Cross Correlators

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University of New Mexico

Astronomy 423 at UNM

Radio Astronomy

Announcements

- LWA observing underway
- Interferometry by Thompson, Moran & Swenson:
- https://www.dropbox.com/s/tpt4l6tlner32zb/2017_book_interferometryandsynthesisinra.pdf?dl=0
- Exam 1 on Wednesday, March 5
- Data showing up on /data/network/recent_data/astr423

eLWA Correlator Status

System	Status	Last Updated
Dispatcher	Running	0 minutes ago
LWA1	Running	0 minutes ago
LWA-SV	Running	0 minutes ago
LWA-NA	Running	0 minutes ago

Project	Observation Date	Raw Size	Status
DW005, 9	2024/12/14 02:00 UTC	3.106 TB	hold for 36 days, 18:47:49
DW005, 8	2024/12/14 02:00 UTC	3.883 TB	hold for 27 days, 21:24:46
DW005, 11	2024/12/20 01:00 UTC	3.106 TB	hold for 47 days, 23:58:35
DW005, 10	2024/12/20 01:00 UTC	4.142 TB	hold for 27 days, 21:24:39
DW005, 12	2024/12/27 02:00 UTC	2.330 TB	hold for 47 days, 1:23:26
DW005, 13	2024/12/27 02:00 UTC	2.330 TB	hold for 47 days, 1:23:20
DT005, 267	2025/02/08 03:00 UTC	6.091 TB	failed-c for 15:01:53
DT005, 268	2025/02/09 04:20 UTC	6.210 TB	correlating for 14:47:50
DT005, 269	2025/02/10 08:50 UTC	6.210 TB	queued for 1 days, 21:59:59
DT005, 270	2025/02/12 11:40 UTC	5.306 TB	completed for 3 days, 22:20:03
DT005, 271	2025/02/12 23:20 UTC	6.210 TB	completed for 5 days, 3:06:37
DT005, 272	2025/02/14 12:30 UTC	6.210 TB	completed for 4 days, 8:08:27
DA004, 8787	2025/02/20 07:10 UTC	4.529 TB	queued for 10:59:59

Outline

- Re-cap of interferometry
  - What is a correlator?
- The correlation function
- Simple correlators
- Spectral line correlators
- Details
  - Sampling and quantization
  - Delay model
- The VLA and LWA correlators

This lecture is complementary to Chapter 4 of ASP 180 and is based on a lecture by Walter Brisken

Re-cap of Interferometry

- What are we fundamentally trying to measure?
- How do we accomplish this in a traditional telescope?
  - Optical or radio
- What changes when we go to a interferometer?
  - A “sparse” telescope
- What do visibilities tell us about the sky?

What is a Correlator?

A correlator is a hardware or software device that combines sampled voltage time series from one or more antennas to produce sets of complex visibilities, V_{ij}.

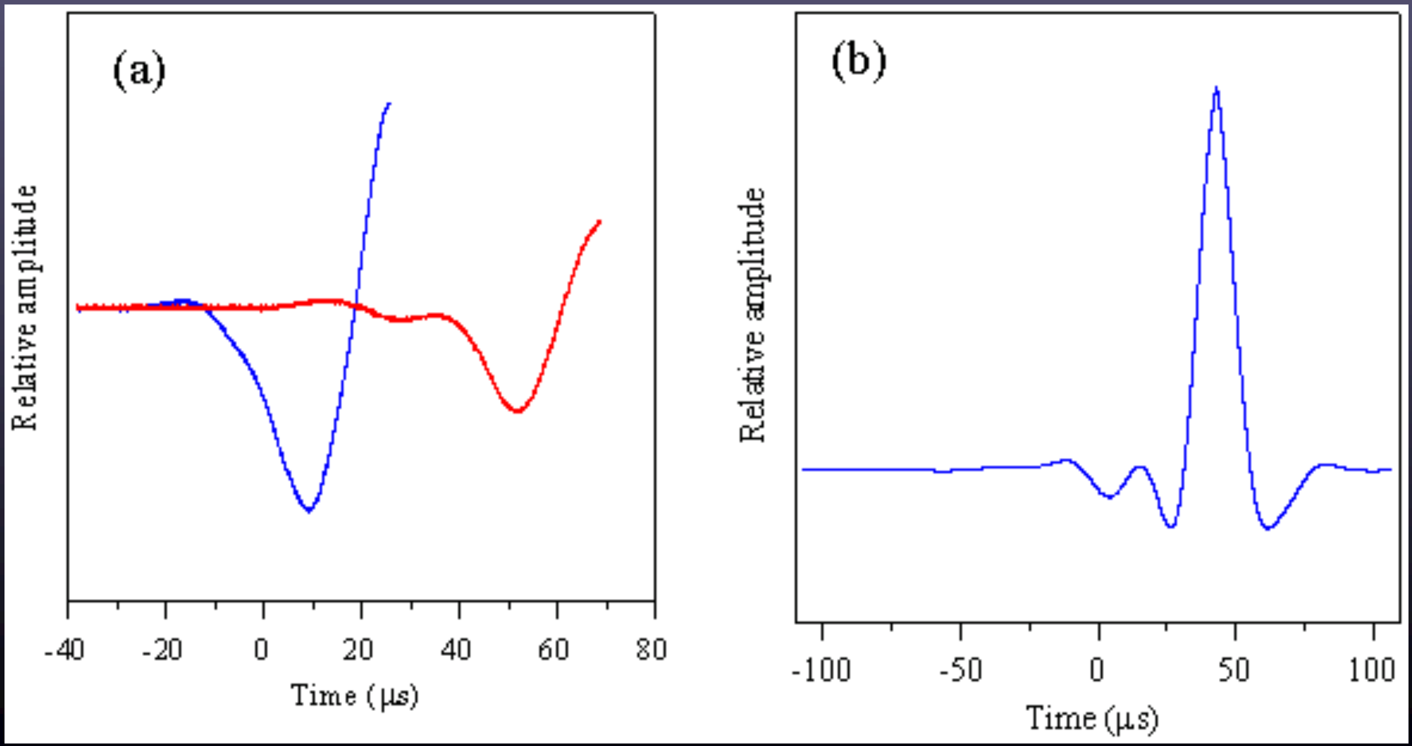
- Visibilities are in general a function of
  - Frequency
  - Antenna pair
  - Time
- They are used for
  - Imaging
  - Spectroscopy / polarimetry
  - Astrometry

The Correlation Function

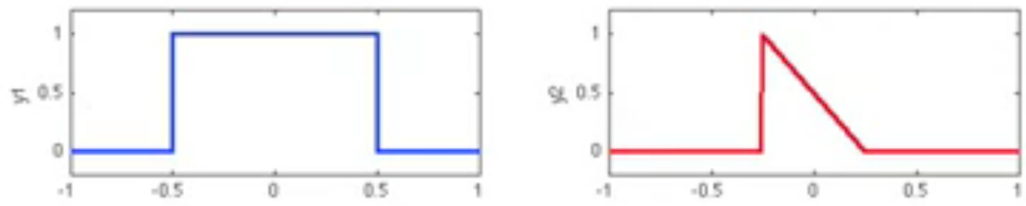
For continuous functions, *f* and *g*, the cross-correlation is defined as:

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

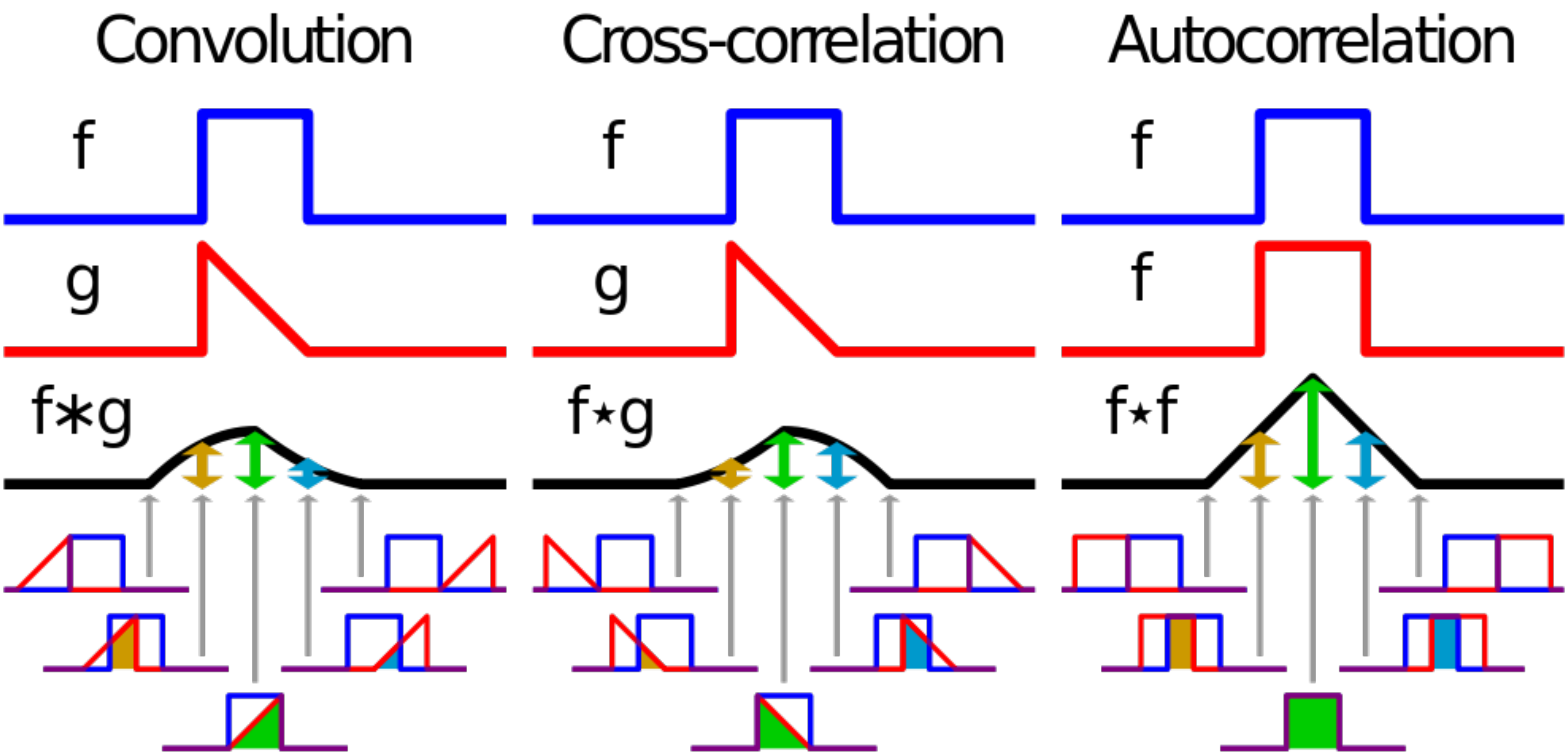
where f^* denotes the complex conjugate of *f*.



Cross Correlation



Correlation and Convolution Functions



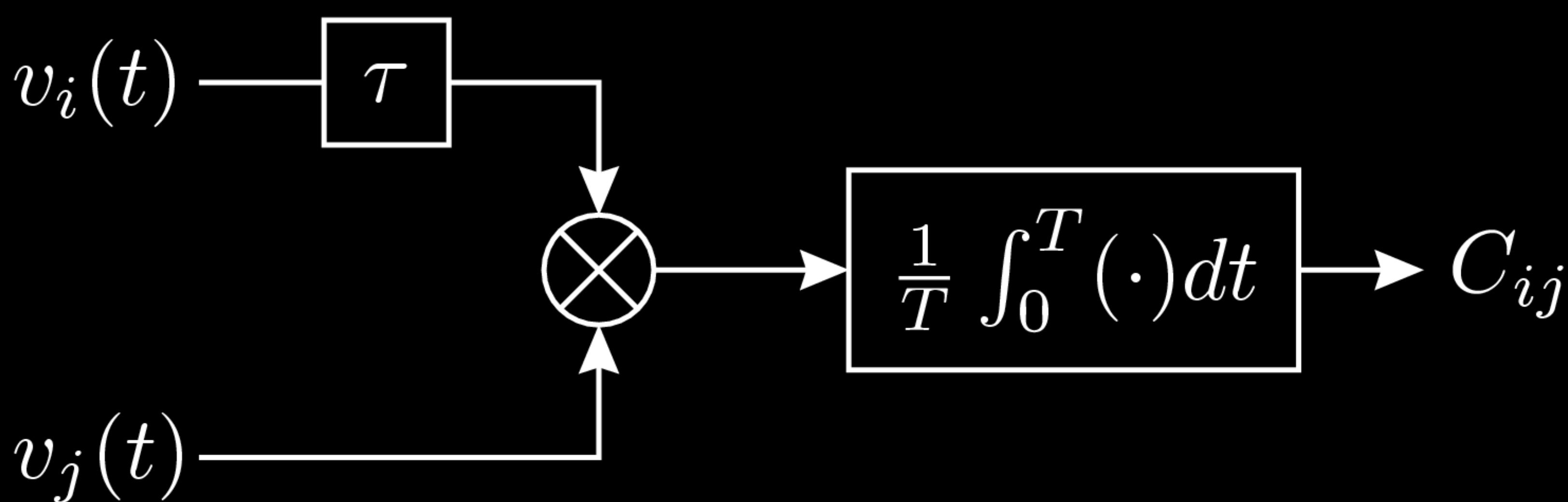
The Correlation Function

$$C_{ij}(\tau) = \langle v_i(t) v_j(t+\tau) \rangle_T$$

- If $i = j$ it is an auto-correlation (AC). Otherwise it is a cross-correlation (CC).
- Useful for
  - Determining timescales (CC and AC)
  - Motion detection (2-D CC)
  - Optical character recognition (2-D CC)
  - Pulsar timing
  - Template matching (CC)
    - Also called "matched filtering"

A Real (valued) Cross Correlator

$$C_{ij}(\tau) = \langle v_i(t) v_j(t+\tau) \rangle_T$$



Visibilities

What astronomers really want is the complex visibility

$$V_{ij} = \langle E_i(t) E_j^*(t+\tau) \rangle$$

where the real part of $E_i(t)$ is the voltage measured by antenna i.

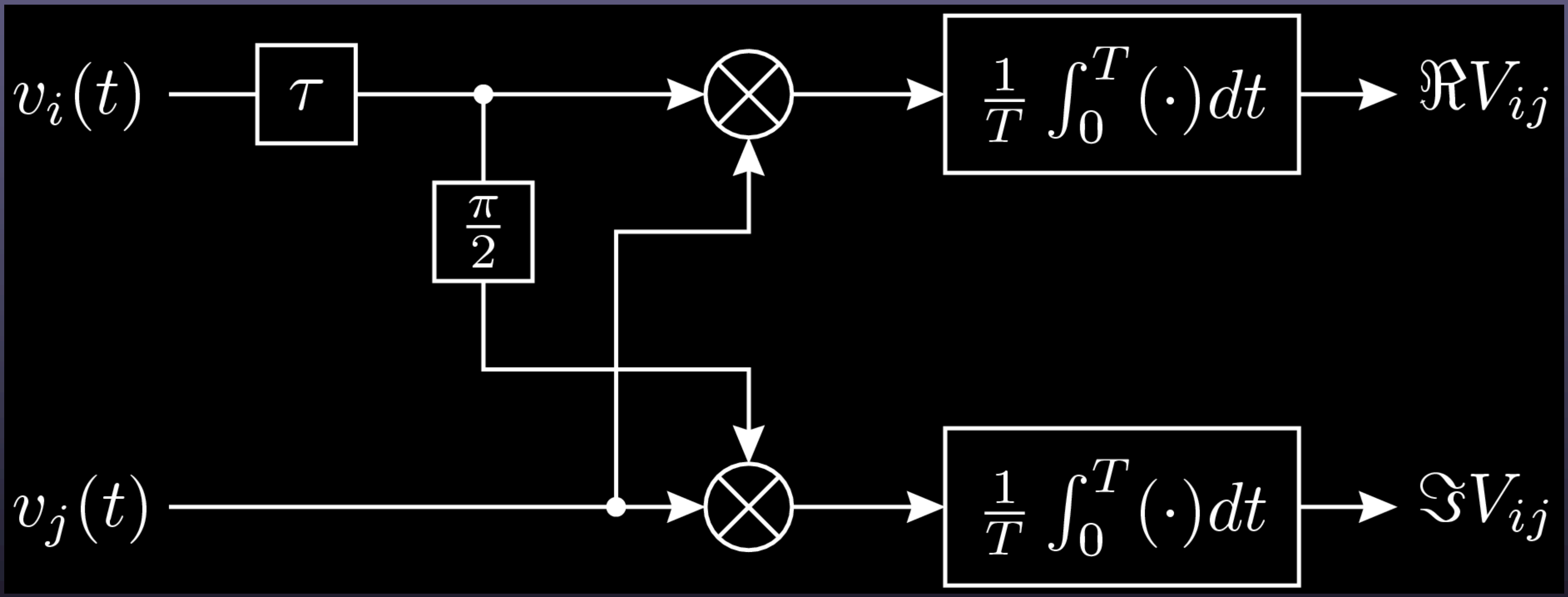
So what is the imaginary part of $E_i(t)$*?*

It is the same as the real part but with each frequency component *phase* lagged by 90 degrees.

$$E_i(t) = v_i(t) + \frac{i}{\pi} \int_{-\infty}^{\infty} \frac{v_i(t')}{t-t'} dt'$$

The Complex Correlator

$$V_{ij} = \langle v_i(t) v_j(t+\tau) \rangle + i \langle \mathcal{H}\left[v_i(t)\right] v_j(t+\tau) \rangle$$



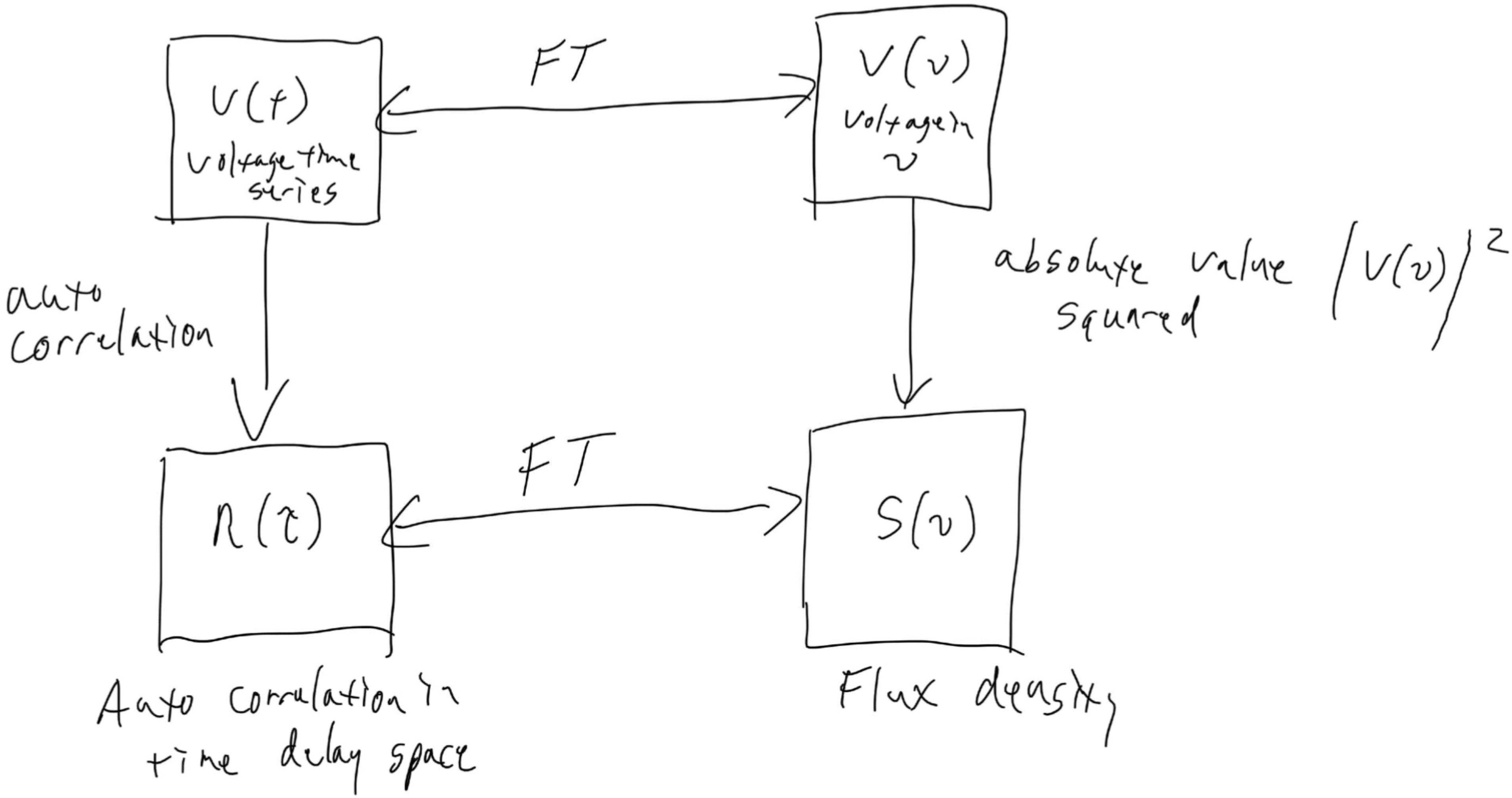
Spectral Line Correlators

- Chop up bandwidth for
  - Calibration
    - Bandpass calibration
    - Fringe fitting
  - Spectroscopy
  - Wide-field imaging
  - (Its all Spectral Line these days)
- Conceptual version
  - Build analog filter bank
  - Attach a complex correlator to each filter

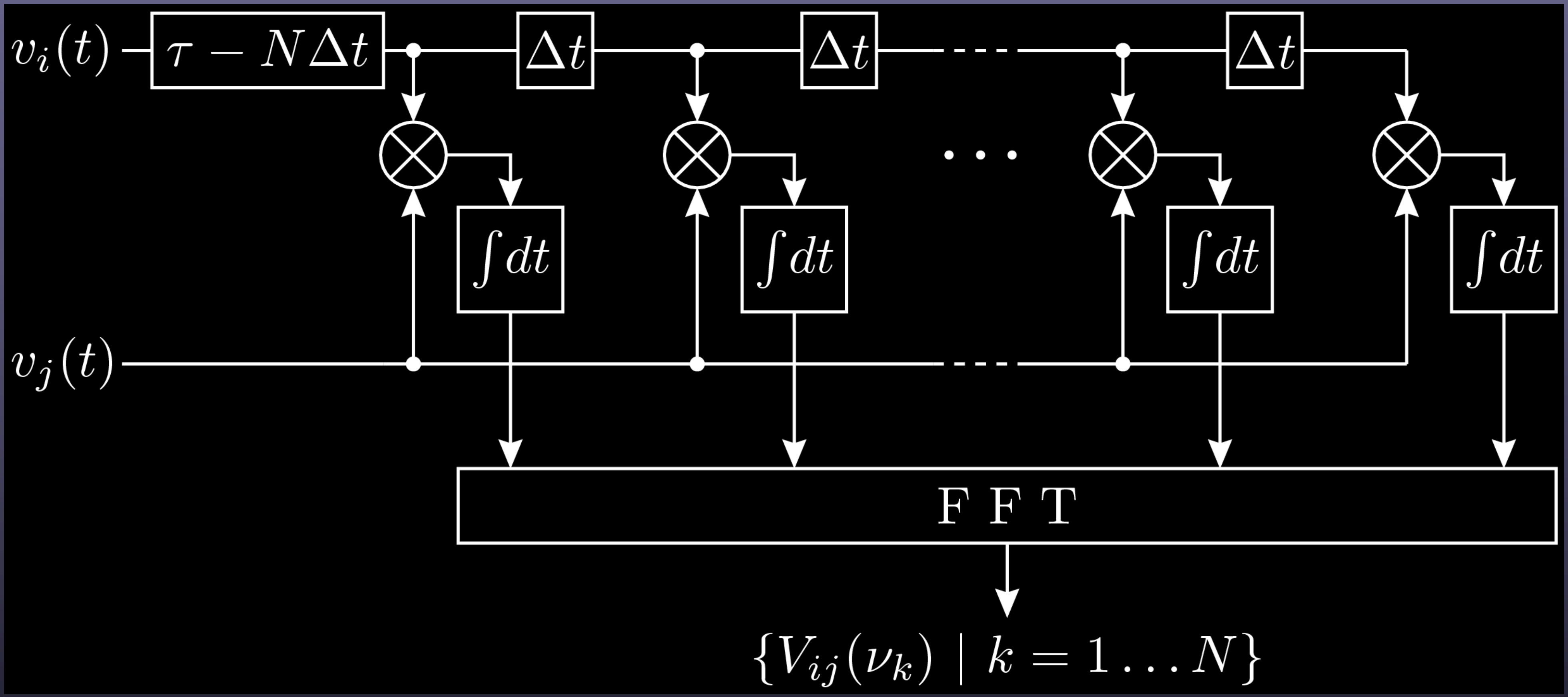
Practical Spectral Line Correlators

- Use a single filter / sampler
  - Easier to calibrate
  - Practical, up to a point
- The FX architecture
  - F : Replace filterbank with digital Fourier transform
  - X : Use a complex-correlator for each frequency channel
  - Then integrate
- The XF architecture
  - X : Measure correlation function at many lags
  - Integrate
  - F : Fourier transform
- Other architectures possible

Radio Astronomy Notes 6-3



The XF Correlator



XF Spectral Response

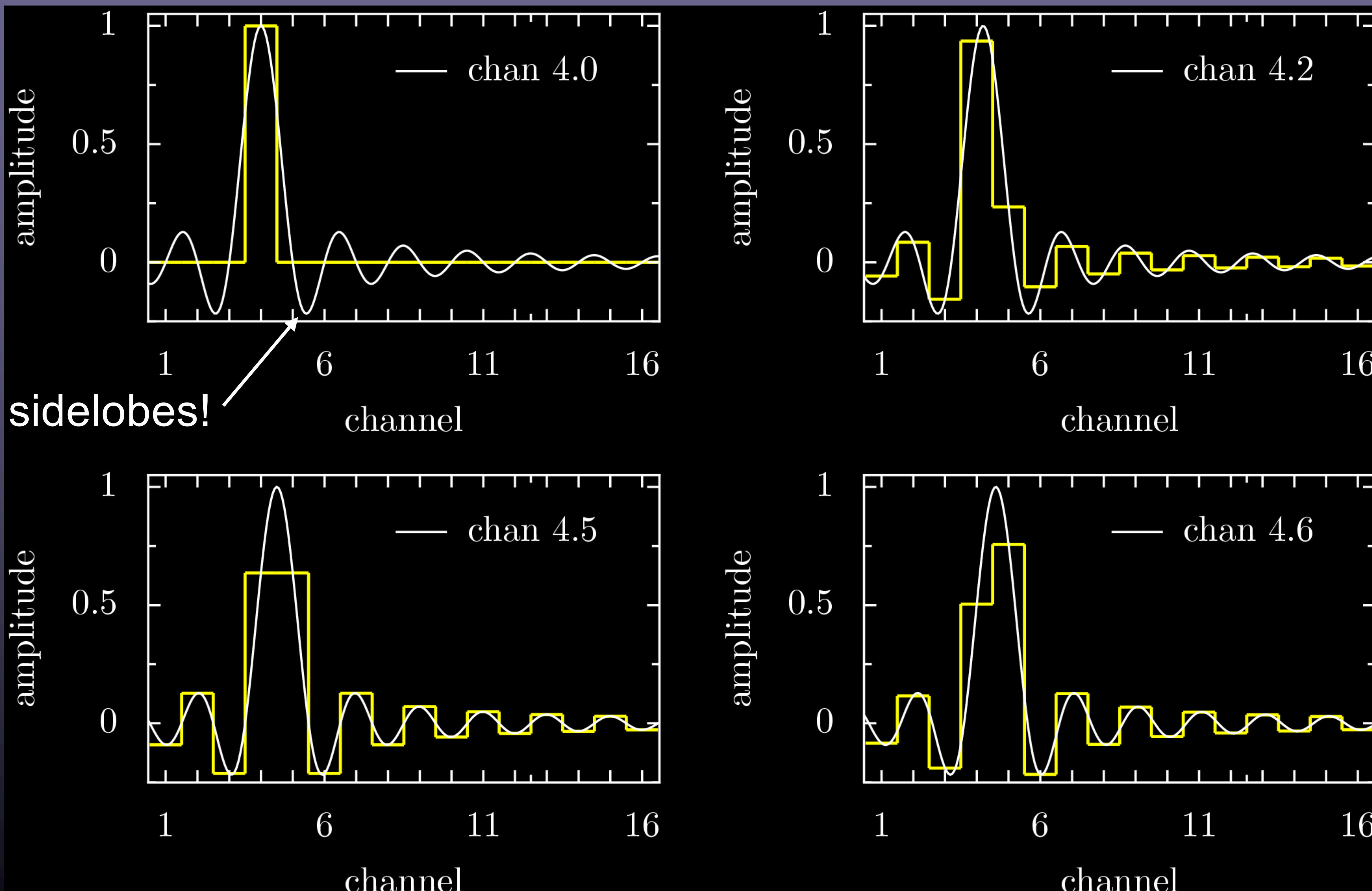
- XF correlators measure lags over a finite delay range

$$V_{ij}(\tau) \quad = \quad \langle v_i(t) v_j(t+\tau) \rangle \cdot \sqcap \left(\frac{t}{N \Delta t} \right)$$

- Results in convolved visibility spectrum

$$\begin{aligned} V_{ij}(\nu) \quad &= \quad \mathcal{F} \left[\langle v_i(t) v_j(t+\tau) \rangle \cdot \sqcap \left(\frac{t}{N \Delta t} \right) \right] \\ &= \quad \mathcal{F} \left[\langle v_i(t) v_j(t+\tau) \rangle \right] \star \mathrm{sinc} \left(N \Delta t \, \nu \right) \end{aligned}$$

XF Spectral Response (2)



22% sidelobes!

Hanning Smoothing

- Multiply lag spectrum by Hanning taper function

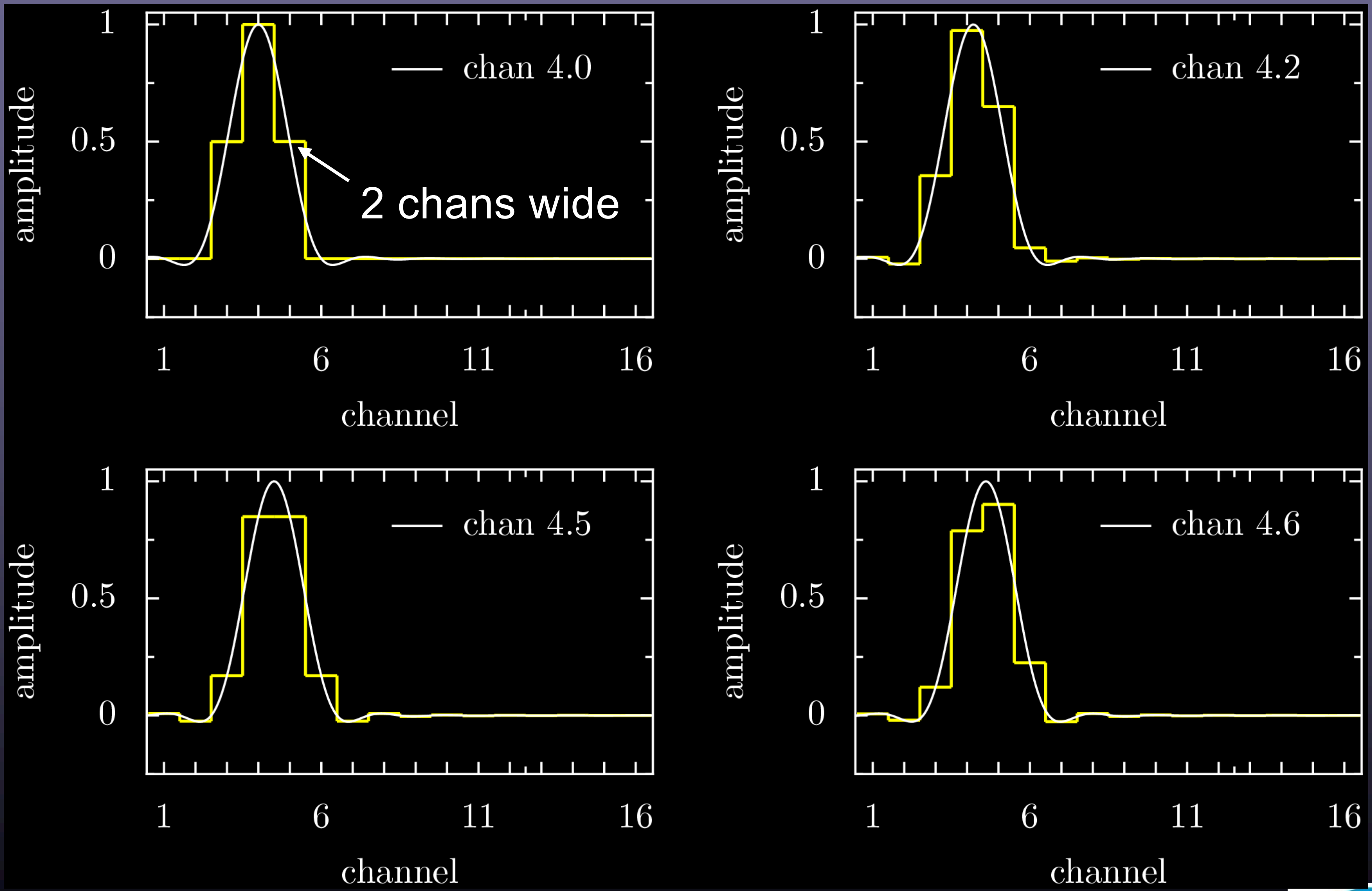
$$H(\tau) = \frac{1}{2}\left(1 + \cos\frac{\pi\tau}{N\Delta t}\right)$$

- This is equivalent to convolution of the spectrum by

$$H(\nu) = \delta(\nu) - \frac{1}{2}\delta\left(\nu - \frac{1}{2N\Delta t}\right) - \frac{1}{2}\delta\left(\nu + \frac{1}{2N\Delta t}\right)$$

- Note that sensitivity and spectral resolution are reduced.

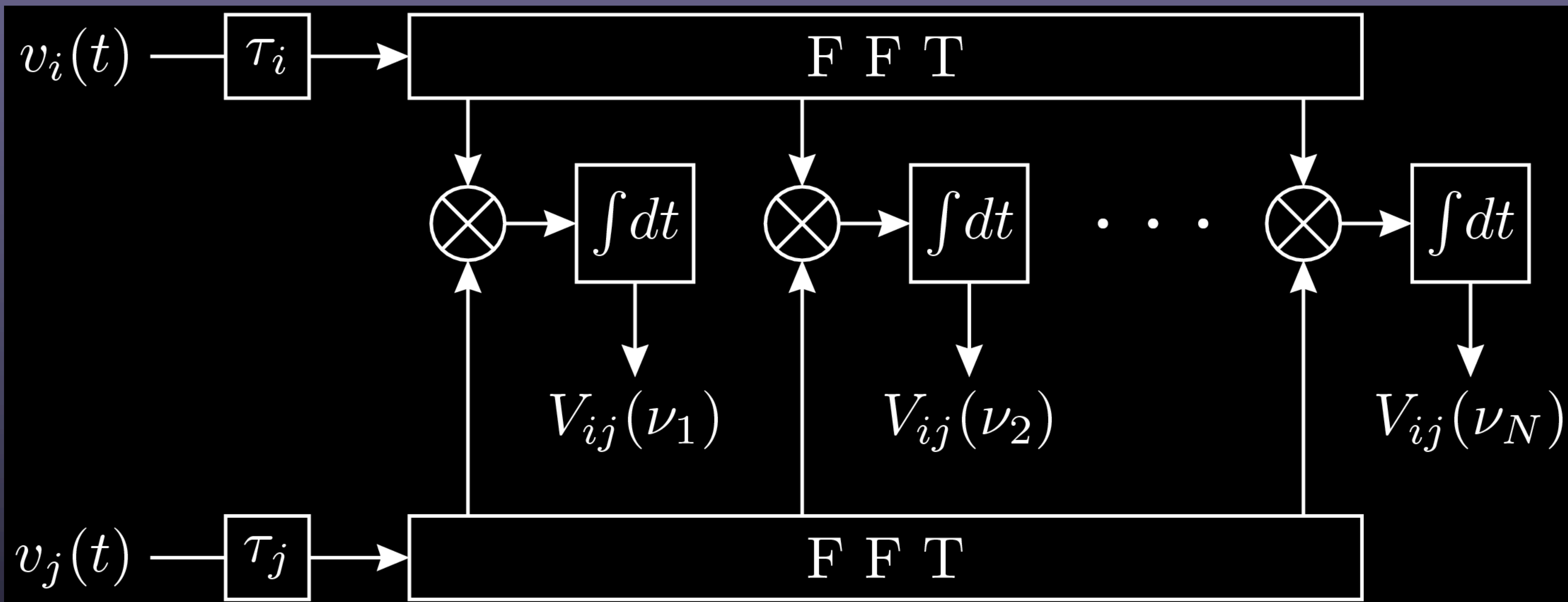
Hanning Smoothing (2)



FX Correlators

- Spectrum is available **before integration**
  - Can apply fractional sample delay per channel
  - Can apply pulsar gate per channel
- Most of the digital parts run *N* times slower than the sample rate
- Fewer computations (compared to XF)

The FX correlator



FX Spectral Response

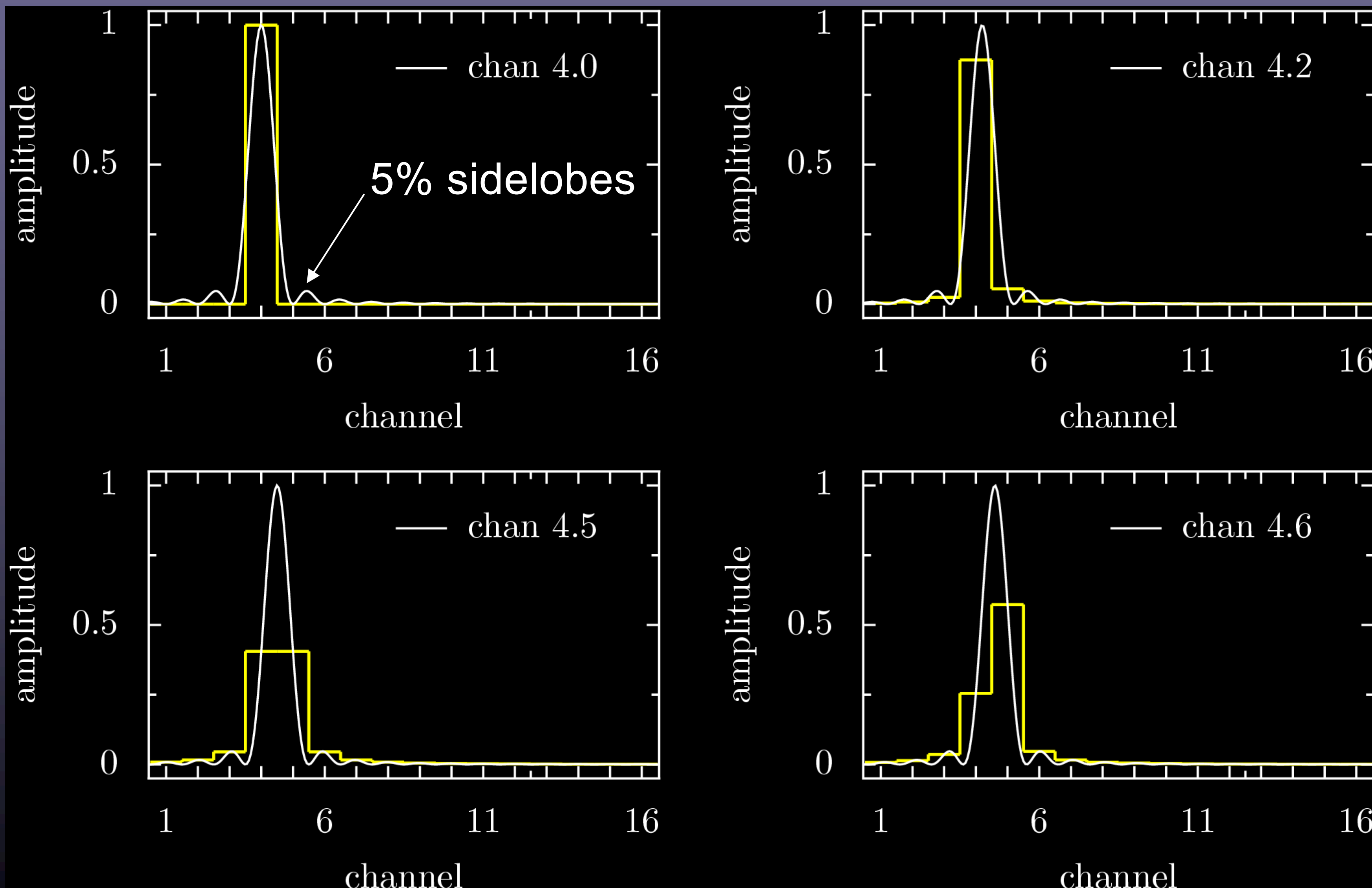
- FX Correlators derive spectra from truncated time series

$$
\begin{aligned}
v(\nu) &= \mathcal{F}\left[v(t)\cdot\sqcap\left(\frac{t}{N\Delta t}\right)\right] \\
&= \mathcal{F}\left[v(t)\right]\star\mathcal{F}\left[\sqcap\left(\frac{t}{N\Delta t}\right)\right] \\
&\propto \mathcal{F}\left[v(t)\right]\star\mathrm{sinc}\left(N\Delta t\nu\right)
\end{aligned}
$$

- Results in convolved visibility spectrum

$$
\begin{aligned}
V_{ij}(\nu) &= \left\langle\left(\mathcal{F}\left[v_i(t)\right]\star\mathrm{sinc}\left(N\Delta t\nu\right)\right)\left(\mathcal{F}\left[v_j(t)\right]\star\mathrm{sinc}\left(N\Delta t\,\nu\right)\right)^*\right\rangle \\
&= \left\langle\mathcal{F}\left[v_i(t)\right]\mathcal{F}\left[v_j(t)\right]^*\right\rangle\star\mathrm{sinc}^2\left(N\Delta t\,\nu\right)
\end{aligned}
$$

FX Spectral Response (2)



Time Series, Sampling, and Quantization

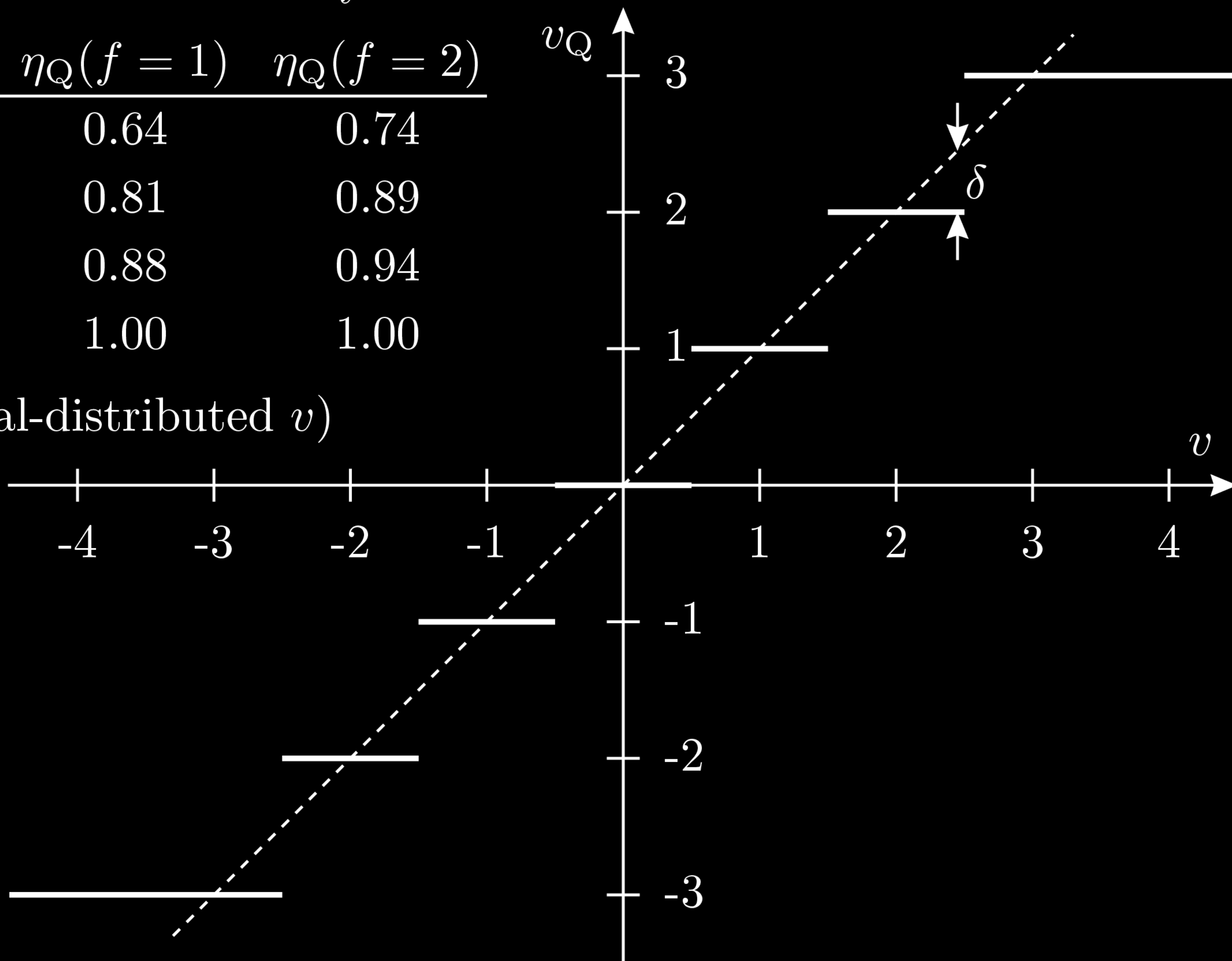
- $\{v_i(t)\}$ are real-valued time series sampled at "uniform" intervals, Δt.
- The sampling theorem allows this to accurately reconstruct a bandwidth of $\Delta\nu = \frac{1}{2\Delta t}$.
- Sampling involves quantization of the signal
  - Quantization noise
  - Strong signals become non-linear
  - Sampling theorem violated!

Quantization Noise

Quantization efficiency

N levels	$\eta_Q(f=1)$	$\eta_Q(f=2)$
2	0.64	0.74
3	0.81	0.89
4	0.88	0.94
∞	1.00	1.00

(For normal-distributed v)



Automatic Gain Control (AGC)

- Normally prior to sampling the amplitude level of each time series is adjusted so that quantization noise is minimized.
- This occurs on timescales very long compared to a sample interval.
- The magnitude of the amplitude is stored so that the true amplitudes can be reconstructed after correlation.

The Correlation Coefficient

- The correlation coefficient, ρ_{ij} measures the likeness of two time series in an amplitude independent manner:

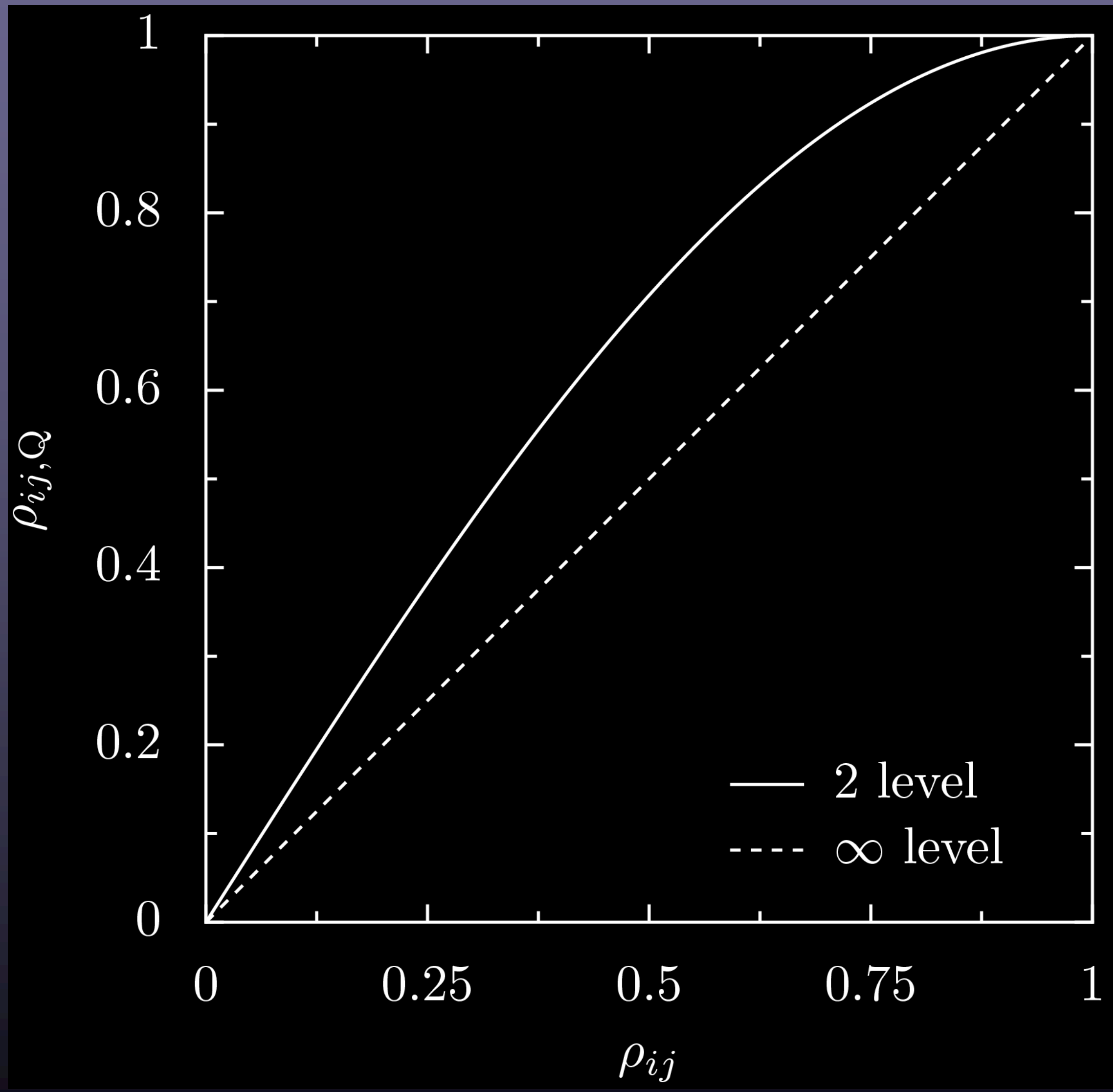
$$\rho_{ij} = \frac{|V_{ij}|}{\sqrt{V_{ii}V_{jj}}}$$

- Normally the correlation coefficient is much less than 1

- Because of AGC, the correlator actually measures the correlation coefficient. The visibility amplitude is restored by dividing by the AGC gain.

Van Vleck Correction

- At low correlation, quantization ***increases correlation***
- Quantization causes predictable non-linearity at high correlation V_{ij}
- Correction must be applied to the real and imaginary parts of separately
  - Thus the visibility phase is affected as well as the amplitude

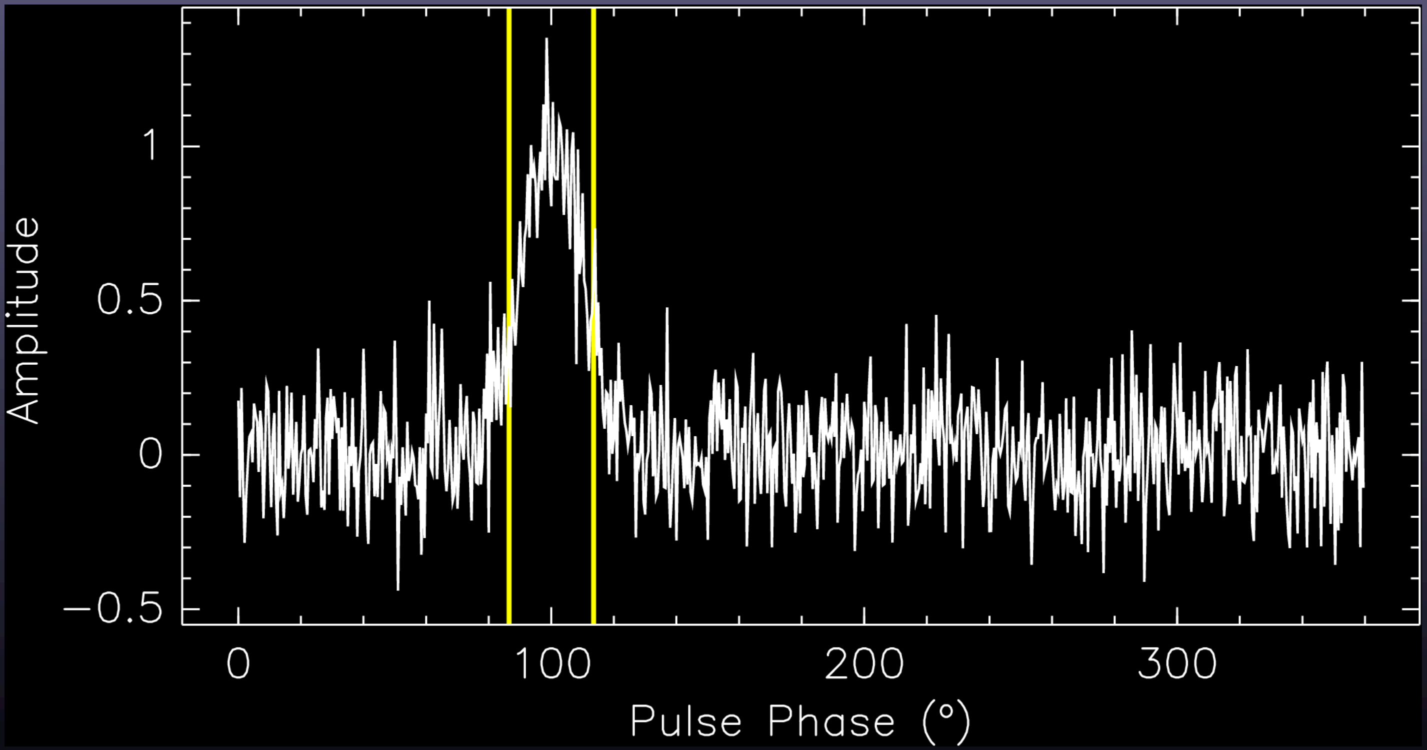


The Delay Model

- τ is the difference between the geometric delays of antenna j and antenna i. It can be + or - .
- The *delay center* moves across the sky
  - τ is changing constantly
- Fringes at the delay center are stopped.
  - Long time integrations can be done
  - Wide bandwidths can be used
- Simple delay models incorporate:
  - Antenna locations
  - Source position
  - Earth orientation
- VLBI delay models must include much more!

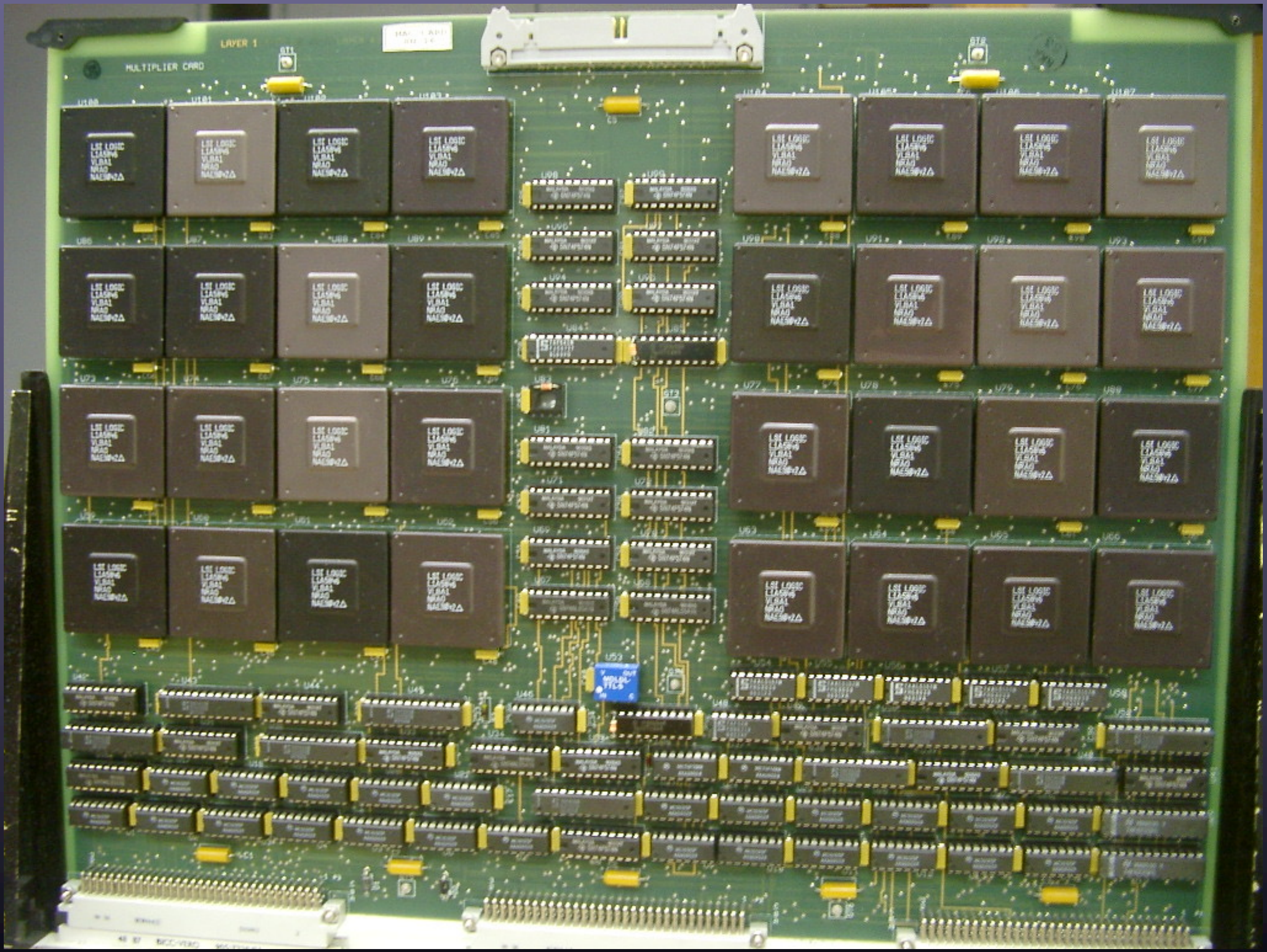
Pulsar Gating

- Pulsars emit regular pulses with small duty cycle
- Period in range 1 ms to 8 s; $\Delta t \ll P_{\mathrm{pulsar}} < T$
- Blanking during off-pulse improves sensitivity
- Propagation delay is frequency dependent

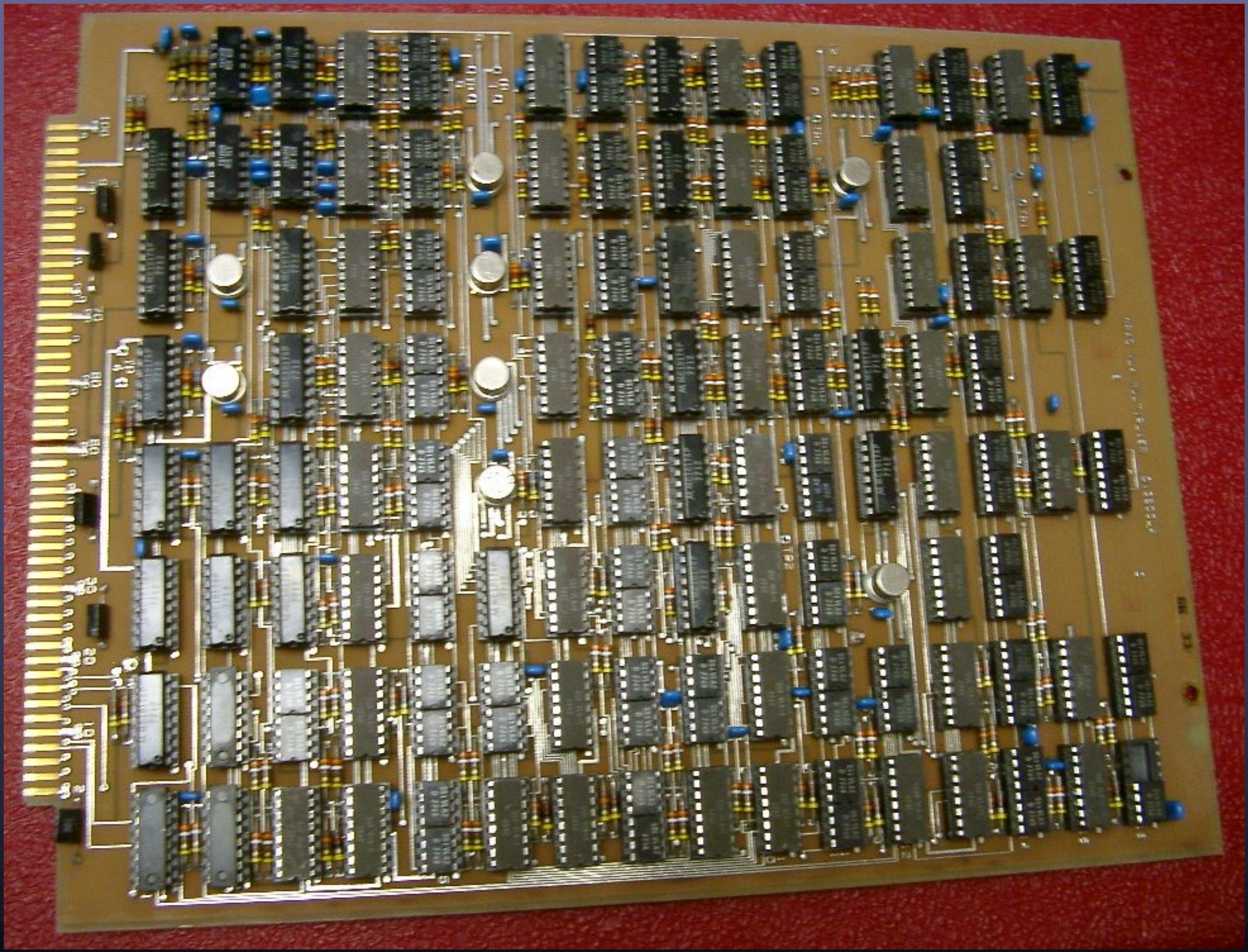


The [old] VLBA Correlator

VLBA Multiply Accumulate (MAC) Card

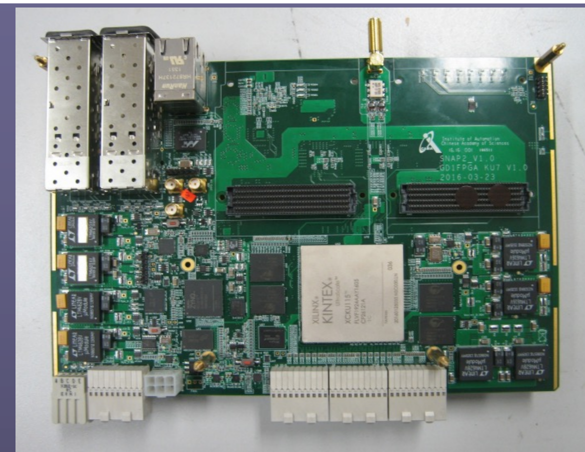


[Old] VLA MAC Card



BEE2-based Correlator

- BEE2: FPGA-based, scalable, modular, upgradeable signal processing system for radio astronomy developed at Berkeley
- ROACH2 boards at LWA-SV
- Being used for several projects
  - 300-station FX correlator for EOR telescope (HERA)
  - 288-station correlator for LWA-OVRO
- Modest hardware cost ($15k/ROACH2 + switch)
  - LWA-SV uses 16 ROACH2 + 7 GPU servers
- Real effort is in the FPGA "firmware"



SNAP2 board

ROACH board

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

The University of New Mexico

Current LWA Correlator

eLWA Correlator Status

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LWA-SV	Running	3 minutes ago
LWA-NA	Running	3 minutes ago

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DA004, 8787	2025/02/20 07:10 UTC	4.529 TB	completed for 1 days, 16:45:10
DA004, 999	2025/02/22 18:00 UTC	3.882 TB	completed for 7:44:35
DA004, 423	2025/02/23 11:34 UTC	3.973 TB	correlating for 2:17:48

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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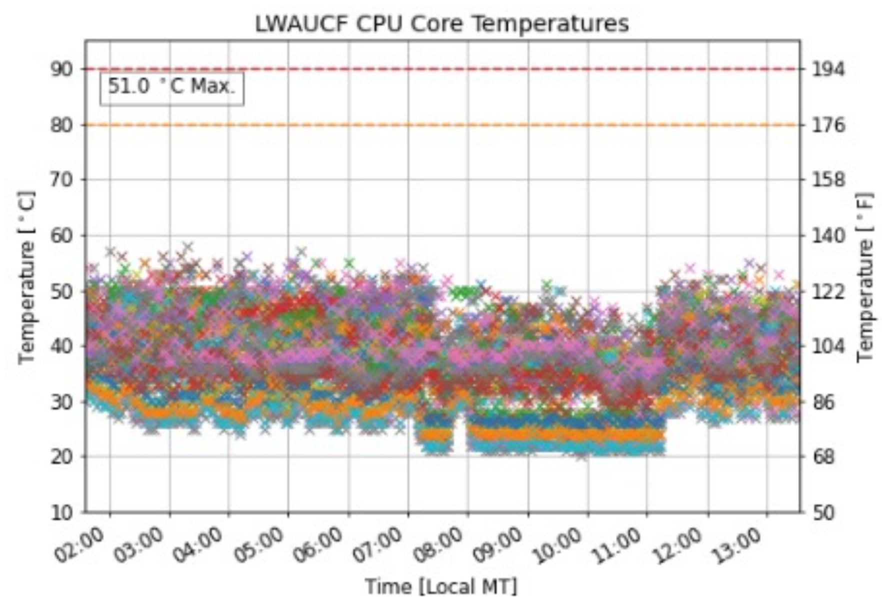
Temperatures



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