





# Calibration and Editing

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Astronomy 423 at UNM Radio Astronomy



# The VLA WIDAR Correlator

- XF architecture duplicated 64 times, or "FXF"
  - Four 2GHz basebands per polarization (3 bit sampling)
  - Digital filterbank makes 16 subbands per baseband
  - 16,384 channels/baseline at full sensitivity
  - 4 million channels with less bandwidth!
- Initially will support 32 stations with plans for 48
- 2 stations at 25% bandwidth or 4 stations at 6.25% bandwidth can replace 1 station input
- Correlator efficiency is about 95%
  - Compare to 81% for VLA
- VLBI and LWA ready





#### Basic Correlator Stages for the LWA

- 1. Correlate LWA1 beams with single dipoles at LWA1 and LWA-SV (success!)
- 2. Correlate LWA1 and LWA-SV using LSL and supercorrelator.py
- 3. Digitize VLA dishes and correlate with LWA1 and LWA-SV (works!) on LWAUCF with LSL supercorrelator.py
- 4. Correlate ~10 LWA stations (the "swarm") using GPU based correlator





# **Current LWA Correlator**



#### **eLWA Correlator Status**

System	Status	Last Updated
Dispatcher	Running	7 minutes ago
LWA1	Running	7 minutes ago
LWA-SV	Running	7 minutes ago
LWA-NA	Running	7 minutes ago

Project	Observation Date	Raw Size	Status
DW005, 9	2024/12/14 02:00 UTC	3.106 TB	hold for 41 days, 19:27:49
DW005, 8	2024/12/14 02:00 UTC	3.883 TB	hold for 32 days, 22:04:45
DW005, 11	2024/12/20 01:00 UTC	3.106 TB	hold for 53 days, 0:38:35
DW005, 10	2024/12/20 01:00 UTC	4.142 TB	hold for 32 days, 22:04:39
DW005, 12	2024/12/27 02:00 UTC	2.330 TB	hold for 52 days, 2:03:26
DW005, 13	2024/12/27 02:00 UTC	2.330 TB	hold for 52 days, 2:03:19
DT005, 267	2025/02/08 03:00 UTC	6.091 TB	correlating for 13:27:49
DT005, 268	2025/02/09 04:20 UTC	6.210 TB	completed for 4 days, 16:46:23
DT005, 269	2025/02/10 08:50 UTC	6.210 TB	completed for 4 days, 2:12:25
DA004, 8787	2025/02/20 07:10 UTC	4.529 TB	completed for 3 days, 13:55:10
DA004, 999	2025/02/22 18:00 UTC	3.882 TB	completed for 2 days, 4:54:35
DA004, 423	2025/02/23 11:34 UTC	3.973 TB	completed for 1 days, 9:55:20
DA004, 9999	2025/02/23 18:00 UTC	3.882 TB	completed for 20:55:15
DA004, 4232	2025/02/24 11:40 UTC	4.102 TB	completed for 11:59:40



#### **Current LWA Correlator**



#### **Disk Usage**

Node	Mount Point	Usage	Free
lwaucf1	/data/local	12T	5.4T
lwaucf2	/data/local	5.2T	13T
lwaucf3	/data/local	13T	4.5T
All	/home	1.5T	5.4T
All	/data/network	153T	55T
lwaucf6	/data/local	1.3T	3.9T

Last retrieved 6 minutes ago.

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#### Temperatures



# **Interferometry Basics**





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### **Fourier Transform Pairs**





### **Fourier Transform Pairs**







#### **The Correlation Function**

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

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

where f \* denotes the complex conjugate of f.





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#### **Fringe Fitting**

2015 ASTR423 VLBA obs 3C279





G. Taylor, Astr 423 at UNM



#### Announcements

- LWA observing going well
- Exam 1 on Wednesday, March 5
- Constants posted (constants.pdf)





### 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<sub>i</sub> & x<sub>j</sub>, 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<sub>i</sub>(t) and providing it to the correlator.





#### What signal is really collected?

 The net signal delivered by antenna *i*, *x<sub>i</sub>(t)*, is a combination of the desired signal, *s<sub>i</sub>(t,l,m)*, corrupted by a factor *J<sub>i</sub>(t,l,m)* and integrated over the sky, and noise, *n<sub>i</sub>(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<sub>i</sub>(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<sub>i</sub>(t,I,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:

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

### • ...and consider how to solve it!





#### The Measurement Equation - Simplified

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

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

$$= \left(\vec{J}_{i}^{vis} \otimes \vec{J}_{j}^{vis*}\right) \int_{\mathcal{J}_{i}} \left(\vec{J}_{i}^{sky} \otimes \vec{J}_{j}^{sky*}\right) \vec{I} (l,m) e^{-i2\pi \left(u_{ij}l+v_{ij}m\right)} dl dm$$

 Next, we recognize that it is often possible to assume J<sup>sky</sup>=1, and we have a relationship between ideal and observed Visibilities:

$$= \left(\vec{J}_{i}^{vis} \otimes \vec{J}_{j}^{vis*}\right) \int_{sky} \vec{I} (l,m) e^{-i2\pi \left(u_{ij}l + v_{ij}m\right)} dl dm$$
$$\vec{V}_{ij}^{obs} = \left(\vec{J}_{i}^{vis} \otimes \vec{J}_{j}^{vis*}\right) \vec{V}_{ij}^{ideal}$$



### Solving the Measurement Equation

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

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

 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<sup>ideal</sup>:

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

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

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





### **Solving the Measurement Equation**

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

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

- 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 antennabased terms is believable as being of astronomical origin
- Closure: calibration-independent observables:
  - Closure phase (3 baselines):

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

• Closure amplitude (4 baselines):

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



**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:

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



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## "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

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			Source	Scan	Madifiana	RA	AC Vel.	AC Freq.	Min HA	Min PA	#
5 <b>1 1 1</b>	41 W   T+		Epoch	Instrument Cfg.	Modifiers	Dec	BD Vel.	BD Freq.	Max HA	Max PA	Total Time
E P 1	<ul> <li>ITA-025</li> </ul>		0137+331=3C48	Attenuator slew	ttenuator slew 1h	1h 37m 41.29943s	/	5.0GHz / 7.0GHz	-3.79	-73.1d	2
E P 1	7A-475		J2000	(1) C32d2A	SetAtnGain	33d 9' 35.1330"		5.0GHz / 7.0GHz	-3.60	-72.3d	00:00:09.945
E P 1	7B-165				8						-
E P 1	7B-267		0137+331=3C48	Attenuator slew	SetAtnGain	1h 37m 41.29943s	/	13.0GHz / 15.0GHz	-3.71	-73.5d	2
E P 1	P 17B-294-CSOsampleCX		J2000	(2) Ku48f2A	Contaroant	33d 9' 35.1330"	/	16.0GHz / 17.0GHz	-3.53	-72.7d	00:00:45.214
E P 18	8A-098		0137+331=3C48	Attenuator setup		1h 37m 41.29943s		2.5GHz	-3.69	-72.7d	1
E P 18	P 18A-017		J2000	(3) S16f2A	SetAtnGain	33d 9' 35,1330"		3.5GHz	-3.68	-72.8d	00:00:39.945
E P 18	8A-369			(-)							
E P 18	8A-023	Project Code: 18A-01/	0137+331=3C48	Flux cal-S	CalBP CalFlux	1h 37m 41.29943s		2.5GHz	-3.68	-72.8d	1
E P 18	8A-205		J2000	(3) S16f2A	ould', oui lux	33d 9' 35.1330"		3.5GHz	-3.61	-73.1d	00:04:00.000
E P 18	8A-317		0137+331=3C48	Flux cal-C		1h 37m 41 29943s	/	5.0GHz / 7.0GHz	-3.60	-73 1d	1
E P 7	RSR0086		12000	(1) C32d2A	CalBP, CalFlux	33d 9' 35 1330"	,	5.0GHz / 7.0GHz	-3 54	-73.4d	00.04.00.000
🖻 P B	Y143		02000	(1) 002024		000 0 00.1000	,	0.0011277.00112	-0.04	10.44	00.04.00.000
🕀 Р 19	<b>P</b> 19A-046		0137+331=3C48	Flux cal-Ku		1h 37m 41.29943s	/	13.0GHz / 15.0GHz	-3.53	-73.5d	1
E P 19	9A-065		J2000	(2) Ku48f2A	Calbr, Calriux	33d 9' 35.1330"	/	16.0GHz / 17.0GHz	-3.46	-73.8d	00:04:00.000
• P S	E SC1006		11942+6900	Phone cal S		196 42m 22 641640		2 5 6 4 7	2 46	100.94	2
E P 20	0A-092		J1042+0009		CalGain	1011 42111 33.04 1048			3.40	112.00	2
E P 20	20B-296 20B-252		J2000	(3) S 1012A		000 9 25.2279		3.36HZ	3.01	112.20	00.02.05.656
E P 20			VLSS J1736.6 +	VLSS J1736.6 +6502	01-7-1	17h 36m 37.528s		2.5GHz	4.62	92.1d	1
	DEM0032		J2000	(3) S16f2A	Obsigt	65d 2' 28.38"		3.5GHz	4.66	91.6d	00:01:34.643
	TDEM003	2		NN/00 1404 440 0700 44		101 11 10 700-		0.5011-	4.00	100.41	
	SB S_C_K	u Band, 02:00:00	NVSS J181412+6	NVSS J181412+670344	ObsTgt	18h 14m 12.762s		2.5GHZ	4.03	102.40	1
	- R SIL	: Attenuator slew	J2000	(3) S16f2A	67d 3			3.5GHz	4.06	101.9d	00:01:41.382
	- R SIL	: Attenuator slew	J1842+6809	Requantizer setup		18h 42m 33.64164s		5.0GHz / 7.0GHz	3.61	109.8d	1
	- R STD: Attenuator setu		J2000	(1) C32d2A	SetAtnGain	68d 9' 25.2279"	/	5.0GHz / 7.0GHz	3.62	109.7d	00:00:09.945
	- R SIL	r Flux cal-S									
	- R SIL	: Requantizer se	J1842+6809	Phase cal C	CalGain	18h 42m 33.64164s		5.0GHz / 7.0GHz	3.62	108.1d	2
	- R SIL	Paguantizar sa	J2000	(1) C32d2A		68d 9' 25.2279"	/	5.0GHz / 7.0GHz	3.72	109.7d	00:01:44.974
		r Flux cal-Ku	VLSS J1736.6 +	VLSS J1736.6 +6502		17h 36m 37.528s		5.0GHz / 7.0GHz	4.73	90.6d	1
		VLSS and NVS	J2000	(1) C32d2A	ObsTgt	65d 2' 28.38"	/	5.0GHz / 7.0GHz	4.76	90.2d	00:01:34.287
	<ul> <li>(1X) VLSS and NVSC</li> <li>(1X) 4C +72.26 S and</li> <li>(1X) AEGL Ku and C</li> </ul>			(.,							
			NVSS J181412+6	NVSS J181412+670344	ObsTat	18h 14m 12.762s	/	5.0GHz / 7.0GHz	4.14	100.7d	1
	E 0 (1X)	AFGL Ku and C	J2000	(1) C32d2A	oborgi	67d 3' 42.83"	/	5.0GHz / 7.0GHz	4.17	100.3d	00:01:41.186
	1 0 (4X)	AFGL Ku Band	11027+7358 Phase cal S		19h 27m 48 49520c		2 5GHz	2.96	124 4d	2	
	- STD: Phase cal Ku		12000	(3) S16f2A	CalGain	73d 58' 1 5700"		3.5GHz	3.03	125.54	00:01:24 954
	B (1X)	4C 19.71 S and	32000	(J) 01012A		100 00 1.0700		0.00112	0.00	120.00	00.01.24.934
	(1X) WISE S and C F		4C +72.26	4C +72.26	OhoTat	19h 8m 23.385s		2.5GHz	3.30	118.5d	1
					Obsigt						

# **Typical LWA observation**

File	Edit Scans [	Data Help								
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ID	Target	Intent	Comments	Start (UTC)	Duration	RA (Hour J2000)	Dec (Deg. J2000)	Tuning 1 (MHz)	Tuning 2 (MHz)	Filter C
1	3c295	fluxcal	None provid	UTC 2025/02/20 07:10:00.000000	0:06:00.000	14:11:20.20	+52:12:09.1	52.000000	72.000000	7
2	3c298	phasecal	None provid	UTC 2025/02/20 07:16:00.000000	0:04:00.000	14:19:08.18	+06:28:34.8	52.000000	72.000000	7
3	m87	target	None provid	UTC 2025/02/20 07:20:00.000000	0:16:00.000	12:30:49.00	+12:23:28.0	52.000000	72.000000	7
4	3c298	phasecal	None provid	UTC 2025/02/20 07:36:00.000000	0:04:00.000	14:19:08.18	+06:28:34.8	52.000000	72.000000	7
5	m87	target	None provid	UTC 2025/02/20 07:40:00.000000	0:16:00.000	12:30:49.00	+12:23:28.0	52.000000	72.000000	7
6 🗌	3c298	phasecal	None provid	UTC 2025/02/20 07:56:00.000000	0:04:00.000	14:19:08.18	+06:28:34.8	52.000000	72.000000	7
7	3c295	fluxcal	None provid	UTC 2025/02/20 08:00:00.000000	0:06:00.000	14:11:20.20	+52:12:09.1	52.000000	72.000000	7
8 🗌	3c298	phasecal	None provid	UTC 2025/02/20 08:06:00.000000	0:04:00.000	14:19:08.18	+06:28:34.8	52.000000	72.000000	7
9	m87	target	None provid	UTC 2025/02/20 08:10:00.000000	0:16:00.000	12:30:49.00	+12:23:28.0	52.000000	72.000000	7
0 10	3c298	phasecal	None provid	UTC 2025/02/20 08:26:00.000000	0:04:00.000	14:19:08.18	+06:28:34.8	52.000000	72.000000	7
11	m87	target	None provid	UTC 2025/02/20 08:30:00.000000	0:16:00.000	12:30:49.00	+12:23:28.0	52.000000	72.000000	7
12	3c298	phasecal	None provid	UTC 2025/02/20 08:46:00.000000	0:04:00.000	14:19:08.18	+06:28:34.8	52.000000	72.000000	7
13	3c295	fluxcal	None provid	UTC 2025/02/20 08:50:00.000000	0:06:00.000	14:11:20.20	+52:12:09.1	52.000000	72.000000	7
14	3c298	phasecal	None provid	UTC 2025/02/20 08:56:00.000000	0:04:00.000	14:19:08.18	+06:28:34.8	52.000000	72.000000	7
15	m87	target	None provid	UTC 2025/02/20 09:00:00.000000	0:16:00.000	12:30:49.00	+12:23:28.0	52.000000	72.000000	7
16	3c298	phasecal	None provid	UTC 2025/02/20 09:16:00.000000	0:04:00.000	14:19:08.18	+06:28:34.8	52.000000	72.000000	7
17	m87	target	None provid	UTC 2025/02/20 09:20:00.000000	0:16:00.000	12:30:49.00	+12:23:28.0	52.000000	72.000000	7
18	3c298	phasecal	None provid	UTC 2025/02/20 09:36:00.000000	0:04:00.000	14:19:08.18	+06:28:34.8	52.000000	72.000000	7
🗌 19	3c295	fluxcal	None provid	UTC 2025/02/20 09:40:00.000000	0:06:00.000	14:11:20.20	+52:12:09.1	52.000000	72.000000	7
20	3c298	phasecal	None provid	UTC 2025/02/20 09:46:00.000000	0:04:00.000	14:19:08.18	+06:28:34.8	52.000000	72.000000	7
21	m87	target	None provid	UTC 2025/02/20 09:50:00.000000	0:16:00.000	12:30:49.00	+12:23:28.0	52.000000	72.000000	7
22	3c298	phasecal	None provid	UTC 2025/02/20 10:06:00.000000	0:04:00.000	14:19:08.18	+06:28:34.8	52.000000	72.000000	7
23	m87	target	None provid	UTC 2025/02/20 10:10:00.000000	0:16:00.000	12:30:49.00	+12:23:28.0	52.000000	72.000000	7
24	3c298	phasecal	None provid	UTC 2025/02/20 10:26:00.000000	0:04:00.000	14:19:08.18	+06:28:34.8	52.000000	72.000000	7
25	3c295	fluxcal	None provid	UTC 2025/02/20 10:30:00.000000	0:06:00.000	14:11:20.20	+52:12:09.1	52.000000	72.000000	7
26	3c298	phasecal	None provid	UTC 2025/02/20 10:36:00.000000	0:04:00.000	14:19:08.18	+06:28:34.8	52.000000	72.000000	7
27	m87	target	None provid	UTC 2025/02/20 10:40:00.000000	0:16:00.000	12:30:49.00	+12:23:28.0	52.000000	72.000000	7
28	3c298	phasecal	None provid	UTC 2025/02/20 10:56:00.000000	0:04:00.000	14:19:08.18	+06:28:34.8	52.000000	72.000000	7





#### **Uncalibrated spectra on 3C286**



Mexico

#### **Bandpass solutions**



#### **Spectra after Fringe-fit and bandpass calibration**



#### **Observed Data vs. UV dist**





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#### **Observed Data – Phase vs. Time**



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#### **Observed Data – Amplitude Spectrum**



#### Gain Amp/Phase Solutions (B calibrator)





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#### **Bandpass Solutions**



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#### Gain Amp/Phase Solutions



#### Corrected Data vs. UV dist





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#### 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
- 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 v > 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  $\lambda/D$
  - 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  $D \sim a$  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:

F:

 $\bullet$ 

- 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)
- Choose strongly polarized source and observe often enough to track variation

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# **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 offsource, LO out-of-lock, etc.). Any such bad data left over? (check operator's logs)
  - Any persistently 'dead' antennas (*J<sub>i</sub>=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<sub>i</sub> 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)!





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#### Radio Frequency Interference (cont)

#### • Growth of telecom industry threatening radioastronomy!



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## 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
- <u>http://www.nrao.edu/whatisra/</u>
- <u>www.nrao.edu</u>
- Synthesis Imaging in Radio Astronomy
- ASP Vol 180, eds Taylor, Carilli & Perley



