Spectral Line Observing I

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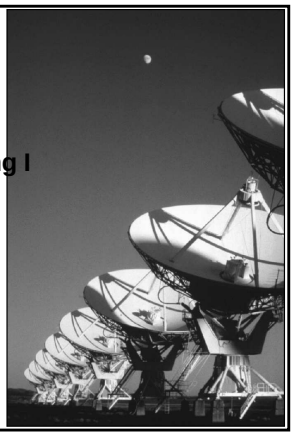


Ninth Synthesis Imaging Summer School
Socorro, June 15-22, 2004

Outline

- Definition & change of title
- Why you need spectral resolution
- Tradeoffs in an imperfect world
- Instrumental response
- Calibration
- Summary

Definition and Change of Title

- Spectral line observations were originally observations of spectral lines (!)
- Nowadays folks talk about observing in "spectral line mode"

➔Multi-channel Observations

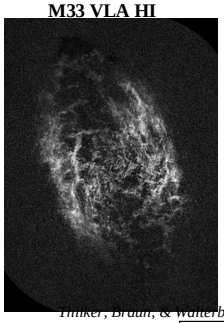
…whatever the scientific rationale

- So: Spectral Line I → Multi-channel Observations
  Spectral Line II → Spectral Line Observations
- In the future,
  all observations will be taken in this mode!

Why you need frequency resolution: spectral lines

- Narrow spectral features
  - spectral lines: spin-flip (HI), recombination lines, rotational/vibrational lines (CO, NH_3, SO, …), masers
    - particularly important in mm/submm (PdBI, SMA, ALMA)
  - artificial signals: satellites, SETI

M33 VLA HI



Thilker, Braun, & Walterbos

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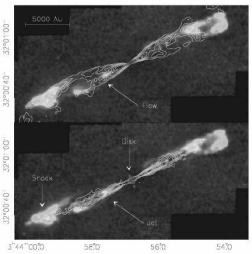
HH211 PdBI CO



Gueth & Guilloteau 1999

Why you need frequency resolution: spectral lines

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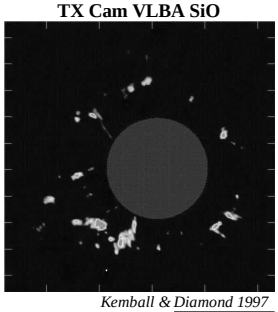
  - artificial signals: satellites, SETI

TX Cam VLBA SiO



Kemball & Diamond 1997

Why you need frequency resolution: spectral lines

7

→requires resolutions as high as a few Hz (SETI, radar), over wide bandwidths (e.g., line searches, multiple lines, Doppler shifts)

→the ideal is many *thousands* of channels – up to millions…

- ALMA multiple lines: over 8 GHz, < 1km/s resolution~1 MHz
  → >8,000 channels
- EVLA HI absorption: 1-1.4 GHz, < 1km/s resolution ~4 kHz
  → >100,000 channels

Why you need frequency resolution: continuum observations

8

- Want maximum bandwidth for sensitivity:
  rms goes as 1/sqrt($\Delta\nu$)
- BUT achieving this sensitivity also requires high spectral resolution:
  - RFI (radio frequency interference)
  - changes in the instrument with frequency
  - changes in the atmosphere with frequency
  - changes in the sources with frequency
  - finding line-free zones

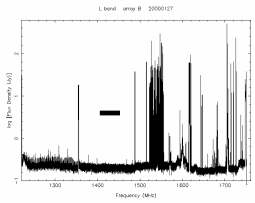
RFI: Radio Frequency Interference

9

- 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
- Can't avoid for GHz bandwidths, low frequencies, or specific lines (e.g., OH)

→frequency-dependent flagging

- e.g., VLA 74/330 MHz



Current VLA, 1.2-1.8 GHz

RFI: Radio Frequency Interference

10

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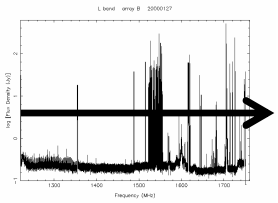
→frequency-dependent flagging

- e.g., VLA 74/330 MHz
- EVLA: 1.2-2 GHz in one go



Current VLA, 1.2-1.8 GHz

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

11

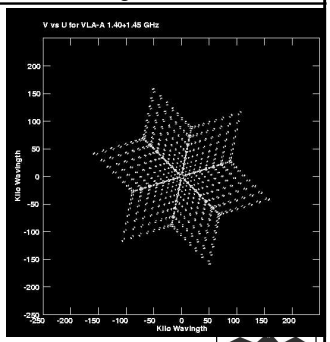
- Primary beam: λ/D
- Band covers λ_1 - λ_2
  → PB changes by
  λ_1/λ_2
- More important at longer wavelengths
  (also more sources)
  - VLA 20cm: 1.4 (1.04)
  - VLA 2cm: 1.05
  - EVLA 20-6cm: 2.0
  - ALMA 1mm: 1.35 (1.03)

F. Owen

Instrument changes with frequency: bandwidth smearing

12

- Interferometric baselines:
  B/λ
- Band covers λ_1 - λ_2
  → baseline changes by
  λ_1/λ_2
  →uv smeared radially
  →more important in larger configurations



Instrument changes with frequency: bandwidth smearing

13

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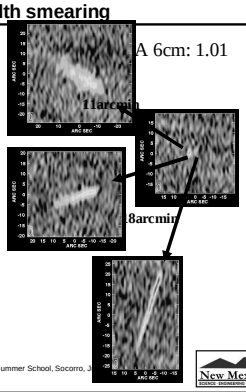
- Produces radial smearing in image



Instrument changes with frequency: bandwidth smearing

14

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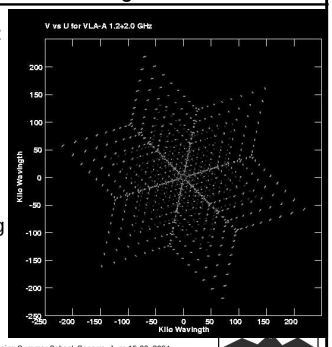
- Produces radial smearing in image
- Huge effect for EVLA

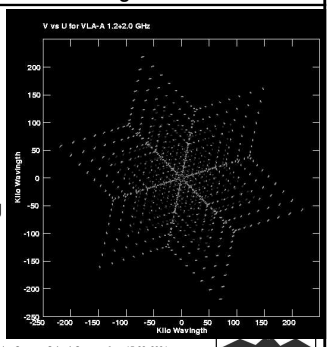


Instrument changes with frequency: bandwidth smearing

15

- Interferometric baselines: B/λ
- Band covers λ_1 - λ_2
  - → baseline changes by
    - λ_1/λ_2
  - →uv smeared radially
  - →more important in larger configurations
- Produces radial smearing in image
- Huge effect for EVLA
- Also a huge plus:

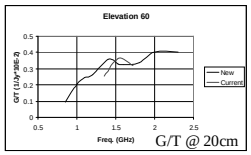
multi-frequency synthesis

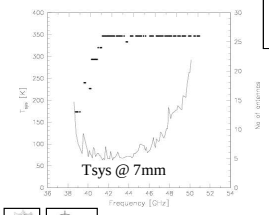


Instrument changes with frequency: calibration issues

16

- Responses of antenna, receiver, feed change with frequency

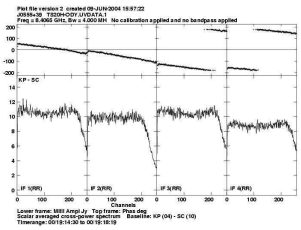




Instrument changes with frequency: calibration issues

17

- Responses of antenna, receiver, feed change with frequency
- Phase slopes (delays) due to incorrect clocks or positions
  - – prime source of non-closing errors (cf. high dynamic range imaging)

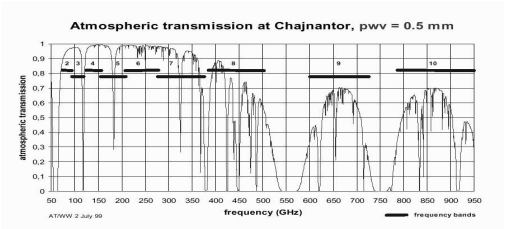


VLBA

Atmosphere changes with frequency

18

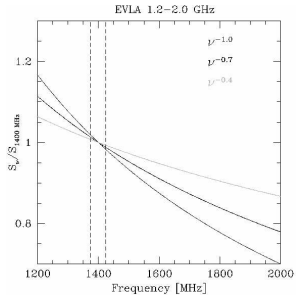
- Opacity, phase (delay), and Faraday rotation change with frequency
  - – generally only important over very wide bandwidths, or near atmospheric lines
  - – an issue for ALMA



Source changes with frequency

19

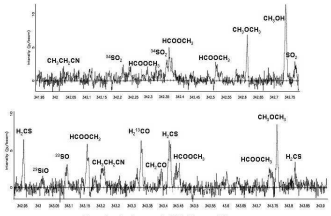
- Continuum is *not* flat (spectral index, spectral curvature), and spectral shape varies from source to source
- Polarized emission: Faraday rotation goes as λ^2
- Annoyances…or scientific opportunities!



Finding line-free zones: spotting the ground under the forest

20

A Hot Core Forest: G12.89+0.49



342 to 344 GHz with the SMA

Forest only observed with high resolution

Brogan & Shirley 2004

The cost of frequency resolution

21

- Hardware
  - LO system: requires flexible frequency tuning & tracking
  - **correlator:** requires more lags → bigger, faster, more expensive
- Software & data analysis
  - amount of data scales as N_{chan}
  - have to deal with all those complications (changing primary beam, uv-coverage, source structure/strength, etc.)
  - seldom simply treat channels independently
    - inefficient and slow: most effects vary smoothly with frequency
    - spectral line: relies on channel-to-channel comparisons → want to put off non-linear algorithms (e.g., deconvolution) as long as possible
    - continuum: interesting parameters (e.g., flux density distribution) are broad-band, and better determined by intelligently using *all* the data at once

Tradeoffs in an imperfect world

22

- Frequency "chunks" (VLA: IFs; VLBA: BBCs) are not infinitely wide
  → separate processing and worries about overlaps
- Correlators are not infinite. Roughly speaking, you can trade off:
  - bandwidth
  - number of channels
  - number of frequency chunks
  - number of polarization products (e.g., RR, LL, LR, RL)
  with certain ancillary restrictions (e.g., how fast data can be written to disk)
- There are additional complications, depending on the cleverness of the correlator engineers (e.g., recirculation)

➔Programming the correlator is a nightmare

➔Choosing the mode you want can be painful

Tradeoffs in an imperfect world: HI in a group of galaxies at the VLA

23

- Bandwidth: >1000 km/s of signal plus **line-free chunk**
  → > 4.7 MHz
- Dual polarization for sensitivity (RR+LL)

➔either

- **1 IF pair** @ 6.25 MHz with 98 kHz= 21 km/s channel sep'n, or
- **2 overlapping IF pairs** @ 3.125 MHz (4 IF products total) with 48 kHz= 10 km/s channel sep'n

BW	Bandwidth	Single IF Mode(1)		Two IF Mode(2)		Four IF Mode(3)	
		No.	Freq.	No.	Freq.	No.	Freq.
Code	MHz	Channels(4)	Separ. kHz	Channels(4) per IF	Separ. kHz	Channels(4) per IF	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

Spectral response

24

- Digital correlators work by a combination of cross-correlation & Fourier transform
- We don't measure an infinite number of Fourier component
  - we don't want to wait forever, so we truncate the lag spectrum
  - we don't have infinitely large correlators
- Truncated lag spectrum corresponds to multiplying true spectrum by box function

➔Spectral response is (sampled) FT of box:

XF correlators: VLA, EVLA, ALMA-I

$\sin \pi x/\pi x$ 22% sidelobes!

FX correlators: VLBA

$(\sin \pi x/\pi x)^2$ 5% sidelobes

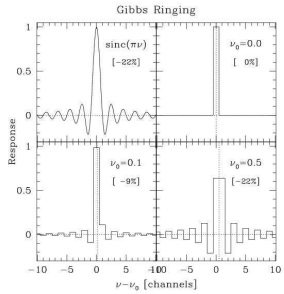
Spectral response: Gibbs ringing

25

- Produces "ringing" in frequency near sharp transitions: the Gibbs phenomenon
  - narrow spectral lines (e.g., masers)
  - band edges
  - baseband (zero frequency)
- Noise equivalent bandwidth:

  1.0 Δν (XF)

  FWHM: 1.2 Δν (XF)



Spectral response: Gibbs ringing

26

- Possible cures:
  - lots of channels (if available, and if you don't care about the spectrum near sharp transitions)
  - keep track of the spectral response during data reduction/analysis
  - smooth the data in frequency (i.e., taper the lag spectrum)
- Most popular approach is Hanning smoothing:

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

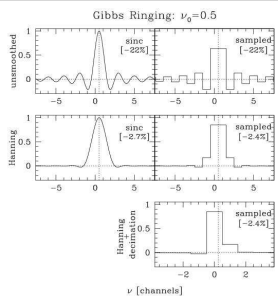
  - simple
  - dramatically lowers sidelobes (below 3% for XF)
  - noise equivalent bandwidth= 2.0 Δν (XF)

    FWHM= 2.0 Δν (XF)

Spectral response: spectral smoothing

27

  - often discard half the channels
  - N.B. noise is still correlated!!! so further smoothing does *not* lower noise by sqrt(N_{chan}) (cf. Juan Uson)



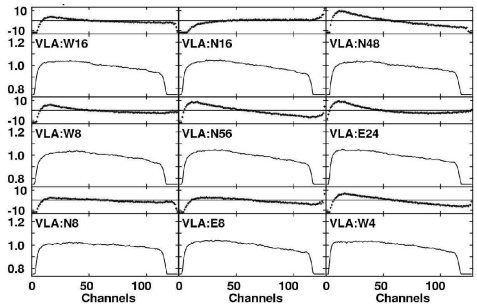
Calibration: the bandpass

28

- 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

Calibration: VLA 1.4 GHz bandpass example

29



Calibration: splitting time & frequency

30

- overall gains can vary quite rapidly, but can be measured easily
- bandpass varies slowly, but requires good SNR in narrow channels

➔separate time and frequency dependence:

$$\mathcal{G}_{ij}(\nu,t) = \mathcal{G}'_{ij}(t)\ \mathcal{B}_{ij}(\nu,t)$$

➔bandpass is *relative* gain of antenna/baseline with frequency.

- Often we explicitly divide the line data by the continuum, which also removes atmospheric and source structure effects.

Calibration: measuring the bandpass

31

- Requires a strong source with known frequency dependence [currently, most schemes assume flat]
- Autocorrelation bandpasses
  - amplitude only (don't determine phase)
  - vulnerable to usual single-dish problems
- Noise source (noise tubes)
  - huge signal → allows baseline-based determinations
  - don't follow same signal path as astronomical signal
  - difficult to remove all frequency structure from noise source
- Astronomical sources
  - strong ones may not be available (esp. at high frequencies)

Calibration: measuring the bandpass

32

- Main difficulty currently is accurate measurement in narrow channels (low SNR)
- Various techniques for improving SNR:
  - solve for antenna-based gains, as in classic self-calibration (AIPS: BPASS)
  - assume bandpass is smooth: smooth the data or the solutions (AIPS: BPASS), or fit some functional form (e.g., polynomial) (AIPS: CPASS)
  - Two-step approach (PdBI, ALMA): remove rapid frequency variations via noise source; then use astronomical sources for lower-order variations

Calibration: dividing by channel 0

33

Deriving the gains $\mathcal{G}'_{ij}(t)$ $\mathcal{B}_{ij}(\nu,t)$ from the observed visibilities $\mathcal{V}obs_{ij}(\nu,t)$ requires some model for the source $\mathcal{V}'_{ij}(\nu,t)$:

$$\mathcal{V}'_{ij}(\nu,t) = \mathcal{G}'_{ij}(t)\ \mathcal{B}_{ij}(\nu,t)\ \mathcal{V}obs_{ij}(\nu,t)$$

If the source is a noise tube or a point-like calibrator, $\mathcal{V}'_{ij}(\nu,t)$ is *constant* over time, and (hopefully!) known over frequency.

If not, we can still derive a model for the source visibilities based on the line-free channels.

In the simplest case that model is simply the average of the line-free visibilities (called the Channel 0 data in AIPS)

$$\mathcal{V}mod_{ij}(t)/\mathcal{G}'_{ij}(t) = \Sigma_{\nu,\ line\text{-}free}\ \mathcal{V}obs_{ij}(\nu,t)$$

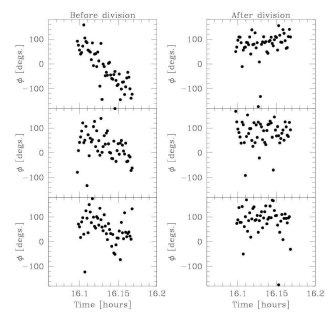
and the bandpass $\mathcal{B}_{ij}(\nu,t)$ is chosen to make

$$\mathcal{V}mod_{ij}(t)/\mathcal{G}'_{ij}(t) = \mathcal{B}_{ij}(\nu,t)\ \mathcal{V}obs_{ij}(\nu,t)$$

Note that this effectively removes both source structure & a changing atmosphere!

Calibration: dividing by channel 0

34



VLA
D config.
1.3cm

Spectral line bandpass: Get it right!

35

- Because $\mathcal{G}'_{ij}(t)$ and $\mathcal{B}_{ij}(\nu,t)$ are separable, multiplicative errors in $\mathcal{G}'_{ij}(t)$ (including phase and gain calibration errors) can be reduced by subtracting structure in line-free channels. Residual errors will scale with the peak remaining flux.
- Not true for $\mathcal{B}_{ij}(\nu,t)$. Any errors in bandpass calibration will always be in your data. Residual errors will scale like peak flux densities in your observed field.

Special topics

36

- Doppler tracking → time-variable frequency, or correct after the fact
  - n.b. gains are function of FREQUENCY, *not* velocity!
- Multiple sub-bands: best to overlap
- Double sub-bands (mostly mm)
- T_{sys} effects of strong lines
- Polarization bandpasses (there *are* strong frequency dependences!)

The future

- 8 GHz bandwidths, and 2:1 frequency coverage in a single observation
- Many thousands of channels
- Extreme frequencies (10s of MHz to THz)

➔every experiment will be a spectral line experiment:

- ✓remove RFI
- ✓track atmospheric & instrumental gain variations
- ✓minimize bandwidth smearing
- ✓allow multi-frequency synthesis, and spectral imaging
- ✓interferometric line searches/surveys
- ✓avoid line contamination
- ✓stack lines (e.g., RRL) to lower the noise

➔a whole new world!