927+7358	Phase cal S	CalGain	19h 27m 48.49520s	--- --- ---	2.5GHz	2.96	124.4d	2
J2000	(3) S16f2A		73d 58' 1.5700"	--- --- ---	3.5GHz	3.03	125.5d	00:01:24.954
4C +72.26	4C +72.26	ObsTgt	19h 8m 23.385s	--- --- ---	2.5GHz	3.30	118.5d	1

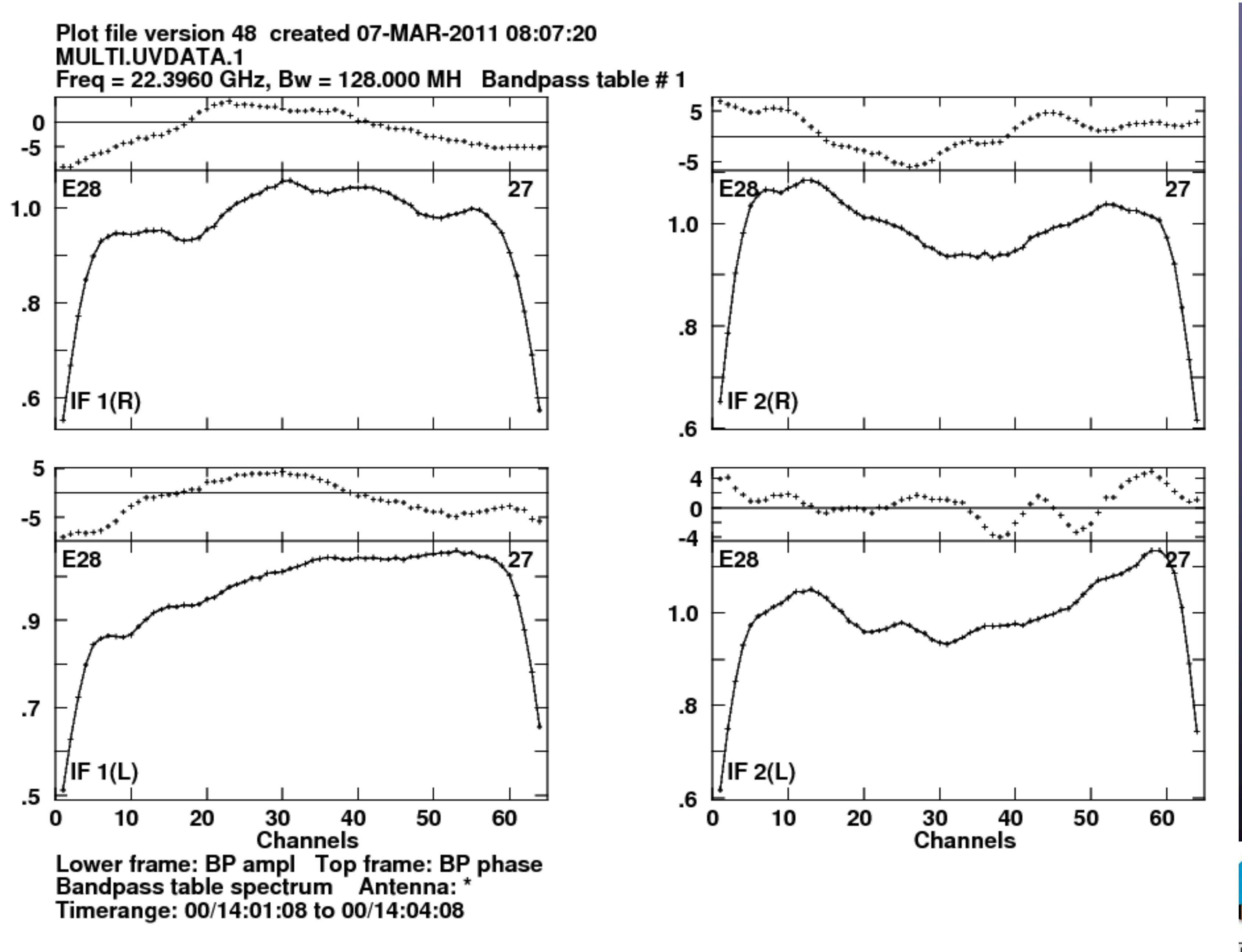
Uncalibrated spectra on 3C286



Plot file version 2 created 07-MAR-2011 07:58:58
MULTI.UVDATA.1
Freq = 22.5240 GHz, Bw = 128.000 MH No calibration applied and no bandpass applied

Lower frame: Milli Ampl Jy Top frame: Phas deg
Scalar averaged cross-power spectrum Several baselines displayed
Timerange: 00/14:06:00 to 00/14:07:00

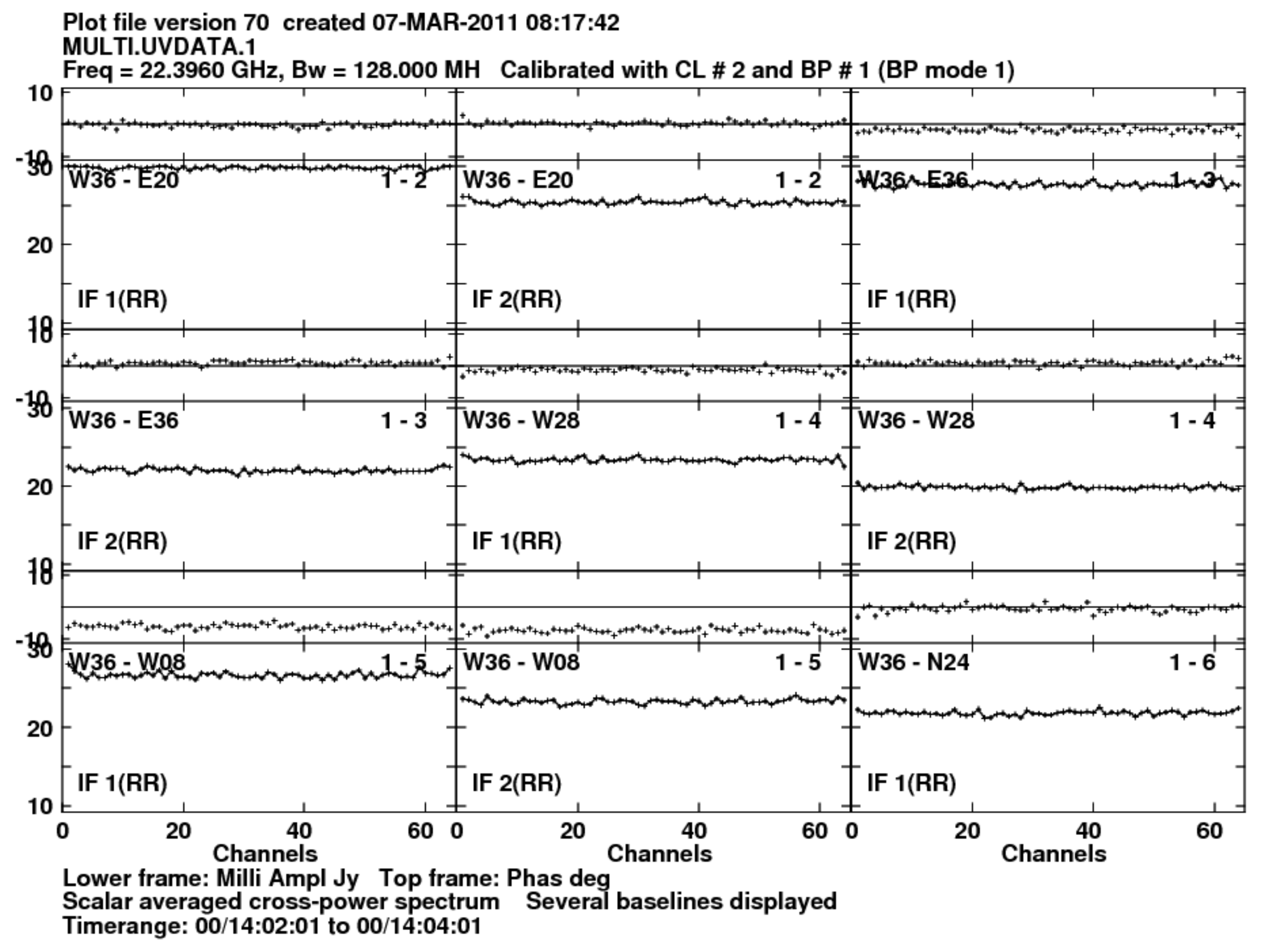
Bandpass solutions



Plot file version 48 created 07-MAR-2011 08:07:20
MULTI.UVDATA.1
Freq = 22.3960 GHz, Bw = 128.000 MH Bandpass table # 1

Lower frame: BP ampl Top frame: BP phase
Bandpass table spectrum Antenna: *
Timerange: 00/14:01:08 to 00/14:04:08

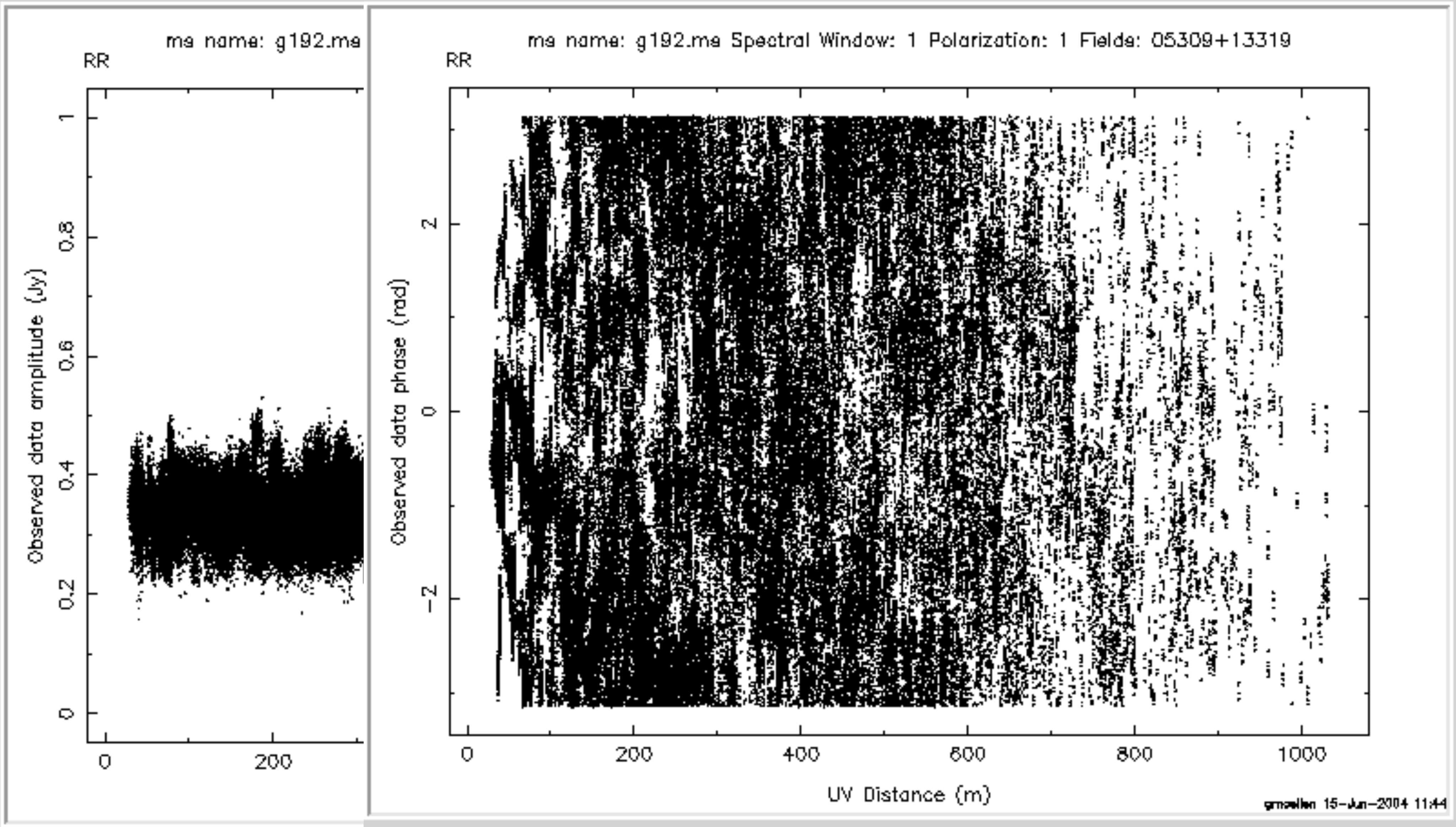
Spectra after Fringe-fit and bandpass calibration



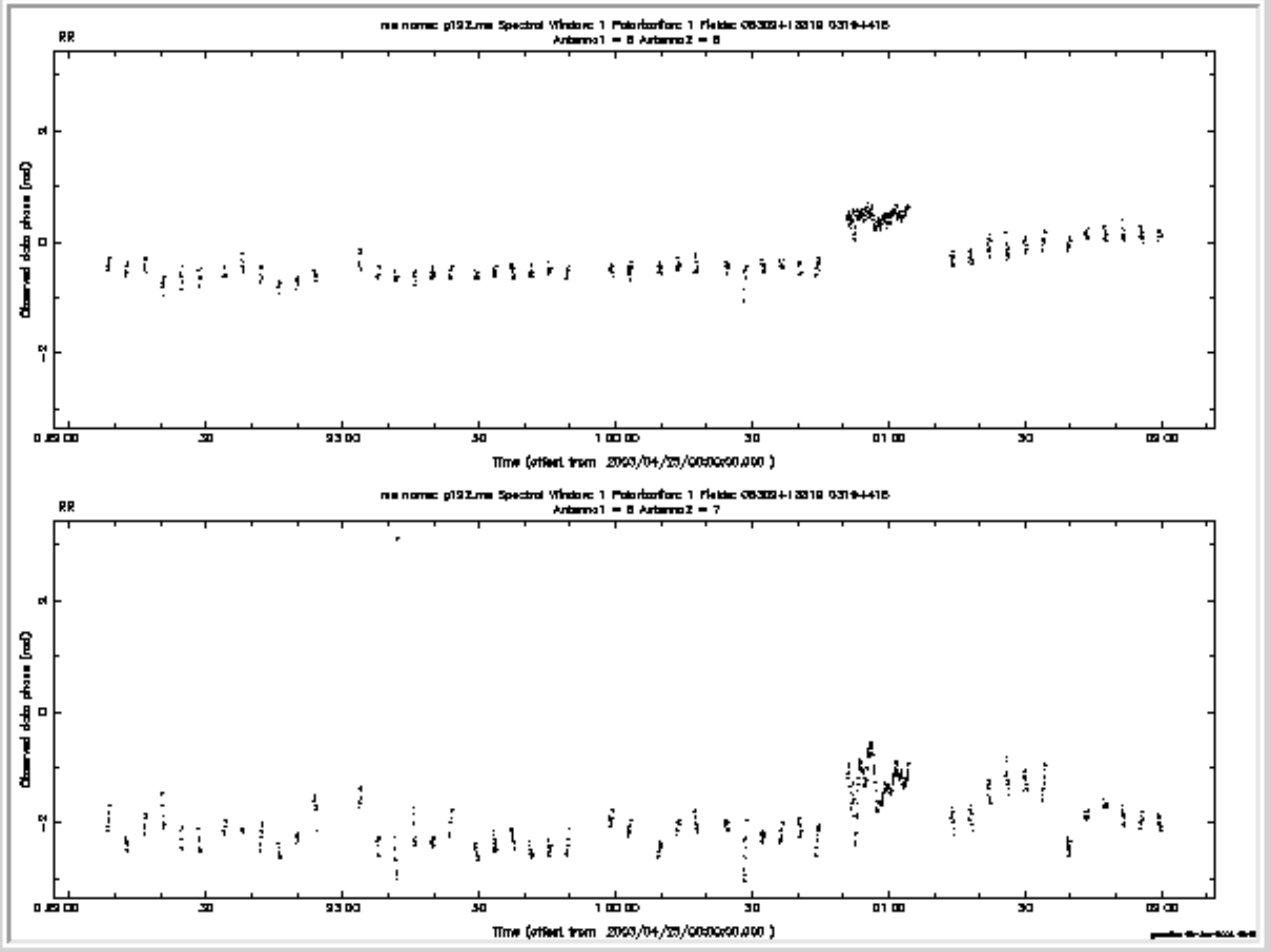
Plot file version 70 created 07-MAR-2011 08:17:42
MULTI.UVDATA.1
Freq = 22.3960 GHz, Bw = 128.000 MH Calibrated with CL # 2 and BP # 1 (BP mode 1)

Lower frame: Milli Ampl Jy Top frame: Phas deg
Scalar averaged cross-power spectrum Several baselines displayed
Timerange: 00/14:02:01 to 00/14:04:01

Observed Data vs. UV dist

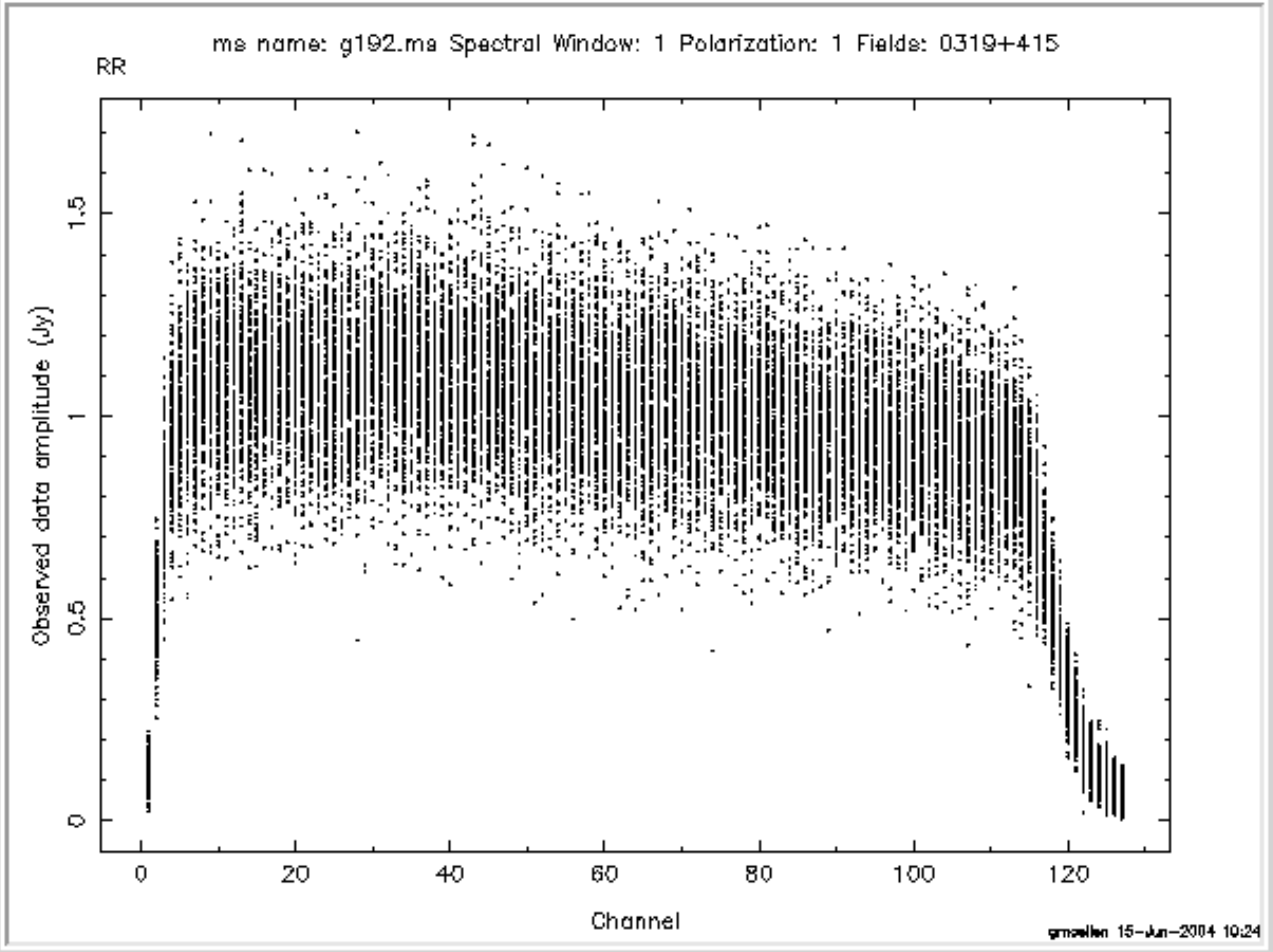


Observed Data – Phase vs. Time

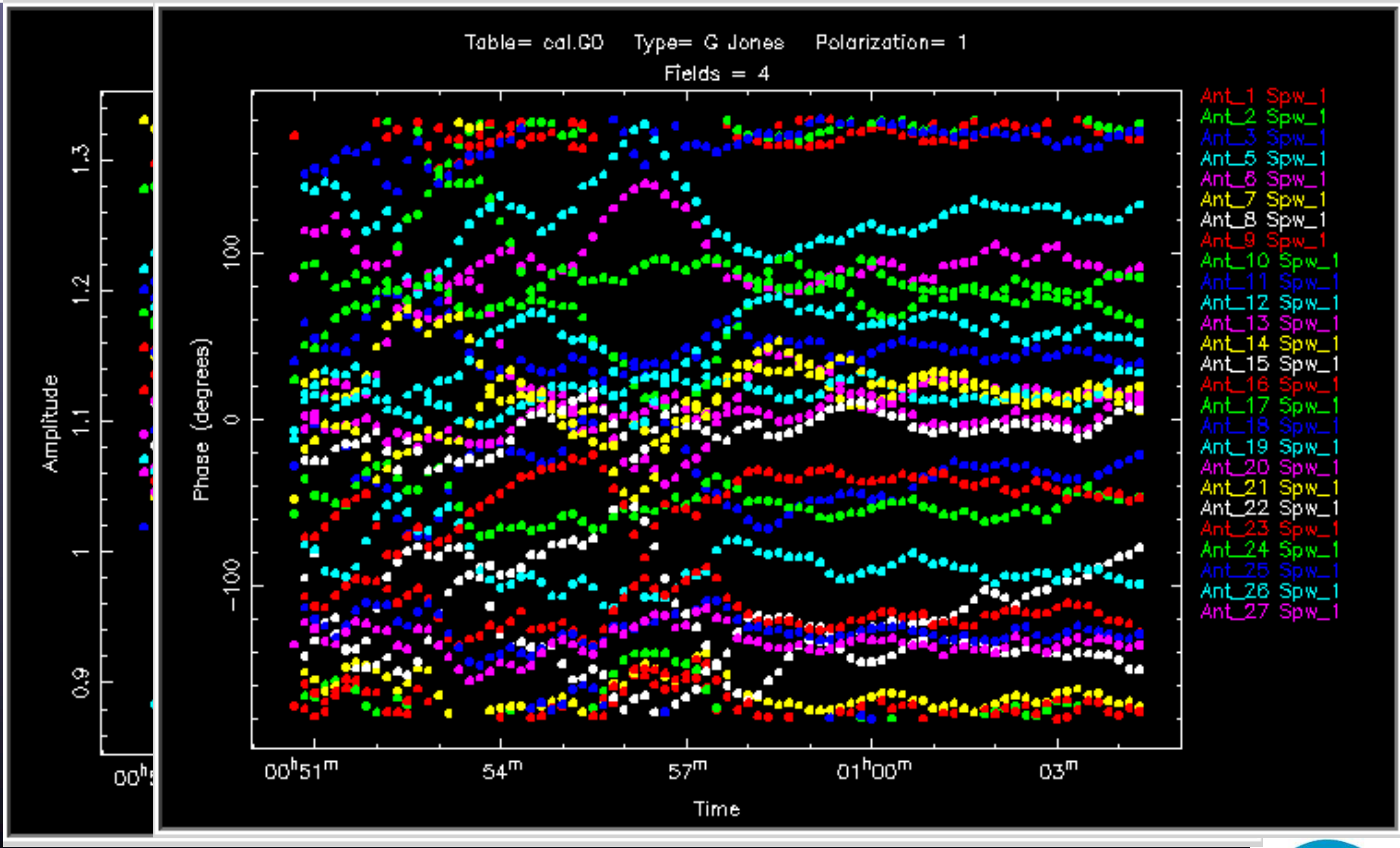


The University of New Mexico

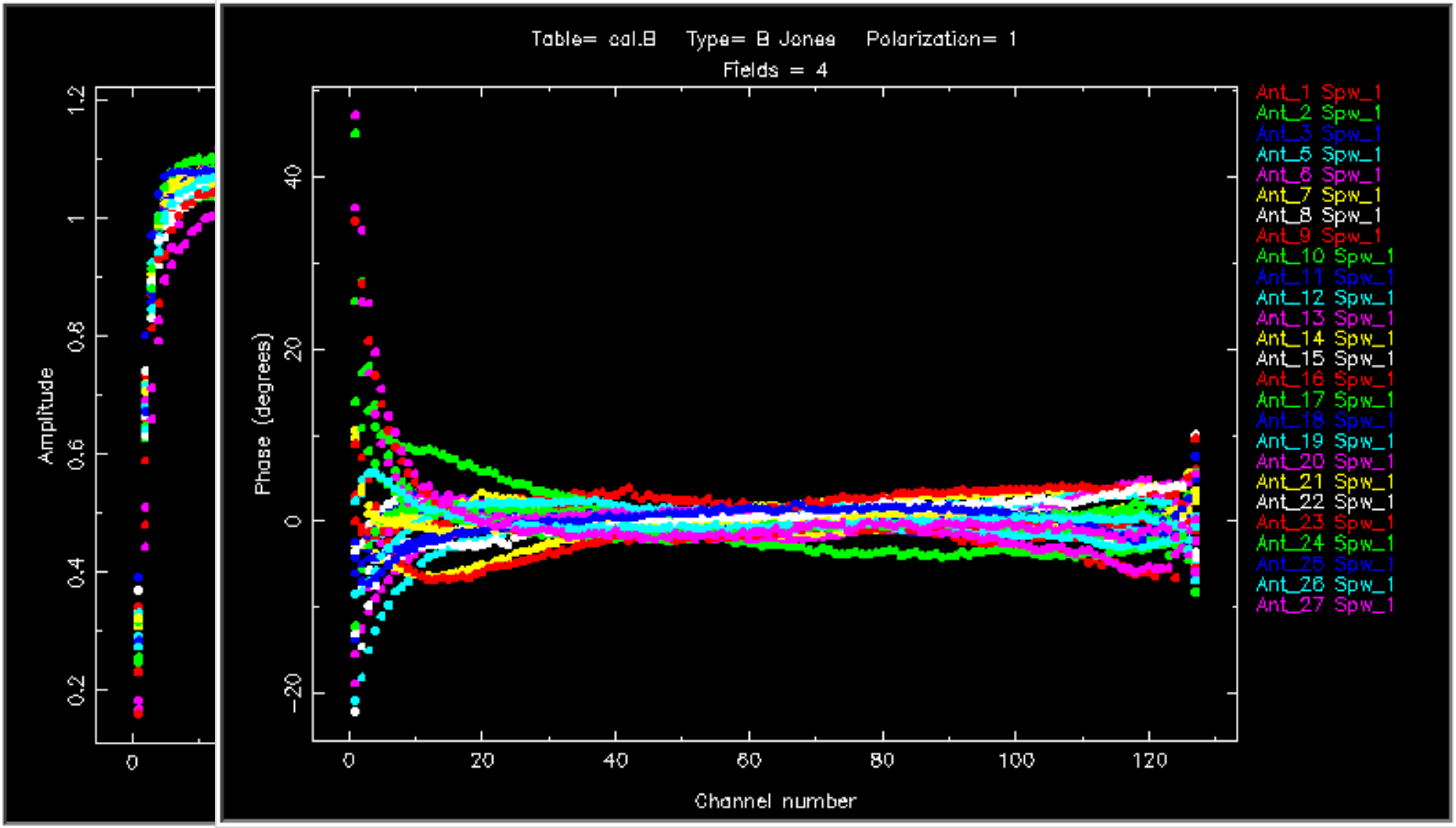
Observed Data – Amplitude Spectrum



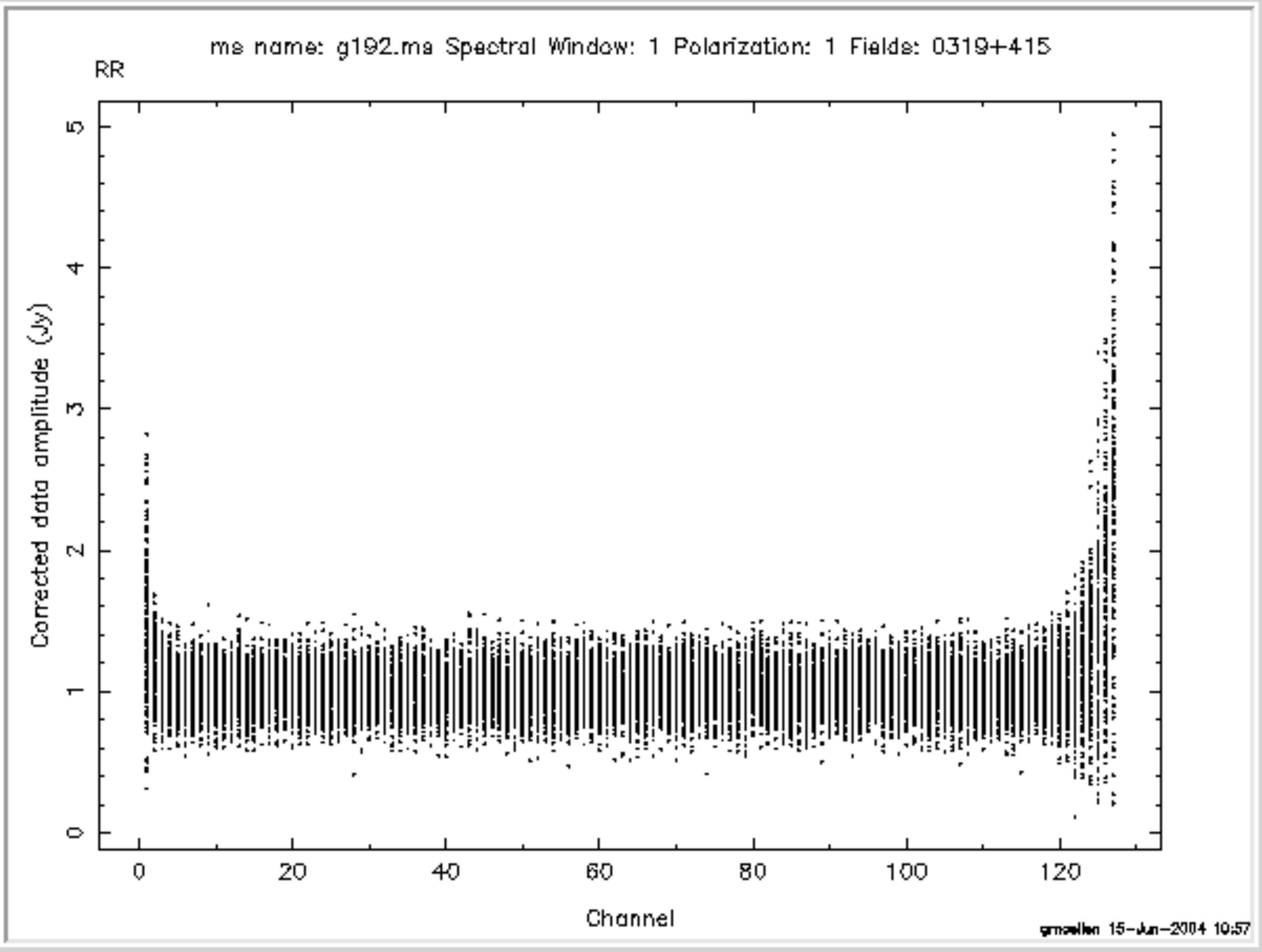
Gain Amp/Phase Solutions (B calibrator)



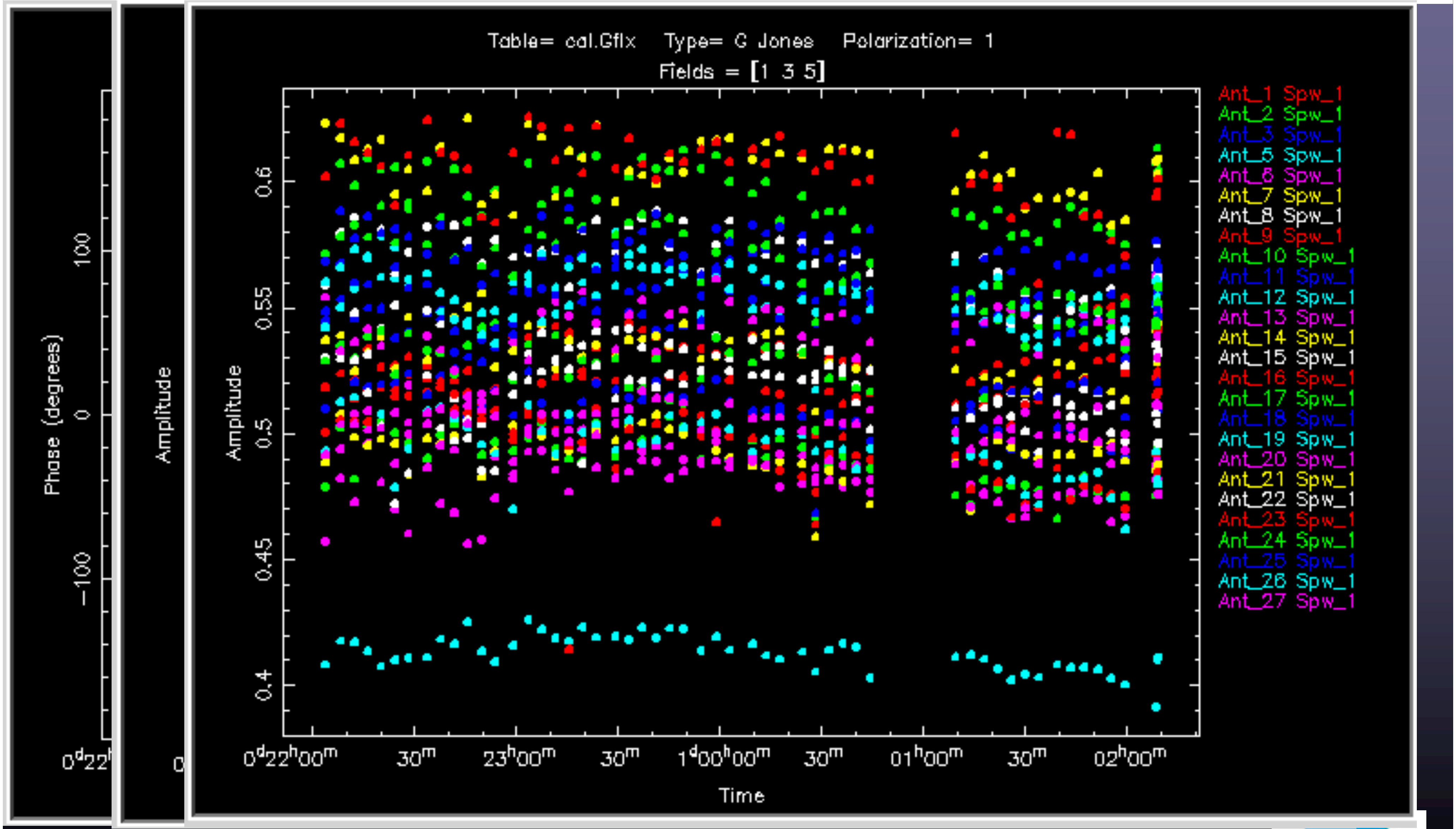
Bandpass Solutions



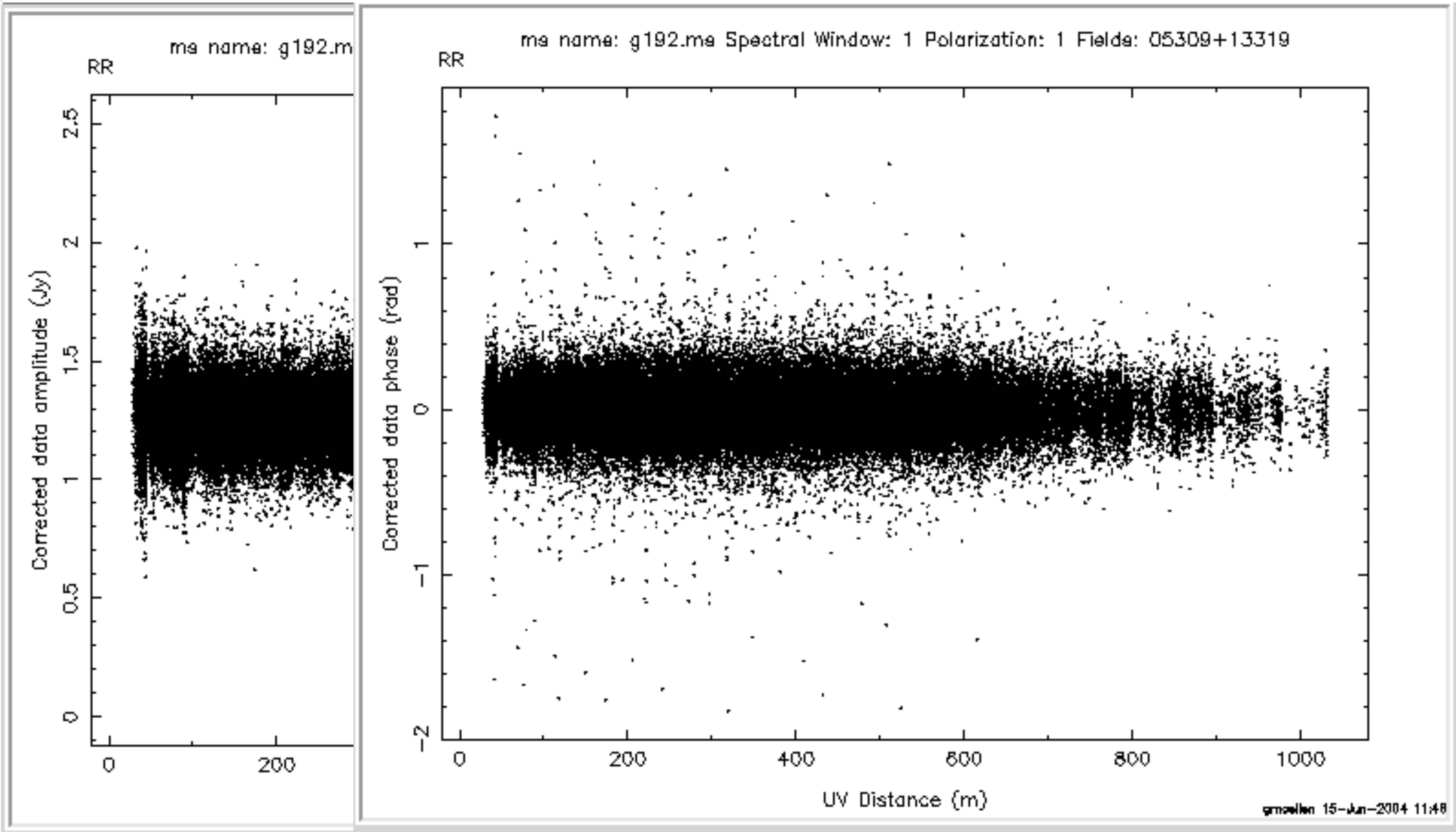
Bandpass-Calibrated Data (Amplitude)



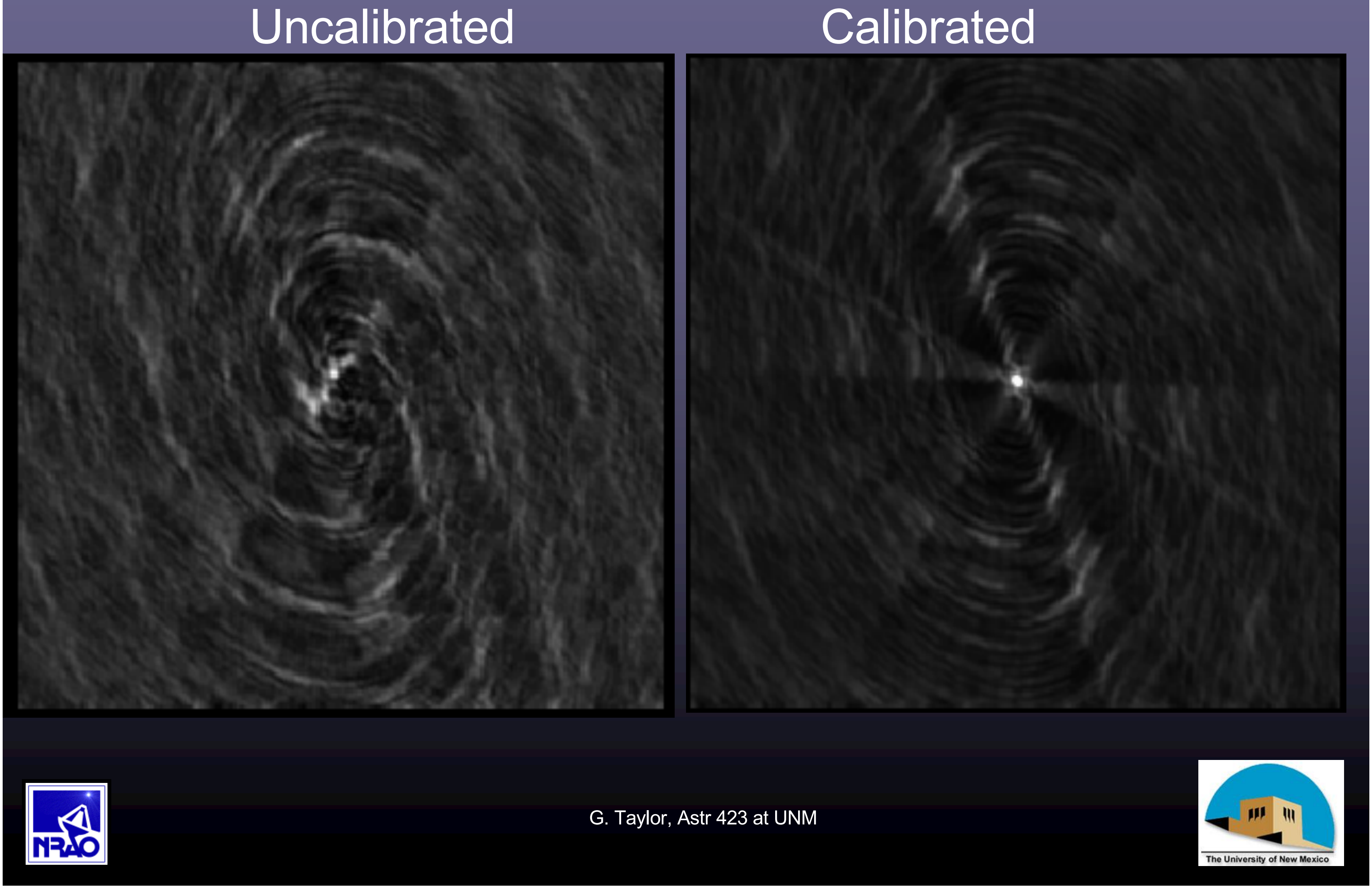
Gain Amp/Phase Solutions



Corrected Data vs. UV dist



Effect of Calibration in the Image Plane



Uncalibrated

Calibrated

A Dictionary of Calibration Components

- J_i contains many components:
    - F = ionospheric Faraday rotation
    - T = tropospheric effects
    - P = parallactic angle
    - E = antenna voltage pattern
    - D = polarization leakage
    - G = electronic gain
    - B = bandpass response
    - K = geometric compensation

$$\overset{\leftrightarrow}{J}_i = \overset{\leftrightarrow}{K}_i \overset{\leftrightarrow}{B}_i \overset{\leftrightarrow}{G}_i \overset{\leftrightarrow}{D}_i \overset{\leftrightarrow}{E}_i \overset{\leftrightarrow}{P}_i \overset{\leftrightarrow}{T}_i \overset{\leftrightarrow}{F}_i$$

- Order of terms follows signal path (right to left)
- Direction-dependent terms involve FT in solution

Tropospheric Effects, *T*

- The troposphere causes polarization-independent amplitude and phase effects due to emission/opacity and refraction, respectively
  - Typically 2-3m excess path length at zenith compared to vacuum
  - Higher noise contribution, less signal transmission: Lower SNR
  - Most important at $\nu > 15$ GHz where water vapor absorbs/emits
  - More important nearer horizon where tropospheric path length greater
  - Clouds, weather = variability in phase and opacity; may vary across array
  - Water vapor radiometry? Phase transfer from low to high frequencies?

Parallactic Angle, *P*

- Orientation of sky in telescope's field of view
  - Constant for equatorial telescopes
  - Varies for alt-az-mounted telescopes:

$$\chi(t) = \arctan\left(\frac{\cos(l)\sin(h(t))}{\sin(l)\cos(\delta) - \cos(l)\sin(\delta)\cos(h(t))} \right)$$

$$l = \text{latitude},\ \ h(t) = \text{hour angle},\ \ \delta = \ \text{declination}$$

  - Rotates the position angle of linearly polarized radiation
  - Analytically known, and its variation provides leverage for determining polarization-dependent effects

Antenna Voltage Pattern, *E*

- Antennas of all designs have direction-dependent gain
  - Important when region of interest on sky comparable to or larger than λ/D
  - Important at lower frequencies where radio source surface density is greater and wide-field imaging techniques required
  - Beam squint: E^p and E^q not parallel, yielding spurious polarization
  - For convenience, direction dependence of polarization leakage (*D*) may be included in *E* (off-diagonal terms then non-zero)

Polarization Leakage, *D*

- Polarizer is not ideal, so orthogonal polarizations not perfectly isolated
  - Well-designed feeds have *D* ~ a few percent or less
  - A geometric property of the feed design, so frequency dependent
  - For *R,L* systems, total-intensity imaging affected as ~*DQ, DU,* so only important at high dynamic range (*Q,U~D~few %*, typically)
  - For *R,L* systems, linear polarization imaging affected as ~*DI,* so almost always important

“Electronic” Gain, *G*

- Catch-all for most amplitude and phase effects introduced by antenna electronics (amplifiers, mixers, quantizers, digitizers)
    - Most commonly treated calibration component
    - Dominates other effects for standard VLA observations
    - Includes scaling from engineering (correlation coefficient) to radio astronomy units (Jy), by scaling solution amplitudes according to observations of a flux density calibrator
    - Often also includes ionospheric and tropospheric effects which are typically difficult to separate unto themselves
    - Excludes frequency dependent effects

Bandpass Response, *B*

- *G*-like component describing frequency-dependence of antenna electronics, etc.
    - Filters used to select frequency passband not square
    - Optical and electronic reflections introduce ripples across band
    - Often assumed time-independent, but not necessarily so
    - Typically (but not necessarily) normalized

Geometric Compensation, *K*

- Must get geometry right for Synthesis Fourier Transform relation to work in real time; residual errors here require “Fringe-fitting”
  - Antenna positions (geodesy)
  - Source directions (time-dependent in topocenter!) (astrometry)
  - Clocks
  - Electronic pathlengths
  - Importance scales with frequency and baseline length

Non-closing Effects:

- Correlator-based errors which do not decompose into antenna-based components
    - Most digital correlators designed to limit such effects to well-understood and uniform scaling laws (absorbed in *G*)
    - Additional errors can result from averaging in time and frequency over variation in antenna-based effects and visibilities (practical instruments are finite!)
    - RFI
    - Virtually indistinguishable from source structure effects
    - Geodetic observers consider determination of radio source structure—a baseline-based effect—as a required *calibration* if antenna positions are to be determined accurately

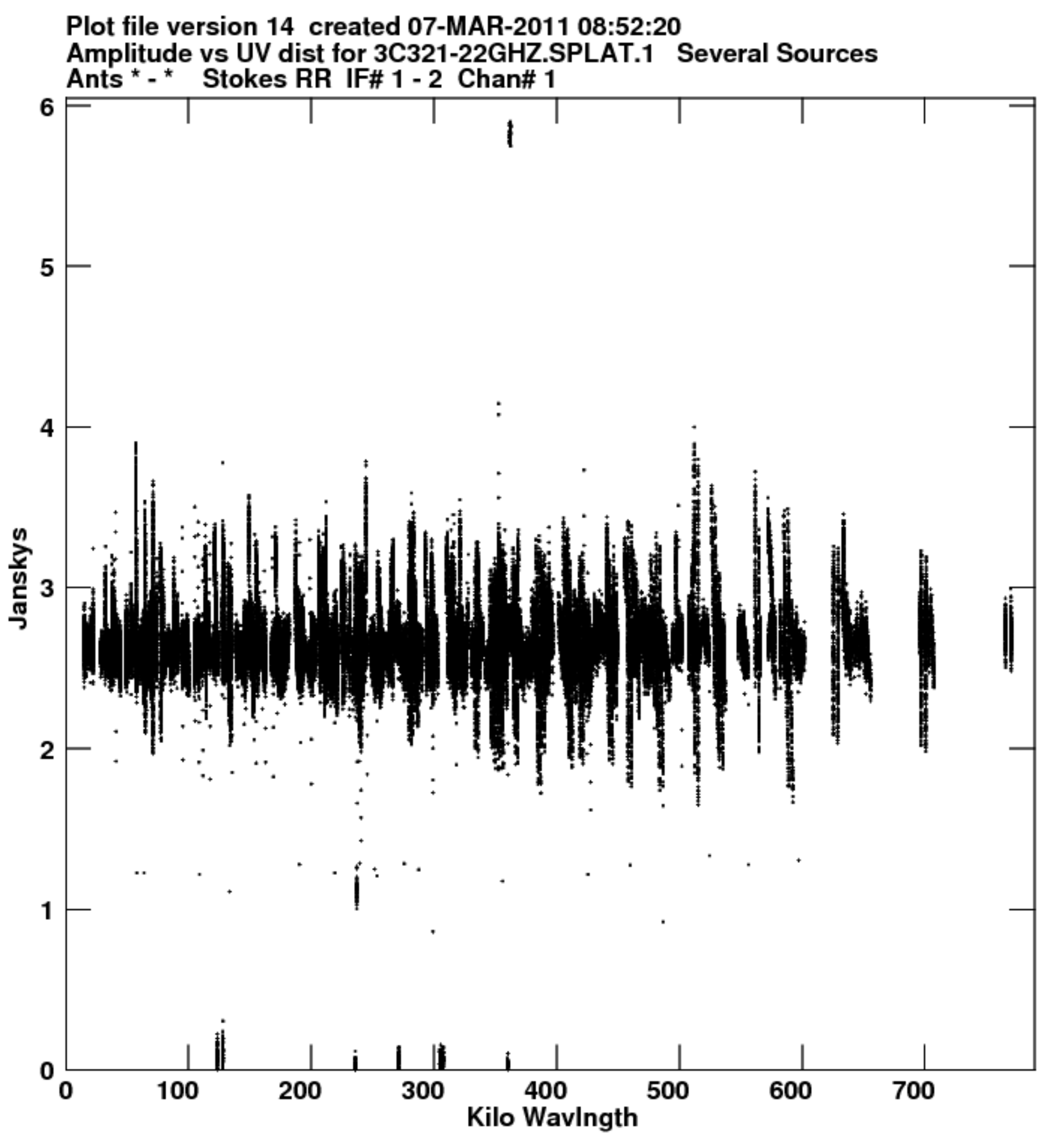
Calibrator Rules of Thumb

- *T, G, K:*
    - Strong and point-like sources, as near to target source as possible
    - Observe often enough to track phase and amplitude variations: calibration intervals of up to 10s of minutes at low frequencies (beware of ionosphere!), as short as 1 minute or less at high frequencies
    - Observe at least one calibrator of known flux density at least once
- *B:*
    - Strong enough for good sensitivity in each channel (often, *T, G* calibrator is ok), point-like if visibility might change across band
    - Observe often enough to track variations (e.g., waveguide reflections change with temperature and are thus a function of time-of-day)
- *D:*
    - Best calibrator for full calibration is strong and pointlike
    - If polarized, observe over a broad range of parallactic angle to disentangle *D*s and source polarization (often, *T, G* calibrator is ok)
- *F:*
    - Choose strongly polarized source and observe often enough to track variation

Data Examination and Editing

- After observation, initial data examination and editing very important
  - Will observations meet goals for calibration and science requirements?
  - Some real-time flagging occurred during observation (antennas off-source, LO out-of-lock, etc.). Any such bad data left over? (check operator's logs)
  - Any persistently 'dead' antennas ($J_i=0$ during otherwise normal observing)? (look at data on strong calibrators)
  - Amplitude and phase should be continuously varying—edit outliers
  - Any antennas shadowing others? Edit such data.
  - Be conservative: those antennas/timeranges which are bad on calibrators are probably bad on weak target sources—edit them
  - Periods of poor weather? (check operator's log)
  - Distinguish between bad (hopeless) data and poorly-calibrated data. E.g., some antennas may have significantly different amplitude response which may not be fatal—it may only need to be calibrated
  - Radio Frequency Interference (RFI)?
  - Choose reference antenna wisely (ever-present, stable response)

A Data Editing Example

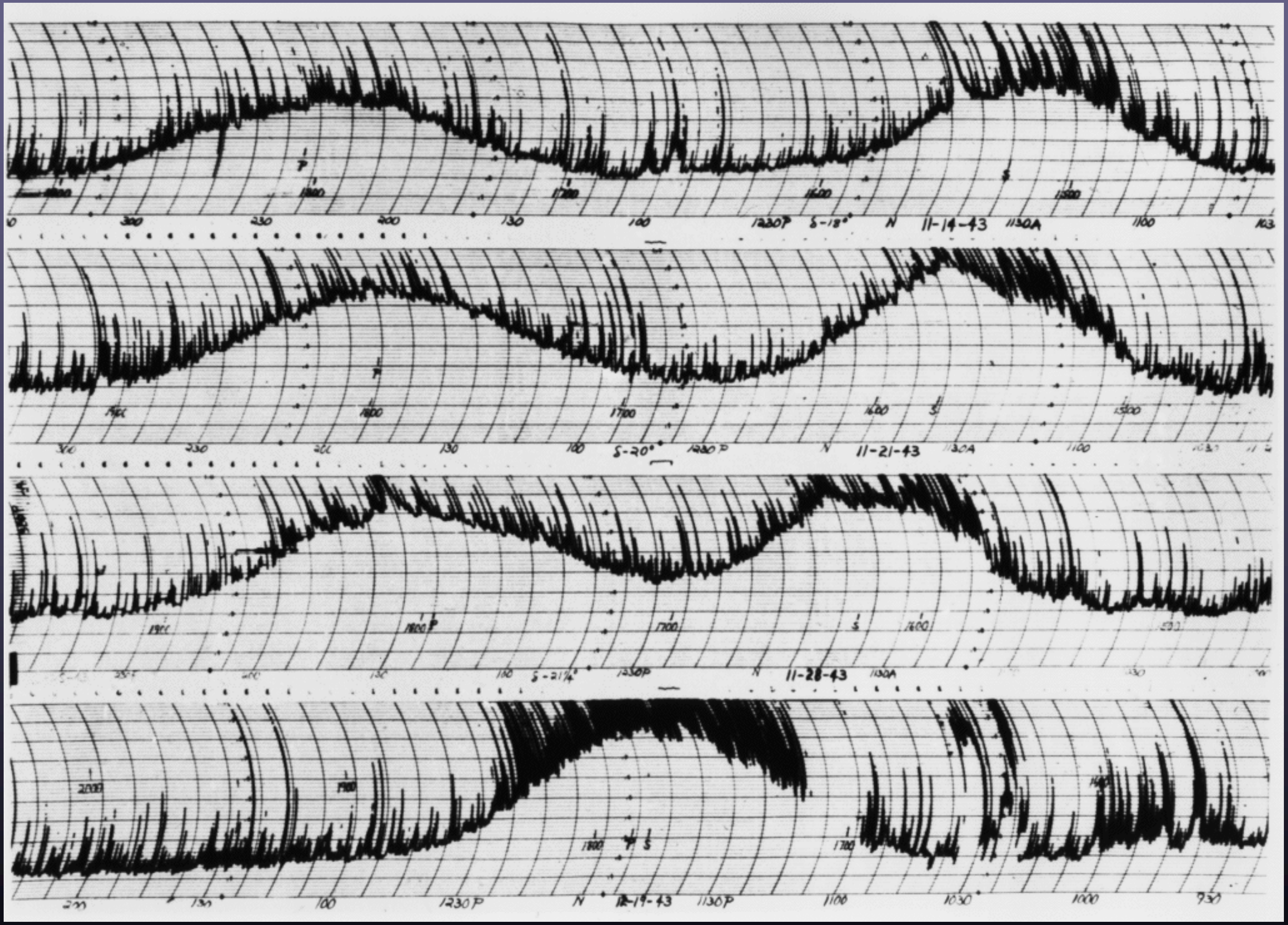


Radio Frequency Interference

- RFI originates from man-made signals generated in the antenna electronics or by external sources (e.g., satellites, cell-phones, radio and TV stations, automobile ignitions, microwave ovens, etc.)
  - Adds to total noise power in all observations, thus decreasing sensitivity to desired natural signal, possibly pushing electronics into non-linear regimes
  - As a contribution to the n_i term, can correlate between antennas if of common origin and baseline short enough (insufficient decorrelation via *geometric delay*)
  - When RFI is correlated, it obscures natural emission in spectral line observations

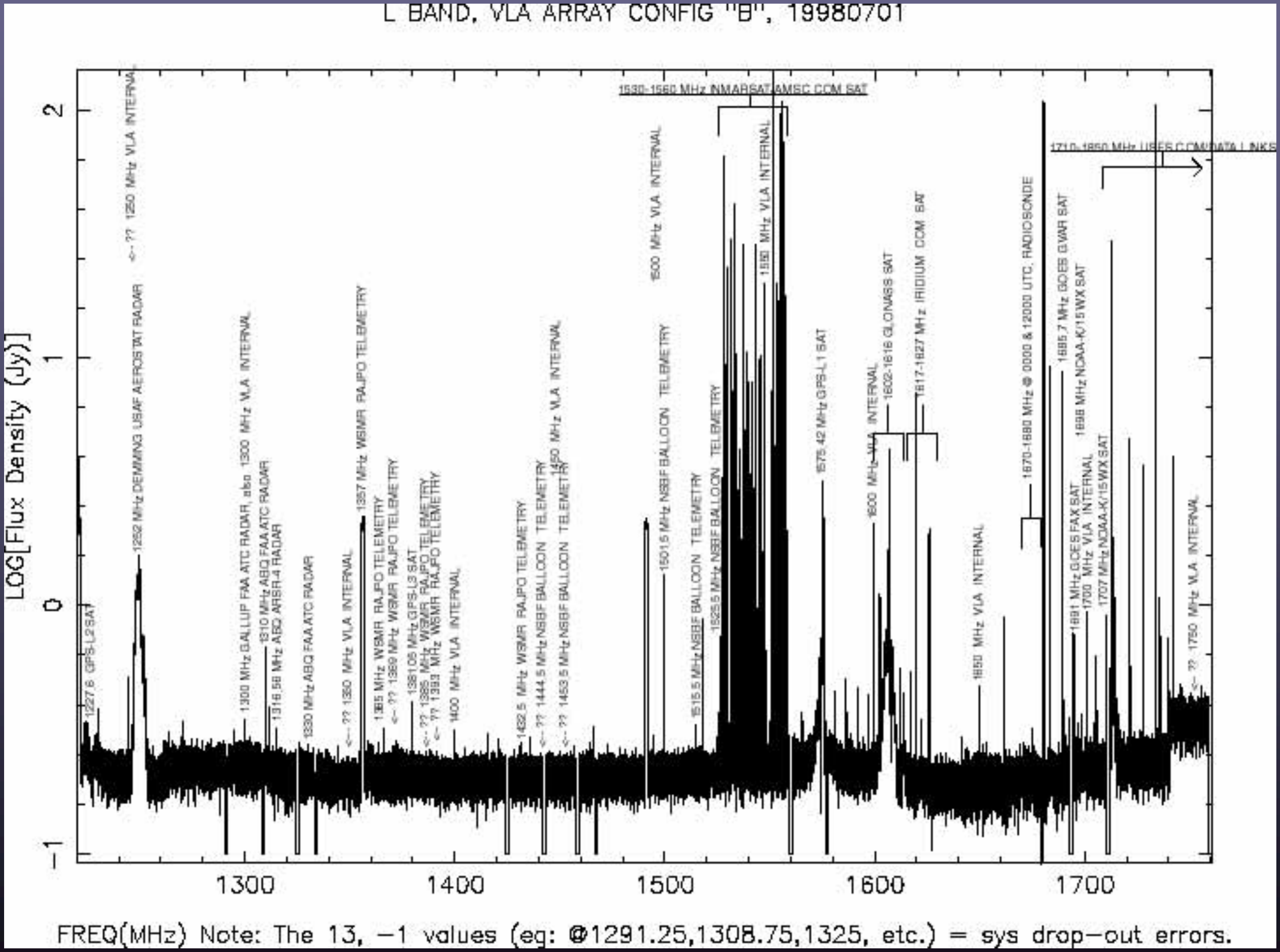
Radio Frequency Interference

- Has always been a problem (Reber, 1944, in total power)!



Radio Frequency Interference (cont)

- Growth of telecom industry threatening radioastronomy!



Radio Frequency Interference (cont)

- RFI Mitigation
  - Careful electronics design in antennas, including notch filters
  - High-dynamic range digital sampling
  - Observatories world-wide lobbying for spectrum management
  - Choose interference-free frequencies (or at least be prepared to throw away lots of bandwidth – VLA 1-2 GHz only ~500 MHz useful)
  - Observe continuum experiments in spectral-line modes so affected channels can be edited
- Various off-line mitigation techniques under study

Summary

- Determining calibration is as important as determining source structure—can't have one without the other
- Calibration dominated by antenna-based effects, permits separation of calibration from astronomical information
- Calibration determination is a single standard fitting problem
- Calibration an iterative process, improving various components in turn
- Strong point sources are the best calibrators
- Observe calibrators according requirements of components
- Data examination and editing an important part of calibration

Further Reading

- http://www.nrao.edu/whatisra/mechanisms.shtml
- http://www.nrao.edu/whatisra/
- www.nrao.edu

- Synthesis Imaging in Radio Astronomy
- ASP Vol 180, eds Taylor, Carilli & Perley