Spectral Line Observing Strategies

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Switching Modes: I. Why switching?

Atmosphere emits and absorbs \( \text{Signal} = \text{Transmission} \times \text{Source} + \text{Atmosphere} \).

- **Optic**: \( \{ \text{Source} \gg \text{Atmosphere} \} \) \( \text{Transmission} \sim 1 \) \( \Rightarrow \) transparent;

- **Radio**: \( \{ \text{Source} \ll \text{Atmosphere} \} \) \( \text{Transmission can be small} \) \( \Rightarrow \) fog.

Bad news: Emission and transmission depends on weather and frequency.

Varying transmission \( \Rightarrow \) Gain calibration (hot/cold/sky).

Atmosphere emission \( \Rightarrow \) Switching mode.
Switching Modes: II. How to?

Position switching
- The telescope cyclically moves between two positions, ON (Source+Atmosphere) and OFF (Atmosphere). ⇒ Subtracting both positions should give you the source signal.
- Difficulties:
  - The OFF source must be devoid of signal ⇒ Sometimes wish to go far away (e.g. out of the Galactic plane).
  - The farther away you go, the more the atmosphere varies ⇒ bad baselines.

Wobbler switching
- The secondary cyclically and quickly moves between three positions: OFF - ON - ON - OFF.
- Advantage: Excellent baselines.
- Inconvenients:
  - Limited wobbling throw.
  - The wobbling direction rotates on the sky.
  ⇒ Your source must be compact.

Frequency switching
- The telescope is always ON source but the tuning frequency cyclically and quickly changes between two phases: $f_{\text{rest}} - f_{\text{throw}}$ and $f_{\text{rest}} + f_{\text{throw}}$.
- Advantages:
  - No need of OFF positions!
  - Lower noise for track observations (not true for On-The-Fly).
- Inconvenients:
  - Presence of atmospheric lines.
  - Negative ghosts.
  - Oscillating baselines (depending on $f_{\text{throw}}$).
Observing Modes (1)

**Line surveys**  Covering full atmospheric windows by multiple frequency settings along a single line of sight.

Example: Horsehead WHISPER (PI: J. Pety, see http://www.iram-institute.org/~horsehead)
Observing Modes (2)

Mapping Imaging a given line over a given sky field of view. Example: M51 viewed in $^{12}\text{CO} \ (J=1-0)$ (PAWS project, PI: E. Schinnerer, see http://www.mpia-hd.mpg.de/PAWS/PAWS/Data.html)

$^{12}\text{CO}(1-0)$ Integrated Emission ($k[T_{mb}]$)
Observing Modes (3)

**Line surveys**  Covering full atmospheric windows by multiple frequency settings along a single line of sight.

**Mapping**  Imaging a given line over a given sky field of view.

**Today cutting edge observing mode**  Convergence of line surveys and mapping (because of wide bandwidth receivers + powerful spectrometers).
Sensitivity estimation (Pety et al., IRAM memo 2009-1)

Radiometer equation for a total power measurement

\[ \sigma = \frac{T_{\text{sys}}}{\eta_{\text{spec}} \sqrt{n_{\text{pol}}} d\nu t}. \]

(1)

Switching \( \Rightarrow \) ON and OFF measurements.

\[ \sigma = \sqrt{\sigma_{\text{on}}^2 + \sigma_{\text{off}}^2} = \frac{T_{\text{sys}}}{\eta_{\text{spec}} \sqrt{n_{\text{pol}}} d\nu t_{\text{sig}}} \quad \text{with} \quad t_{\text{sig}} = \frac{t_{\text{on}} t_{\text{off}}}{t_{\text{on}} + t_{\text{off}}}, \]

(2)

**Tracked observations** Frequency switching is twice as fast as position switching.

**Frequency switching**

\[ t_{\text{on}} = t_{\text{off}} = \eta_{\text{tel}} t_{\text{tel}} \quad \Rightarrow \quad t_{\text{sig}} = \frac{t_{\text{on}}}{2} = \frac{t_{\text{off}}}{2} = \frac{\eta_{\text{tel}} t_{\text{tel}}}{2} \quad \Rightarrow \quad \sigma_{\text{fsw}} = \frac{\sqrt{2} T_{\text{sys}}}{\eta_{\text{spec}} \sqrt{d\nu n_{\text{pol}}} \eta_{\text{tel}} t_{\text{tel}}}. \]

(3)

**Position switching**

\[ t_{\text{on}} = t_{\text{off}} = \frac{\eta_{\text{tel}} t_{\text{tel}}}{2} \quad \Rightarrow \quad t_{\text{sig}} = \frac{t_{\text{on}}}{2} = \frac{t_{\text{off}}}{2} = \frac{\eta_{\text{tel}} t_{\text{tel}}}{4} \quad \Rightarrow \quad \sigma_{\text{psw}} = \frac{2 T_{\text{sys}}}{\eta_{\text{spec}} \sqrt{d\nu n_{\text{pol}}} \eta_{\text{tel}} t_{\text{tel}}}. \]

(4)
Radiometer equation for a total power measurement

\[ \sigma = \frac{T_{\text{sys}}}{\eta_{\text{spec}} \sqrt{n_{\text{pol}} d\nu t}}. \]  

(5)

Switching \( \Rightarrow \) ON and OFF measurements.

\[ \sigma = \sqrt{\sigma_{\text{on}}^2 + \sigma_{\text{off}}^2} = \frac{T_{\text{sys}}}{\eta_{\text{spec}} \sqrt{n_{\text{pol}} d\nu t_{\text{sig}}}} \quad \text{with} \quad t_{\text{sig}} = \frac{t_{\text{on}} t_{\text{off}}}{t_{\text{on}} + t_{\text{off}}}, \]  

(6)

On-The-Fly observations Time spent per independent beams in the covered field of view. \( (n_{\text{beam}}: \text{number of independent beams}). \)

Frequency switching

\[ \sigma_{\text{fsw}} = \frac{\sqrt{2} n_{\text{beam}} T_{\text{sys}}}{\eta_{\text{spec}} \sqrt{d\nu n_{\text{pol}} \eta_{\text{tel}} t_{\text{tel}}}}. \]  

(7)

Position switching Sharing OFF among many ONs (ON-ON-ON-ON-OFF-ON-ON-ON-OFF-...)  

\[ \sigma_{\text{psw}} = \frac{\left(\sqrt{n_{\text{beam}}} + \sqrt{n_{\text{submap}}}\right) T_{\text{sys}}}{\eta_{\text{spec}} \sqrt{d\nu n_{\text{pol}} \eta_{\text{tel}} t_{\text{tel}}}}. \]  

(8)

Relative efficiency

\[ \frac{\sigma_{\text{psw}}}{\sigma_{\text{fsw}}} = \frac{1}{\sqrt{2}} \left(1 + \sqrt{\frac{n_{\text{submap}}}{n_{\text{beam}}}}\right) \geq 1 \quad \Rightarrow \quad \frac{n_{\text{beam}}}{n_{\text{submap}}} = n_{\text{on/off}} \geq \frac{1}{3 - 2\sqrt{2}} \sim 6. \]  

(9)
Observing Strategy with 2SB Receivers: I. Definition

2 polarizations x 2 sidebands x 2 intermediate frequency processors:

```
LAS90> file in red/survey-1
LAS90> find /line 100.5
LAS90> list /toc
```

Number of setups........ 6

- HORSEHEAD 100.5 30MEOHUI-F01 8 (16.7%)
- HORSEHEAD 100.5 30MEOVUI-F02 8 (16.7%)
- HORSEHEAD 100.5 30MEOHUO-F05 8 (16.7%)
- HORSEHEAD 100.5 30MEOHL0-F06 8 (16.7%)
- HORSEHEAD 100.5 30MEOVUO-F07 8 (16.7%)
- HORSEHEAD 100.5 30MEOVL0-F08 8 (16.7%)

Choose carefully whether to tune LSB or USB because receiver temperatures will not be identical.
Observing Strategy with 2SB Receivers: III. Ghost Lines

<table>
<thead>
<tr>
<th>Line</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>30MEOHLO-F06</td>
<td>1.00600029E+05</td>
</tr>
<tr>
<td>30MEOVLO-F08</td>
<td>1.00600029E+05</td>
</tr>
<tr>
<td>30MEOHLI-F01</td>
<td>9.60000008E+04</td>
</tr>
<tr>
<td>30MEOLI-F02</td>
<td>9.60000008E+04</td>
</tr>
<tr>
<td>30MEOHLO-F06</td>
<td>9.9700027E+04</td>
</tr>
<tr>
<td>30MEOVLO-F08</td>
<td>9.9700027E+04</td>
</tr>
<tr>
<td>30MEOHLI-F01</td>
<td>9.6900009E+04</td>
</tr>
<tr>
<td>30MEOLI-F02</td>
<td>9.6900009E+04</td>
</tr>
</tbody>
</table>

Rest Frequency (MHz)

Spectral Line Observing Strategies

J. Pety, 2015
Observing Strategy with 2SB Receivers: III. Ghost Lines

98; 1 HORSEHEAD 96459.6 30MEOHLO–F06 0:26–SEP–2011 R:26–SEP–2011
RA: 05:40:54.27 DEC: −02:28:00.0 Eq 2000.0 Offs: −5.0 +0.0
Unknown tau: 0.088 Tsys: 140. Time: 45. min El: 46.6
N: 37275 Io: 84794.3 VO: 10.50 Dv: −0.1455 LSR
F0: 100600.029 Df: 4.8829E−02 Fi: 113100.317

30MEOHLO–F06 1.006000029E+05
30MEOVLO–F08 1.006000029E+05
30MEOHLO–F01 9.60000008E+04
30MEOHLO–F02 9.60000008E+04
30MEOHLO–F06 9.9700027E+04
30MEOVLO–F08 9.9700027E+04
30MEOHLO–F01 9.6900009E+04
30MEOHLO–F02 9.6900009E+04

Rest Frequency (MHz)
Effect of a Regular Sampling On Mapping:
I. Periodic Replication

Image Plane

\( f(x) \)

\( \text{II}\left( \frac{x}{r} \right) \)

\( \text{III}\left( \frac{x}{r} \right) f(x) \)

\( \frac{1}{2s} f(x) \)

\( \frac{1}{2s^2} f(x) \)

\( \frac{1}{2s^3} f(x) \)

\( t(s) \)

\( \tau\text{II}(\tau s) \)

\( \tau\text{III}(\tau s) \cdot F(s) \)

\( (2s)^{-1} \text{III}\left( \frac{s}{2s} \right) \cdot F(s) \)

\( s_c \)

Source brightness

Regular Sampling function

Result for a fine sampling

Result for critical sampling (Nyquist’s criterion)

Result for a coarse sampling

Effect of a Regular Sampling: II. Aliasing

Image Plane

\[ f(x) \]

\[ x \]

\[ \lambda \]

\[ \frac{\lambda}{2D} \]

\[ s_c \]

\[ s_d \]

\[ s_r \]

\[ F(s) \]

\[ g(x) \]

\[ A \]

\[ B \]

\[ C \]

\[ D \]

Aliasing = Folding of spatial frequencies outside the transfer function into it.

\[ \Rightarrow \text{Nyquist sampling: } \frac{\lambda}{2D}. \]
Gridding through convolution and resampling:

I. Kernel properties

2D Gaussian whose FWHM depends on the MAP%RESO parameter.

MAP%RESO = 0 (Default)
Kernel FWHM = 10.7/3 = 3.6"

MAP%RESO = 15
Kernel FWHM = sqrt(15^2 - 10.7^2) = 10.5"
Gridding through convolution and resampling:

II. Sampling results in image plane: 1. Fully sampled case

- Frequency: 230 GHz ⇒ 30m resolution: 10.7″.
- Point source of 1 K brightness. Beam dilution ⇒ ~ 0.9 K peak brightness.
- 4″ sampling between the rasters.
- 1″ sampling along the rasters.
- Default gridding kernel.

Observing grid: $\Delta_0=4''$, $\Delta_p=1''$

Point source offset: (0″,0″)

Point source offset: (1″,1″)

Point source offset: (2″,2″)

MAP%RESO = 0
Gridding through convolution and resampling:

II. Sampling results in image plane: 2. Undersampled case #1

- Frequency: 230 GHz ⇒ 30m resolution: 10.7″.
- Point source of 1 K brightness. Beam dilution ⇒ ~ 0.9 K peak brightness.
- 8″ sampling between the rasters.
- 1″ sampling along the rasters.
- Default gridding kernel.

\[
\text{Observing grid: } \Delta_o = 8\text{″}, \Delta_p = 1\text{″}
\]

Point source offset: (0″, 0″)  
Point source offset: (2″, 2″)  
Point source offset: (4″, 4″)

\[
\text{MAP\%RESO} = 0
\]
Gridding through convolution and resampling:

II. Sampling results in image plane: 3. Undersampled case #2

- Frequency: 230 GHz $\Rightarrow$ 30m resolution: 10.7″.
- Point source of 1 K brightness. Beam dilution $\Rightarrow \sim 0.9$ K peak brightness.
- 12″ sampling between the rasters.
- 1″ sampling along the rasters.
- Default gridding kernel.

Observing grid: $\Delta_o=12″$, $\Delta_p=1″$

Gridding through convolution and resampling:

III. Sampling results in $uv$ plane

- Frequency: 230 GHz $\Rightarrow$ 30m resolution: $\theta_{fwhm} = 1.2 \frac{\lambda}{D} = 10.7\arcsec$.

- Nyquist criterion: $\frac{\lambda}{2D} \neq \frac{\theta_{fwhm}}{2}$.

![Sampling: 8\arcsec](image1)

![Sampling: 12\arcsec](image2)
Gridding through convolution and resampling:
IV. Trying to rescue undersampled cases by smoothing
1. Fully sampled case results in image plane

- Frequency: 230 GHz $\Rightarrow$ 30m resolution: 10.7″.
- Point source of 1 K brightness. Beam dilution $\Rightarrow \sim 0.51$ K peak brightness.
- 4″ sampling between the rasters.
- 1″ sampling along the rasters.
- Final resolution: 15″ equivalent to a 22m-telescope...

Observing grid: $\Delta_o = 4″$, $\Delta_p = 1″$

Point source offset: (0″,0″)  
Point source offset: (1″,1″)  
Point source offset: (2″,2″)

MAP%RESO = 15
Gridding through convolution and resampling:

IV. Trying to rescue undersampled cases by smoothing

1. Fully sampled case results in image plane

- Frequency: 230 GHz $\Rightarrow$ 30m resolution: 10.7$''$.
- Point source of 1 K brightness. Beam dilution $\Rightarrow \sim 0.32$ K peak brightness.
- 4$''$ sampling between the rasters.
- 1$''$ sampling along the rasters.
- Final resolution: 19$''$ equivalent to a 17m-telescope...

Observing grid: $\Delta_0=4''$, $\Delta_p=1''$

Point source offset: $(0'',0'')$

Point source offset: $(1'',1'')$

Point source offset: $(2'',2'')$

MAP%RESO = 19
Gridding through convolution and resampling:
IV. Trying to rescue undersampled cases by smoothing
   1. Fully sampled case results in image plane

- Frequency: 230 GHz $\Rightarrow$ 30m resolution: 10.7$''$.
- Point source of 1 K brightness. Beam dilution $\Rightarrow\sim 0.22$ K peak brightness.
- 4$''$ sampling between the rasters.
- 1$''$ sampling along the rasters.
- Final resolution: 23$''$ equivalent to a 14m-telescope...

Observing grid: $\Delta_o=4''$, $\Delta_p=1''$

Point source offset: (0$''$,0$''$)  Point source offset: (1$''$,1$''$)  Point source offset: (2$''$,2$''$)

\[ MAP\%RESO = 23 \]
Gridding through convolution and resampling: IV. Trying to rescue undersampled cases by smoothing

1. Fully sampled case results in image plane

- Frequency: 230 GHz $\Rightarrow$ 30m resolution: 10.7$''$.
- Point source of 1 K brightness. Beam dilution $\Rightarrow \sim 0.16$ K peak brightness.
- 4$''$ sampling between the rasters.
- 1$''$ sampling along the rasters.
- Final resolution: 27$''$ equivalent to a 12m-telescope...

Observing grid: $\Delta_o=4''$, $\Delta_p=1''$

MAP%RESO = 27
Gridding through convolution and resampling:
IV. Trying to rescue undersampled cases by smoothing

2. Undersampled case results in image plane

- Frequency: 230 GHz ⇒ 30m resolution: 10.7″.
- Point source of 1 K brightness. Beam dilution ⇒ ∼ 0.51 K peak brightness.
- 12″ sampling between the rasters.
- 1″ sampling along the rasters.
- Final resolution: 15″ equivalent to a 22m-telescope...

Omitting grid: \( \Delta_0=12″, \Delta_p=1″ \)

Point source offset: (0″,0″)  Point source offset: (3″,3″)  Point source offset: (6″,6″)
Gridding through convolution and resampling:
IV. Trying to rescue undersampled cases by smoothing

2. Undersampled case results in image plane

- Frequency: 230 GHz \Rightarrow 30m resolution: 10.7''.
- Point source of 1 K brightness. Beam dilution \Rightarrow \sim 0.32 K peak brightness.
- 12'' sampling between the rasters.
- 1'' sampling along the rasters.
- Final resolution: 19'' equivalent to a 17m-telescope...

Observe grid: \Delta_o=12'', \Delta_p=1''

Point source offset: (0'',0'')

Point source offset: (3'',3'')

Point source offset: (6'',6'')

MAP%RESO = 19
Gridding through convolution and resampling:

IV. Trying to rescue undersampled cases by smoothing

2. Undersampled case results in image plane

- Frequency: 230 GHz ⇒ 30m resolution: 10.7″.
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- 1″ sampling along the rasters.
- Final resolution: 23″ equivalent to a 14m-telescope...

Observing grid: $\Delta_o=12''$, $\Delta_p=1''$

Point source offset: (0″,0″)  Point source offset: (3″,3″)  Point source offset: (6″,6″)

MAP%RESO = 23
Gridding through convolution and resampling:

IV. Trying to rescue undersampled cases by smoothing

2. Undersampled case results in image plane

- Frequency: 230 GHz ⇒ 30m resolution: 10.7″.
- Point source of 1 K brightness. Beam dilution ⇒ \( \sim 0.16 \) K peak brightness.
- 12″ sampling between the rasters.
- 1″ sampling along the rasters.
- Final resolution: 27″ equivalent to a 12m-telescope...

Observing grid: \( \Delta_o=12″ \), \( \Delta_p=1″ \)

Point source offset: (0″,0″)  
Point source offset: (3″,3″)  
Point source offset: (6″,6″)

\[
\text{MAP}\%\text{RESO} \ = \ 27
\]
IV. Trying to rescue undersampled cases by smoothing

3. Undersampled case results in \( uv \) plane

- Frequency: 230 GHz \( \Rightarrow \) 30m resolution: 10.7\".
- Final resolution: 15\" equivalent to a 22m-telescope...

![Graphs showing gridding through convolution and resampling](image-url)
IV. Trying to rescue undersampled cases by smoothing

3. Undersampled case results in $uv$ plane

- Frequency: 230 GHz $\Rightarrow$ 30m resolution: 10.7″.
- Final resolution: 19″ equivalent to a 17m-telescope...
Gridding through convolution and resampling:

IV. Trying to rescue undersampled cases by smoothing

3. Undersampled case results in $uv$ plane

- Frequency: 230 GHz $\Rightarrow$ 30m resolution: 10.7$''$.
- Final resolution: 23$''$ equivalent to a 14m-telescope...
Gridding through convolution and resampling:

IV. Trying to rescue undersampled cases by smoothing

3. Undersampled case results in $uv$ plane

- Frequency: 230 GHz $\Rightarrow$ 30m resolution: 10.7″.
- Final resolution: 27″ equivalent to a 12m-telescope...

Spectral Line Observing Strategies

J. Pety, 2015
Can you observe wider sky area through undersampling?

In general, no because sensitivity limited.
Only if If the limiting factor is the maximum telescope speed.

Does undersampling save observing time?

No Reaching a given sensitivity depends on the time spent per independent beam, not on the sky coverage (Pety, IRAM memo #2009-1, version 1.1).

Slightly Less overheads to cover the same sky area.

⇒ Drawbacks far outweigh advantages.
⇒ Undersampling is discouraged at IRAM.
Difficulties of blind deconvolution of error beams

Why deconvolving error beams? At high frequency, a large fraction of the flux comes from the error beams (e.g. ~ 50% at 1 mm for the 30 m).

What is blind deconvolution? It uses only data and general a priori (e.g. positivity). It does not use other datasets.

Difficulties

• The beam shape may depend on elevation.
• Error beams can be extremely wide ⇒ missing information outside the mapped region.
• Non-uniform noise coverage ⇒ shift-variant telescope response.
•Baselining scheme (adaptative windowing) ⇒ shift-variant telescope response.