Spectral Line Observing I

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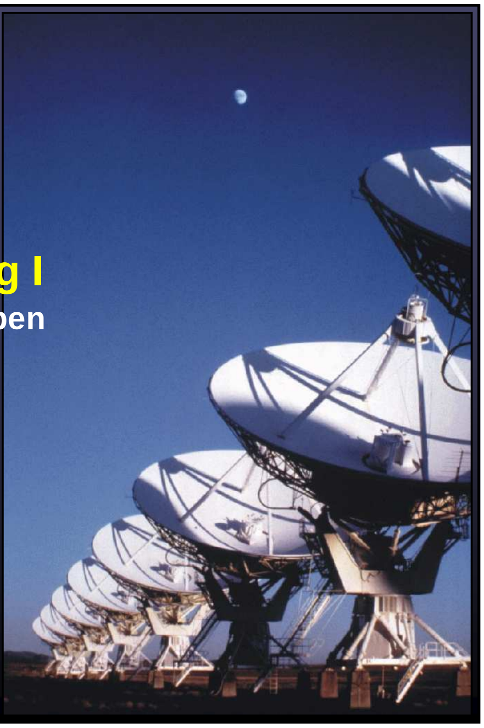
NRAO/Socorro



Tenth Summer Synthesis Imaging Workshop

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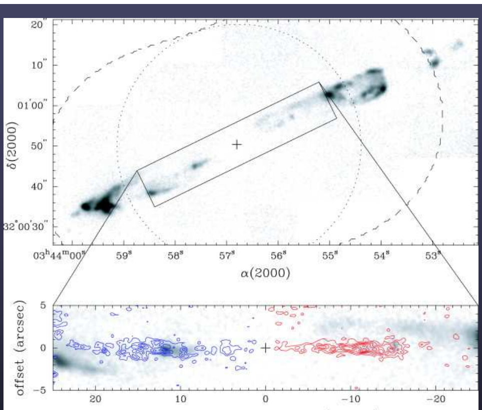
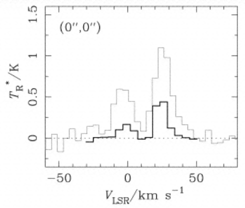
Introduction

- Most of what you have heard about so far has applied to a single spectral channel with some frequency width, $\delta\nu$
- Many astronomical problems require many channels across some total bandwidth, $\Delta\nu$
  - Source contains an emission/absorption line from one of the many atomic or molecular transitions available to radio telescopes (HI, OH, CO, H_2O, SiO, H_2CO, NH_3,…)
  - Source contains continuum emission with a significant spectral slope across $\Delta\nu$
- There are also technical reasons why dividing $\Delta\nu$ into many spectral channels of width $\delta\nu$ may be a good idea

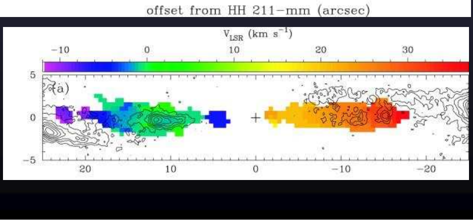
Why you need frequency resolution: spectral lines

- Need sufficient channels to be able to resolve spectral features
  - Example: SiO emission from a protostellar jet imaged with the VLA





Chandler & Richer (2001)



Why you need frequency resolution: spectral lines

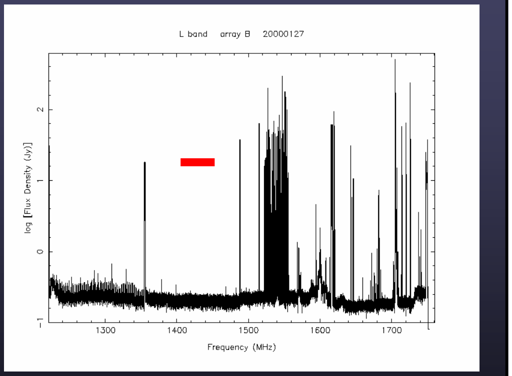
- Requires resolutions as high as a few Hz (SETI, radar), over wide bandwidths (e.g., line searches, multiple lines, Doppler shifts)
- Ideally want many *thousands* of channels – up to millions:
  - ALMA multiple lines: over 8 GHz, < 1km/s resolution~1 MHz $\Rightarrow$ >8,000 channels
  - EVLA HI absorption: 1-1.4 GHz, < 1km/s resolution ~4 kHz $\Rightarrow$ >100,000 channels

Why you need frequency resolution: continuum observations

- Want maximum bandwidth for sensitivity:
  - Thermal noise ∝ 1/sqrt(Δν)
- BUT achieving this sensitivity also requires high spectral resolution:
  - Source contains continuum emission with a significant spectral slope across Δν
  - Contaminating narrowband emission:
    - line emission from the source
    - RFI (radio frequency interference)
  - Changes in the instrument with frequency
  - Changes in the atmosphere with frequency

RFI: Radio Frequency Interference

- Mostly a problem at low frequencies (<4 GHz)
- Getting worse
- Current strategy: avoid
  - Works for narrow bandwidths (e.g., VLA: 50 MHz) or higher frequencies
- Cannot avoid for GHz bandwidths, low frequencies (e.g., VLA 74/330 MHz), or emission lines associated with the source (e.g., OH)
- Can require extensive frequency-dependent flagging of the data during post-processing



RFI at the VLA, 1.2-1.8 GHz

VLA continuum bandwidth:
Δν = 50 MHz

RFI: Radio Frequency Interference

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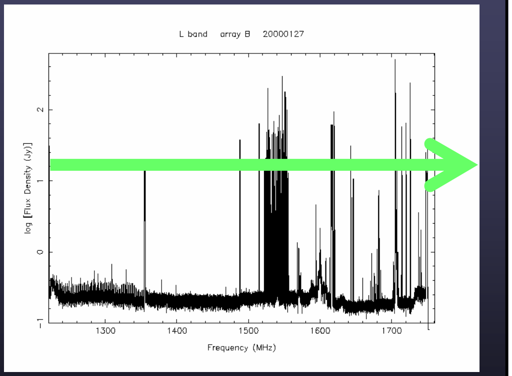
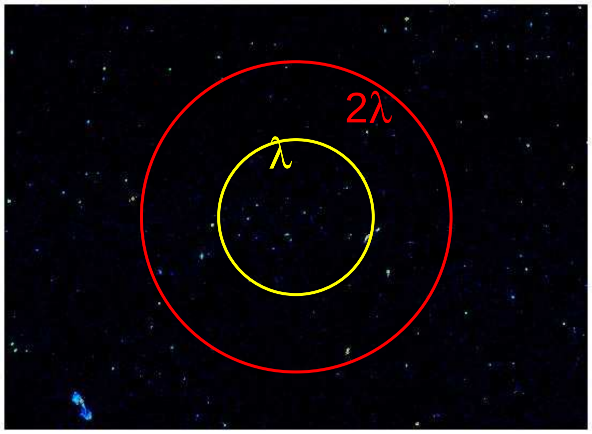


RFI at the VLA, 1.2-1.8 GHz

EVLA: 1.2-2 GHz in one go

Instrument changes with frequency: primary beam/field-of-view

- $\theta_{PB} = \lambda/D$
- Band covers λ_1–λ_2
- θ_{PB} changes by λ_1/λ_2
  - More important at longer wavelengths:
  - VLA 20cm: 1.04
  - VLA 2cm: 1.003
  - EVLA 6cm: 2.0
  - ALMA 1mm: 1.03

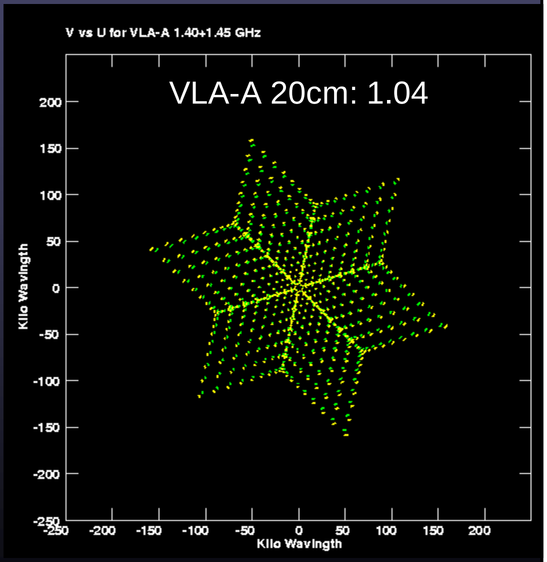


F. Owen

Instrument changes with frequency: bandwidth smearing

- Fringe spacing = λ/B
- Band covers λ_1–λ_2
  - Fringe spacings change by λ_1/λ_2
  - *uv* samples smeared radially
  - More important in larger configurations: remember from Rick's lecture, need

$$\frac{\Delta\nu}{\nu}\frac{\theta}{\theta_{res}} << 1$$



VLA-A 20cm: 1.04

Instrument changes with frequency: bandwidth smearing

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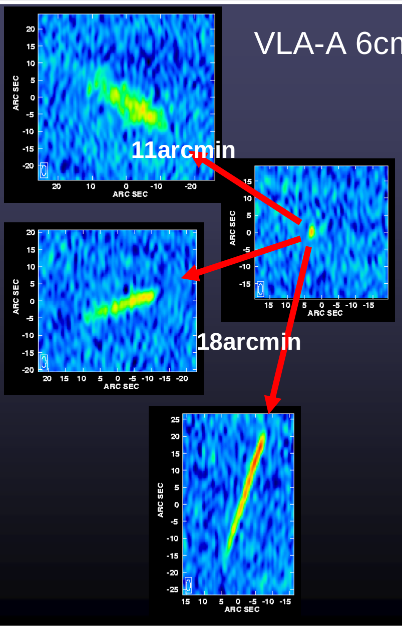
- Produces radial smearing in image

VLA-A 6cm: 1.01



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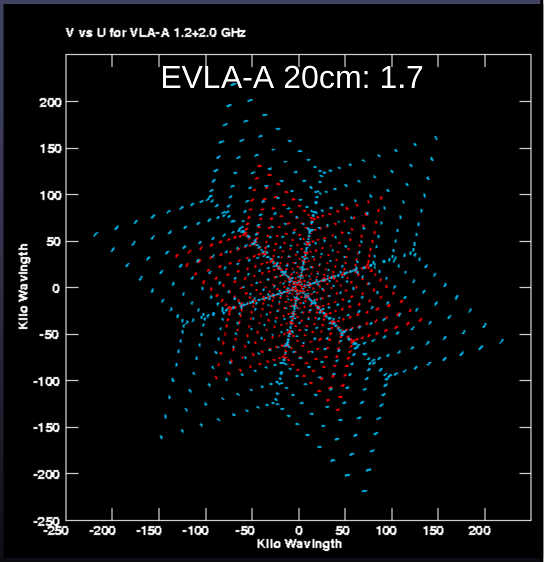
  - More important in larger configurations
- Produces radial smearing in image
- Huge effect for EVLA



Instrument changes with frequency: bandwidth smearing

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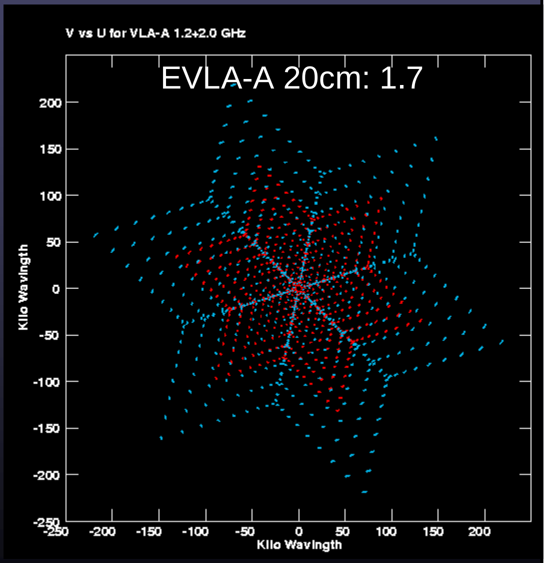
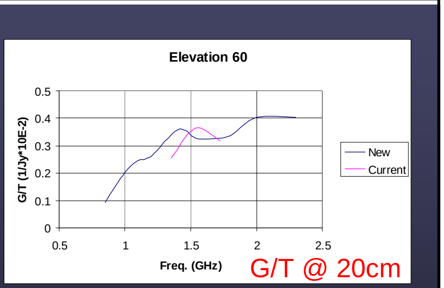
  - More important in larger configurations
- Produces radial smearing in image
- Huge effect for EVLA
- Also a huge plus:

multi-frequency synthesis

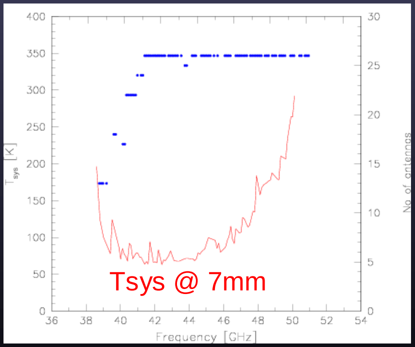


Instrument changes with frequency: calibration issues

- Responses of antenna, receiver, feed are a function of frequency



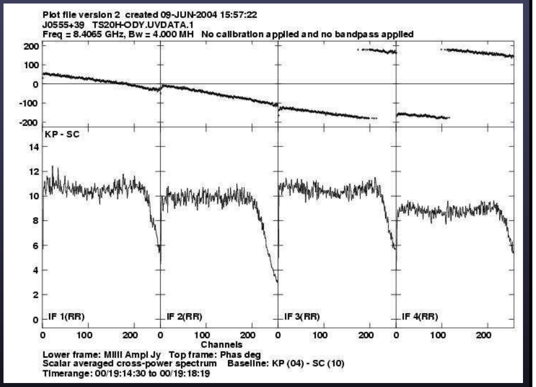
G/T @ 20cm



Tsys @ 7mm

Instrument changes with frequency: calibration issues

- Responses of antenna, receiver, feed are a function of frequency
- Response of electronics a function of frequency
- Phase slopes (delays) can be introduced by incorrect clocks or positions



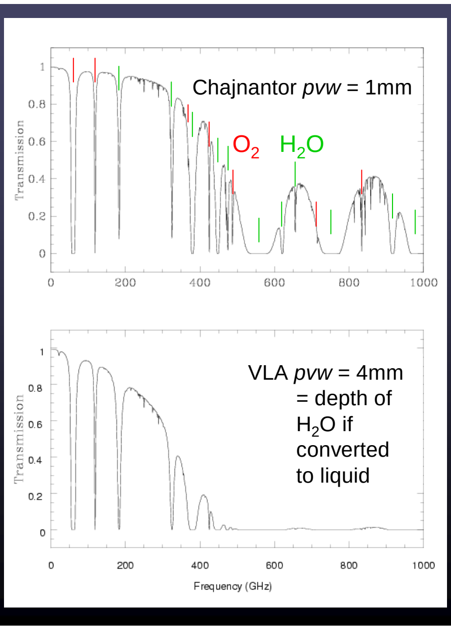
Plot file version 2 created 09-JUN-2004 15:57:22
J0555+39 TS20H-ODY.UVDATA.1
Freq = 8.4065 GHz, Bw = 4.000 MH No calibration applied and no bandpass applied

Lower frame: Milli Ampl Jy Top frame: Phas deg
Scalar averaged cross-power spectrum Baseline: KP (04) - SC (10)
Timerange: 00/19:14:30 to 00/19:18:19

VLBA

Atmosphere changes with frequency

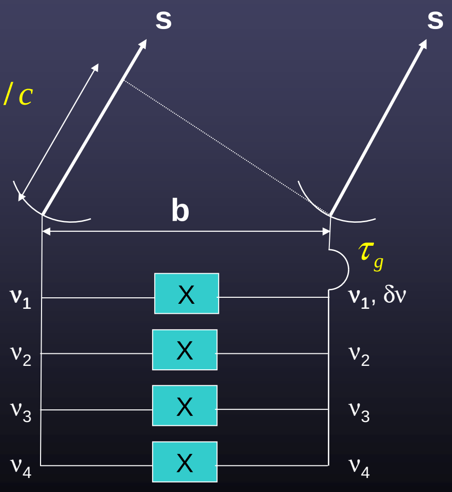
- Atmospheric transmission, phase (delay), and Faraday rotation are functions of frequency
  - Generally only important over very wide bandwidths, or near atmospheric lines
  - Will be an issue for ALMA



Spectroscopy with an interferometer

- Simplest concept: filter banks

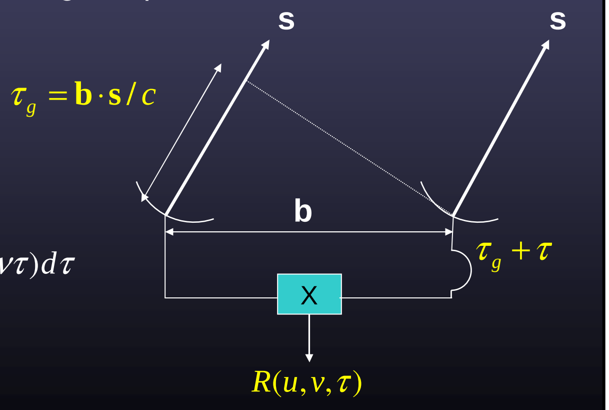
$$\tau_g = \mathbf{b} \cdot \mathbf{s} / c$$



- Output from correlator is $r(u,v,\nu)$
- Very limited in its capabilities scientifically

Spectroscopy with an interferometer

- Lag (XF) correlator: introduce extra lag τ and measure correlation function for many (positive and negative) lags; FT to give spectrum



$$r(u,v,\nu)= \int_{-\infty}^{+\infty} R(u,v,\tau)\exp(-2\pi i\nu\tau)\,d\tau$$

Spectroscopy with an interferometer

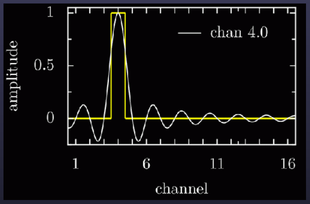
- In practice, measure a finite number of lags, at some fixed lag interval, $\Delta\tau$
- Total frequency bandwidth = $\frac{1}{2\Delta\tau}$
- For N spectral channels have to measure 2N lags (positive and negative), from –NΔτ to +(N–1)Δτ (zero lag included)
- Spectral resolution δν = $\frac{1}{2N\Delta\tau}$ (Nyquist)
- Note: equal spacing in frequency, not velocity
- Very flexible: can adjust N and Δτ to suit your science
- FX correlator: Fourier transform the output from each individual antenna and then correlate (similar in concept to filter banks, but much more flexible)

Trade-offs in an imperfect world

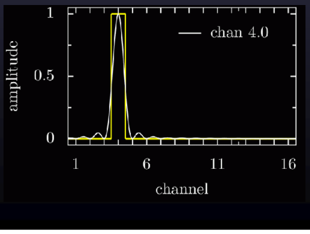
- Because the correlator can only measure a finite number of lags, roughly speaking you can trade off:
  - bandwidth
  - number of channels
  - number of frequency “chunks” (VLA: IFs; VLBA: BBCs)
  - number of polarization products (e.g., RR, LL, LR, RL)
- XF correlators: VLA, EVLA, ALMA
- FX correlators: VLBA

Consequences of measuring a finite number of lags

- Truncated lag spectrum corresponds to multiplying true spectrum by a box function
- In spectral domain, equivalent to convolution with a sinc function
- XF correlators:
  FT is baseline-based,
  ⇒ sinc, 22% sidelobes



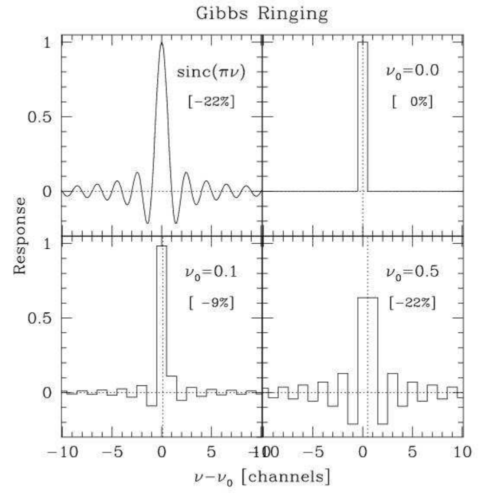
- FX correlators:
  FT is antenna-based
  ⇒ sinc^2, 5% sidelobes



Cf. Walter’s lecture

Spectral response of the correlator: Gibbs ringing

- Produces “ringing” in frequency near sharp transitions: the Gibbs phenomenon
  - Narrow spectral lines
  - Band edges
  - Baseband (zero frequency)
- Noise equivalent bandwidth 1.0 $\delta\nu$ (XF)
- FWHM 1.2 $\delta\nu$ (XF)
- Increasing N does not fix the problem – it merely confines the ringing closer to the sharp features

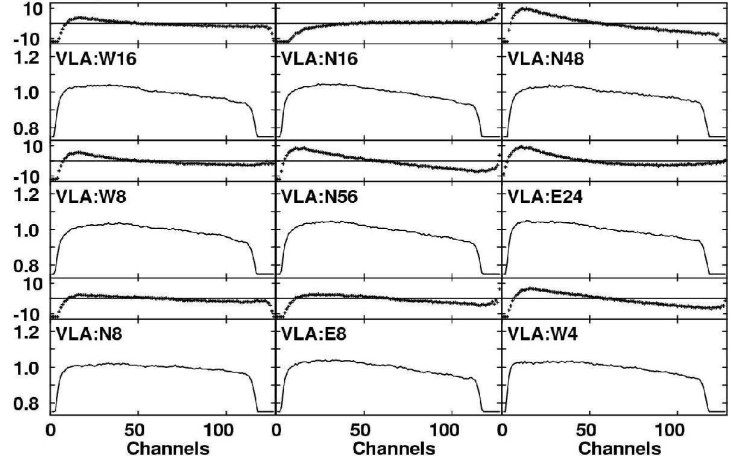


Spectral response of the instrument: bandpass

- Response (gain) of instrument as function of frequency
- Single dish
  - mostly due to standing waves bouncing between the feed and the subreflector
  - can be quite severe, and time variable
- Interferometer
  - standing waves due to receiver noise vanish during cross-correlation
  - residual bandpass due to electronics, IF system, etc. is generally quite stable (exception: VLA “3 MHz” ripple)
  - atmosphere at mm/submm wavelengths

Spectral response of the instrument: bandpass

- Example for 1.4 GHz, VLA



Practical considerations: Hanning smoothing

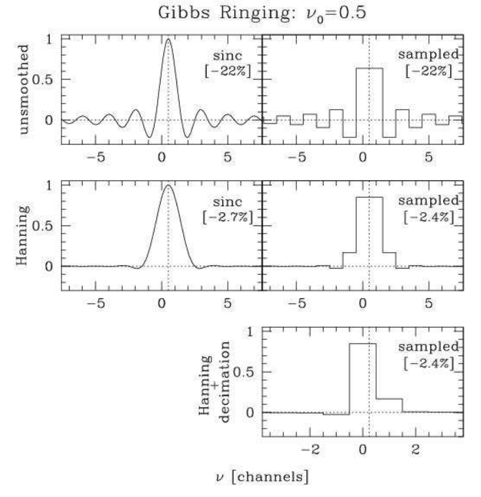
- How to correct for spectral response of the correlator? Weak line ⇒ do nothing; otherwise, smooth the data in frequency (i.e., taper the lag spectrum)
- Most popular approach is to use Hanning smoothing

$$S_h(\nu_i) = \frac{S(\nu_{i-1}) + 2S(\nu_i) + S(\nu_{i+1})}{4}$$

  - Simple
  - Dramatically lowers sidelobes (below 3% for XF)
  - Noise equivalent bandwidth = 2.0 $\delta\nu$ (XF)
  - FWHM = 2.0 $\delta\nu$ (XF)

Practical considerations: Hanning smoothing

- Often discard half the channels
- Note: noise is still correlated. Further smoothing does not lower noise by sqrt(N_{chan})
- Can request "online" Hanning smoothing with VLA, but can also smooth during post-processing



Practical considerations: measuring the bandpass

- Overall gains can vary quite rapidly, but can be measured easily
- Bandpass varies slowly (usually), but requires good S/N in narrow channels
- Separate time and frequency dependence:

$$\mathcal{J}_{ij}(\nu,t) = \mathcal{B}_{ij}(\nu)\ \mathcal{G}_{ij}(t)$$

- Bandpass is the *relative* gain of an antenna/baseline as a function of frequency
  - Often we explicitly divide the bandpass data by the continuum, which also removes atmospheric and source structure effects

Measuring the bandpass

- Requires a strong source with known frequency dependence (currently, most schemes assume flat)
- Autocorrelation bandpasses
  - Amplitude only (cannot determine phase)
  - Vulnerable to usual single-dish problems
- Noise source
  - Very high S/N, allows baseline-based determinations
  - Does not follow same signal path as the astronomical signal
  - Difficult to remove any frequency structure due to the noise source itself
- Astronomical sources
  - Strong sources may not be available (problem at high frequencies)

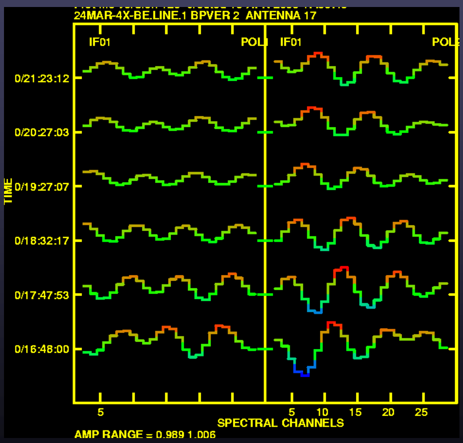
Measuring the bandpass

- Main difficulty currently is accurate measurement in narrow channels, and achieving sufficient S/N
- How to define “sufficient”?
  - To correct for the shape of the bandpass every complex visibility spectrum will be divided by a complex (baseline-based) bandpass, so the noise from the bandpass measurement degrades all the data
  - For astronomical bandpass measurements, need to spend enough integration time on the bandpass calibrator so that $(S/N)_{bpcal} > (S/N)_{source}$
- May need multiple observations to track time variability

Measuring the bandpass

- VLA “3 MHz ripple” due to standing waves in the waveguide
- E.g.: VLA antenna 17 amplitude, X-Band
- Magnitude ~ 0.5%
- Typical for all VLA antennas

Amplitude



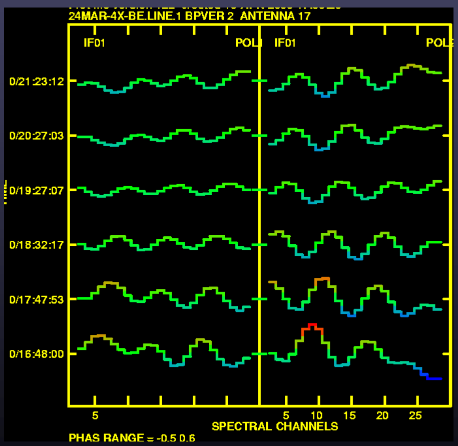
RCP LCP

Measuring the bandpass

- VLA ripple in phase
- Magnitude ~ 0.5 degrees
- For spectral dynamic ranges >100 need to observe BP calibrator every hour
- For the EVLA this will be much less of a problem

For more details on solving for and applying the bandpass calibration see Lynn’s lecture

Phase



RCP LCP

Doppler tracking

- Can apply a Doppler correction in real time to track a particular spectral line in a given reference frame
  - E.g., Local Standard of Rest (LSR), solar system barycentric
  - $v_{radio}/c = (\nu_{rest}-\nu_{obs})/\nu_{rest}$
  - $v_{opt}/c = (\nu_{rest}-\nu_{obs})/\nu_{obs}$
- Remember, the bandpass response is a function of *frequency* not velocity
- Applying online Doppler tracking introduces a time-dependent AND position-dependent frequency shift – Doppler tracking your bandpass calibrator to the same velocity as your source will give a different *sky* frequency for both

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Doppler tracking

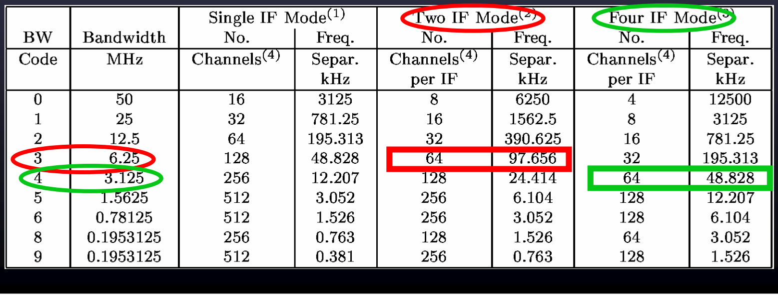
- For high spectral dynamic range, do not Doppler track – apply corrections during post-processing
- Future: online Doppler tracking will probably not be used for wide bandwidths
  - Tracking will be correct for only one frequency within the band and the rest will have to be corrected during post-processing in any case

Special topics

- Multiple sub-bands: best to overlap
- Polarization bandpasses: there are strong frequency dependences

Correlator set-ups: bandwidth coverage and velocity resolution

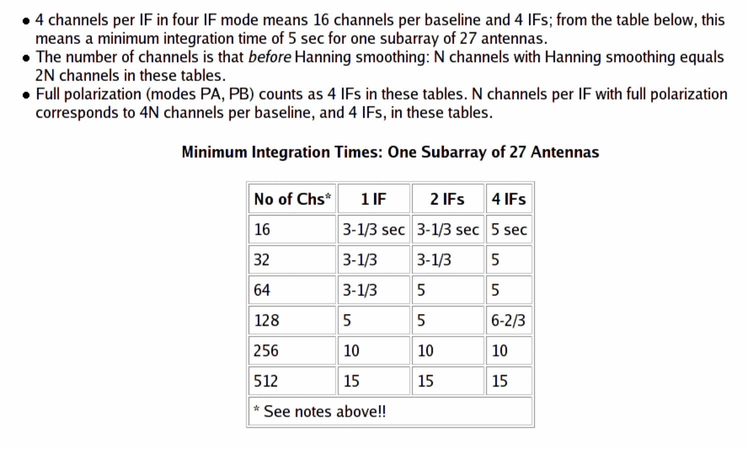
- VLA example, HI in a group of galaxies: need velocity coverage >1000 km/s plus some line-free channels for continuum, centered at ν = 1.4 GHz
  - Require total bandwidth νΔv/c > 5 MHz
- Dual polarization for sensitivity (RR+LL)
  - Either **1 IF pair** @ 6.25 MHz with 98 kHz = 21 km/s resolution
  - Or **2 overlapping IF pairs** @ 3.125 MHz (4 IF products total) with 49 kHz = 10.5 km/s resolution



		Single IF Mode(1)		Two IF Mode(2)		Four IF Mode(3)	
BW Code	Bandwidth MHz	No. Channels(4)	Freq. Separ. kHz	No. Channels(4) per IF	Freq. Separ. kHz	No. Channels(4) per IF	Freq. Separ. kHz
0	50	16	3125	8	6250	4	12500
1	25	32	781.25	16	1562.5	8	3125
2	12.5	64	195.313	32	390.625	16	781.25
3	6.25	128	48.828	64	97.656	32	195.313
4	3.125	256	12.207	128	24.414	64	48.828
5	1.5625	512	3.052	256	6.104	128	12.207
6	0.78125	512	1.526	256	3.052	128	6.104
8	0.1953125	256	0.763	128	1.526	64	3.052
9	0.1953125	512	0.381	256	0.763	128	1.526

Minimum integration time for the VLA

- The VLA correlator cannot cope with high data rates, so there is a minimum integration time you can have for a given number of channels (this will be much less of a problem with the EVLA):



- 4 channels per IF in four IF mode means 16 channels per baseline and 4 IFs; from the table below, this means a minimum integration time of 5 sec for one subarray of 27 antennas.
- The number of channels is that *before* Hanning smoothing: N channels with Hanning smoothing equals 2N channels in these tables.
- Full polarization (modes PA, PB) counts as 4 IFs in these tables. N channels per IF with full polarization corresponds to 4N channels per baseline, and 4 IFs, in these tables.

Minimum Integration Times: One Subarray of 27 Antennas

No of Chs*	1 IF	2 IFs	4 IFs
16	3-1/3 sec	3-1/3 sec	5 sec
32	3-1/3	3-1/3	5
64	3-1/3	5	5
128	5	5	6-2/3
256	10	10	10
512	15	15	15
* See notes above!!			

The future

- 8 GHz instantaneous bandwidths, 2:1 frequency coverage in a single observation
- Correlators with many thousands of channels
- Every experiment will be a “spectral line” experiment
  - Remove RFI
  - Track atmospheric and instrumental gain variations
  - Minimize bandwidth smearing
  - Allow multi-frequency synthesis, and spectral imaging
  - Interferometric line searches/surveys: astrochemistry, high-redshift galaxies
  - Avoid line contamination (find line-free continuum)