

Guide to Planning Observations with SOFIA/GREAT

1. Introduction

GREAT is a heterodyne receiver, similar to HIFI on Herschel, 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 ν_s with that from a local oscillator (LO) at a specified (and precisely controlled) frequency ν_{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 ν_{LO} and separated from ν_{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 in the signal band.

A detailed description of the GREAT instrument and its performance during Basic Science can be found in the GREAT special issue (Heyminck et al. 2012, A&A, 542, L1). However, as the instrument is regularly being upgraded and the performance improves, always check the GREAT team web page for the latest information (<http://www3.mpifr-bonn.mpg.de/div/submmtech/>).

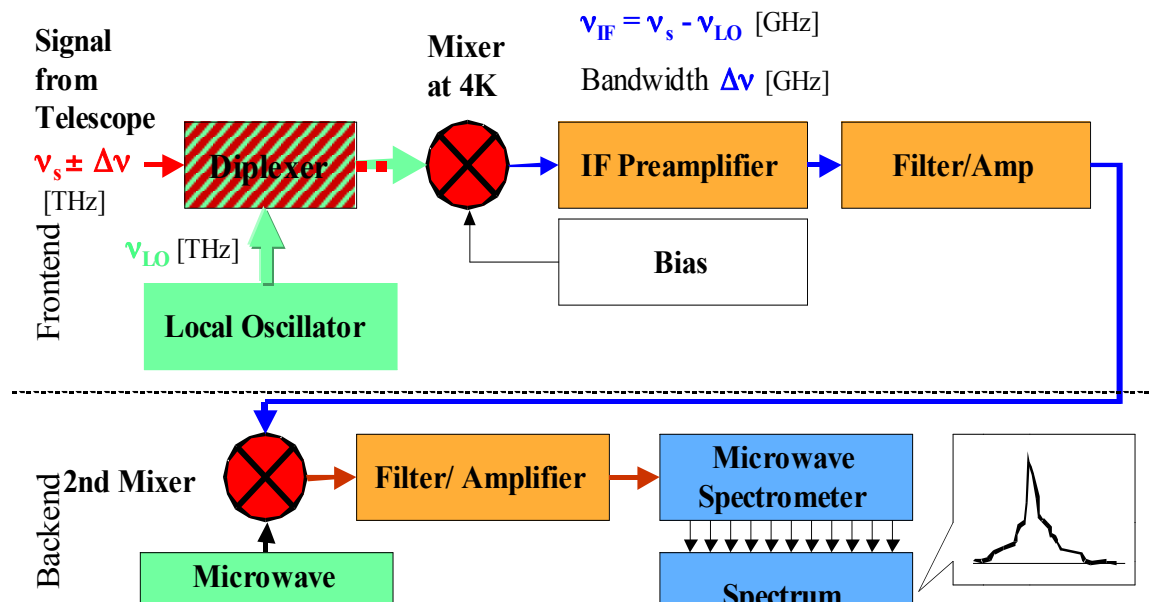


Fig. 1: Schematics of one GREAT receiver channel. The second mixer-stage is needed to match the operational frequencies of the first mixer-element to that of the microwave spectrometer.

2. Front-end Set-Up

GREAT is a dual-channel heterodyne instrument. The user must select a different mixer for each channel. These are then operated simultaneously. The mixers that are currently operational are listed in the table below. Not every mixer configuration will be available at any given time. Also, not all frequencies have been checked, so there may be gaps where the LOs do not provide enough power to pump the mixer. Please check the [GREAT website](#) or the SOFIA helpdesk for the latest information.

Front-end	Frequencies [THz]	Lines of Interest
Low frequency L1 ¹	1.25-1.39	CO (11-10) ₂ (12-11), OD, SH, H ₂ D ⁺ , etc.
	1.42-1.52	CO 13-12, [NII], etc.
Low frequency L2	1.81-1.91	CO 16-15, [CII], NH ₃ 3-2, OH ² Π _{1/2} , etc.
upGREAT LFA	1.900536 +/- 0.005	[CII]
Mid frequency Ma	2.49-2.56	¹⁸ OH ² Π _{3/2}
Mid frequency Mb	2.67-2.68	HD 1-0
High frequency H	4.74477749	[OI]

In Cycle 5, GREAT offers two configurations:

1. L1-LFA, employing L1 in one dewar and the Low Frequency Array (LFA) in the second dewar. The upGREAT (LFA) array consists of 2x7 pixels (H and V polarization).
2. L2-H, employing L2 in one dewar and H in the second dewar. This configuration simultaneously covers the important cooling lines [CII] and [OI], although L2 can also be tuned to molecular lines within that band.

3. Back-end Set-Up

Each of the two installed mixers is provided with XFFTS Fast Fourier Transform spectrometers. The XFFTS has a 2.5 GHz bandwidth and 64,000 channels, providing a resolution of 44 kHz.

The usable instantaneous bandwidth is generally less than that covered by the XFFTS. The L1 mixer has a double side band (DSB) receiver temperature of 800 K averaged over a 1 GHz bandwidth. The usable bandwidth is ~ 3.5 GHz, but with higher receiver temperatures at the edge of the band. For L2/upGREAT LFA, the DSB receiver temperatures are ~1100 K, also averaged over a 1 GHz bandwidth. The receiver temperature for the H-channel is 1100 K over 1.9 GHz, which corresponds to a velocity range of only 120 km/s. The tunability of the H-Channel is limited because the LO, a Quantum Cascade Laser can only be tuned in discrete steps.

¹ The gap in the L1 coverage between 1.39-1.42 THz matches the frequencies that are blocked by the atmosphere

4. Observing Modes

Four basic observing modes are currently offered:

- 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. It is typically ≤ 30 seconds, but can be adjusted during the flight if necessary. If shorter integration times are used, one gets a better cancellation of the sky fluctuations, but adds to overheads and therefore reduces 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 will result in poor baselines. If you cannot identify a reference position within 30 arcmin from your source position, choose a reference position say half way between your source and measure it against your clean reference position.

- 2) **Dual Beam Switching (DBS) mode.** In this mode the secondary mirror is chopping between the target (signal) and a sky position (reference) at a rate of 1 Hz. The maximum chop throw must be < 10 arcmin, set by the limits of the chopping secondary. In addition, the telescope nods between the signal and the reference, typically ≤ 40 seconds. Because the time between the on- and off-source measurements is small (usually 1 s), 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. Keep the chop throw as small as possible, preferably in the range of 60 – 120 arcseconds. Large chop throws introduce coma, i.e. distorts the beam, and uncertainties in the chop throw results in pointing errors, if there is a difference between the chop throw and the nod.

- 3) **Raster mapping.** This mode is for small maps or strips, where one needs relatively long integration times per map point. A typical example would be a small 3 x 3 map (9 points) with 30 seconds per map point. Raster maps can be done in either beam switched or position switch mode. For larger maps of bright lines the preferred mode is on-the fly mapping (see below), which is more efficient. However, even for a small map the OTF mode is more efficient as long as the lines is bright enough so that one can reach the required signal to noise within 20 or 30 repeats of the map.

- 4) **On-The-Fly (OTF) mapping.** In this mode the telescope starts with the reference position and then scans along a row (at constant latitude if the map rotation is zero – the default), while the backends are continuously integrating the incoming signal. An average is recorded after the telescope has moved a fraction (typically half to 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 again moves to the 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. The grid size must be the same in both latitude and longitude, and an individual map must be a rectangle.

On SOFIA, OTF mapping is more efficient than raster mapping in position switch mode, only if the integration time per position is small. Thus, on-the-fly mapping is the preferred mode when we want to map the distribution of a relatively bright line over a large area (e.g., a map of the [C II] 158 μm line in a molecular cloud). For faint emission, it is therefore better to stick to raster mapping.

The size of the scan is limited by the stability of the receiver and atmosphere and the time spent on the scan is therefore typically limited to less than 30 seconds. The typical integration time per position is 1sec/map point, and is usually between 0.5 and 2.0 seconds. For a large map one therefore has to break up the map into a number of sub-maps.

For detailed information about upGREAT mapping, see Appendix 2.

5. Sensitivity and Observing Time Estimation

Sensitivities and observing time estimates can be obtained with the online tool <http://great.sofia.usra.edu/cgi-bin/great/great.cgi>. It calculates either the signal-to-noise ratio for a given line brightness and integration time (ON+OFF), or the integration time (ON+OFF) needed to reach a certain RMS noise level for one point on the sky (ON minus OFF). These integration times do not include tuning, chopping, slewing and other observatory overheads. The total time, including all overheads, is determined in SPT or SSspot after entering the time calculated by the online GREAT time estimator.

As for other heterodyne receivers that use hot and cold loads to measure the receiver temperature, the intensity units are Kelvin (K). The intensity scale used in the online tool is brightness temperature T_R^* . This relates to the measured antenna temperature as $T_A^* = T_R^* \eta_{fss}$ and the main beam temperature (corrected for losses in the side lobes) as $T_{MB} = T_R^* / \eta_{MB}$. For GREAT, $\eta_{fss} = 0.97$ and in bands L1, L2/LFA, and H η_{MB} is in the range of 0.65 to 0.70. A detailed description of the GREAT intensity calibration is given

in Appendix 3. It also contains worked out examples for different observing modes, as well as unit conversions.

The online GREAT time estimator is also useful to determine in which sideband the line of interest is best put, taking into account the atmospheric transmission. System temperatures for the line in the USB or LSB are given, as well as a plot showing the line locations for either LO tuning in comparison with the atmospheric transmission.

6. SSpot Entries

SSpot has observation templates (AORs) for the GREAT Single Point, Raster Map and OTF Map modes. The following information needs to be provided:

- Source velocity (LSR) and rest frequencies of the lines to be observed with mixers 1 and 2. The specific mixers (see the table in section 2) to use must be selected with the buttons. The flight team will decide the optimal LO frequencies for observing these lines (USB versus LSB, position of the line in the IF), taking into account frequency-dependent system performance and atmospheric transmission. If you have specific requests, such as observing other lines in the same setting, please note those in the comments section of the AOR template.
- If you are searching for a line or if you are uncertain about how strong, and at what velocity your line will be, do at least one frequency shift. The easiest way to do this is create a second AOR, and to change the source velocity (V_{LSR}) by something like 10 to 20 km/s. The mixer will have to be retuned and a new calibration done, which involves a small cost in time (~2 minutes).
- You do not have to choose a backend. Data get automatically recorded on the available backends.
- For all observing modes, the integration time per point on the sky must be entered. This should not be more than ~60 seconds, although for Dual Beam Switch Mode our default is 80 seconds (40 second in each nod position). If longer exposures are needed, which is almost always the case, please increase the number of cycles. For maps, ‘cycles’ indicates the number of times the maps are repeated.
- Plan each AOR so that it does not take longer than about half an hour to execute. If you are making a big OTF map, make it into a set of smaller maps. With the entry “Minimum Contiguous Exposure Time” you can specify the minimum acceptable observing time in case the observation has to be split over multiple parts for, e.g., efficient flight planning.
- For all AORs, the instrument mode ‘Total Power’ refers to position switch.
- In OTF mode, the ‘Single Beam Switch’ instrument mode is rarely used. Position switch is preferred.
- In Dual Beam Switch Mode (for point and raster map AORs), a chopping angle can be specified, defined in the usual ‘North through East’ direction.
- Choose your reference position as close to your source as possible--absolutely no farther away than half a degree and preferably within 10 – 15 arcminutes of your

source. A reference position that is more than half a degree away from your target is not likely to work and may result in really poor baselines. The same is true if you observe in beam switched mode. For most observations a chop throw of 100" or less should be sufficient. Large chop throws degrade the pointing of the telescope, introduce coma into the beam and degrade the data quality.

Appendix 1: Mapping with upGREAT

The upGREAT Low Frequency Array (LFA) is a 2x7-beam heterodyne array arranged in a hexagonal pattern with a central beam. The spacings between the beams are approximately 2 beam widths (about 34 arcsec). For efficient mapping, the array is typically rotated by 19.1 degrees relative to the scan direction, resulting in a projected pixel spacing of 11 arcsec (see Figure 6). The array can be rotated independent of scanning direction for maximum flexibility of observation planning.

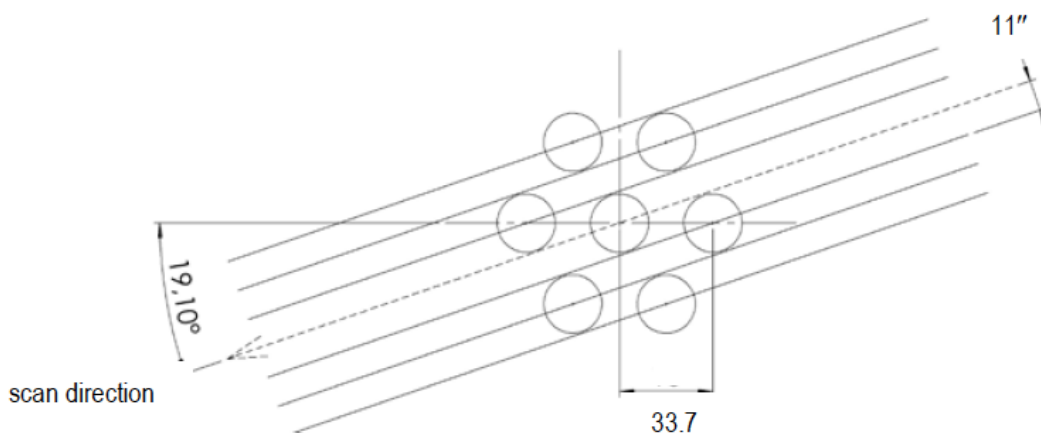


Fig 2. The footprint of the 2x7-pixel upGREAT LFA. To maximize mapping efficiency, the array is rotated by 19.1 degrees relative to the scan direction, resulting in a projected offset of 11 arcseconds between pixels. Note that the size of the circles do not represent the size of the beam size at 1.9 THz, which is about 14 arcseconds.

In general, the mapping schemes are flexible, and the detailed map parameters will depend on the goals of the project. To demonstrate this, below are two examples of how one could map the same region with upGREAT. The area of interest in both examples is a 77x77" region centered on NGC7027 (the thick blue box in Figures 3 and 4).

Example 1:

In this example, the rotated array makes four total scans—two in the RA direction and two in the Dec direction (see Fig. 3). Because the projected pixel separation of 11 arcseconds is larger than the beam size at 1.9 THz (14 arcseconds), two scans in each direction are required to fully sample the area. These scans are separated by 5.5

arcseconds (1/2 of the projected pixel separation), resulting in a slightly oversampled map.

To ensure that all pixels cover a part of the central region of the map during each scan, the scans start and end $\frac{1}{2}$ of the array width before and after the central region. To get evenly spaced sampling, we select a 5.5 arcsecond step size along the rows. This step size, along with the $\frac{1}{2}$ array length added to the beginning and end of the scan, results in a total scan length of 143 arcseconds (26 steps).

If we select 1 second integration time per point, each scan will take 26 seconds, and the off integration for each scan will take $\sqrt{26} \approx 5$ seconds. Thus, for the 4 scans that comprise the map, the total on+off time will be approximately 125 seconds. Including a factor of two for overhead, the total time for this map would be a little over four minutes, and each position in the central region of the map would have an integration time of ~ 8 seconds (4 seconds from each polarization).

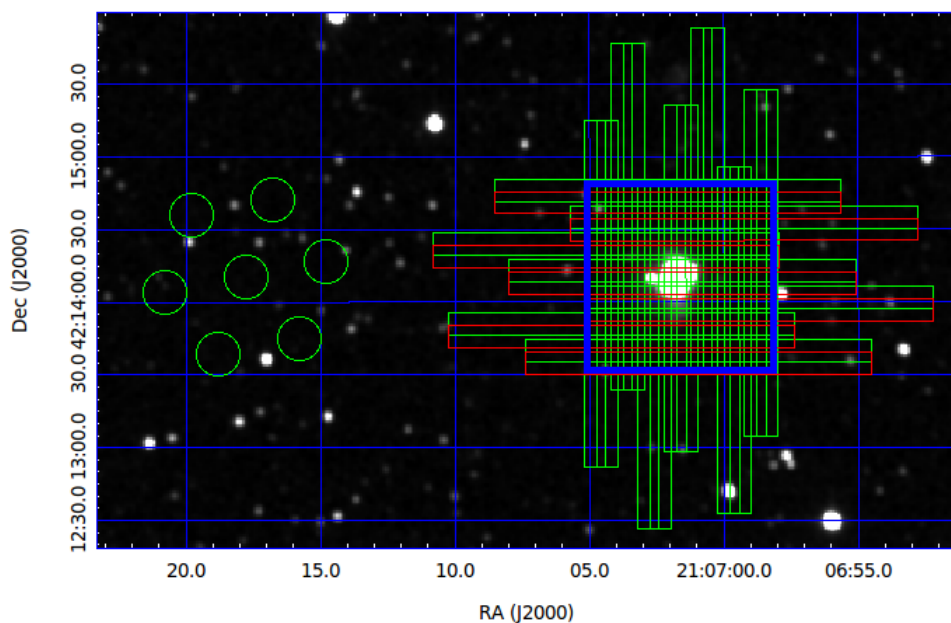


Fig 3. Overlay of map described in Example 1. Each long rectangle represents the region covered by a pixel during a scan. The red rectangles show the first scans of the map. The thick blue square shows the fully sampled region of the map. Green circles show the 2x7 pixels of the upGREAT array at the off position.

The pattern described in this example can serve as a ‘base unit’ for larger maps—it can be extended in the x- and/or y- directions to obtain fully sampled maps that cover a larger area.

For instructions on how to use this mapping mode in SSpot, please refer to the Guide to Planning OTF Maps with the upGREAT Array, found on the SOFIA Science Center web pages.

Example 2:

In this example, we design an observation such that the final map is comprised of 7 fully sampled maps (one from each pixel) of the central region. As with Example 1, the scans start $\frac{1}{2}$ of the array width before the central region in the RA direction. In addition, to ensure that each pixel creates a fully sampled map of the central region, the scans also start $\frac{1}{2}$ of the array height below the central region. When the observations of the map start, the top of the array is aligned with the bottom of the map, and each subsequent row is $\frac{1}{2}$ beam (7 arcseconds) above the prior one (see Figure 8). We use a 7 arcsecond step size along the row, which will result in a fully sampled map.

For this map, a scan length of 140 arcseconds is sufficient to cover the central region and $\frac{1}{2}$ of the array width before and after the central region. This scan length is also a multiple of the step size, which is a requirement for (up)GREAT maps. Based on the scan length and step size, each scan will have 20 points. Here we again select an integration time of 1 second per point, so each scan will take 20 seconds. The off position will require $\sqrt{20} \approx 4.5$ seconds, for a total of 24.5 seconds per scan. The entire map (including starting the map $\frac{1}{2}$ of the array width below the central region and ending the map $\frac{1}{2}$ of the array width above the central region) is made up of 20 rows. Thus, the total on+off time for the entire map is 490 seconds; after including a factor of 2 for overhead, the whole map takes about 17 minutes. Every point within the central region would have an integration time of 14 seconds (the combination of 2 polarizations x 7 maps, one for each pixel, with an integration time of 1 second each).

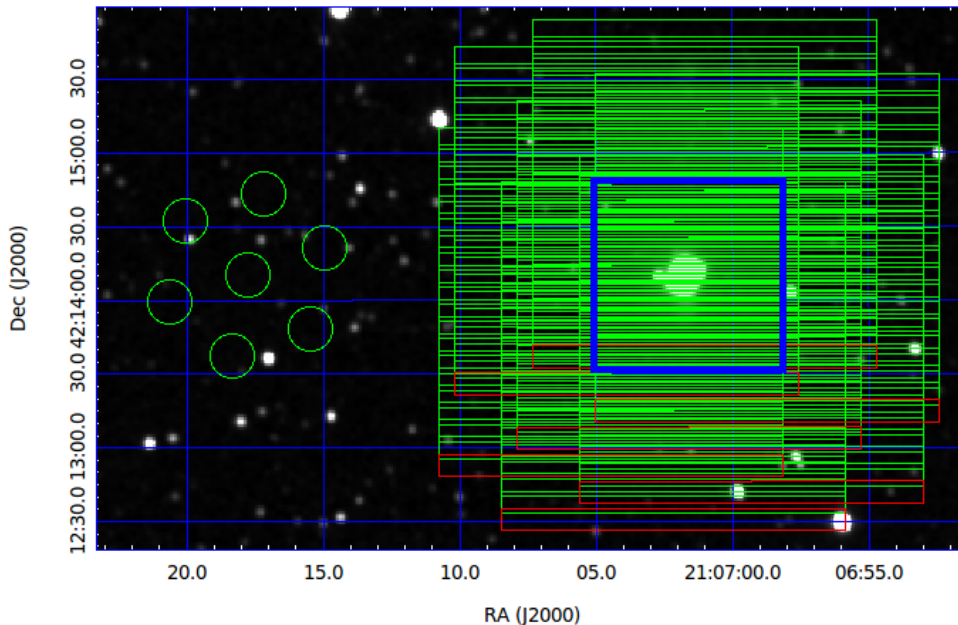


Fig 4. Overlay of map described in Example 2. Each long rectangle represents the region covered by a pixel during a scan. The red rectangles show the first scans of the map. The thick blue square shows the fully sampled region of the map. Green circles show the 7 pixels of the upGREAT array at the off position.

Summary:

When creating a mapping strategy, observers will have to weigh many factors, including the area to be mapped, the required integration time per point, and of course the scientific objectives. Both examples above result in fully (or over-) sampled maps of the central region, but require different amounts of time to complete, and have very different integration times and coverage outside of the central region. In Example 2, the entire central region is mapped by each pixel, while in Example 1, a point in the central region may be mapped by only a few pixels. These are all important pieces of information to consider when planning mapping observations with upGREAT.

Appendix 2: GREAT Sensitivity Calculations

The GREAT sensitivities and integration times are calculated with the online tool <http://great.sofia.usra.edu/cgi-bin/great/great.cgi>. Here, the background of these calculations and some worked out examples are presented.

Because of the way a heterodyne receiver is calibrated (i.e. measuring the receiver temperature, T_{rx} , 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^* , (The asterisk refers to values after correction for sky transmission, telescope losses and rearward spillover, see e.g. Kutner and Ulich, ApJ, 250, 341 (1981)) or the main beam brightness temperature, T_{mb} , are used. Similarly, the noise is expressed in temperature units as well, ΔT_A^* or ΔT_{mb} , and the sensitivity (or signal-to-noise ratio) of the observations are given by the ratio of the source temperature and the rms temperature of the spectrum. In order to calculate these quantities, we first must estimate the single sideband (SSB) system temperature, T_{sys} , which also includes losses from the atmosphere and the telescope. T_{sys} is given by

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

where

T_{rx} is the double side band (DSB) receiver temperature;

T_{sky} is the radiation temperature of the sky

T_s is the continuum temperature of the source. This term is usually completely negligible (unless you observe an extremely bright object (like Jupiter, Saturn or Sgr B2) and is therefore set to 0 in the GREAT time estimator.

T_{tel} is the Rayleigh-Jeans 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, which is true for the HEB mixers used by GREAT.

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, available on the SOFIA webpage. The GREAT time estimator calls ATRAN directly, so if you are estimating the integration time you need using the time estimator, there is no need to run ATRAN separately. T_{sky} depends on η_{sky} and the ambient temperature of the sky (T_{amb}) where the signal is absorbed and can be derived from the expression

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

where $J(T_{\text{amb}})$ is the mean Rayleigh-Jeans (R-J) temperature of the atmosphere, which we assume to have a physical temperature of 220 K at 41,000 ft, resulting in $J(T_{\text{amb}}) = 177.5$ K at 1.9 THz. 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, with a physical temperature ~ 230 K ($J_{\text{tel}} = 187.4$ K at 1.9 THz). If we assume an η_{tel} of 0.92, then $T_{\text{tel}} = 14.8$ K.

As an example, let us calculate the system temperature at the [CII] fine structure line at 157.74 μm (1.9005369 THz). In this example we calculate what we would have at the beginning of a flight, when we are still at low altitude. We therefore 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 $\sim 76\%$, which gives $T_{\text{sky}} = 42.6$ K. For a receiver temperature $T_{\text{rc}} = 1100$ K, Equation (1) therefore predicts a single sideband system temperature $T_{\text{sys}} = 3301$ K when observing the sky.

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

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

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. 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 we expect the Full Width Half Maximum (FWHM) of the line to be a few km/s, and we will therefore calculate the rms for a velocity resolution of 1 km/s, corresponding to a frequency resolution of 6.3 MHz. Since both backends for L2 have much higher resolution, this is not a problem. We can easily bin the spectrum to our desired velocity resolution. For an observation with 3 pairs of 40 seconds in each beam, or $t = 4$ min, and assuming the backend degradation factor $\kappa=1$, we then find $\Delta T_A^* = 0.17$ 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.

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

where η_{fss} is the forward scattering efficiency, usually measured for a very extended source (like the Moon). For GREAT $\eta_{fss} = 0.97$. Therefore our brightness rms temperature, $\Delta T_R^* = 0.18$ K.² Note: The GREAT time estimator assumes the line temperature in T_R^* , and *not in main beam brightness temperature*, $T_{mb} = T_R^* / \eta_{mb}$, which is for a source that just fills the main beam.

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_ν , using the standard relation

$$S_\nu = 2 \times k \times \eta_{fss} \times T_A^* / A_{eff} \quad (6)$$

where k is the Boltzmann 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. $A_{eff} = \eta_a \times A_g$. For the measured main beam efficiency in early April 2013 (0.67) and a Half Power Beam Width (HPBW) of ~ 14.1 arcsec (± 0.3 arcsec) I therefore derive an aperture efficiency³ of 55 ± 2 %, equation (6) yields the following simple form for the 2.5 m SOFIA telescope:

$$S \text{ (Jy)} = 971 \times T_A^* \text{ (K)} \text{ or within errors } \sim 1000 \times T_A^* \text{ (K)} \quad (7)$$

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 a Gaussian with a Full Width Half Maximum (FWHM) of $= 5$ km/s, i.e. 31.8 MHz, the integrated line intensity is given by $1.065 \times T_{peak} \times \Delta\nu$, where $\Delta\nu = 31.8$ MHz. If we take T_{peak} equal to our rms antenna temperature, we find using Equation 7 that our 4 minute integration therefore corresponds to a one sigma brightness limit of $\sim 6.1 \times 10^{-17}$ W/m^2 for a 5 km/s wide line observed with 1 km/s resolution. If we only aim for a detection, we can probably degrade the resolution to 2 km/s. In this case we gain a square root of 2, and therefore our one sigma detection limit is 4.3×10^{-17} W/m^2 .

When you are writing a proposal, you normally go the other way around. You have an estimate how wide and how bright the line is expected to be, and you know what signal to noise you need for your analysis. Let's assume we want to observe the [CII] 158 μm line

² The GREAT Time estimator (<http://great.sofia.usra.edu/cgi-bin/great>) gives $\Delta T_R^* = 0.18$ K, for USB tuning, which agrees with what we get.

³ The beam efficiency is directly related to the aperture efficiency by the expression $\eta_{mb} / \eta_a = A_g \times \Omega_{mb} / \lambda^2$, where Ω_{mb} is the main beam solid angle and λ the wavelength we observe at.

in T Tauri, a young low-mass star. Podio et al. (2012, A&A, 545, A44) find a line intensity of $7.5 \cdot 10^{-16} \text{ W m}^{-2}$ for the Herschel PACS observations, which are unresolved in velocity (the PACS velocity resolution is $\sim 240 \text{ km/s}$ for [CII]). Here we want to velocity resolve the line to see if it is outflow dominated or whether it is emitted from a circumstellar disk or both. We therefore need a velocity resolution of 1 km/s or better. If we assume that the line is outflow dominated with a FWHM of say 20 km/s (127.2 MHz ; little or no contribution from the circumstellar disk) we get a peak antenna temperature (using equation 7) of 0.52 K or a radiation temperature T_R^* of 0.55 K . In this case we want a SNR of at least 10 and a velocity resolution of 1 km/s or better. Let's check whether it is feasible. If we plug in the values we have in the GREAT time estimator (assume 40 degrees elevation, standard atmosphere, and we fly at 41000 ft) or we can estimate it from the equations given above.

With these assumptions ATRAN gives us an atmospheric transmission of 0.86 integrated over the receiver band-pass. The L2 receiver temperature is 1100 K (DSB). Using Equation 2, we find that the sky only adds 24.9 K to the system temperature and from Equation 1 we therefore get $T_{\text{sys}} = 2881 \text{ K}$. Since we want to reach a signal to noise of 10, the rms antenna temperature $\Delta T_A^* = 0.052 \text{ K}$. We can now solve for the integration time using Equation 4, where we set $\Delta v = 6.338 \text{ MHz}$ (1 km/s resolution). In this case $t = 1937 \text{ sec}$ or 32.3 min . The PACS observations show the emission to be compact, so we can do the observations in Dual Beam Switch Mode, with a chop throw of 60 arcsecond . Both Dual BMSW and position switch are currently estimated to have an overhead of 100% and a setup time for tuning and calibration of 2 minutes (which get added when you enter the observations in SPT, the SOFIA proposal tool). Our observation would therefore take 60 minutes , which is completely feasible. The GREAT exposure time calculator gives $t = 1930 \text{ sec}$. The difference is negligible.

Sensitivity for an on-the fly map:

Example: For a map of the [CII] line (Half Power Beam Width, HPBW $\sim 14 \text{ arcsec}$), we need to sample the beam about every 7 arcsec . If we read out the average once per second, i.e we have a scan rate of 7 arcsec/second . To do a 3 arcmin scan will therefore take 26 sec , resulting in 26 map points, let us make it 27 , to get an odd number of points. We therefore need to spend 5.2 seconds on the reference position. We ignore the time it takes the telescope to slew to the next row and any time needed for calibration. For a $3 \text{ arcmin} \times 3 \text{ arcmin}$ map, i.e. 27×27 positions with a cell size of 7 arcsec times 7 arcsec . The integration time for each row is therefore $5.2 + 27$ seconds or 32.2 seconds/row . The total integration time for the map is therefore 14.5 minutes . We definitely want to do one repeat, so the total integration time is therefore 29 minutes . For on-the fly maps SPT assumes a 100% overhead and 2 minute setup for tuning and calibration. The total duration of the 2 maps is therefore 61.9 minutes . Therefore a $3 \text{ arcmin} \times 3 \text{ arcmin}$ map in the [C II] line is entirely feasible.

Our 3 by 3 arcmin² map with one repeat has an integration time of 2 seconds per map point⁴. However, since we critically sampled the map, each beam is covered by 3.6 data points, which increases the sensitivity by a factor of 1.9. For typical observing conditions, 41000 feet, 30 degrees elevation, the GREAT time estimator gives us an rms temperature/map point of 1.27 K for a velocity resolution of 1 km/s, corresponding to an rms limit of 1.27 K/1.9 or ~0.7 K/beam.

⁴ Remember that the time estimator uses the total integration time (on+off). Here we therefore have to use 4 second as integration time to investigate the sensitivity limit per map point.