Spectral Line Observing Strategies

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6th IRAM 30m Summer School
Sep. 23 - Sep. 30 2011, Pradollano
Switching Modes: I. Why switching?

Atmosphere emits and absorbs $Signal = Transmission \times Source + Atmosphere$.

- **Optic:** \[
\begin{aligned}
&\{ Source \gg Atmosphere \\
&\quad Transmission \sim 1 \\
\end{aligned}
\] \Rightarrow transparent;

- **Radio:** \[
\begin{aligned}
&\{ Source \ll Atmosphere \\
&\quad Transmission \text{ can be small} \\
\end{aligned}
\] \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.
Position switching

- The telescope cyclically moves between two positions, ON (Source+Atmosphere) and OFF (Atmosphere). \( \Rightarrow \) Subtracting both positions should give you the source signal.

- Difficulties:
  - The OFF source must be devoid of signal \( \Rightarrow \) Sometimes wish to go far away (e.g. out of the Galactic plane).
  - The farther away you go, the more the atmosphere varies \( \Rightarrow \) 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.
  \( \Rightarrow \) 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

**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

\[ \sigma = \frac{T_{sys}}{\eta_{spec} \sqrt{n_{pol} d\nu t}}. \] (1)

Switching ⇒ ON and OFF measurements.

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

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

Frequency switching

\[ t_{onoff} = t_{on} = t_{off} \quad \Rightarrow \quad t_{sig} = \frac{t_{on}}{2} = \frac{t_{off}}{2} = \frac{\eta_{tel} t_{tel}}{2} \quad \Rightarrow \quad \sigma_{fsw} = \frac{\sqrt{2} T_{sys}}{\eta_{spec} \sqrt{d\nu n_{pol} \eta_{tel} t_{tel}}}. \] (3)

Position switching

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

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

(9)
Choose carefully whether to tune LSB or USB because receiver temperatures will not be identical.
Observing Strategy with 2SB Receivers: II. Ghost Lines

98; 1 HORSEHEAD 96459.6 30MEOHLO–F06 0:22–SEP–2011 R:22–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 V0: 10.50 Dv: -0.1455 LSR
F0: 100600.029 Df: 4.8829E–02 Fi: 113100.317

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Effect of a Regular Sampling On Mapping:

I. Periodic Replication

Image Plane

\[ f(x) \]

\[ \Pi \left( \frac{x}{T} \right) \]

\[ \Pi \left( \frac{x}{T} \right) f(x) \]

\[ \frac{1}{2s_f} \rightarrow \Pi (2s_f x) f(x) \]

\[ \frac{1}{s_c} \rightarrow \Pi \left( \frac{s}{2s_c} \right) f(s) \]

\[ (2s_c)^{-1} \Pi \left( \frac{s}{2s_c} \right) f(s) \]

\[ s_c \]

\[ s \]

\[ T(s) \]

\[ s_c \]

Source brightness

Regular Sampling function

Result for a fine sampling

Result for critical sampling (Nyquist’s criterion)

Result for a coarse sampling

Spectral Line Observing Strategies

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Effect of a Regular Sampling: II. Aliasing

Image Plane

$u v$ Plane

\[ f(x) \]

\[ s_c \]

\[ s_d \]

\[ F(s) \]

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

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

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

$\Rightarrow$ 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: Δ₀=4″, Δₚ=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.

Observing grid: $\Delta_o=8″$, $\Delta_p=1″$

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

MAP%RESO = 0
Gridding through convolution and resampling:

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

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

Observing grid: Δ₀=12″, Δᵢ=1″

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

MAP%RESO = 0
Gridding through convolution and resampling:

III. Sampling results in \( uv \) plane

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

- Nyquist criterion: \( \frac{\lambda}{2D} \left( \neq \frac{\theta_{fwhm}}{2} \right) \).

Gridding through convolution and resampling:

IV. Trying to rescue undersampled cases by smoothing

1. Fully sampled 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.
- 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″)

Spectral Line Observing Strategies

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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: \( \Delta_o=4″, \Delta_p=1″ \)

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

\[ \text{MAP\%RESO} = 19 \]
Gridding through convolution and resampling:
IV. Trying to rescue undersampled cases by smoothing

1. Fully sampled case results in image plane

- Frequency: 230 GHz ⇒ 30m resolution: 10.7″.
- Point source of 1 K brightness. Beam dilution ⇒ ~ 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: Δ₀=4″, Δₚ=1″

![Point source offset: (0″,0″)](image)
![Point source offset: (1″,1″)](image)
![Point source offset: (2″,2″)](image)

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 ⇒ 30m resolution: 10.7″.
- Point source of 1 K brightness. Beam dilution ⇒ ∼ 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 $\Rightarrow$ 30m resolution: 10.7″.
- Point source of 1 K brightness. Beam dilution $\Rightarrow$ $\sim$ 0.51 K peak brightness.
- 12″ sampling between the rasters.
- 1″ sampling along the rasters.
- Final resolution: 15″ equivalent to a 22m-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 = 15

Spectral Line Observing Strategies  
J. Pety, 2011
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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- 12″ sampling between the rasters.
- 1″ sampling along the rasters.
- Final resolution: 19″ equivalent to a 17m-telescope...

Observing grid: $\Delta_0=12''$, $\Delta_p=1''$

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Gridding through convolution and resampling:

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Gridding through convolution and resampling:
IV. Trying to rescue undersampled cases by smoothing

3. Undersampled case results in $uv$ plane

- Frequency: 230 GHz ⇒ 30m resolution: 10.7″.
- Final resolution: 15″ equivalent to a 22m-telescope...

![Graphs showing natural and aliased transfer functions with sampling at 8″ and 12″](image-url)
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: 19$''$ equivalent to a 17m-telescope...

![Graphs showing gridding through convolution and resampling with undersampled cases.](image-url)
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″.
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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...

![Graphs of natural transfer, aliased transfer, convolved transfer for different sampling resolutions](image-url)
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. \( \sim 50\% \) 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 \( \Rightarrow \) missing information outside the mapped region.
- Non-uniform noise coverage \( \Rightarrow \) shift-variant telescope response.
- Baseline scheme (adaptative windowing) \( \Rightarrow \) shift-variant telescope response.