OBSERVATIONAL METHODS IN RADIO ASTRONOMY I: SINGLE-DISH

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INTRODUCTION
THE MM-SUBMM WINDOW
THE MM-SUBMM WINDOW: spectral line surveys

Orion KL Tercero et al. 2010
THE MM-SUBMM WINDOW: velocity channel maps

IRC+10216; CO J=2-1
Cernicharo et al. 2015
GOALS / QUESTIONS

Goals
• Measure the signal emitted from a particular region in the sky
• Obtain spectral or spatial information of the source
• Determine chemical and/or physical properties

Questions
• Measurement fidelity
• Calibration

Not covered in this talk
• Receivers and backends
ANTENNAS
RADIOTELESCOPES

JCMT

APEX

GBT

IRAM

GTM
Parabolic primary dish, but different positions of the receivers:

- Cassegrain: hyperbolic, convex subreflector
- Gregory: elliptical, concave subreflector behind the prime focus (e.g. Effelsberg)
- Nasmyth: hyperbolic subreflector and flat tertiary mirror (e.g. IRAM 30m, APEX)
- Offset Cassegrain: “half” parabolic and hyperbolic subreflector (e.g. GBT)

Advantages of the different optical configurations:

- Secondary focus: 5-10 times larger f/D ratios, less sensitive to lateral focus offsets, increase effective area, decrease spillover
- Nasmyth system: receivers are not tilted with elevation, more space in rx cabin
- Offset Cassegrain: less blockage by subreflector and support structure, less standing waves
## Radiotelescopes

<table>
<thead>
<tr>
<th>Obs.</th>
<th>D (m)</th>
<th>$\nu$ (GHz)</th>
<th>$\lambda$ (mm)</th>
<th>HPBW (’’)</th>
<th>Latitude (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRAM</td>
<td>30</td>
<td>70 – 345</td>
<td>4 – 0.7</td>
<td>35 – 7</td>
<td>+37</td>
</tr>
<tr>
<td>GTM</td>
<td>50 (32)</td>
<td>(73 – 116, 230)</td>
<td>4 – 0.85</td>
<td>20 – 6</td>
<td>+19</td>
</tr>
<tr>
<td>APEX</td>
<td>12</td>
<td>230 – 1200</td>
<td>1.3 – 0.3</td>
<td>30 – 6</td>
<td>−22</td>
</tr>
<tr>
<td>JCMT</td>
<td>15</td>
<td>210 – 710</td>
<td>2 – 0.2</td>
<td>20 – 8</td>
<td>+20</td>
</tr>
<tr>
<td>Herschel</td>
<td>3.5</td>
<td>500 – 2000</td>
<td>0.6 – 0.1</td>
<td>43 – 11</td>
<td>space</td>
</tr>
</tbody>
</table>

- Collecting area: $\lambda/D$
- Angular resolution: $\lambda/D$
ANTENNA THEORY: POWER PATTERN

- Reciprocity theorem: antenna in emission
- Distribution of electric field on the dish: \( E_{ant}(x,y) \)
- Far field radiated by the dish:
  \[ E_{ff}(l,m) \propto \mathcal{F}[E_{ant}(x,y)] \]
- Power emitted \( \propto |E_{ff}(l,m)|^2 \)
- Power pattern: \( P(l,m) \propto |E_{ff}(l,m)|^2 \)
- Beam solid angle:
  \[ \Omega_A = \int_{4\pi} P(\Omega) d\Omega \]
- Effective area:
  \[ A_e = \eta_A \cdot A_{geom} \rightarrow \eta_A : aperture efficiency \]
- Fundamental relation:
  \[ A_e \cdot \Omega_A = \lambda^2 \]
ANTENNA THEORY: POWER PATTERN

Main beam solid angle:

\[ \Omega_{MB} = \int_{\text{main lobe}} P(\Omega) \, d\Omega \]

Main beam efficiency:

\[ \eta_B = \frac{\Omega_{MB}}{\Omega_A} \]
POWER COLLECTED
BY AN ANTENNA

- Power from a monochromatic point source, collected by an area $A_e$:
  \[ P_\nu = \frac{1}{2} A_e \cdot S_\nu \quad [\text{W Hz}^{-1}] \]

Flux density $S_\nu$ measured in Jy: \( 1 \text{Jy} = 10^{-26} \text{ J s}^{-1} \text{ m}^{-2} \text{ Hz}^{-1} \)

- If source is extended:
  \[ \delta P_\nu = \frac{1}{2} A_e \cdot I_\nu \cdot \delta \Omega \quad [\text{W Hz}^{-1}] \]

Brightness $I_\nu$ measured in Jy sr-1: \( 1 \text{Jy sr}^{-1} = 10^{-26} \text{ J s}^{-1} \text{ m}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1} \)

Source flux density is: \( S_\nu = \int_{\Omega_s} I_\nu(\Omega) \, d\Omega \)

BUT observed flux density is: \( S_{obs} = \int_{\Omega_s} P(\Omega)I_\nu(\Omega) \, d\Omega < S_\nu \)
TEMPERATURE SCALES
BLACK BODY RADIATION

Planck Law: \[
B_\nu(T) = \frac{2\hbar \nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1}
\]

Rayleigh-Jeans approximation:
\[h\nu < < kT \rightarrow B_\nu(T) = \frac{2\nu^2}{c^2} kT\]

**Brightness temperature:** temperature a black body would have to match the observed intensity of an extended source at frequency \(\nu\):
\[
I_\nu(\Omega) = B_\nu(T_b) \rightarrow T_b = \frac{c^2}{2k\nu^2} I_\nu(\Omega) = \frac{\lambda^2}{2k} I_\nu(\Omega)
\]

\[
S_\nu = \int_{\Omega_s} I_\nu(\Omega) d\Omega = \frac{2k}{\lambda^2} T_b \Delta \Omega
\]
BLACK BODY RADIATION

Planck Law:

$$B_\nu(T) = \frac{2\hbar \nu^3}{c^2} \frac{1}{e^{\hbar \nu/kT}-1}$$

Rayleigh-Jeans approximation:

$$h\nu \ll kT \rightarrow B_\nu(T) = \frac{2\nu^2}{c^2} kT$$

**Brightness temperature:** temperature a black body would have to match the observed intensity of an extended source at frequency $\nu$:

$$I_\nu(\Omega) = B_\nu(T_b) \rightarrow T_b = \frac{c^2}{2k\nu^2} I_\nu(\Omega)$$

$$S_\nu = \int_{\Omega_s} I_\nu(\Omega) d\Omega = \frac{2k}{\lambda^2} T_b \Delta \Omega$$

NOTE this is not valid in the mm and low T:

$$\frac{\nu}{GHz} \ll 20.84 \frac{T}{K}$$

At T=10K: 230 GHz~208.4K (cold dark clouds)
ANTENNA TEMPERATURE: $T_A$

- Johnson noise: in thermal equilibrium, the power produced by a resistor is determined by its physical temperature:
  \[ p_\nu = kT \]  
  (Nyquist theorem)

- We can define an equivalent antenna temperature: 
  \[ p_\nu = kT_A \]

- As seen before: 
  \[ p_\nu = \frac{Ae}{2} \int_{\Omega_s} P(\Omega) I_\nu(\Omega) d\Omega \]

\[ T_A(\Omega) = \frac{Ae}{2k} \int_{\Omega_s} I_\nu(\Omega) P(\Omega) d\Omega \quad \text{; using} \quad A_e \cdot \Omega_A = \lambda^2 \]

\[ T_A(\Omega) = \frac{1}{\Omega_A} \int_{\Omega_s} \frac{\lambda^2}{2k} I_\nu(\Omega) P(\Omega) d\Omega = \frac{1}{\Omega_A} \int_{\Omega_s} T_b P(\Omega) d\Omega \]
Atmosphere effects, at a given $\nu$:

\[
T_A = T_b e^{-\tau_\nu} + T_{atm} (1 - e^{-\tau_\nu})
\]

Antenna temperature corrected by atmospheric absorption:

\[
T'_A = T_A e^{-\tau_\nu}
\]

Note that for space telescopes, e.g. Herschel:

\[
T'_A = T_A
\]
ANTENNA TEMPERATURE: $T_A^*$

- Correct for rear-sidelobes: measure the power received only from the forward $2\pi$ sr:

\[
T_A^* = \frac{1}{P_{2\pi}} \int_{\Omega_s} T_b P(\Omega) d\Omega
\]

\[
T_A^* = \frac{P_{4\pi}}{P_{2\pi}} T_A' = \frac{T_A'}{F_{eff}}
\]

- Forward efficiency:

\[
F_{eff} = \frac{P_{2\pi}}{P_{4\pi}}
\]
MAIN BEAM TEMPERATURE: $T_{MB}$

- Take into account main-beam and error-lobes
- Same as $T^*_A$ but within the main beam instead of $2\pi$:

$$T_{MB} = \frac{1}{P_{MB}} \int_{\Omega_s} T_b P(\Omega) d\Omega = \frac{P_{4\pi}}{P_{MB}} T'_A$$

- Beam efficiency:

$$B_{eff} = \frac{P_{MB}}{P_{4\pi}}$$

$\rightarrow$  

$$T_{MB} = \frac{T'_A}{B_{eff}} = \frac{F_{eff}}{B_{eff}} T^*_A$$

what we measure is $T^*_A$ or $T_{MB}$ which are NOT $T_b$
• **Small sources:** $\Omega_s << \Omega_{MB} : \quad T_{MB} \approx T_b \frac{\Omega_s}{P_{MB}} < T_b$  
  \rightarrow \text{beam dilution}

• **Large sources:** $\Omega_s >> \Omega_{MB} : \quad T_A^* \approx T_b \int_{2\pi} P(\Omega) d\Omega / P_{2\pi} \approx T_b$

• **Special case:** $\Omega_s = \Omega_{MB} : \quad T_{MB} = T_b \int_{\Omega_s} P(\Omega) d\Omega / P_{MB} = T_b$

• **General case:** $\Omega_s \sim \Omega_{MB} : \quad T_A^* = T_b \int_{\Omega_s} P(\Omega) d\Omega / P_{2\pi}$

• Usually, $T_{MB}$ is used assuming “the source fills the beam”, but…

\[
\begin{align*}
\Omega_s < \Omega_{MB} & \quad \rightarrow \quad T_b > T_{MB} \\
\Omega_{MB} < \Omega_s < 2\pi & \quad \rightarrow \quad T_{MB} > T_b > T_A^* \\
2\pi < \Omega_s & \quad \rightarrow \quad T_A^* > T_b
\end{align*}
\]
FROM KELVIN TO JANSKY

- Flux density: 
  \[ S_v = \int_{\Omega_s} I_v(\Omega) d\Omega = \frac{2k}{\lambda^2} \int_{\Omega_s} T_b d\Omega \]

- Power received by the antenna: 
  \[ kT'_A = k \frac{T_A^*}{F_{eff}} = \frac{1}{2} A_e \cdot S_v \]

  \[ \Rightarrow \quad \frac{S_v}{T_A^*} = \frac{2k}{A} \frac{F_{eff}}{\eta_A} \quad \text{[Jy K}^{-1}] \]

- Depends on the antenna
- Values are tabulated, e.g. for IRAM 30m:
  range from \( \sim 6 \) @ 90 GHz, to \( \sim 11 \) @ 340 GHz
CALIBRATION
Calibration needs to account for:

- **Atmosphere:**
  - Emission/absorption at frequency $\nu$
  - Turbulence producing phase drifts

- **Full detection system:**
  - Antenna characteristics and loosees
  - Receivers: gain, noise, stability
  - Cables, backends, etc.

Questions:

- How to convert counts at the backend level, to power in physical units
- How to correct for the atmospheric contribution
CALIBRATION

• What we measure…

\[ C_{sou} = \chi \left[ T_{rec} + F_{eff} e^{-\tau\nu} T_{sou} + T_{sky} \right] \]

where

\[ T_{sky} = F_{eff} (1 - e^{-\tau\nu}) T_{atm} + (1 - F_{eff}) T_{amb} \]

- \( T_{rec} \): noise contribution from the receiver
- \( T_{sky} \): noise contribution from the atmosphere (\( T_{atm} \)), and the receiver cabin and ground (\( T_{amb} \))

→ Details in Lecture by Luis Velilla on friday

• Correct for atmospheric emission and stability (atmospheric and instrumental)

→ switching bw ON and OFF positions (observing modes)
CALIBRATION: $T_{\text{sys}}$ and noise

*System temperature:* gives a measure of the noise including all sources, from the sky to backends

→ Statistical noise in our spectra (radiometer formula):

$$\sigma = \frac{T_{\text{sys}}}{\sqrt{d\nu \cdot \Delta t}}$$

- $d\nu$: spectral resolution
- $t_{\text{on}}/t_{\text{off}}$: ON/OFF integration time
- $\Delta t$: depends on the observing mode
OBSERVING MODES: position switching

- The telescope cyclically moves between two positions, ON (Source+Atmosphere) and OFF (Atmosphere)
  → Subtracting both positions gives the source signal
- Cons:
  - OFF position without any signal → need to go far away sometimes (and spend time moving the antenna)
  - If OFF position is far, atmosphere varies → bad baselines
- \( t_{on} = t_{off} = t_{tot}/2 \) → \( \Delta t = t_{tot}/4 \) →

\[
\sigma_{psw} = \frac{2 \cdot T_{sys}}{\sqrt{d\nu \cdot t_{tot}}}
\]
OBSERVING MODES: wobbler switching

- The secondary cyclically and quickly moves between the ON and OFF (usually symmetric OFF – ON – ON – OFF)
- Pros: very good baselines
- Cons:
  - Limited wobbling throw
  - Always in one antenna direction → rotates in the sky
  → Source must be compact

\[ t_{on} = t_{off} = \frac{t_{tot}}{2} \rightarrow \Delta t = \frac{t_{tot}}{4} \rightarrow \]

\[ \sigma_{WSW} = \frac{2 \cdot T_{sys}}{\sqrt{d \nu \cdot t_{tot}}} \]
OBSERVING MODES: frequency switching

- The tuning frequency cyclically and quickly changes between two phases: \( f_{\text{rest}} - f_{\text{throw}} \) and \( f_{\text{rest}} + f_{\text{throw}} \)

- Pros: The telescope is **always** ON source
  - No need for OFF positions
  - Lower loise

- Cons:
  - Limited frequency throw \( \rightarrow \) narrow lines
  - Presence of negative ghosts \( \rightarrow \) low line density
  - Presence of atmospheric lines
  - Strong ripples in the baselines (standing waves)

- \( t_{\text{on}} = t_{\text{off}} = t_{\text{tot}} \rightarrow \Delta t = t_{\text{tot}}/2 \rightarrow \)

\[
\sigma_{\text{fsw}} = \frac{\sqrt{2} \cdot T_{\text{sys}}}{\sqrt{dv \cdot t_{\text{tot}}}}
\]
OBSERVING MODES: on-the-fly mapping

- The telescope continuously slew through the source with time to map it. The result is a cube of spectra.

- Nr of independent measurements:
  \[ n_{beam} = \frac{A_{map}}{A_{beam}} \]

- \( t_{on}^{beam}, t_{off}^{beam} \):
  \[ \Delta t = \frac{t_{on}^{beam} \cdot t_{off}^{beam}}{t_{on}^{beam} + t_{off}^{beam}} \]

- Linear scanning speed and area speed:
  \[ v_{area} = v_{linear} \Delta \theta \]

- Nyquist sampling: \( \Delta \theta = \theta/2 \)
OBSERVING MODES: on-the-fly mapping

- The telescope continuously slew through the source with time to map it. The result is a cube of spectra.

- Frequency switching:

  \[ t_{on}^{beam} = t_{off}^{beam} = t_{tot}/n_{beam} \rightarrow \Delta t = t_{tot}/2n_{beam} \rightarrow \]

  \[ \sigma_{fsw} = \frac{\sqrt{2n_{beam}} \cdot T_{sys}}{\sqrt{dv \cdot t_{tot}}} \]

- Position switching: share same OFF for multiple ONs

  ON-ON-ON-OFF-ON-ON-ON-OFF-...

  submap

  \[ \sigma_{psw} = \frac{\sqrt{n_{beam} + n_{submap}}}{n_{beam}} \cdot T_{sys} \]

  \[ \frac{\sigma_{psw}}{\sigma_{fsw}} = \frac{1}{\sqrt{2}} \left( 1 + \sqrt{\frac{n_{submap}}{n_{beam}}} \right) \geq 1 \]
GOALS / QUESTIONS

Goals
- Measure the signal emitted from a particular region in the sky
- Obtain spectral or spatial information of the source
- Determine chemical and/or physical properties

Questions
- Measurement fidelity: $\eta_A, \eta_B, F_{\text{eff}}, B_{\text{eff}}$
- Calibration
  - Gain calibration: $C_{\text{source}} \rightarrow T^*_A, T_{MB} \rightarrow S_V$
  - Observing switching modes: remove noise contribution from the atmosphere and whole detection system
**BUT THERE’S MORE...**

- **Real antenna:**
  - Real beam pattern
  - Error beams
  - Antenna deformations: astigmatism, coma, etc.

- **Other calibration measurements needed during observations:**
  - Pointing: optimize with direction Az, El (gravity)
  - Focus: optimize secondary position in $z$ (temperature)

- ** Receivers:** e.g. *image band rejection* (SSB, DSB,..)
- **Backends:** bandwidth and spectral resolution
FURTHER READING

• “Tools of Radio Astronomy”, T.L. Wilson, K. Rohlfs, S. Hüttemesiter

• IRAM 30m and interferometry schools:
  http://www.iram-institute.org/EN/content-page-67-7-67-0-0-0-0.html

• NRAO Radio Astronomy essentials web course:
  https://science.nrao.edu/opportunities/courses/era

• IRAM technical reports
  http://www.iram-institute.org/EN/content-page-161-7-66-161-0-0-0.html