CO Observing Cheat Sheet

Quick reference for sensitivity, beam areas, and line ratios : a simple guide for when mass sensitivity gets confusing

1. Sensitivity concepts : single dish vs. interferometer

- **Sensitivity for a single dish** (e.g. IRAM 30m) measures *surface brightness* per **single, (relatively large) beam**. This is very efficient for smooth, extended emission; no spatial filtering, nothing is "resolved out".
- **Sensitivity when computed for an interferometer** (e.g. ALMA) measures *surface brightness* per **synthesized beam**, i.e. the angular resolution. This is fantastic for compact/clumpy emission, potentially able to detect very small masses indeed (see next point !); the downside is that it can filter out very smooth, large-scale emission beyond the *maximum recoverable scale (MRS, i.e. Largest Angular Scale LAS)* unless short spacings/total power observations are included.
- **Key pitfall when comparing "total mass sensitivity":** which instrument "wins" depends on the *spatial structure of the gas.* If the CO is clumpy on arcsecond scales, an interferometer like ALMA can detect far smaller masses per clump (no beam dilution). But if the CO is smooth over tens of arcseconds, a single dish reaches brightness (column-density) thresholds much faster and captures all the flux. Because the sensitivity is strongly dependent on the source structure, giving a single number for sensitivity comparisons isn't easy, and could even be meaningless.
  Another way to express this is that while ALMA might be phenomenally sensitive to a single clump of a very low mass, if that same clump were slightly more extended, it would no longer be detectable even though it would still be within the main beam ! It really is sensitive to column density more than to total mass.
- **It's all about averaging : resolution matters !** If a source has a uniform spectral profile, then you need the same sensitivity temperature to detect it in each channel as you do if you averaged over the whole line width. This sounds like you don't gain anything from degrading your resolution, but not so – *reaching the same sensitivity at a worse velocity resolution requires much less integration time !*

2. Which beam/s to use for sensitivity estimates ?

- **Single dish:** use the **telescope beam FWHM** at the observing frequency.
- **Interferometer:** for sensitivity per "pixel," use the **synthesized beam** (angular resolution). The **primary beam** only sets the *field of view* of a pointing.
- **Total mass estimate:** If the source *uniformly fills* the map, you may multiply a per-beam mass threshold by the number of synthesized beams covering the source area. If the emission is clumpy/patchy, do *not* blindly multiply; detectability is governed by peak surface brightness per synthesized beam.

- **Brightness sensitivity with interferometers can be traded for resolution** via a *uv*-taper, increasing the synthesized beam area and improving surface-brightness sensitivity (at the cost of angular resolution), while still respecting the array's LAS.

3. From integrated brightness to molecular surface density

- Define the CO integrated brightness (per spatial beam) as

$$I_{\rm CO} = \sum_{\rm line} T_{\rm mb}\,\Delta v \qquad [{\rm K\,km\,s^{-1}}].$$

  Looks nasty, but to calculate I, all you do is multiply the (main beam) temperature by the line width. That's all there is to it. The *main beam* temperature is a sort-of idealised variable; the actual observed *antenna* temperature depends on real-world conditions and some correction factors – for the IRMA 30m, these are quite small, and can be approximated as unity for a first-order estimate. More on this below.

- Milky Way–like conversion (includes He):

$$\Sigma_{\rm mol}\;[{\rm M_\odot\,pc^{-2}}] \;=\; 4.35\,I_{\rm CO(1\text{–}0)}[Kkm/s]$$

$$\Sigma_{\rm mol}\;[{\rm M_\odot\,pc^{-2}}] \;=\; 6.70\,I_{\rm CO(2\text{–}1)}[Kkm/s]$$

  These equations assume $R_{21} \equiv I_{21}/I_{10} \approx 0.65$.

- Note the units ! In this calculation, **line width is "baked in":** integrating across the profile already accounts for width. For a per-channel estimate, use the channel brightness $T_{\rm mb}$ and channel width Δv directly. Simples ! (Just remember that a broader line is easier to detect only if integrated over its whole width)

Comparison to HI: H I masses are derived from *flux density* (Jy) integrated over velocity, $M_{\rm HI} \propto D^2 \int S_\nu\,dv$ (${\rm Jy\,km\,s^{-1}}$). In practice, a top-hat approximation (peak × width) is often used. For CO we commonly work in *brightness temperature* (K), where $I_{\rm CO}$ is explicitly the *integral* of $T_{\rm mb}$ over velocity. So the flux calculation is not so different between CO and H I, really – what *is* different is that for H I we can easily calculate the total mass sensitivity, whereas for CO this is much more strongly dependent on the nature of the source.

5. From surface density to total mass

Given $\Sigma_{\rm mol}$ (from $I_{\rm CO}$) and the physical beam area $A_{\rm beam}$, the mass contained within one beam is given by :

$$M_{\rm mol,\,beam} \;=\; \Sigma_{\rm mol} \;\times\; A_{\rm beam}.$$

For a uniformly filled source of area $A_{\rm src}$, the total mass sensitivity scales as $\propto (A_{\rm src}/A_{\rm beam})$. For clumpy sources, use the per-synthesised beam (angular resolution) threshold; summing over beams is not appropriate unless emission fills them.

Remember to use the area of a Gaussian beam, not a simpler circular approximation. This is given by :

$$\Omega_{\rm beam} = \frac{\pi}{4\ln 2}\,\theta^2_{\rm FWHM} \;\approx\; 1.133\,\theta^2_{\rm HPBW}.$$

So in physical units this is easy :

$$A_{\mathrm{beam}}\ [\mathrm{pc}^2] = 1.133\ \times\ \mathrm{FWHM}^2\ [\mathrm{pc}^2].$$

(*Reference:* https://www.cv.nrao.edu/ sransom/web/A5.html equation 3.118)

6. Calculate the sensitivity temperature

If you want to detect a mass M_{H2} *per spectral resolution element* (channel width ΔV) at N_σ within a spatial beam of area A_{bm} (pc^2), the required **main-beam** temperature (see below) *rms* is

$$\boxed{T_{\mathrm{mb}}\ =\ \frac{M_{\mathrm{H2}}}{\alpha_{\mathrm{CO}}\ \Delta V\ A_{bm}\ N_\sigma}}$$

Where the α_{CO} factors are 4.35 for CO(1-0) and 6.7 for CO(2-1), as above.

Note that the IRAM Exposure Time Calculator requires as input the antenna temperature T_A^*. As mentioned earlier this is similar to the main-beam temperature (correct to zeroth or first order) but not identical ! But the conversion is very simple. The IRAM 30m efficiencies are given by the *forward efficiency* F_{eff} and the *main-beam efficiency* B_{eff}. The relation is

$$T_{\mathrm{mb}}\ =\ \frac{F_{\mathrm{eff}}}{B_{\mathrm{eff}}}\,T_A^*, \quad \Rightarrow \quad T_A^*\ =\ T_{\mathrm{mb}}\,\frac{B_{\mathrm{eff}}}{F_{\mathrm{eff}}}.$$

Typical values (check the current IRAM table for exact numbers at your frequency):

- $\sim$115 GHz: $F_{\mathrm{eff}} \approx 94$, $B_{\mathrm{eff}} \approx 78 \Rightarrow B/F \approx 0.83$.
- $\sim$230 GHz: $F_{\mathrm{eff}} \approx 92$, $B_{\mathrm{eff}} \approx 59 \Rightarrow B/F \approx 0.64$.

Use these to convert the idealised main beam temperatures, required for the mass sensitivity equations, to the practical antenna temperatures required for input into the IRAM ETC.
(*Reference:* The official IRAM efficiencies can be found here : https://publicwiki.iram.es/Iram30mEfficiencies)

7. Physics of the CO(2–1)/(1–0) line ratio R_{21}

- The line ratio $R_{21} \equiv I_{21}/I_{10}$ is mainly an **excitation** probe (density, temperature, optical depth, beam filling). Typical disk values are $R_{21} \sim$ 0.6–0.8; dense/warm gas can approach ~ 1; diffuse/sub-thermal gas can be $\lesssim 0.5$.
- **Metallicity** affects the CO–H_2 conversion (α_{CO}): at lower Z, CO is under-abundant/under-shielded relative to H_2 ("CO-dark" H_2), so α_{CO} increases (often by $\sim$ 2–10× from $\sim 0.5Z_\odot$ down to $\sim 0.2Z_\odot$). This does *not* change the instrumental sensitivity, but it does scale the inferred H_2 mass : there will be a different amount of CO present relative to the H_2.
- Measuring both 1–0 and 2–1 lets you determine R_{21} (excitation clue) and cross-check mass estimates. This can provide comparisons with standard Milky Way or other values.

8. Quick walkthrough

1. Try to estimate the total expected MH_2 in your target within your pointing(s). Typically the molecular fraction is assumed to be 10–20% of the HI mass, but stellar mass to H_2 relations are also available (e.g Feldmann R., 2020, Commun. Phys. 3, 226). Note that like the HI fraction, the H_2 fraction can vary, and there's the added complication that CO is not a perfect tracer. Sensitive observations can at least place constraints on whether the emission is Milky Way-like, either in terms of actual H_2 mass or the relation between H_2 and CO.

2. Consider the line width of your source. The H_2 is likely to be found in clumps but these should still follow the same basic kinematics as the atomic gas, so it could potentially be spread over the same velocity width as the HI. If the star-forming region is very centrally concentrated, the line width of the molecular gas may be lower.

3. Compute the physical area of the beam as per section 5, using the Gaussian area formula rather than approximating as a circle. Do this for both CO(1-0) and (2-1), accounting for the different frequencies (use the online calculators for this :
https://whosespectrallineisitanyway.streamlit.app/
https://angularsizepy.streamlit.app/).

4. Compute for both lines the CO main-beam temperature using the boxed equation in section 5. Remember to account for how much CO you expect per channel and set the mass accordingly, using the channel width for the velocity resolution. If you think the CO will be everywhere and want to maximise sensitivity with minimum integration time, use the full line width and total mass rather than the per-channel values.

5. Follow the rest of section 5 to convert this main-beam temperature into an antenna temperature. This is the value you input into the IRAM ETC to compute the integration time. This may give very different values for the different lines ! If at all possible, try and observe both as this gives you information on whether the line ratio is similar to the Milky Way, as well as providing different estimates of the total mass. Use only one line if the integration time would be prohibitive.

6. *Reference note 1.* CO(1-0) has a rest frequency of 115 GHz. At 5 km/s resolution, to reach 10, 5, 1 mK antenna temperatures requires observing times of 35 minutes, 2.3 hours, and 58 hours respectively.

7. *Reference note 2.* CO(2-1) has a rest frequency of 230 GHz. At 5 km/s resolution, to reach 10, 5, 1 mK antenna temperatures requires observing times of 5 minutes, 20 minutes, and 8 hours respectively.