Guide to observation planning with GREAT

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GREAT is a heterodyne receiver designed to observe spectral lines in the THz region with high spectral resolution and sensitivity. Heterodyne receivers work by mixing the signal from a source at a given frequency $\nu_s$ with that from a local oscillator (LO) at a specified (and precisely controlled) frequency $\nu_{LO}$ and amplifying the result. The mixing results in two frequency bands, called the signal and the image bands, located symmetrically on either side of $\nu_{LO}$ and separated from $\nu_{LO}$ by the intermediate frequency $\nu_{IF} = |\nu_s - \nu_{LO}|$. GREAT operates in double sideband mode, i.e. both the image and signal bands are equally sensitive to incoming radiation. By definition the spectral line of interest is always centered in the signal band, which can be chosen to be either above (Upper Side Band, USB) or below the LO frequency (Lower Side Band, LSB); see Figure 1 below. For sources rich in spectral lines, care has to be taken so that a spectral line in the image band does not overlap or blend with the line is the signal band. After a brief summary of the GREAT L-L configuration, we describe the basic observing modes, when to use which mode and finish up with a guide to estimate the sensitivities for the instrument. A more complete description of the GREAT instrument and its capabilities can be found on the SOFIA web page and the GREAT team web page (http://www.mpifr.de/div/submmtech/index.html).

**Fig. 1:** Schematics of one GREAT receiver channel. The second mixer-stage is needed to match the operational frequencies of the first mixer-element to that of the microwave spectrometer.
GREAT is a dual-channel heterodyne instrument. The front-end unit of consists of two independent dewars each containing a set of 4 mixers (labeled L#1, L#2, M, and H), sensitive to different specific frequencies (low, medium, and high). The two mixers (one in each dewar) can be operated simultaneously. GREAT will use the low frequency configuration (Low-Low or L-L, employing L#1 in one dewar and L#2 in the second dewar) for basic science. The L#1 mixer band covers the frequency range from 1.25 – 1.5 THz while the L#2 band covers the frequency range 1.8 – 1.92 THz. The configuration includes a set of backends consisting of two acousto-optical array spectrometers (AOSs) with 4 x 1 GHz bandwidth and 1 MHz spectral resolution¹, and four ultra-high-resolution Chirp transform spectrometers (CTSs) with 200 MHz bandwidth and 50 kHz resolution. Each CTS can be centered on a particular line in the bandpass, and are used to achieve very high velocity resolution, for example when resolving a narrow absorption line. The double sideband receiver temperature is ~ 1600 K and 2100 K for L#1 and L#2, respectively. These values will be updated as soon as more accurate data are available.

Three observing modes will be available:

1) Position switching mode. In this mode the telescope alternates (nods) between the target and a nearby reference position free of emission spending equal amount of time on each position. From the difference of each pair of spectra, i.e. target – reference, often called ON – OFF, the GREAT software produces a spectrum, which is largely corrected for atmospheric and instrumental effects. The integration time spent on a single target position depends on the stability of the receiver and how fast the atmosphere fluctuates, but is typically less than 30 seconds. If we use shorter integration times, we get a better cancellation of the sky fluctuations, but at the same time we add overheads and therefore reduce the observing efficiency. The ON – OFF cycle is repeated until the required sensitivity is reached.

Position switching is used when we want to observe one or a few positions of an extended source, like a large molecular cloud. If the reference position is far from the target position, e.g., 30 arcmin or more, changes in the sky background may result in poor baselines.

2) Beam switching (chop and nod). In this mode the secondary mirror is chopping between the target (signal) and a sky position (reference) at a rate of 1 – 2 Hz. The maximum chop throw must be < 10 arcmin, set by the limits of the chopping secondary. At a slower rate the telescope nods between the signal and the reference, typically somewhere between 5 and 30 seconds. The difference, signal – reference, produces a spectrum similar to what we get in position switching mode. Because the

¹ The resolution of the AOS varies somewhat from array to array and is in the range of 1.08 – 1.14 MHz for AOS1, with an average of ~ 1.12 MHz. The channel spacing is 0.57 MHz.
chopping secondary continuously produces a difference between the target and the sky, this mode results in better sky cancellation and hence better baseline stability.

Beam switching is typically used for point or compact sources, because the chop throw has to be larger than half of the source size (if we a centered on a symmetrical source).

3) On-the-fly mapping. In this mode the telescope scans in longitude along a line of constant latitude, a row, while the backends are continuously integrating the incoming signal and record an average after the telescope has moved a fraction (typically one third) of the beam size. Each average therefore corresponds to a point on the sky with a finite width. At the end of the row the telescope moves to a reference position where it integrates $\sqrt{N}$ times the integration time per point, where $N$ is the number of points in a row. After all positions in the row and the reference position are completed, the telescope steps about half a beam width in latitude and does a new scan + reference. This process is repeated until we have built up a map of the desired size. The whole map is repeated until the required sensitivity is reached.

On-the-fly mapping is the preferred mode when we want to map the distribution of a relatively bright line over a large area, like making a map of the [C II] 158 $\mu$m line in a molecular cloud. It is much more efficient than point by point mapping, because the main overheads result from the telescope slewing to the reference position and to the beginning of the next row, whereas the telescope slew times can be a substantial fraction of the total time spent on mapping in a point by point map (raster map). For small maps one can also do an on-the-fly map in beam switch mode.

The size of the scan is limited by the stability of the receiver and atmosphere and the time spent on the scan and reference position is therefore typically limited to less than 30 seconds. The minimum integration time per position depends on the size of the map, because the software needs to be able to read and buffer all the points in row.

Estimating time requirements and sensitivity.

Because of the way a heterodyne receiver is calibrated (i.e. measuring the receiver temperature, $T_{re}$, with a hot and a cold load), the logical intensity unit for a heterodyne observation is temperature, expressed in Kelvin (K). Either the antenna temperature, $T_A^*$, or the brightness temperature, $T_r^*$, are used. (The asterisk refers to values after correction for sky transmission.) Similarly, the noise is expressed in temperature units as well, $\Delta T_A^*$ or $\Delta T_r^*$, and the sensitivity (or signal-to-noise ratio) of the observations are given by the ratio of the signal temperature and the noise temperature. In order to calculate these quantities, we first must estimate the single sideband system temperature, $T_{sys}$, which also includes losses from the atmosphere and the telescope. $T_{sys}$ is given by

$$T_{sys} = 2 \times [T_{re} + \eta_{tel}T_{sky} + \eta_{tel}T_{src} + T_{tel}] / (\eta_{tel} \times \eta_{sky}) \tag{1}$$
where

\[ T_{rc} \] is the double side band receiver temperature;
\[ T_{sky} \] is the sky temperature;
\[ T_{src} \] is the source temperature;
\[ T_{tel} \] is the telescope temperature;
\[ \eta_{\text{sky}} \] is the fraction of radiation transmitted through the atmosphere; and
\[ \eta_{\text{tel}} \] is the efficiency of the telescope, which includes ohmic losses and spillover.

The factor 2 in expression (1) assumes that the noise temperature is the same in both signal and image band. This is not always true, although this will be assumed throughout this document. If a double sideband receiver is unbalanced, the factor 2 should be replaced by the expression \( [1 + T_{\text{sys}}(\text{sig})/T_{\text{sys}}(\text{im})] \).

The transmission of the atmosphere, \( \eta_{\text{sky}} \), at the altitude, observing frequency and airmass that we plan to observe at, can be estimated using the atmospheric transmission code ATRAN, which will be made available on the SOFIA webpage. \( T_{\text{sky}} \) depends on \( \eta_{\text{sky}} \) and the physical temperature of the sky where the signal is absorbed and can be derived from the expression

\[ T_{\text{sky}} = J_{\text{sky}} \times (1 - \eta_{\text{sky}}) \quad \text{(2)} \]

where \( J_{\text{sky}} \) is the mean radiation (blackbody) temperature of the atmosphere, which we assume to be around 225 K at 41,000 ft. Likewise the telescope temperature, \( T_{\text{tel}} \), is related to \( \eta_{\text{tel}} \) by

\[ T_{\text{tel}} = J_{\text{tel}} \times (1 - \eta_{\text{tel}}) \quad \text{(3)} \]

where \( J_{\text{tel}} \) is the radiation temperature of the telescope, about 230 K. If we assume an \( \eta_{\text{tel}} \) of 0.92, which should not be too far off, we find \( T_{\text{tel}} = 18.4 \) K.

As an example, let us calculate the system temperature at the [CII] fine structure line at 157.74 \( \mu \)m. We assume that we fly at an altitude of 39,000 ft and observe at an elevation of 30 degree. For a standard atmospheric model this corresponds to a transmission of \( \sim 75\% \), which gives \( T_{\text{sky}} = 56.3 \) K. For a receiver temperature \( T_{rc} = 2100 \) K, Equation (1) therefore predicts a single sideband system temperature \( T_{\text{sys}} = 6290 \) K when observing the sky.

Now we are ready to calculate the sensitivity. The rms antenna temperature, (corrected for the atmospheric absorption), \( \Delta T_{A}^{*} \), for both position switching and beam switching is given by

\[ \Delta T_{A}^{*} = (2 \times T_{\text{sys}} \times \kappa) \times (t \times \Delta \nu)^{-0.5} \quad \text{(4)} \]

where \( \kappa \) is the backend degradation factor, \( t \) is the total integration time of the number of on and off pairs that we plan to take, and \( \Delta \nu \) is the frequency resolution of our spectra.
Strictly speaking, $\Delta \nu$ is the noise bandwidth, which can be slightly different than the frequency resolution, depending on the design of the spectrometer. For our example, the 1 MHz resolution of the AOS is overkill, and we will bin the spectra to a resolution of 5 MHz or 9 channels (= 0.79 km/s at the frequency of the [C II] line), i.e. $\Delta \nu \sim 5$ MHz. For an observation with 2 pairs of 15 seconds in each beam, or $t = 1$ min, and assuming the backend degradation factor $\kappa = 1$, we then find $\Delta T_A^* = 0.72$ K, which is the one sigma rms antenna temperature.

To convert antenna temperature to brightness temperature $T_r^*$, we have to make one more correction.

$$T_r^* = T_A^* / \eta_{fss}$$

(5)

where $\eta_{fss}$ is the forward scattering efficiency, usually measured for a very extended source (like the Moon). Let us assume $\eta_{fss} = 0.9$. Therefore our brightness rms temperature, $\Delta T_r^* = 0.8$ K.

If we want to express our results in flux density, $S_\nu$, rather than brightness temperature, we can convert antenna temperature, $T_A$, to flux density, $S_\nu$, using the standard relation

$$S_\nu = 2 \times k \times T_A^* / A_{\text{eff}}$$

(6)

where $k$ is the Boltzmann constant, and $A_{\text{eff}}$ is the effective area of the telescope. $A_{\text{eff}}$ is related to the geometrical surface area of the telescope, $A_{\text{tel}}$, by the aperture efficiency, $\eta_{\text{ap}}$, i.e. $A_{\text{eff}} = \eta_{\text{ap}} \times A_{\text{tel}}$. For an assumed aperture efficiency of 75%, equation (6) yields the following simple form for the 2.5 m SOFIA telescope:

$$S (\text{Jy}) = 750 \times T_A^* (K)$$

(7)

Normally we use Jy only for spatially unresolved sources, but we can also use relation (7) to convert line intensities into W/m$^2$, which maybe a more familiar unit for the far infrared community. If we assume that the [CII] line we are observing is Gaussian with a Full With Half Maximum (FWHM) of $= 5$ km/s, i.e. 31.7 MHz (57 channels), the rms brightness temperature limit, $\Delta T_r^* = 0.32$ K for the 1 min integration we considered above. Assuming a Gaussian line shape results in an integrated line intensity of $1.065 \times T_{\text{peak}} \times \Delta \nu$. By the use of Equation 7 our 1 minute integration therefore corresponds to a one sigma brightness limit of $\sim 8.1 \times 10^{-17}$ W/m$^2$ for a 5 km/s wide line.

Sensitivity for an on-the-fly map:

Example: For a map of the [CII] line (Half Power Beam Width, HPBW ~ 16 arcsec), we need to sample the beam about every 6 arcsec. If we read out the average every one third of a second, we need a scan rate of 18 arcsec/second. To do a 10 arcmin scan will therefore take 33.3 sec, resulting in 100 map points. We therefore need to spend 3 seconds on the reference position and it probably takes us 2 – 3 seconds to slew to the reference position and the same amount to the next row. For a full Nyquist sampled map
we need to step 8 arcsec in latitude, i.e. we end up with a map of 100 x 75 positions with a cell size of 6 arcsec times 8 arcsec. From the above we can estimate that a single row takes about 40 seconds. Therefore the map will take 50 minutes and we should probably calibrate, i.e. measure the system temperature of the receiver, every 15 minutes or so, suggesting it will take about an hour for one map. We want at least one repeat. Therefore a 10 arcmin x 10 arcmin map in the [C II] line will therefore require 2 hrs of observing time.

Our 10 by 10 arcmin² map used one 1/3 seconds per map point. However, since we over sampled the map slightly, each position in the map is covered by 4 data points, which increases the sensitivity by a factor of 2. For $\Delta v \sim 5$ MHz, the one sigma rms brightness temperature, $\Delta T_r^* = 5.1$ K. Since the brightness temperature of the [CII] line in a galactic PDR region can be several hundred K, even a single coverage of our map, would give more than sufficient signal to noise to examine both the brightness variations and velocity structure of the PDR.