

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 mixing results in two bands, the signal and the image band, separated in sky frequency (ν_s) to either side of the local oscillator (LO) frequency (ν_{LO}) by the intermediate frequency (ν_{IF}). GREAT operates in double sideband mode, i.e. both bands are equally sensitive to incoming radiation, although the spectral line of interest is always centered in the signal band, which can be 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 in 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.

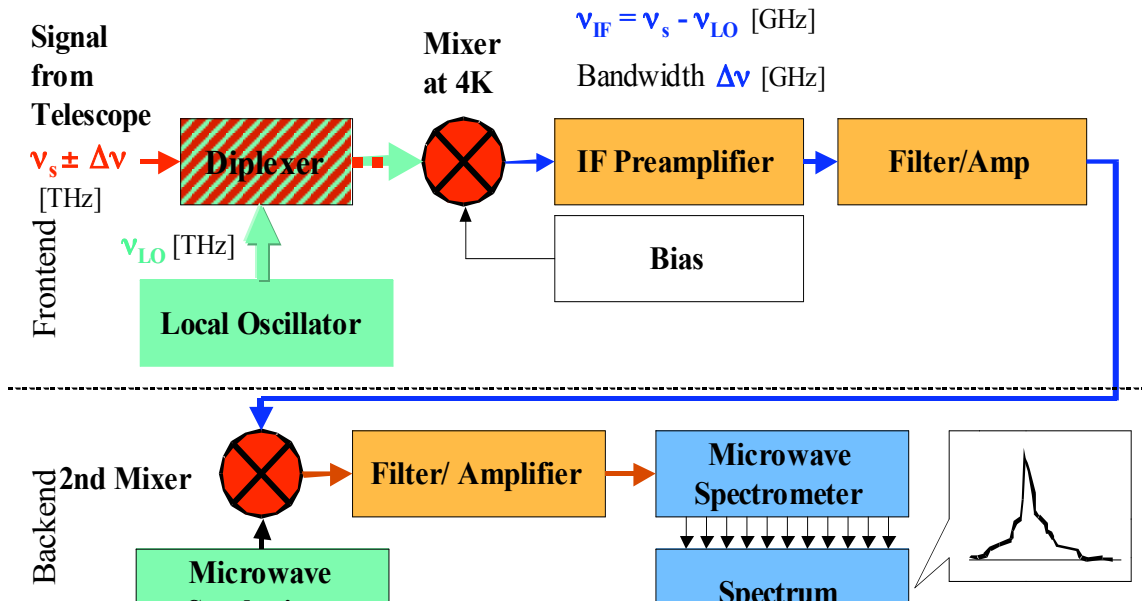


Fig. 1: Schematics of one GREAT receiver channel. The second mixer-stage is needed to match the operational frequencies of the first mixer-element to that of the microwave spectrometer.

GREAT will have their low frequency configuration (Low-Low or L-L) available for basic science. The front-end unit has two independent dewars; one for each mixer (L#1 and L#2). Both mixers can be used simultaneously. The L#1 covers the frequency range

from 1.25 – 1.5 THz, L#2 the frequency range 1.8 – 1.92 THz. The configuration includes a sets of backends: 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. The latter, i.e. each CTS can be centered on a particular line in the bandpass for which we need very high velocity resolution, like 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 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, like 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) with a slow rate, 1 – 2 Hz. The maximum chop throw is set by the chopping secondary and is limited to chop throws of < 10 arcmin. 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 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 are centered on a symmetrical source).

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.

- 3) On-the-fly mapping. In this mode the telescope scans 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 of the beam size, typically about a third of the beam size. At the end of the row the telescope moves to a reference position where it integrates \sqrt{N} times the integration time per cell, where N is the number of points in a row. After all position in the row and the reference position is completed, the telescope steps about half a beam width in longitude 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 CII 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.

The logical intensity unit for a heterodyne receiver is antenna temperature, T_A , which is expressed in Kelvin (K), because of the way a heterodyne receiver is calibrated, i.e. measuring the receiver temperature, T_{rc} , with a hot and a cold load. The single sideband system temperature, T_{sys} , which also includes losses from the atmosphere and the telescope, is given by

$$T_{sys} = 2 \times [T_{rx} + \eta_{tel}T_{sky} + T_{tel}] / (\eta_{tel} \times \eta_{sky}) \quad (1)$$

where

T_{rx} is the double side receiver temperature

T_{sky} is the sky temperature

T_{tel} is the telescope temperature

η_{sky} is the fraction of radiation transmitted through the atmosphere, and

η_{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, and the factor 2 should therefore be replaced by the expression $[1 + T_{sys}(sig)/T_{sys}(im)]$.

The transmission of the atmosphere, η_{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_{sky} depends on η_{sky} and the physical temperature of the sky where the signal is absorbed and can be derived from the expression

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

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

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

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

As an example, let us calculate the system temperature for the [CII] fine structure line at 157.74 μm in an extended source. We assume that we fly at 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. Expression (1) therefore predicts a single sideband system temperature, $T_{\text{sys}} = 6260$ K

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

$$\Delta T_A^* = (2 \times T_{\text{sys}} \times \kappa) / \sqrt{(t \times \Delta\nu)} \quad (4)$$

where κ 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. Strickly speaking $\Delta\nu$ is the noise bandwidth, which can be slightly different than the frequency resolution, depending on the design of the spectrometer. For us the 1 MHz resolution of the AOS is an 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 [CII] 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 ignoring the backend degradation factor, we then get $\Delta T_A^* = 0.72$ 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.

$$T_r^* = T_A^* / \eta_{\text{fss}} \quad (5)$$

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

If we want to express our results in flux density, S_ν , rather than brightness temperature, we can convert antenna temperature, T_A , to flux density, S , using the standard relation

$$S = 2 \times k \times T_A^* / A_{\text{eff}} \quad (6)$$

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

$$S (\text{Jy}) = 750 \times T_A^* (\text{K}) \quad (7)$$

Normally we only use Jy 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 Width 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 $\sim 8.1 \times 10^{-17} \text{ W/m}^2$ 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 [CII] 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 $\Delta\nu \sim 5$ 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.