Spectral Line Observing

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Introduction

• Spectral line observers use many channels of width $\delta \nu$, over a total bandwidth $\Delta \nu$. Why?

• Science driven: science depends on frequency (spectroscopy)
  – Emission and absorption lines, and their Doppler shifts
  – Slope across continuum bandwidth

• Technical reasons: science does not depend on frequency (pseudo-continuum)
• Need high spectral resolution to resolve spectral features
  – Example: SiO emission from a protostellar jet imaged with the VLA (Chandler & Richer 2001).

• High resolutions over large bandwidths are useful for e.g., doppler shifts and line searches => many channels desirable!
Pseudo-continuum

• Science does not depend on frequency, but using spectral line mode is favorable to correct for some instrumental responses:
  – Avoid limitations of bandwidth smearing
  – Avoid limitations of beam smearing
  – Avoid problems due to atmospheric changes as a function of frequency
  – Avoid problems due to signal transmission effects as a function of frequency

• A spectral line mode also allows editing for unwanted, narrow-band interference.
Instrument response: beam smearing

- $\theta_{PB} = \lambda/D$

- Band covers $\lambda_1$ to $\lambda_2$
  $\Rightarrow \theta_{PB}$ changes by $\lambda_1/\lambda_2$

- More important at longer wavelengths:
  - VLA 20cm: 1.04
  - VLA 2cm: 1.003
  - EVLA 20cm: 2.0
  - ALMA 1mm: 1.03

F. Owen
Instrument response: bandwidth smearing

- Also called chromatic aberration
- Fringe spacing = $\lambda/B$
- Band covers $\lambda_1$ to $\lambda_2$
  - Fringe spacings change by $\lambda_1/\lambda_2$
  - $uv$ samples smeared radially
  - More important in larger configurations, and for lower frequencies
- Huge effects for EVLA

Pseudo-continuum uses smaller ranges to be averaged later.
Instrument frequency response

- Responses of antenna receiver, feed, IF transmission lines, electronics are a function of frequency.

- Phase slopes (delays) can be introduced by incorrect clocks or positions.

Tsys @ 7mm VLA

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
  - An issue for ALMA

Chajnantor $p_{vw} = 1$mm

VLA $p_{vw} = 4$mm

$O_2$, $H_2O$

$= depth of H_2O if converted to liquid$
Radio Frequency Interference (RFI)

- Avoid known RFI if possible, e.g. by constraining your bandwidth.
- Possible in some cases but not always.

RFI at the VLA, 1.2-1.8 GHz

VLA continuum bandwidth: 50 MHz

RFI at MK, 1.6 GHz

EVLA: 1.2-2 GHz in one go
Observations: data editing and calibration

- Not fundamentally different from continuum observations, but a few additional items to consider:
  - Presence of RFI (data flagging)
  - Bandpass calibration
  - Doppler corrections
  - Correlator setup
  - Larger data sets
Editing spectral line data

• Start with identifying problems affecting all channels, by using a frequency averaged 'Channel 0' data set.
  – Has better SNR.
  – Copy flag table to the line data.

• Continue with checking the line data for narrow-band RFI that may not show up in averaged data.
  – Channel by channel impractical, instead identify features by using cross-power spectra (POSSM).
  – Is it limited in time? Limited to specific telescope (VLBI) or baseline length (VLA)?
  – Flag based on the feature using SPFLG, EDITR, TVFLG, WIPER.
• Note: avoid excessive frequency dependent editing, since this introduces changes in the $u,v$-coverage across the band.
Spectral response

• For spectroscopy in an XF correlator (VLA, EVLA) additional lags are introduced and the correlation function is measured for a large number of lags.
  – The FFT gives the spectrum.

• However, we don't have infinitely large correlators and infinite amount of time, so we don't measure an infinite number of Fourier components.
  – A finite number or lags means a truncated lag spectrum, which corresponds to multiplying the true spectrum by a box function.
  – The spectral response is the FT of the box, which for an XF correlator is a sinc($\pi x$) function with nulls spaced by the channel separation: 22% sidelobes!
Spectral response: Gibb's ringing

• Thus, this produces a "ringing" in frequency called the Gibbs phenomenon.

• Occurs at sharp transitions:
  – Narrow banded spectral lines (masers, RFI)
  – Band edges
  – Baseband (zero frequency)
Gibb's ringing: remedies

- Increase the number of lags, or channels.
  - Oscillations reduce to ~2% at channel 20, so discard affected channels.
  - Works for band-edges, but not for spectral features.

- Smooth the data in frequency (i.e., taper the lag spectrum)
  - Usually Hanning smoothing is applied, reducing sidelobes to <3%.

\[
S_h(\nu_i) = \frac{S(\nu_{i-1}) + 2S(\nu_i) + S(\nu_{i+1})}{4}
\]
Bandpass calibration

• We need the total response of the instrument to determine the true visibilities from the observed:

\[ V_{ij}(t, \nu)_{\text{obs}} = V_{ij}(t, \nu)G_{ij}(t) \]

• The bandpass shape is a function of frequency, and is mostly due to electronics of individual antennas.
  – Usually varies slowly with time, so we can break the complex gain \( G_{ij}(t) \) into a fast varying frequency independent part, \( G'_{ij}(t, \nu) \), and a slowly varying frequency dependent part \( B_{ij}(t, \nu) \):

\[ V_{ij}(t, \nu)_{\text{obs}} = V_{ij}(t, \nu)G'_{ij}(t)B_{ij}(t, \nu) \]

• \( G'_{ij}(t) \) is calibrated as for continuum, and the process of determining \( B_{ij}(t, \nu) \) is the bandpass calibration.
Why bandpass calibration is important

• Important to be able to detect and analyze spectral features:
  – Frequency dependent amplitude errors limit the ability of detecting weak emission and absorption lines.
  – Frequency dependent phase errors can lead to spatial offsets between spectral features, imitating doppler motions.
  – Frequency dependent amplitude errors can imitate changes in line structures.

• For pseudo-continuum, the dynamic range of final image is limited by the bandpass quality.
Example ideal and real bandpass

- In the bandpass calibration we want to correct for the offset of the real bandpass from the ideal one (amp=1, phase=0).
- The bandpass is the relative gain of an antenna/baseline as a function of frequency.
How BP calibration is performed

• To compute the bandpass correction, a strong continuum calibrator is observed at least once.

• The most commonly used method is analogous to channel by channel self-calibration (AIPS task BPASS)
  – The calibrator data is divided by a source model or continuum, which removes atmospheric and source structure effects.
  – Most frequency dependence is antenna based, and the antenna-based gains are solved for as free parameters.

• This requires a high SNR, so what is a good choice of a BP calibrator?
How to select a BP calibrator

- Select a continuum source with:
  - High SNR in each channel
  - Intrinsically flat spectrum
  - No spectral lines

- Not required to be a point source, but helpful since the SNR will be the same in the BP solution for all baselines.

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Spectra of three potential calibrators. Only the bottom one is ok.

- Too noisy
- Spectral feature
- Strong, no lines: OK
How long to observe a BP calibrator

- Applying the BP calibration means that every complex visibility spectrum will be divided by a complex bandpass, so noise from the bandpass will degrade all data.

- Need to spend enough time on the BP calibrator so that \( \text{SNR}_{\text{BPcal}} > \text{SNR}_{\text{target}} \). A good rule of thumb is to use

\[
\text{SNR}_{\text{BPcal}} > 3 \times \text{SNR}_{\text{target}}
\]

which then results in an integration time:

\[
t_{\text{BPcal}} = 3 \times (\frac{\text{S}_{\text{target}}}{\text{S}_{\text{BPcal}}})^2 t_{\text{target}}
\]
Assessing quality of BP calibration

- Examples of good-quality bandpass solutions for 2 antennas.
- Solutions should look comparable for all antennas.
- Mean amplitude ~1 across useable portion of the band.
- No sharp variations in amplitude and phase; variations are not dominated by noise.
- Phase slope across the band indicates residual delay error.

L. Matthews
Bad quality bandpass solutions for 4 antennas

- Amplitude has different normalization for different antennas
- Noise levels are high, and are different for different antennas

![Graphs showing bandpass solutions for 4 antennas.](image-url)
Before accepting the BP solutions, apply to a continuum source and use cross-correlation spectrum to check:

- That phases are flat
- That amplitudes are constant
- That the noise is not increased by applying the BP
Spectral line bandpass: get it right!

- $G'_{ij}(t)$ and $B_{ij}(v,t)$ are separable, and multiplicative errors in $G'_{ij}(t)$ (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.

- This is not true for $B_{ij}(v,t)$ - any errors in the bandpass calibration will always be in your data. Residual errors will scale as continuum fluxes in your observed field.
Doppler tracking

- Observing from the surface of the Earth, our velocity with respect to astronomical sources is not constant in time or direction.

- Doppler tracking can be applied in real time to track a spectral line in a given reference frame, and for a given velocity definition:

\[
V_{\text{radio}}/c = (v_{\text{rest}} - v_{\text{obs}})/v_{\text{rest}}
\]

\[
V_{\text{opt}}/c = (v_{\text{rest}} - v_{\text{obs}})/v_{\text{obs}}
\]
### Rest frames

<table>
<thead>
<tr>
<th>Correct for</th>
<th>Amplitude</th>
<th>Rest frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nothing</td>
<td>0 km/s</td>
<td>Topocentric</td>
</tr>
<tr>
<td>Earth rotation</td>
<td>&lt; 0.5 km/s</td>
<td>Geocentric</td>
</tr>
<tr>
<td>Earth/Moon barycenter</td>
<td>&lt; 0.013 km/s</td>
<td>E/M Barycentric</td>
</tr>
<tr>
<td>Earth around Sun</td>
<td>&lt; 30 km/s</td>
<td>Heliocentric</td>
</tr>
<tr>
<td>Sun/planets barycenter</td>
<td>&lt; 0.012 km/s</td>
<td>SS Barycentric (~Helioc)</td>
</tr>
<tr>
<td>Sun peculiar motion</td>
<td>&lt; 20 km/s</td>
<td>Local Standard of Rest</td>
</tr>
<tr>
<td>Galactic rotation</td>
<td>&lt; 300 km/s</td>
<td>Galactocentric</td>
</tr>
</tbody>
</table>

Start with the topocentric frame, the successively transform to other frames. Transformations standardized by IAU.
However, the bandpass shape is really a function of \textit{frequency}, not velocity!

- Applying doppler tracking will introduce a time-dependent and position dependent frequency shift.
- If you doppler track your BP calibrator to the same velocity as your source, it will be observed at a different sky frequency!
- In this case, apply corrections during post-processing instead.
- Given that wider bandwidths are now being used (EVLA, SMA, ALMA) online doppler tracking is unlikely to be used in the future (tracking only correct for a single frequency).
Continuum subtraction

- Spectral line data often contains continuum emission, either from the target or from nearby sources in the field of view.
  - This emission complicates the detection and analysis of line data

Spectral line cube with two continuum sources (structure independent of frequency) and one spectral line source.

Roelfsma 1989
Continuum subtraction: basic concept

- Use channels with no line features to model the continuum
- Subtract this continuum model from all channels
Why do continuum subtraction?

- Spectral lines easier to see, especially weak ones.
- Easier to compare the line emission between channels.
- Deconvolution is non-linear: can give different results for different channels since \( u,v \)-coverage and noise differs (results usually better if line is deconvolved separately).
- If continuum sources exists far from the phase center, we don't need to deconvolve a large field of view to properly account for their sidelobes.

To remove the continuum, different methods are available: visibility based, image based, or a combination thereof.
Visibility based continuum subtraction (UVLIN)

- A low order polynomial is fit to a group of line free channels in each visibility spectrum, the polynomial is then subtracted from whole spectrum.

- Advantages:
  - Fast, easy, robust
  - Corrects for spectral index slopes across spectrum
  - Can do flagging automatically (based on residuals on baselines)
  - Can produce a continuum data set

- Restrictions:
  - Channels used in fitting must be line free (a visibility contains emission from all spatial scales)
  - Only works well over small field of view $\theta << \theta_s \nu / \Delta \nu_{\text{tot}}$
UVLIN restriction: small field of view

- A consequence of the visibility of a source being a sinusoidal function

- For a source at distance $l$ from phase center observed on baseline $b$:
  \[ V = \cos \left( \frac{2\pi v l}{c} \right) + i \sin \left( \frac{2\pi v l}{c} \right) \]

This is linear only over a small range of $\nu$ and for small $b$ and $l$. 
Image based continuum subtraction (IMLIN)

• Fit and subtract a low order polynomial fit to the line free part of the spectrum measured at each spatial pixel in cube.

• Advantages:
  – Fast, easy, robust to spectral index variations
  – Better at removing point sources far away from phase center (Cornwell, Uson and Haddad 1992).
  – Can be used with few line free channels.

• Restrictions:
  – Can't flag data since it works in the image plane.
  – Line and continuum must be simultaneously deconvolved.
Visualizing spectral line data

• After mapping all channels in the data set, we have a spectral line data *cube*.

• The cube is 3-dimensional (RA, Dec, Velocity). To visualize the information we usually make 1-D or 2-D projections:
  
  – Line profiles (1-D slices along velocity axis)
  – Channel maps (2-D slices along velocity axis)
  – Position-velocity plots (slices along spatial dimension)
  – Moment maps (integration along the velocity axis)
Example: line profiles

- Line profiles show changes in line shape, width and depth.
- Right: EVN+MERLIN 1667 MHz OH maser emission and absorption spectra in III Zw35.
Example: channel maps

- Channel maps show how the spatial distribution of the line feature changes with frequency/velocity.

- Right: Contours continuum emission, grey scale 1667 MHz OH line emission in III Zw35.
Example 2-D model: rotating disk

\[ V_{\text{cir}} \sin i \cos \Theta \]

\[ V_{\text{cir}} \sin i \]

\[ -V_{\text{cir}} \sin i \cos \Theta \]

\[ -V_{\text{cir}} \sin i \]

Mean Velocity Field

Channel Maps
Example: position-velocity plots

- PV-diagrams show, for example, the line emission velocity as a function of radius. Here along a line through the dynamical center of the galaxy.

- Greyscale & contours convey intensity of the emission.

L. Matthews
Moment analysis

- You might want to derive parameters such as integrated line intensity, centroid velocity of components and line widths - all as functions of positions. Estimate using the moments of the line profile:

\[
I_{\text{tot}}(\alpha, \delta) = \Delta \nu \sum_{i=1}^{N_{\text{chan}}} S_{\nu}(\alpha, \delta, \nu_i) \quad \text{(Total intensity (Moment 0))}
\]

\[
\bar{\nu}(\alpha, \delta) = \frac{\sum_{i=1}^{N_{\text{chan}}} v_i S_{\nu}(\alpha, \delta, \nu_i)}{\sum_{i=1}^{N_{\text{chan}}} S_{\nu}(\alpha, \delta, \nu_i)} \quad \text{(Intensity-weighted velocity (Moment 1))}
\]

\[
\sigma_{\nu}(\alpha, \delta) = \sqrt{\frac{\sum_{i=1}^{N_{\text{chan}}} (v_i - \bar{\nu}(\alpha, \delta))^2 S_{\nu}(\alpha, \delta, \nu_i)}{\sum_{i=1}^{N_{\text{chan}}} S_{\nu}(\alpha, \delta, \nu_i)^2}} \quad \text{(Intensity-weighted velocity dispersion (Moment 2))}
\]
Moment analysis

Moment 0 = \int S_\nu \, dv
Moment 1 = \langle V \rangle
= \frac{\int S_\nu \, v \, dv}{\int S_\nu \, dv}

Moment 2 = \langle V^2 \rangle^{1/2}
= \sqrt{\frac{\int S_\nu \, (v - \langle V \rangle)^2 \, dv}{\int S_\nu \, dv}}

Flux = S_\nu \, (mJy)

Velocity (km/s)
Moment maps

Moment 0
(Total Intensity)

Moment 1
(Velocity Field)

Moment 2
(Velocity Dispersion)
Moment maps: caution!

- Moments sensitive to noise so clipping is required
  - Higher order moments depend on lower ones so progressively noisier.

- Hard to interpret correctly:
  - Both emission and absorption may be present, emission may be double peaked.
  - Biased towards regions of high intensity.
  - Complicated error estimates: number or channels with real emission used in moment computation will greatly change across the image.

- Use as guide for investigating features, or to compare with other $\lambda$.

- Alternatives…?
  - Gaussian fitting for simple line profiles.
  - Maxmaps shows emission distribution.
Visualizing spectral line data: 3-D rendering

Display produced using the 'xray' program in the karma software package (http://www.atnf.csiro.au/computing/software/karma/)