SOFIA

Stratospheric Observatory for Infrared Astronomy

GREAT

Handbook for Archive Users

K. Kaplan, R. Klein - SOFIA
R. Higgins, Y. Okada
J. Stutzki
J. L. Verbena
C. Guevara
& the GREAT Team

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K. Kaplan, R. Klein - SOFIA
R. Higgins, Y. Okada, J. Stutzki, J. L. Verbena, C. Guevara and the GREAT Team
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GREAT Handbook for Archive Users

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Universities Space Research Association

1. ESSENTIAL INFORMATION

Table 1: General information about GREAT

Instrument wavelength total range[1]	63 < λ < 612 μm (0.4900–4.7448 THz)
Image Quality (Beam size)[1]	6-52" (diffraction-limited at above wavelength range)
Array size[1]	2×7 upGREAT-LFA configuration 1×7 upGREAT-HFA configuration 1×1 4GREAT configuration (w/ 4 frequencies simultaneously)
Spectral Resolution	Up to R=10^8
Main observing modes[2]	Chop/Nod, Total Power, On-the-Fly Mapping
SOFIA observing cycles in service	Early Science, Cycle 1 to Cycle 9
Years in service	2010 to 2022
Built by	MPIR and U. Cologne (PIs: Rolf Güsten, Jürgen Stutzki)

[1]See Table 2 and Section 2. ; [2]See Section 2.

Table 2: GREAT Channel Parameters[1]

Channels	Frequency Range [THz]	T_{rec} Double Sideband	FWHM	Astronomical Lines of Interest
upGREAT HFA	4.7447 +/− 100 km/s	1250 K	6"	[OI]
upGREAT LFA-H	1.835–2.007	1000 K	15"	[CII], CO, OH$^2\pi_{1/2}$
upGREAT LFA-V	1.835–2.007 2.060–2.065	1000 K	15"	[OI], [CII], CO, OH$^2\pi_{1/2}$
4GREAT	2.490–2.590	3300 K	12"	OH$^2\pi_{3/2}$, ^{18}OH$^2\pi_{3/2}$
	1.240–1.395 1.427–1.525	1100 K	19"	[NII], CO, OD, HCN, SH, H_2D^+
	0.890–0.984 0.990–1.092	>600 K 300 K	25"	CO, CS
	0.491–0.555 0.560–0.635	<150 K	50"	NH_3, [CI], CO, CH

[1]For a more comprehensive list, see Table 3.

2. INSTRUMENT DESCRIPTION

2.1 GREAT OVERVIEW

The German Receiver for Astronomy at Terahertz Frequencies (GREAT) was a modular far-IR heterodyne instrument on SOFIA that provided high-resolution spectra (up to $R = 10^8$) over a frequency range of 0.4900–4.7448 THz. GREAT was a PI class instrument built and operated by the MPI für Radioastronomie and University of Cologne (with minor partners from the MPI für Sonnensystemforschung and the DLR-Institut für optische Sensorsysteme/Humboldt University, Berlin). It was continuously upgraded over its lifetime to improve its capabilities and sensitivity.

The spatial resolution (Gaussian beam size on the sky) was set by the diffraction limit of the telescope, ranging from 6.3-52.0 arcsec FWHM, depending on the frequency. Each channel consisted of a set of optics, a Local Oscillator (LO), and a set of mixers (two polarizations and/or array pixel configurations). Heterodyne instruments like GREAT work by mixing the signal from the source in the sky with the monochromatic signal from the LO, which is tuned to a precisely controlled frequency. This signal mixing results in two frequency bands on the sky called the signal and image bands, which are folded on top of each other in the intermediate frequency (IF) band. The band containing the spectral line of interest is the signal band and the opposite band is the image band. GREAT was operated in double sideband mode (DSB), where the image and signal bands are not separated and are equally sensitive to incoming radiation.

For each channel, the central frequency of the signal band was tuned (via tuning the LO frequency) to match a project's spectral feature of interest. Each channel had a window of frequencies it could be tuned to, limited by LO power and the atmosphere. Fine-tuning the LO frequency, including Doppler tracking to compensate for the observer's line-of-sight (LOS) velocity relative to the local standard of rest (LSR) velocity frame, was used to ensure that spectral lines or telluric features in the image band overlapped or blended as little as possible with the line of interest in the signal band and that the spectral line of interest was shifted in the IF band to a position with the lowest noise level. Starting in 2014, the GREAT backends were eXtended bandwidth Fast Fourier Transform Spectrometers (XFFTS). Each XFFTS had a bandwidth of 4 GHz (roughly 2500 to 250 km s^{-1}) and a resolution of 244 kHz (corresponding to 0.15 down to 0.015 km s^{-1}). Before the XFFTSs, GREAT used Acousto-Optical Spectrometers (AOS) with approx. 4 GHz bandwidth, and an earlier generation of FFTSs with approx. 2 GHz bandwidth.

The raw data are provided at full spectral resolution except for data taken early in the SOFIA program. The data can be binned or smoothed from the highest spectral resolution to the scientifically useful resolution $\Delta\nu$, thereby lowering the rms-noise per spectral element in proportion to $1/\sqrt{\Delta\nu}$.

Observations were either a single pointing on the sky for a deep observation of a specific target or the beams scanned across the sky to generate maps. In both cases, regular observations of an OFF position, i.e., a sky position free of source emission, were subtracted from the ON position spectra to remove the telescope and sky emission and the receiver noise equivalent intensity, which was nearly identical in the ON and OFF observation, as well as to compensate for offsets caused by the drifting receiver gain. These reference observations had to be done on a timescale short enough so that the rms noise at a scientifically useful spectral resolution (the lower, the broader) was larger than the drift amplitude at that time scale; the turn-over time is called the Allan-variance timescale (Schieder & Kramer 2001).

The GREAT instrument had the capability to configure multiple channels through its two separate cryostat mounts, though the available configurations varied over time. Sections 2.2 and 2.3 deliver the channels and configurations, respectively, while Section 2.4 provides technical details about the instrument. Reference subtraction is covered in Section 2.5.1, and observing modes are explained in Section 2.6. Section 3. covers temperature scales typical for heterodyne instruments, sensitivities, system temperatures, and other performance parameters. Section 4.1 describes the different GREAT data products, with Level 4 data products being the most processed and typically including absolute flux calibrated, atmospheric transmission corrected, baseline subtracted single spectra or apps The calibration and processing steps for the data are summarized in Section 4.2, and useful software for GREAT data is listed in Section 4.3. Section 5. presents the two SOFIA Legacy Programs executed with GREAT as an example of large datasets.

It is important to note that while SOFIA flew above most of the Earth's atmosphere, GREAT data was affected by air. Figure 9 shows the atmospheric transmission and telluric absorption features around the [CII] line, highlighting the rapid variation within the bandwidth. Section 4.2 details how the data processing handles the atmosphere, and the resulting products are stored in the Level 3 data listed in Section 4.1.2

2.2 DESCRIPTION OF CHANNELS

Table 3: Summary of GREAT Channels

Channel	IRSA/DCS/AOR Channel Names	Frequency Range (GHz)	Pixels	DSB Receiver Temp. (K)	Beam FWHM (arcsec)	Lines of Interest	Observing Cycle Commissioned	Observing Cycles Available	Notes
upGREAT LFA	GRE_LFA	1830-2070[a]	14 (7×2)	1000[g]	14.1 (at 1.9 THz)[b]	[CII] 158 μm, [OI] 145 μm, OH, CH, CO, HeH^+	3 [a]	4-9 [a]	Consists of LFAH & LFAV, two overlapping 7-pixel arrays of horizontal and vertical polarization. Upgrade of L2.
upGREAT HFA	GRE_HFA	4744.777749	7	1250[g]	6.3 (at 4.74 THz)[b]	[OI] 63 μm	4 [b]	5-9 [b]	Single polarization (HFAV) 7-pixel array. Upgrade of H.
4GREAT 4G1	GRE_4G	480-640[c]	1	100-140[c]	52 (at 0.53 THz)[c]	[CI] 609 μm, NH_3, CO, CH	5[c]	6-9[c]	
4GREAT 4G2	GRE_4G	960-1120[c]	1	300-600[c]	27 (at 1.038 THz)[c]	CO, CS	5[c]	6-9[c]	
4GREAT 4G3	GRE_4G	1200-1600[c]	1	100-1200[c]	20 (at 1.337 THz)[c]	[NII] 205 μm, CO, OD, HCN, SH, H_2D^+	5[c]	6-9[c]	Upgrade of L1.
4GREAT 4G4	GRE_4G	2500-2700[c]	1	3000[c]	10.5 (at 2.675 THz)[c]	OH $^2\Pi_{3/2}$, ^{18}OH $^2\Pi_{3/2}$	5[c]	6-9[c]	Upgrade of Ma.
L1	GRE_L1	1250-1500[d]	1	500[d]	21.3 (at 1.337 THz)[c], 19.6 (at 1.469 THz)[e]	[NII] 205 μm, CO, OD, SH, H_2D^+, HCN, HCO^+	Early Science[e]	1-5	Upgraded to 4GREAT 3.
L2	GRE_L2	1810-1910[d]	1	600[d]	15.0 (at 1.88 THz)[e]	[CII] 158 μm, OH, CO	Early Science[e]	1-4	Upgraded to LFA.
M	GRE_M1	2490-2520[d]	1	1500[d]	11.4 (at 2.51 THz)[e]	OH $^2\Pi_{3/2}$	Early Science[e]	1-2	Upgraded to 4GREAT 4.
H	GRE_H	4744.777749[d]	1	800[d]	6.3 (at 4.74 THz)	[OI] 63 μm	3	4-5	Upgraded to HFA.

[a]Risacher et al. (2016a); [b]Risacher et al. (2018); [c]Durán et al. (2020); [d]Risacher et al. (2016b); [e]Heyminck et al. (2012)

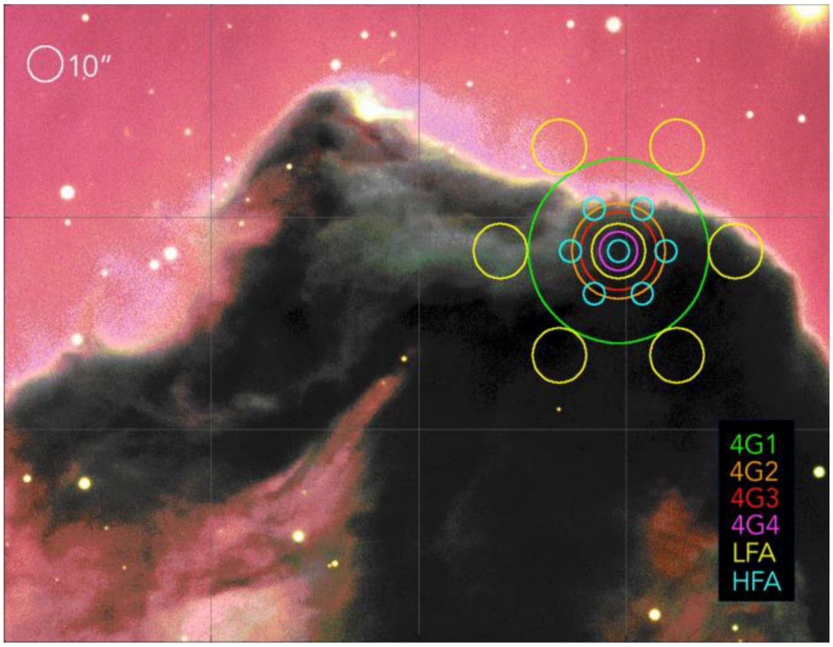


Figure 1 *Comparison of the footprints for the HFA, LFA, and 4GREAT channels from [Durán et al. (2020)](). The LFA and HFA each consisted of seven pixels, with six in a hexagonal pattern around the central pixel. The four 4GREAT channels were all single pixels. The 4GREAT pixels and the central pixels of the LFA and HFA were all spatially co-aligned on the sky. The diffraction limit of the telescope set the beam sizes. The size of the circles in the figure represents the full width of each channel's beam at half maximum (FWHM).*

2.2.1 upGREAT HFA, GRE_HFA

The upGREAT High-Frequency Array (HFA) was designed to look exclusively at the [OI] 63 µm line, a significant cooling line in interstellar gas (there are no other strong lines of astronomical interest nearby in frequency, and the available QCL-LO systems have a very limited tuning range). The LO was a Quantum Cascade Laser (QCL) with a narrow tuning range limited to the [OI] 63 µm frequency of 4.74477749 THz (with a tuning range of roughly +250 to -100 km s^{-1} in LSR velocity). The telluric [OI] line had to be in the signal or image band because it was used for the channel's frequency calibration, for QCL frequency locking during observations, and to correct for the QCL-LO's frequency drift in post-processing.

The HFA was an upgrade of the single-pixel H channel and consisted of a 7-pixel array arranged with 6 pixels in a hexagonal geometry around a central pixel. Each pixel had a spatial resolution (beam FWHM) of 6.3 arcseconds and was separated from adjacent pixels by 13.8 arcseconds. Unlike the LFA, the HFA consisted of only one polarization (HFAV; the upgrade to the second polarization was not implemented due to cost reasons and the foreseeable limited operational time of SOFIA when the HFA came on board). It was commissioned starting in Cycle 4 and offered for general science in Cycles 6-9. During these cycles, the HFA was always in one of the cryostat mounts and was available in configurations parallel either with the LFA or 4GREAT. Because of this, projects not focused on the [OI] 63 µm line could still use the HFA to observe the line for ancillary data. The HFA's central pixel was spatially co-aligned either with the central pixel of the LFA, or with the pixels of 4GREAT. More details on the HFA can be found in Risacher et al. (2018) and Risacher et al. (2016).

2.2.2 upGREAT LFA, GRE_LFA

The upGREAT Low-Frequency Array (LFA) was a robust channel tunable to frequencies between 1.835-2.007 THz. It was an upgrade from the single-pixel L2 channel. It was designed to primarily observe the [CII] 158 µm line, the primary cooling line of interstellar gas over various conditions. The LFA was split into two polarization subarrays: Horizontal (LFAH) and Vertical (LFAV). Each polarization subarray used a separate LO system consisting of a solid-state multiplier chain locked via a synthesizer to the GPS frequency standard. Each subarray was composed of 7 pixels like the HFA, with 6 pixels arranged in a hexagonal geometry around a central pixel. The spatial multiplexing advantage allowed more efficient spatially extended [CII] emission mapping. Each pixel had a spatial resolution (beam FWHM) of 14.1 arcseconds (at 1.9 THz) and was separated from adjacent pixels by 31.8 arcseconds. The pixels for the two subarrays were spatially co-aligned on the sky for a total of 14 pixels at seven positions. The central pixels for both subarrays were spatially co-aligned with the central pixel of the HFA. The two subarrays could be tuned independently or adjusted to the same frequency, doubling the effective exposure time. As the high-frequency multiplier chains were driven at the limit, they aged and had to be overhauled or replaced regularly. The astronomically interesting [OI] 145 µm line was at the edge of the tunable LO band. The different LO chains over time did not always cover the line. It happened that at times this line was tunable in both polarizations, or only in one, or not at all. From Cycle 8 onward, the line could only be observed with LFAV, which had a sufficiently large tuning range from 2.060 to 2.065 THz. The LFA was commissioned in Cycle 3 and made available for general science in Cycles 4-9. More details on the LFA can be found in Risacher et al. (2018) and Risacher et al. (2016).

2.2.3 4GREAT, GRE_4G

The 4GREAT Array consisted of a stack of four separate channels, called 4G1, 4G2, 4G3, and 4G4, with frequency ranges of 0.48-0.64, 0.96-1.12, 1.20-1.60, and 2.50-2.70 THz, respectively. Each channel was a single pixel with its own LO multiplier chain LO system and tunable within its range of frequencies. All four channels operated in parallel, optically separated by polarization and a dichroic beam splitter, thus allowing the four 4G channels of 4GREAT to operate simultaneously with the HFA in the second cryostat. With the simultaneous coverage of five astronomical lines of interest in the same spot on the sky, 4GREAT (plus the HFA) was designed to optimize the observing time for astrochemical studies, either of compact sources or by absorption spectroscopy against close background sources. The pixels for all four channels were spatially co-aligned with each other and the HFA central pixel to within a few arcseconds on the sky. More details on 4GREAT can be found in Durán et al. (2020).

2.2.4 Earlier Receivers

2.2.4.1 L1

The single-pixel L1 channel was commissioned during Early Science and was available until Cycle 5. It covered two frequency ranges dubbed L1a and L1b: 1.25-1.39 THz and 1.42-1.52 THz. The gap in frequencies was due to L1a and L1b using separate LO chains and telluric absorption between 1.39-1.42 THz. After Cycle 5, L1 was replaced with 4GREAT channel 4G3. More details on L1 can be found in Heyminck et al. (2012) and Pütz et al. (2012).

2.2.4.2 L2

The single pixel L2 channel was commissioned during early science and was available until Cycle 4. One of its main science goals was to observe the [CII] 158 µm line, and it was tunable to a range of frequencies from 1.81-1.91 THz. After Cycle 4, it was replaced with the LFA. More details on L2 can be found in Heyminck et al. (2012) and Pütz et al. (2012).

2.2.4.3 M

The single pixel M channel was commissioned during Early Science and was available until Cycle 2. It covered a frequency range of 2.49-2.52 THz. The 4GREAT channel 4G4 later covered a similar frequency range. More details on M can be found in Heyminck et al. (2012) and Pütz et al. (2012).

2.2.4.4 H

The single-pixel H channel was designed to observe the [OI] 63 µm line at 4.74477749 THz and was limited to a narrow range of frequencies around 4.74477749 THz. It was commissioned in Cycle 3 and was available for general science in Cycles 4-5. In Cycle 6, it was replaced by the 7-pixel HFA. Details on the H channel can be found in Heyminck et al. (2012) and Büchel et al. (2015).

2.3 GREAT CONFIGURATIONS

GREAT had two separate cryostat mounts, which allowed for multiple channel configurations. The available configurations changed depending on the Observing Cycle and instrument upgrades. **Error! Reference source not found.**4 lists the configurations and when they were in use. Note that during commissioning and early usage of the LFA and HFA channels, the respective keywords in the data archive and the data files (see also Appendices A through C) may in specific cases show the older channel type i.e., L2 and H, respectively. From the data it should be obvious where keywords were not updated properly.

Table 4: Overview of the channel configurations and when they were used

Cryostat Mount 1	Cryostat Mount 2	Cycles Used
HFA	LFA	5-9
HFA	4GREAT	6-9
HFA	L2	4-5
H	LFA	4
H	L2	3-4
L1	LFA	3-5
L1	L2	Early Science-4
M	L2	Early Science-2

2.4 INSTRUMENT DESIGN

2.4.1 Basics of Heterodyne Receivers

GREAT was a heterodyne receiver. Heterodyne receivers are common in radio astronomy and operate by down-converting the frequency of the incoming sky signal to a lower frequency where the signal can be amplified and processed further, e.g., being spectrally analyzed. An overview of how they work will be given here, but detailed explanations can be found in many textbooks, e.g., Tools of Radio Astronomy (Wilson et al. 2009). The signal from the target is collected by the telescope and passed into a mixer, where the signal from the sky is mixed with the signal from a local oscillator (LO). Mixers are non-linear devices combining the sky signal and the LO signal. To first order, the quadratic non-linearity mixes the monochromatic LO-frequency ν_{LO} with the band of sky frequencies ν_s to the band of intermediate frequencies ν_{IF}:

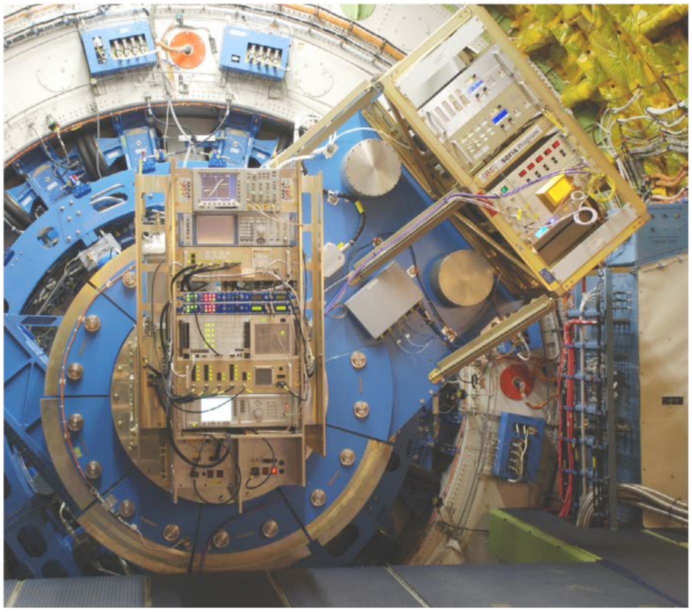
$$\nu_{IF}=|\nu_{LO}-\nu_s|$$

The intermediate frequency (IF) band covers a relatively small range of frequencies when the LO frequency is closest to the signal frequency range. For GREAT, the IF band was typically in the GHz frequency range which could easily be amplified first by cooled low-noise amplifiers located in the cryostat together with the cryogenically operated mixers, then further processed and amplified in the warm IF electronics and spectrally analyzed by the spectrometer backend of the heterodyne instrument. The IF range accepted by the backend defined the instantaneous bandpass. For GREAT, ν_{LO} and ν_s were in the THz range; the LO tuning range and the mixer reception bandwidth in the THz range defined the tuning range of each GREAT channel.

The received sky frequencies ν_s fall into two sidebands i.e., $\nu_s = \nu_{LO} \pm \nu_{IF}$. They are the upper sideband (USB, "+") and lower sideband (LSB, "-"). In single sideband (SSB) receivers, one sideband is suppressed (by methods going beyond what is discussed here). In double sideband (DSB) receivers like GREAT, both the USB and LSB are transferred to the ν_{IF} band, and their signals overlap i.e., are added. The sideband with the line frequency of interest is called the signal band while the other sideband is called the image band. In heterodyne receivers, the LO frequency is typically tuned so that a spectral line of interest falls in the low noise part of the IF-bandpass and for DSB receivers additionally so that no spectral features (telluric or astronomical) from the image band overlap in ν_{IF} with the spectral line of interest.

2.4.2 GREAT Components

GREAT was mounted at the SOFIA telescope's Nasmyth focus on the science instrument flange. The main optics, electronics, and cryostats were mounted on the end of the flange. The backend was mounted on the counterweight rack. Figure 2 shows GREAT mounted on the flange, with the diagram on the right showing the instrument layout.



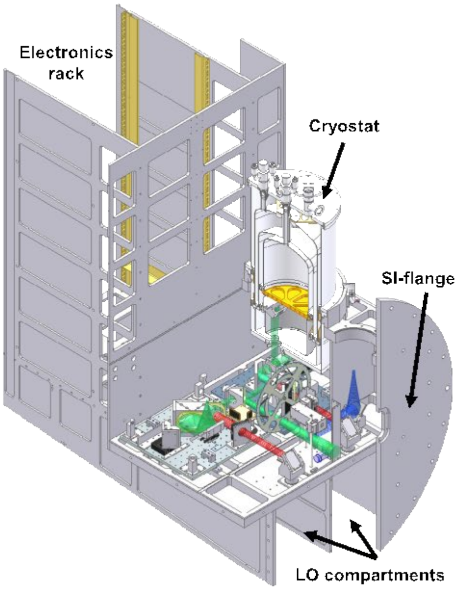


Figure 2 *From Heyminck et al. (2012). (Left) Image of GREAT mounted on the SOFIA instrument flange. The components of the instrument are mounted on the end of the flange seen near the center of the image, while the backend is mounted on the counterweight in the upper right of the image. (Right) Diagram showing the GREAT components mounted on the end of the flange.*

Figure 3 illustrates how the signal from the SOFIA telescope was passed through and processed by each GREAT component. For upGREAT (LFA, HFA, and 4GREAT), the signal from the telescope passed through a de-rotator to compensate for sky rotation in the instrument focal plane. The signal then passed through a dichroic (or multiple dichroic and polarizers), which split the light by frequency and polarization and directed it to the various frequency-specific GREAT channels. The light then passed into the channel optics where it was combined with the signal from the channel's LO, which were then both coupled to the mixer in the cryostat. The mixer converted the frequency of the signal ν_s to the IF ,ν_{IF} which was then amplified by low noise amplifiers at the mixer output. Outside the cryostat, the signal was passed to the backend, where it was further amplified and processed by the IF processor.

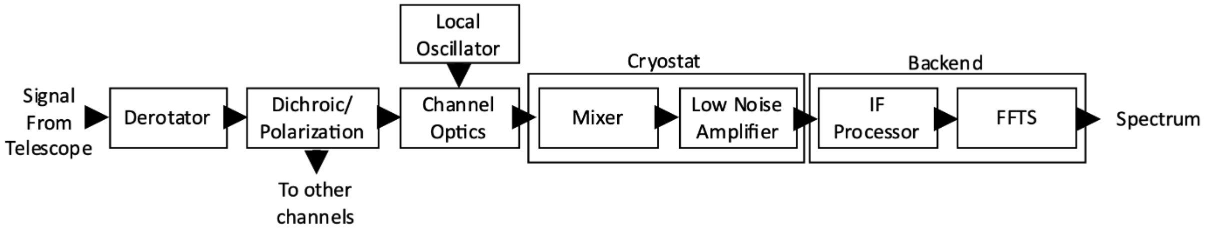


Figure 3 *Chart for GREAT showing how the signal from the telescope passed through each component of the instrument for a single channel before finally ending up as the Level 1 data. This chart is based on Figure 3 in Risacher et al. (2018).*

The signal was then turned into a spectrum by eXtended bandwidth Fast Fourier Transform Spectrometers (XFFTS) on the backend to generate the Level 1 data. GREAT's receivers were all DSB, so the resulting spectrum merged the signal and image bands.

2.4.2.1 Local Oscillators

The Local Oscillators (LOs) were unique to each of their channels and were continuously modified and upgraded during the lifetime of the instrument. The LOs used for most of the channels (LFA, 4GREAT, L1, L2, and Ma) were solid-state multiplier chains. (Crowe et al. 2011, Risacher et al. 2016b). The LFA had two LOs, one for each subarray LFAH and LFAV, which were mixed with the 7 pixels of their respective subarrays. For the high-frequency channels (HFA and H), the LO was a quantum cascade laser (Richter et al. 2015, Risacher et al. 2016b). Like the LFA subarrays, the HFA's 7 pixels shared the same LO. See Table 5 below for references for each channel.

2.4.2.2 Mixers

The channels receiving frequencies higher than 1 THz all used hot electron bolometric (HEB) mixers, the only type of low-noise mixers available at the highest frequencies; their IF bandwidth was relatively limited, with 3dB noise roll-off at about 3 GHz. The exceptions were 4GREAT 4G1 and 4G2, which, due to their lower frequency, used superconductor–insulator–superconductor (SIS) mixers; these were highly non-linear mixers which had a very wide IF bandwidth and substantially lower noise. Like the LOs, each channel had its own unique mixer. See Table 5 below for references for each channel.

Table 5: Summary of GREAT Channels

Channel	LO	Mixer	Reference
upGREAT LFA	Solid-state multiplier chain	Hot electron bolometric (HEB)	Risacher et al. (2016b)
upGREAT HFA	Quantum cascade laser	Hot electron bolometric (HEB)	Risacher et al. (2016b), Richter et al. (2015)
4GREAT 4G1	Solid-state multiplier chain	superconductor–insulator–superconductor (SIS)	Durán et al. (2020)
4GREAT 4G2	Solid-state multiplier chain	superconductor–insulator–superconductor (SIS)	Durán et al. (2020)
4GREAT 4G3	Solid-state multiplier chain	Hot electron bolometric (HEB)	Durán et al. (2020)
4GREAT 4G4	Solid-state multiplier chain	Hot electron bolometric (HEB)	Durán et al. (2020)
L1	Solid-state multiplier chain	Hot electron bolometric (HEB)	Heyminck et al. (2012), Pütz et al. (2012)
L2	Solid-state multiplier chain	Hot electron bolometric (HEB)	Heyminck et al. (2012), Pütz et al. (2012)
M	Solid-state multiplier chain	Hot electron bolometric (HEB)	Heyminck et al. (2012), Pütz et al. (2012)
H	Quantum cascade laser	Hot electron bolometric (HEB)	Risacher et al. (2016b), Büchel et al. (2015), Richter et al. (2015)

2.4.2.3 Backends

The GREAT instrument used XFFTSs as backends (Klein et al. 2012). Each XFFTS had a bandwidth of 4 GHz and 16,384 channels, thus providing a spectral resolution of 244 kHz, which corresponds to a resolution of $\Delta v=15$ m s^{-1} or $R=1.9\times10^{7}$ at 4.7 THz and $\Delta v=150$ m s^{-1} or $R=2.0\times10^{6}$ at 500 GHz. Typically, the spectra were re-binned to a lower resolution to increase the signal-to-noise ratio. The full theoretical bandwidth of 245 km s^{-1} at 4.7 THz or 2400 km s^{-1} at 500 GHz is not fully usable. The useful bandwidth depends on the noise over the bandpass and the atmospheric transmission.

Before the XFFTSs, GREAT used a combination of Acousto-Optical Spectrometers (AOS) with approximately 4 GHz bandwidth, and an earlier generation of FFTSs with approximately 2 GHz bandwidth (Heyminck et al. 2012).

2.5 OBSERVING MODES

2.5.1 Reference Subtraction

Drifts in the gain of any receiver or detector cause spurious offsets by drifting reference intensity. These must be compensated by reference measurements that subtract the possibly drifting reference intensity on timescales fast enough so that the drift amplitudes stay smaller than the RMS noise level of the measurement. As the RMS noise reduces proportional $1/\sqrt{\Delta\nu}$, such reference measurements must be taken faster for broader bandwidth signals. Thus, low-spectral resolution observations such as extragalactic lines and/or observations with a strong continuum signal need faster reference switch time. The timescale on which the RMS noise is equal to the drift amplitude is called the Allan-variance time scale. For GREAT it was typically as small as order of 1 second for broadband signals, or 10 up to 100 seconds for narrow lines (order of several km/s line width). GREAT used one of two methods for reference subtraction: Beam Switching for short stability time scales, and Total Power for longer stability time scales.

Beam Switching, also known as “Chopping”, involved switching the telescope’s secondary mirror to one or two reference positions near the science target with a frequency of the order of 1 Hz. For Total Power observations, the telescope was moved to a defined reference position on the sky on timescales of about half a minute. Appendix D has more details on Chopping and Total Power observations.

Fast Beam Switching with small “slew,” i.e., chopper transition times, resulted in better reference subtraction and baseline stability but, due to the limited chopper throw of SOFIA, was limited in how far from the source the reference positions could be. Total Power only allowed relatively infrequent reference measurements due to the relatively slow telescope slewing motion to the OFF position but allowed for reference positions further away from the source. It was thus unavoidable for extended source, i.e., mapping, and observations, even with compromising on the observing efficiency due to the slow slews. However, mapping allowed observing many ON source positions within one ON-OFF cycle, minimizing the lost time on the ON-OFF slew.

There are two ways to tell from the data which reference subtraction method was used. The first is to look in the Level 4 FITS-file header. The header keyword *CHPAMP1* will have a positive value for Beam Switching but will equal 0.0 for Total Power[1]. The second is to check the In-Flight log PDF included as an ancillary file with the Level 3 and 4 data. The log will show the observing script used. The script will have `chopped` in the name if it is a Beam Switching observation and `totalpower` in the name if it is a Total Power observation. Some older logs might not show this information, so check the Level 4 FITS-file header instead for these cases. shows which observing scripts correspond to which reference subtraction modes.

2.5.2 Beam Switching

In all beam-switching modes, equal time is spent on and off the source. Beam-switching modes were most often used for point or compact sources where nearby reference positions were clear of emission. The chop throw and angle (CCW from north) set the reference positions relative to the source. The secondary mirror typically chopped at a rate between 0.6 and 1.3 Hz. Because the time between the ON and OFF positions was short (~1 s), Beam Switching typically resulted in better sky cancellation and baseline stability than Total Power. Smaller chop throws between 60 and 180 arcsec were usually preferred to limit pointing errors (and possibly beam distortions such as coma) and in particular to avoid baseline ripples due to standing wave differences between the optical paths of the two chopper positions (heterodyne instruments are particularly sensitive to phase differences). For the same reason, GREAT only used a symmetric chop, never an asymmetric chop. The differences between symmetric and asymmetric chopping are detailed in Appendix D.

In Single Beam Switching (SBS) mode, the telescope typically was not nodded because a symmetrically placed second reference position would not have been emission-free. In Dual Beam Switching (DBS) mode, the telescope was nodded by the same amount as the total chop throw. See Appendix D for more details. In the vast majority of cases with GREAT, DBS mode was used instead of SBS mode. DBS mode resulted in better baseline stability, as the double difference subtracted the baseline ripple due to the optical path differences between the two chop positions to the second order. DBS mode also removed asymmetric reference emission to the second order.

2.5.3 Total Power

Total Power mode involved alternating the telescope position between the source and a defined reference position on the sky near the source position, free from emission line contamination. The time intervals between visiting the reference position (including the slew times of the telescope) were chosen based on the Allan time of the system and were significantly longer than in Beam Switching mode (~30 sec). Sometimes, if a suitable reference position could not be identified within 30 arcminutes to 1 degree of the target, an intermediate reference position (often called "near-off") was selected instead, even if it potentially had some emission from the line of interest. This intermediate position was then measured against a faraway reference position (often called "far-off") with no line emission so that any contamination at the intermediate reference position could be accounted for and removed. See also Appendix D.

[1] The value of CHPAMP1 is the chop amplitude i.e., the total chop throw or the separation between the source and the reference position is twice as large. The value is in units of arcseconds.

2.6 OBSERVATION TYPES - ASTRONOMICAL OBSERVING TEMPLATES

GREAT had several different pointing and mapping modes. The way the telescope was pointed at or scanned over a source was set by various Astronomical Observing Templates (AOTs). For the LFA and HFA multi-pixel arrays, the telescope pointing was relative to the central pixel.

It is not immediately apparent which AOT was used for a given observation, as this information is not propagated to the Level 3 and 4 data headers. The In-Flight Log, which is among the ancillary files (Section 0), usually reports the GREAT observing scripts used, from which the AOT can be inferred. The observing script used is also listed in the Level 1 FITS file header keyword *AOT_ID*.

Table 6 shows the AOT type and reference subtraction method used for a given GREAT observing script.

Table 6: AOT types and respective script names

AOT Type	Script for Total Power	Script for Beam Switching
Single Point Spectra	*singlepoint_totalpower.sh*	*singlepoint_chopped.sh*
Raster Map	*raster_totalpower_map.sh*	*raster_chopped_map.sh*
Classical OTF	*otf_totalpower_map.sh*	*otf_chopped_map.sh*
Array OTF	*array_otf_totalpower_map.sh*	*array_otf_chopped_map.sh*
Honeycomb OTF	*pattern_otf_totalpower_map.sh*	*pattern_otf_chopped_map.sh*

2.6.1 Single Point Spectra

The simplest type of observation was a single point spectrum where the telescope was pointed at a single on-source position on the sky. It was typically used to observe point sources or faint sources that required long integration times. The optimum signal-to-noise of the ON-OFF difference spectrum was reached by spending equal time on the ON-source and OFF-source positions.

2.6.2 Raster map

Raster mapping was essentially a collection of single-point observations used to create small maps where a relatively long integration time per map point was needed. It was used on compact sources and for projects that only required sparse spatial sampling (e.g., multiple pointings across an outflow).

To optimize the observing efficiency in Total Power mode, the same OFF observation could be used as a reference for several ON-source positions, thus spending a larger fraction of the total observing time on the ON-source map positions. The highest signal-to-noise for each map position was reached by making the OFF-source observations $\sqrt{N}$-times longer than each ON-source position for an ON-OFF cycle with N ON-source observations for a single OFF-source reference. The total cycle of N ON-source and one OFF-source positions had to be shorter than the Allan stability of the instrument for the desired spectral resolution.

Note that in case the ON-source observations are averaged to a lower angular resolution, e.g., by averaging *m* ON-source observations, the above choice of OFF-source duration results in a noise level decreasing slower than $1/\sqrt{m}$, as the noise in the subtracted OFF-position is identical, i.e., not independent, for each ON-source position. If the goal was a map with an angular resolution corresponding to the average of *m* ON-positions, the optimal choice for the length of the OFF-position would have been $\sqrt{m \times N}$ longer. This setting was occasionally used in select programs.

2.6.3 On-The-Fly Map

In an On-The-Fly (OTF) map, the telescope scanned along a series of rows while the backends continuously integrated the incoming signal. An average was recorded after the telescope had moved for the time t_{on}. The scanning speed was typically selected such that the telescope moved about half of the beam width during that time, so that the resulting map was fully sampled. OTF could be performed in Total Power mode as well as in Beam Switching mode.

OTF in Total Power mode was designed to optimize the use of the observing time by taking the maximum possible number of ON-source positions per OFF within the stability time. With *n* such average dumps per scan, the total duration of the OTF scan $(n + \sqrt{n})t_{\text{on}} + t_{\text{slew}}$ could not exceed the timescale on which the receivers were stable (Allan Variance). The observations were more efficient the larger *n* was, as the ratio of the integration time spent off-source to on-source was $\sqrt{n^{-1}}$.

For Beam Switching, the ratio was always 1 as n=1. Nevertheless, OTF in Beam Switching was more efficient than raster mapping as it avoided the slew-time between the (closely spaced) ON-source positions. In Beam Switching mode, the secondary mirror chopped while the telescope scanned along each row. That meant that the reference positions formed a map offset by the chop throw. This corresponded to a single beam switch for a pointed observation. When a double beam switch was requested, the same row was repeated with a nodded beam for each row of the OTF map.

Total Power mode was usually used for large maps since it maximized the time on the source and allowed choosing relatively distant reference positions. For compact ,e.g., Honeycomb (see below) maps, Beam Switching was often used for improved baseline stability.

2.6.4 Classical OTF Map

For so-called "Classical" OTF mapping, each array pixel created a fully sampled rectangular map. For the LFA and HFA, the result was seven overlapping rectangular maps. Classic OTF mapping was the only available OTF AOT to create fully sampled maps using the single-pixel 4GREAT array and the old single pixel channels. Figure 4 shows a rectangular area of the sky covered by a Classical OTF map example.

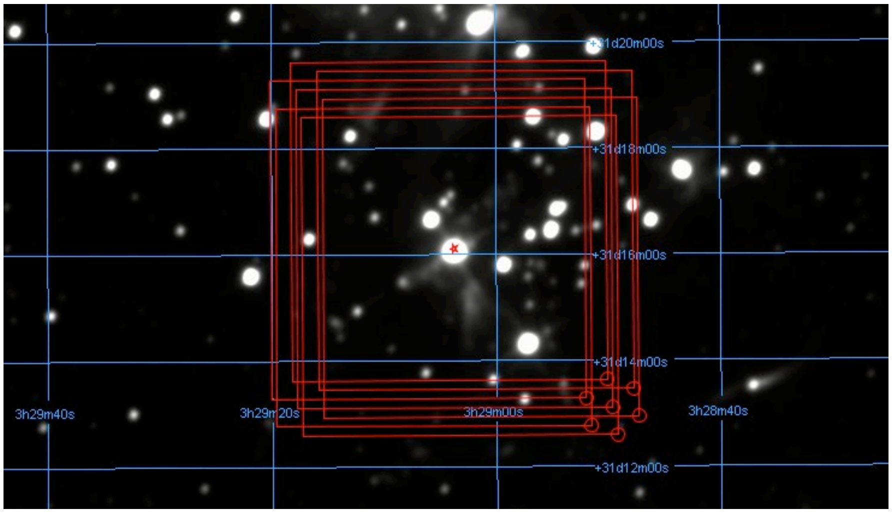


Figure 4 *Example overlay of a Classical OTF map for the LFA. Each red rectangle shows the region mapped by one of the LFA pixels. The footprint of the array is shown by the red circles on the bottom right and marks the starting position of the map. The central region of the map is covered once by each pixel of the array.*

2.6.5 Array OTF Map

Array OTF maps can fully sample a given area by interleaving sparse OTF scans. With a properly aligned array footprint a full and complete coverage of the source is achieved. Array OTF maps thus only made sense for the multi-pixel LFA or HFA arrays. An Array OTF map with the hexagonal array footprint was done with the array rotated by 19.1 degrees relative to the scan directions (see Figure 5) so that each map point was covered by a single pixel of the array after two such scans. The goal was to efficiently create fully sampled maps. Array OTF maps were often used to observe large regions that didn't need deep integrations.

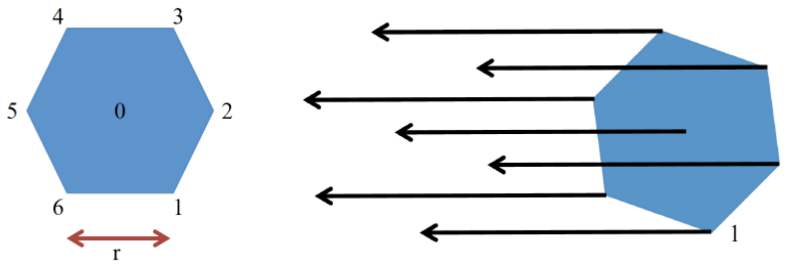


Figure 5 *Array configuration and an illustration of how a rotation of the array of 19.1 degrees allows equidistant scans.*

The basic unit of the array mapping was called the "block," which consisted of a single or multiple scans of the same length in the same direction. An illustration of a block can be seen in Figure 6.

Array OTF maps typically combined several blocks, as seen in

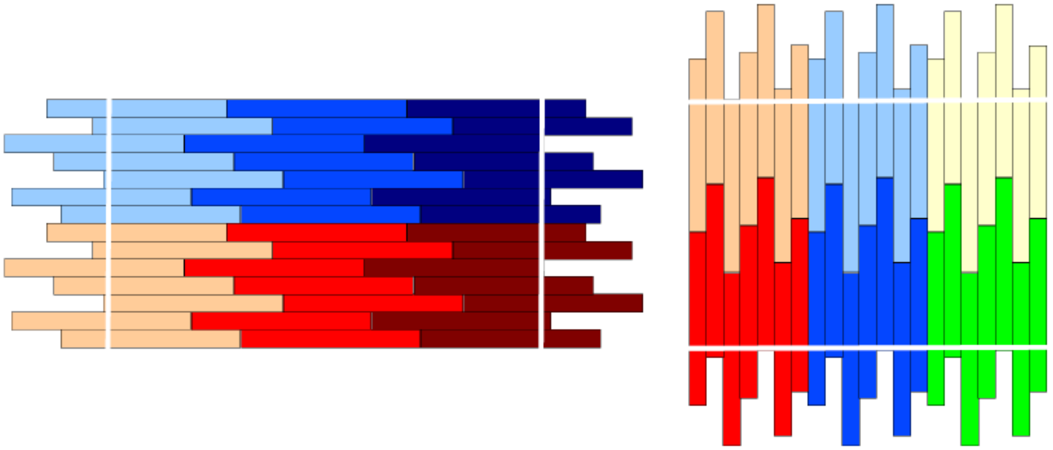


Figure 7. A single map could consist of any number of blocks and could scan in the x- or y-direction or both. Occasionally overlapping scans were done in both directions to minimize striping effects caused by the different characteristics of individual array pixels.

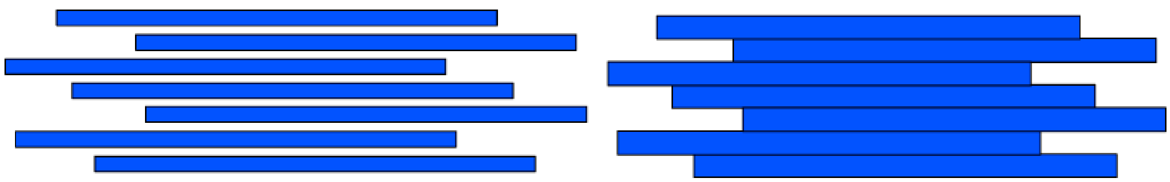


Figure 6 *(Left) Example of a block with a single scan. The gaps between the scanned pixels indicate an under-sampled map. (Right) Example of a block with two scans. This block is fully sampled in the direction perpendicular to the scan direction. The second scan fills in the gaps in the single-scan block.*

When the HFA and LFA were operated in parallel, Array OTF maps needed to be optimized to only one of the arrays, as the size and pixel spacing of the arrays was different between the HFA and LFA. Note that the other array does not get fully sampled maps, as even though the LFA beam size is larger than the HFA, the LFA does not have a fully sampled map in parallel with an HFA Array OTF map.

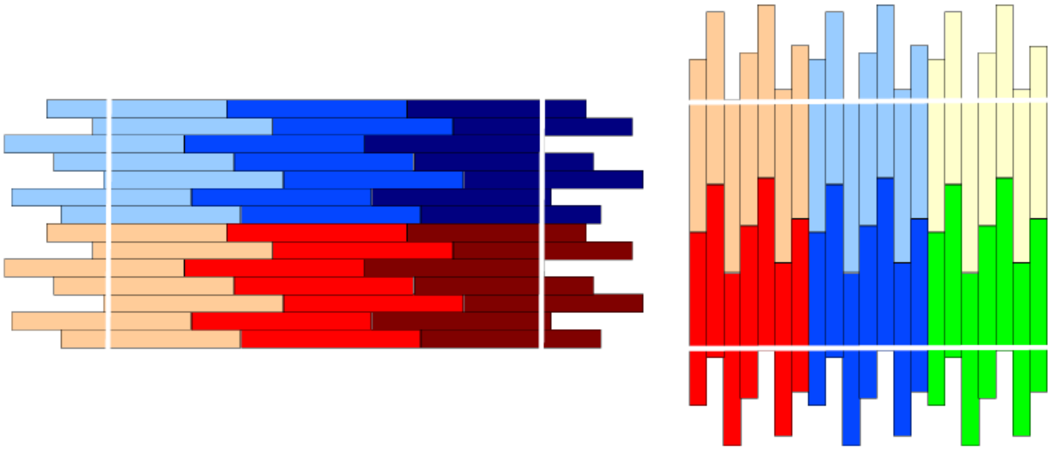


Figure 7 *Examples of Array OTF maps with multiple blocks combined to create larger maps in the (left) x and (right) y directions.*

2.6.1 Honeycomb OTF Map

A Honeycomb OTF map was the preferred mapping mode for mapping compact objects comparable in size to the array footprint used (either the LFA or HFA). Instead of scanning rows like Classical or Array OTF maps, the telescope followed a small 25-point hexagonal pattern to fully sample the gaps between each array pixel on the sky. Figure 8 shows how all pixels were scanned and combined to fill the mapping area using this pattern. The resulting map was spatially fully sampled at the resolution of the respective array. This had an advantage over raster maps in terms of observing efficiencies, and also avoided the issue of wasted integration time outside the region of interest, depending on the size and geometry of the target, by avoiding not fully covered edges common to the Classical OTF and Array OTF maps. On the other hand, similar to array-OTF mode, this mode was affected by different pixel performance, which to some degree was compensated for by rotating the array for a certain fraction of the observations so that different outer pixels covered different areas on the sky.

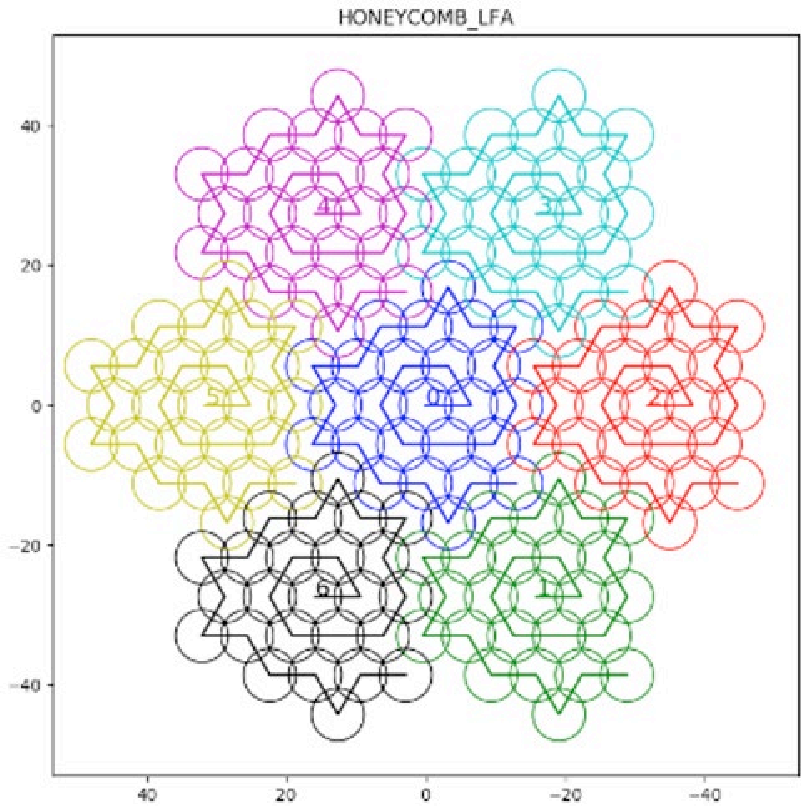


Figure 8 *Example Honeycomb pattern for the LFA with all pixels showing how the pointings mesh together. Each color represents a separate pixel in the array, and the line shows the motion of the scan. The units of the axes are in arcseconds. The pattern for the HFA was a factor of 2.7× smaller since the pattern scales with the array size*.

3. INSTRUMENT PERFORMANCE

3.1 INTENSITY SCALES

In radio astronomy, and thus also for GREAT, *brightness temperatures* in units of Kelvin are used to measure intensities. For the specific intensity of a signal, I_ν (e.g., in erg s^{-1} cm^{-1} Hz^{-1} sr^{-1}), the brightness temperature T_B is defined as:

$$T_B = \frac{\lambda^2}{2k_B} I_\nu = \frac{c^2}{2k_B \nu^2} I_\nu$$

where λ is the wavelength, ν is the frequency, c is the speed of light, and k_B is the Stefan-Boltzmann constant. The defined brightness temperature of a blackbody intensity $I_\nu = B_\nu(T)$ (Planck's law) is then equal to the physical temperature T in the Rayleigh-Jeans limit ($h\nu << kT$).

Guan et al. (2012) discuss the GREAT calibration, which was the procedure to obtain the calibration factor i.e., the factor converting counts from the spectrometer output to brightness temperature using difference measurements against internal hot- and cold-loads, how to correct for atmospheric absorption, and many more details.

Different brightness temperature scales, or definitions, were being used depending on which component of the total receiver input was referred to by the measured intensity. The "antenna temperature" T_A referred to the total intensity entering the receiver input; it would be the intensity that the receiver would see if it were embedded in a blackbody cavity of a given temperature.

The calibrated GREAT data is provided in two different temperature scales:

- The "corrected" forward-beam antenna (brightness) temperature T_A^*, which is the intensity seen in the full forward beam response of the antenna pattern (i.e., excluding all wide sidelobes possibly terminating at ambient material beyond the telescope mirror, etc.) and corrected for the transmission of the atmosphere. This would be the temperature seen pointing the telescope outside the atmosphere towards a very extended (i.e., excluding the backward sidelobes, etc.) blackbody source on the celestial sphere.
- The main-beam brightness temperature T_{MB}, which is the intensity seen in the central lobe of the antenna pattern (the main beam) and corrected for the atmospheric transmission. This would be the brightness temperature seen when pointing the telescope outside the atmosphere towards a blackbody source well covering the main beam (but not the sidelobes) of the telescope.

Depending on the angular/spatial extent of the source intensity, one of these two scales would be appropriate. The observed brightness temperature was the intrinsic source intensity distribution on the sky convolved with either the forward beam pattern of the telescope or convolved with the main beam pattern of the telescope.

These different temperature scales were related by efficiencies that are determined by measuring the antenna temperature of sources of known brightness and size and correcting for the atmospheric transmission:

$$\frac{T_A}{e^{-\tau}} = F_{\text{eff}} T_A^* = B_{\text{eff}} T_{\text{MB}}$$

The forward efficiency F_{eff} relates T_A^*, and the beam efficiency B_{eff} relates T_{MB} to the antenna temperature corrected for atmospheric losses or the antenna temperature of an antenna outside of the atmosphere (here represented as $\frac{T_A}{e^{-\tau}}$ and often denoted with T'_A). For GREAT on SOFIA, F_{eff}=0.97. It was high because the spillover of a Gaussian beam illuminating the telescope beyond the large tertiary was negligible; the spillover beyond the secondary mirror ended up on the blank sky, and the diffraction pattern of the central blockage of the secondary mirror was reflected largely onto the blank sky by the primary mirror. The beam efficiencies B_{eff} were determined for each flight series and usually stated in the ancillary documents for each data release (Section 0). Typical values were around $B_{\text{eff}}\approx 0.66$, given by the coupling of the diffraction pattern of the Gaussian illumination with edge taper around 11 dB onto the secondary with its large central blockage/scatter cone that shadowed the large central blockage of the tertiary mirror and tertiary mirror mount. Each channel and array pixel had a unique B_{eff} value. Sometimes the notation η_{mb} is used for B_{eff}.

While the above practical definition of the beam efficiency B_{eff} is often used, it can also be written as

$$B_{\text{eff}} = \frac{\Omega_{\text{MB}}}{\Omega_{\text{A}}} = \frac{A_e}{\lambda^2}\Omega_{\text{MB}} \text{ with } A_e\Omega_{\text{A}} = \lambda^2$$

where Ω_{MB} and Ω_{A} are the solid angle of the antenna's main beam and its total solid angle (antenna pattern integrated over 4π), respectively, and its effective collecting area is A_e. This formulation allows the brightness temperatures to be converted to spectral flux densities S_ν e.g., units of Jansky.

The spectral energy density P_ν (or equivalent antenna temperature T_{A}) received by an antenna sensitive to one polarization over an effective collecting area of A_e from a source with a spectral flux density S_ν integrated over the antenna pattern through an atmosphere with an optical depth of τ would be:

$$P_\nu = k_B T_{\text{A}} = \frac{1}{2} A_e e^{-\tau} S_\nu$$

Solving for S_ν and using the above relations:

$$S_\nu = \frac{2k_B}{A_e}\frac{T_A}{e^{-\tau}} = \frac{2k_B}{A_e} B_{\text{eff}} T_{\text{MB}} = \frac{2k_B}{\lambda^2}\Omega_{\text{MB}} T_{\text{MB}} = \frac{2k_B}{\lambda^2}\Omega_{\text{MB}}\frac{F_{\text{eff}}}{B_{\text{eff}}} T_A^*$$

Thus e.g., for a gaussian beam at λ=157.741µm ([CII]) with an FWHM θ=14.1" i.e., $\Omega_{\text{MB}} = 1.133\theta^2 = 5.294\times10^{-9}$ sr:

$$S_\nu = 588\frac{\text{Jy}}{\text{K}} T_{\text{MB}} = 864\frac{\text{Jy}}{\text{K}} T_A^*$$

with B_{eff}=0.66 and F_{eff}=0.97. These conversion factors, also known as antenna sensitivities, don't change much with frequency or wavelength as Ω_{MB} scales as λ^2. However, changes of ± 20% are seen due to varying efficiencies between the channels.

It might be useful to not only convert spectral flux densities between Jansky and Kelvin, but also have the conversion factors for integrated line fluxes handy. Integral line fluxes are often expressed in units of "K km s^{-1}". To derive the conversion, the above formula needs to be integrated over frequency and velocity respectively. Here is an example again for the [CII] line:

$$\int S_\nu d\nu = 588 \frac{\mathrm{Jy}}{\mathrm{K}} \frac{d\nu}{dv} \int T_{\mathrm{MB}} dv = 0.372 \left(10^{-16} \frac{\mathrm{W}}{\mathrm{m}^2}\right) \left(\frac{\mathrm{K\,km}}{\mathrm{s}}\right)^{-1} \int T_{\mathrm{MB}} dv \text{ with } \frac{dv}{d\nu} = \lambda = 157.741 \mu\mathrm{m}$$

Note that this conversion factor does depend on the wavelength.

Table 7 below gives *typical* conversion factors for the receivers at an example frequency for each receiver using the values from Table 3 and references therein.

Table 7: Typical performance parameters for each channel

	HFA	LFA	4G4	4G3	4G2	4G1	L1a	L1b	L2	Ma
Freq. [THz]	4.7448	1.9005	2.510	1.337	1.038	0.530	1.461	1.383	1.9005	2.510
Beam FWHM ["]	6.3	14.1	10.5	20	27	52	21.3	19.6	15	11.4
B_{EFF}	0.64	0.66	0.57	0.62	0.55	0.61	0.54	0.54	0.51	0.58
S_ν/T_{MB} [Jy/K]	731	588	568	585	643	621	792	601	665	670
$S_\nu d_\nu/T_{\mathrm{MB}}dv$ [10^{-16} W/K km s^{-1}]	1.16	0.372	0.576	0.261	0.233	0.110	0.386	0.277	0.422	0.561

3.2 SENSITIVITY AND SYSTEM TEMPERATURE

The noise temperature ΔT_A^* (forward-beam brightness temperature scale) of a spectrum is given by the radiometer formula

$$\Delta T_A^* = T_{\mathrm{sys}} \sqrt{\frac{2}{\Delta\nu\, t_{\mathrm{on}}}}$$

and depends on the system temperature T_{sys}, the on-source integration time t_{on} (assuming the same time is spent at the reference position), and the spectral resolution $\Delta\nu$. For total power on-the-fly observations the time spent on- and off-source is not equal, but the time spent at the reference position is $\sqrt{N} t_{\mathrm{on}}$ when N is the number of on-source position observed between observing the reference position and t_{on} is the time spent at each on-source position. In this case, the noise temperature is

$$\Delta T_A^* = T_{\text{sys}} \sqrt{\frac{1+\sqrt{1/N}}{\Delta\nu\, t_{\text{on}}}} \; .$$

The system temperature is a combination of the receiver temperature T_{rec}, the telescope and sky brightness temperature, T_{tel} and T_{sky} respectively, which vary strongly with frequency, divided by the also frequency-dependent sky transmission $e^{-\tau_\nu}$:

$$T_{\text{sys}} = 2\frac{T_{\text{rec}} + F_{\text{eff}}T_{\text{sky}} + T_{\text{tel}}}{F_{\text{eff}}e^{-\tau_\nu}}$$

The factor 2 is there because GREAT had double sideband receivers and both sidebands contributed equally to the system temperature. The sky fills the full forward antenna response and thus the forward efficiency F_{eff} moderates the sky brightness temperature. The denominator scales the system temperature from the antenna temperature scale to the forward-beam brightness temperature T_A^*. See also Section 3.1.

The telescope background had a relatively low brightness temperature of about T_{tel}=5 K (Rayleigh-Jeans corrected brightness temperature for the SOFIA telescope at around 190 K was between 100 and 180 K depending on the frequency, and the emissivity of the telescope is around 3%). The frequency dependence comes from the conversion from the physical temperature to the Rayleigh-Jeans brightness temperature.

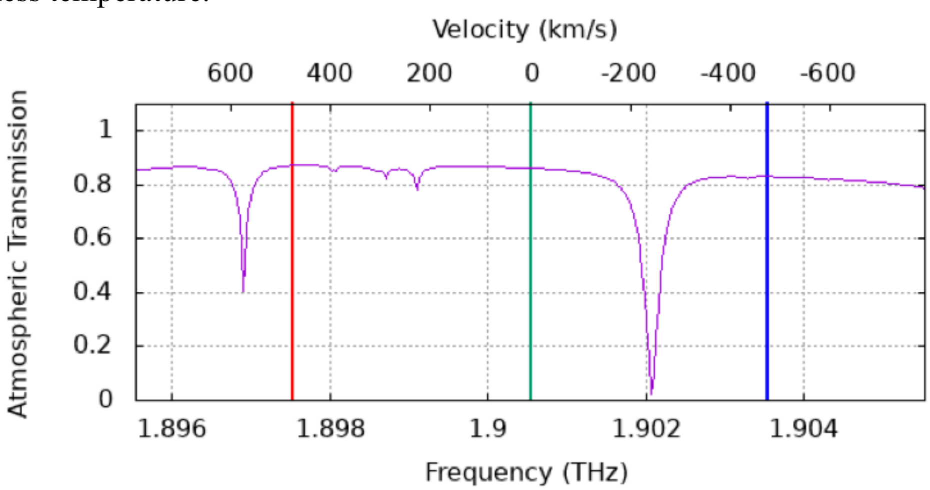


Figure 9 *Atmospheric transmission around the [CII] line for typical observing conditions on SOFIA. The green line is at the frequency of the [CII]. The red and blue lines are at the frequencies which appear at the same intermediate frequency (IF) as the [CII] line when observing the [CII] line in the upper or lower sideband, respectively.*

The sky background had a similar physical temperature, but the emissivity varied strongly with frequency. Figure 9 is a plot of the atmospheric transmission around 1.9 THz for a typical observing altitude and water vapor content of the atmosphere. While the transmission was mostly around 0.86 there were narrow absorption features where the transmission dropped considerably. Conversely, the emissivity was mostly around 0.14 but could be nearly 1. Therefore, the sky's brightness temperature T_{sky} ranged from about 20 to 150 K depending on the frequency.

Especially for the high-frequency channels, the receiver temperature was the largest contribution to the system temperature. Figure 10, Figure 11, and Figure 12 depict receiver temperatures for the LFAH, HFA, and 4GREAT, respectively. These represent typical receiver temperatures and noise characteristics across the bandwidth of each channel.

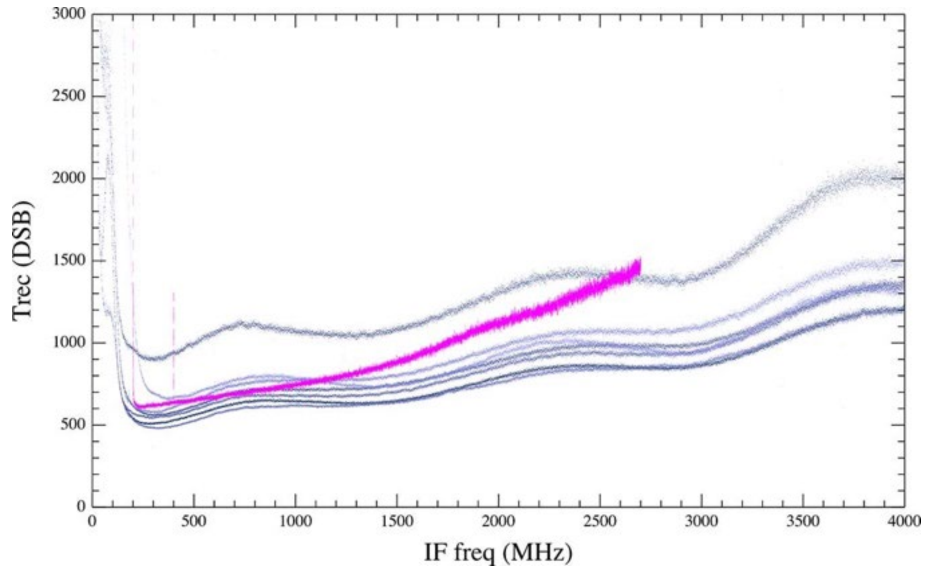


Figure 10 *LFAH receiver temperature curves from Risacher et al. (2016) for all seven pixels in the array. The purple line is the single-pixel L2 receiver for comparison.*

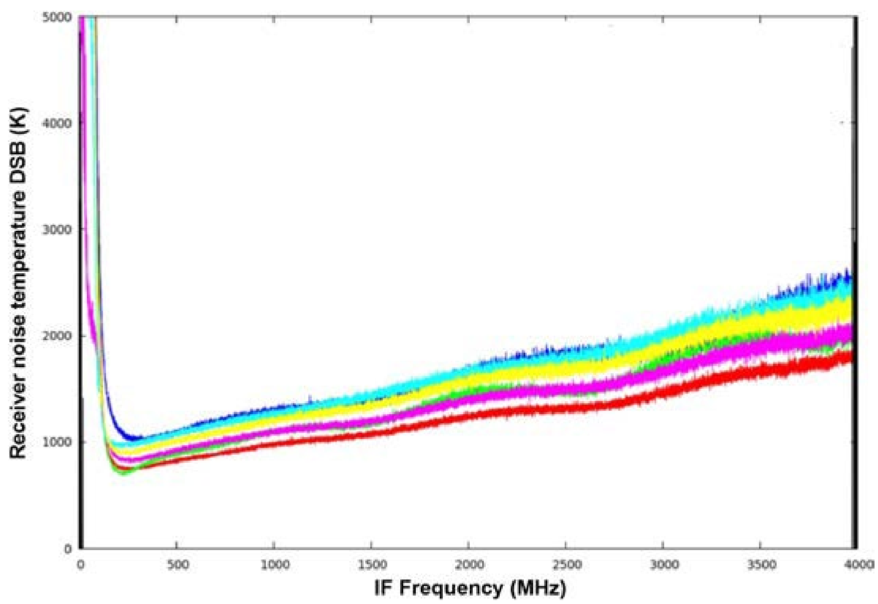


Figure 11 *HFA receiver temperature curves from Risacher et al. (2018) for all seven pixels in the array*.

For an observation, the frequency of the local oscillator was tuned so that the sky frequency range of interest plus some space to estimate baselines next to the range would appear at intermediated frequencies (IF) where the receiver temperature was low and fairly uniform. Another consideration was that the frequency range of interest would be free of atmospheric absorption features that came in from the image band.

The Level 3 data provides the measured receiver temperature and the combined system temperature (among other intermediate data products) as a function of frequency. See Section 4.1.2.1.

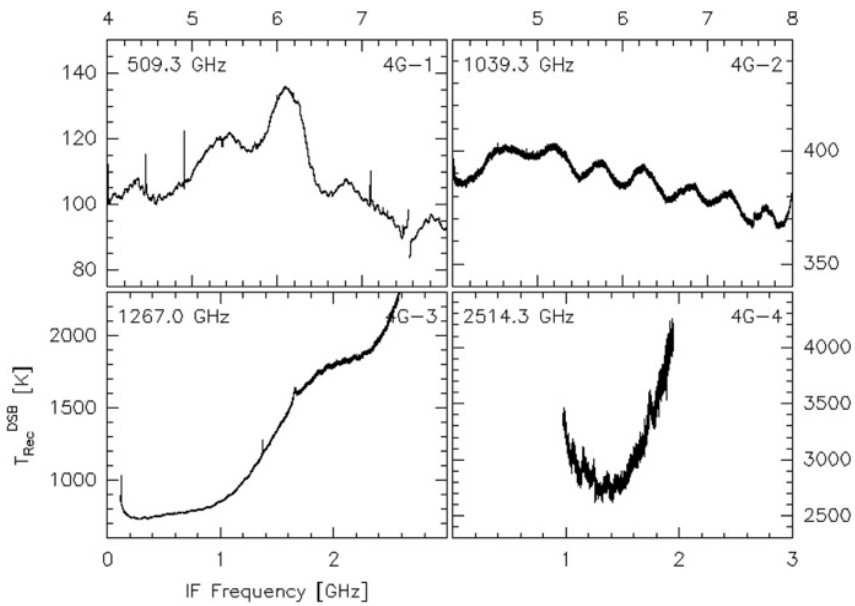


Figure 12 *4GREAT receiver temperature curves from Durán et al. (2020) for the four 4GREAT channels.*

3.3 PERFORMANCE PARAMETERS

The important calibration parameter was the main beam efficiency B_{eff} (Section 3.1). It was measured by observing a well-known source smaller than the beam. A planet was observed at the beginning of each flight series when available, and beam efficiencies and sizes were determined and used to calibrate the data for that series and future series until a new measurement could be done. Table 8 and

list all the main beam efficiency and size measurements made with the month and year when they were made. For the array receivers, the values are averaged over the array. The beam efficiencies vary only a few percent between the pixels. The main beam efficiencies can also be found in each data release along with the individual values for each pixel of the array receivers. The beam efficiencies determined in May 2019 were used for all subsequent observations. Later measurements confirmed these values. The beam size is given as full-width half maximum (FWHM) in arcseconds. The values determined in November 2018 were adopted for the remainder of the flight series.

Table 8: Main Beam Efficiencies B_{eff}

	L1 1.4 THz	L2 1.9 Thz	H 4.9 THz	M 2.5 THz	<LFA> 1.9 THz	<HFA> 4.9 THz	4G1 0.53THz	4G2 1.0THz	4G3 1.3THz	4G4 2.7THz
Apr 2011	0.55	0.51		0.58						
Apr 2013	0.67	0.65		0.7						
May 2014	0.7	0.67	0.67							
Jan 2015	0.65	0.69	0.67							
May 2015	0.64	0.69	0.67		0.69					
Dec 2015	0.69	0.68	0.69		0.67					
May 2016	0.66	0.69	0.63		0.65					
Oct 2016	0.69	0.69			0.65	0.63				
Feb 2017	0.65				0.63					
June 2017					0.7	0.63	0.62	0.58		0.70
May 2018					0.65	0.63	0.61	0.55	0.62	0.57
Nov 2018					0.66	0.63	0.62	0.56	0.60	0.52
May 2019					0.65	0.68	0.51	0.59	0.71	0.57

Table 9: FWHM beam sizes in arcseconds

	L1 1.4 THz	L2 1.9 THz	H 4.9 THz	M 2.5 THz	<LFA> 1.9 THz	<HFA> 4.9 THz	4G1 0.53THz	4G2 1.0THz	4G3 1.3THz	4G4 2.7THz
Apr 2011	20.1									
Apr 2013										
May 2014	19.1	14.1	6.6	11						
Jan 2015										
May 2015										
Dec 2015		14.8	6.1							
May 2016	19.1	14.8								
Oct 2016	19.8	15.1	6.3							
Feb 2017	19.3				14					
June 2017										
May 2018					14.1	6.3	52.00	26.90	23.81x22.96	10.50
Nov 2018					14.1	6.3	55.20	25.70	19.70	10.60

See also: https://www.mpifr-bonn.mpg.de/4482918/calibration

4. DATA

4.1 DATA DESCRIPTION

Data products from GREAT in the SOFIA IRSA Archive are available in three different processing levels: Levels 1, 3, and 4. These data products come in either FITS-files or as CLASS files. FITS is a common astronomical data format (for details, see https://fits.gsfc.nasa.gov/), and CLASS is part of the GILDAS software collection designed to process sub-mm and radio data (see https://www.iram.fr/IRAMFR/GILDAS/). The Institut de Radioastronomie Millimétrique (IRAM, Grenoble, France) maintaining GILDAS has supported GREAT-specific extension to the GILDAS header block etc., which are now part of the standard distribution.

Level 1 is the raw data consisting of many FITS-files per AOR (Astronomical Observing Request). The files are as written by the GREAT instrument during the observing flights and only useful with access to the calibration procedures or by checking detailed metadata in the header. They also include post-flight corrections for the pointing, beam efficiencies, and possibly LO-setting (for the HFA channel) determined in the post-flight data analysis for each campaign.

Level 3 and 4 data have been created by the team working for the Principal Investigator of the GREAT instrument (the GREAT Team) as described in Section 4.2. The Level 3 data files released by the GREAT Team to the Principal Investigators, who requested the respective observations, have been split by source and frequency for ingestion into the archive. Level 3 data come as a tar-file containing calibrated and calibration data together with ancillary files like data release notes. Level 4 is the final averaged or otherwise combined science data depending on the observing mode. These are typically single spectra for single-pointing observations or spectral data cubes for mapping observations. Level 4 data in the archive can be downloaded in two forms: FITS-files or tar-files. The tar-files contain the Level 4 data in CLASS file format along with ancillary files. For Guaranteed Time Observing (GTO) projects of the GREAT Team, Level 3 and 4 data have been or will be submitted to the archive when the data are published. The GTO Level 3 and 4 data files will not contain ancillary data release files (see Section 0).

The GREAT instrument always observed more than one transition simultaneously. In general, the transitions had different priorities for the program requesting the observations. Therefore, the instrument may have been optimized for the high priority transition during the observations if tradeoffs had to be made. Similarly, during the data reduction the processing from Level 3 to Level 4 may have concentrated on the high priority transitions and expected spectral features. Reviewing the ancillary files coming with the data (Section 0) to understand the context in which the data was acquired is highly recommended.

More details on the different processing levels can be found in the next sections starting with Level 4, the most processed data product available for all GREAT observations.

4.1.1 Level 4 – General Structure

There are always two Level 4 data products at IRSA for each GREAT observation:

- a tar-file and
- a FITS-file.

The tar-file contains a Level 4 CLASS data file, which is the final data product that is processed and combined from the Level 3 spectra. The final data product consists of either averaged spectra or spectral data cubes. The tar-file also contains ancillary files (see Section 0) including CLASS-script(s) that created the Level 4 CLASS data file from the Level 3 spectra.

For spectra obtained with heterodyne instruments, typical data artefacts are baseline distortions or baseline wiggles (quasi periodic baseline distortions). They typically result from standing waves of the sky-, hot-, and/or cold-signal or from the local oscillator (LO) signal in optical cavities along the respective signal path. The length of the standing wave cavity determines the period of the baseline ripple, and as the standing waves from the different signals (sky, hot, cold, LO) are potentially different, their standing wave patterns merge to a more complex baseline structure. In a perfectly stable system, the resulting pattern is stable or even subtracts out in the hot/cold-, respective ON/OFF-source difference. In a real system with time variable drifts of the mechanics and electronics, the subtraction is not perfect, and the resulting difference is modulated by the gain-factor of the detector (or its inverse) across the spectrometer bandwidth. In addition, the slightly different standing wave patterns from the signal- and image-sideband are folded together. One source of such baseline structure in GREAT resulted from the opto-mechanical and/or thermal modulation introduced by the cryo-cooler motion, synchronous with the cryo-cooler mechanical cycle. Therefore, to minimize these effects, for total power observations, the length of the ON- and OFF-measurements was selected as integer multiples of the cryo-cooler period; for chopped observations, the chopper frequency was chosen to be synchronous with (sub-)harmonics of the cryo-cooler cycle. The resulting baseline distortions are quite complex and are traditionally removed by fitting higher order polynomials to the (windowed) spectra.

A more advanced method is being developed by the GREAT team. It uses a principal component analysis (PCA) of the baseline features visible in the differences of the OFF-source spectra (thus excluding characteristics of the ON-source spectral features, which obviously should not be subtracted), and determining the time-variable amplitudes of these principal components by least-square fitting to the ON-OFF spectra. This method works quite well for chopped data, because the fast time series of adjacent OFF-source chop positions gives a good sample of the instrument variation, whereas the sparse and longer time-averaged OFF-source data of total power observations do not provide a good sampling of the instrument baseline features. Data reduced with the PCA method may be made available via IRSA as user contributed data in the future.

The FITS-file contains the same data as the CLASS data file in the tar-file, and is provided since FITS is a more common data format. The data can be contained in several FITS-extensions. Even if the data will only be accessed via the FITS-file, retrieving the tar-file and reviewing the ancillary files is highly recommended, as they may contain important comments on the content, quality, and calibration factors (see Section 0). Typically, there is one FITS-file per observation, source, and frequency. The Level 4 data should be in T_{MB} units, but there are instances where the data are calibrated on the T_A^* scale as was appropriate given the science goals of the project. Check the header and/or the ancillary documents. The header keywords are listed and explained in Appendices A through C.

The data can come from several flights and are often only associated with one of the flights in the IRSA database.

4.1.1.1 Level 4 - Single Point Data

For single point observations, there is one or more FITS-files per AOR and one tar-file per FITS-file. The Level 4 FITS-file will contain average spectra. The exact contents of the Level 4 FITS-file will depend on the science goals of the project. For example, a single point observation of an extended source using the LFA might have 14 averaged spectra, while an absorption experiment toward a point source might have only a single average spectrum. The naming convention for Level 4 single point files in general is: 'PIString'_'Source'_'Line'.great.fits, where 'Source' and 'Line' are the target name and observed transition, respectively. 'PIString' identifies the Principal Investigator for this observation and the project.

4.1.1.2 Level 4 - Mapping Observations

For mapping projects (any mapping mode), there is one FITS-file and one tar-file per AOR and frequency.

The Level 4 FITS-file contains a data cube with two spatial and one frequency/velocity axis. There can be instances where the NAXIS keyword can be set to 4 rather than 3, but then NAXIS4 will be set to 1. The naming convention for the maps in general is: 'PIString'_'Source'_'Line'.lmv.fits, where 'Source' and 'Line' are replaced by the target name and observed transition, respectively. 'PIString' identifies the Principal Investigator for this observation and the project.

For the FEEDBACK program (PI: A.G.G.M. Tielens and N. Schneider, program ID 07_0077), the data cubes were not created by the GREAT Team but at the SOFIA Science Center. All Level 3 data was taken as is from the archive and combined into an lmv-data cube using the CLASS-task `xy_map`. See also Section 5.1

4.1.2 Level 3

Level 3 data are fully calibrated, individual spectra prepared by the GREAT Team after each flight series. Before ingestion into the archive the original data files were split by AOR and frequency into the data files described in the following. For each GREAT AOR of a project, there should be one tar-ball for each frequency in the AOR and for each flight in which the AOR was observed.

A tar-ball named `YYYY-MM-DD_GR_FNNN_PP_PPPP_NN_FFFFFFF.tar` should contain several ancillary files (see Section 0) and the following data files:

- `YYYY-MM-DD_GR_FNNN_PP_PPPP_NN_FFFFFFF.F`**`_Tant.great`**: A CLASS-file containing the source spectra in units of the forward-beam brightness temperature, T_A^*, and additional spectra. All source scans are available as separate spectra. For the array receivers, each pixel and polarization are also separate. Nothing has been averaged yet. The source spectra are the product of the calibration procedure (Section 4.2.1), but the file also contains various intermediate calibration results. More details can be found below.
- `YYYY-MM-DD_GR_FNNN_PP_PPPP_NN_FFFFFFF.F`**`_Tmb.great`**: A CLASS-file containing the source spectra from the `*Tant.great` file only but converted to main-beam temperatures, T_{MB}. The CLASS-script reading the original i.e., unsplit by AOR and frequency, `*Tant.great`-file and creating the original `*Tmb.great`-file should be among the ancillary files. Often, it is called `Convert-Tant-to-Tmb.class`.

The file name format YYYY-MM-DD_GR_FNNN_PP_PPPP_NN_FFFFFFF.F is comprised of YYYY-MM-DD - the flight date (universal time), GR - a literal that stands for GREAT, FNNN - the flight number, PP_PPPP - the SOFIA Plan ID, which becomes the AOR ID with the attached number NN (could be one or more digits), and finally FFFFFFF.F - the observed frequency in MHz.

4.1.2.1 Level 3 – Intermediate Calibration Results

The YYYY-MM-DD_GR_FNNN_PP_PPPP_NN_FFFFFFF.F_Tant.great-file is a CLASS file containing many different types of intermediate and calibration spectra next to the source spectra. The details on how these spectra are derived can be found in the appendix of Guan et al. (2012). The source spectra are identified in CLASS by the source name. Other types of spectra are named as follows (not all types may be contained in all Level 3 files):

- **TREC (SSB[2]):** Single Sideband Receiver Temperature
  This is the measured receiver noise temperature over the bandpass.
- **TSYS (SSB[2]):** Single Sideband System Temperature
  This is the system noise temperature of the bandpass i.e., the noise contributions from the receiver and the atmosphere combined.
- **S-H_OBS:** Observed calibrated sky minus hot-load spectrum (SKY-HOT)
  This is the data the atmospheric model is fitted to derive the atmosphere's optical depth.
- **S-H_FIT:** This is the result of the atmospheric fit to the S-H_OBS data.
- **TAU_SIG, TAU_IMG:** The atmospheric optical depth in the signal and image band derived from the atmospheric fit to S-H_OBS.
- **TAU_AVG:** Average atmospheric optical depth as derived from comparing sky spectra to the hot load spectra.
- **HOT-COLD:** Measured difference (in counts) between the hot and cold load, which is used to calibrate the receiver response in T_A (Antenna temperature).
- **THOT_SIG, THOT_IMG, TCOLD_SIG, TCOLD_IMG:** Brightness temperatures of the hot and cold loads in the signal and image bands across the bandpass.
- **CAL_SIG, CAL_IMG:** Derived flux calibration factors for the signal and image band.
- **SKY-DIFF:** Difference between consecutive sky measurements.

4.1.3 Level 1

The Level 1 data files are FITS-files that contain a binary table with the raw GREAT data for one scan. Depending on the observing mode, a scan can be e.g., numerous data points of an OTF map, a beam-switch observation of a single point, or a hot/cold-load measurement. An observation generally consists of many scans. The raw Level 1 data are uncalibrated and not useful without access to the calibration procedures (Section 4.2). Pointing observations and some engineering data in the SOFIA archive typically have only the Level 1 data.

[2] For spectral lines, the Single Sideband Temperature is the appropriate scale because the lines come from one of the sidebands. For continuum measurement, which comes from both sidebands, the Double Sideband Temperature would be appropriate and is half of the Single Sideband Temperature for GREAT because GREAT has a sideband ratio of 1.

4.1.4 Ancillary files

Data releases were made after each flight series of GREAT. For each open time observing program that collected data during a GREAT flight series, the GREAT Team made a data release containing all Level 3 and 4 data created from the observations and released the data together with the ancillary files listed below. These ancillary files can be found in the Level 3 and Level 4 tar-files, which contain:

- Several **PDF**-files; typically, there are:
  - A release letter from the Principal Investigator for the GREAT instrument describing the released data set.
  - A letter on the data reduction from the responsible scientist with accompanying remarks.
  - An overview for the released dataset with calibration factors and other details on the data reduction, possibly also including comments on detections and plots of the data.
  - An excerpt of the in-flight observing log.
- One or more **CLASS**-scripts, which were used to convert the data from the T_A^* temperature scale to the T_{MB} temperature scale and convert the Level 3 data product to the Level 4 data product. The script converting the data from T_A^* to T_{MB} contains the main beam efficiencies also listed in the overview document. Often this script is called `Convert-Tant-to-Tmb.class`. Other times, there is only one script doing the conversion and the processing from Level 3 to Level 4, which typically includes subtracting baselines, smoothing by re-binning, and, for mapping projects, reprojecting the data into a spectral cube. *These scripts are only provided for reference. It should not be expected that these scripts will run without any adjustments.* These scripts were written for the data as originally distributed by the GREAT Team containing all the data from one flight series and one project in one `*Tant.great` and one `*Tmb.great`-file. Before the data was ingested into the SOFIA archive, these data files were split by source and frequency. To run these scripts on the data files from the archive, not only the file name of the file to be read will need to be changed, but also what should be processed.
- A **png-file** (for older data an eps or ps-file) showing a visualization of the Level 4 data product. The png-file is shown in IRSA as a preview for the Level 4 data product. The visualization may not be included in the Level 3 tar-file.

4.2 DATA CALIBRATION AND PROCESSING

A very rough overview of the data reduction steps performed by the GREAT instrument team is given in this section and in the flow chart in Figure 13. The data reduction and calibration essentially follow the "chopper wheel" method for single-dish radio telescopes as described in publications like Kutner & Ulich (1981) and Downes (1989). The details of the GREAT data processing, especially the atmospheric calibration for the observations with GREAT, are described by Guan et al. (2012).

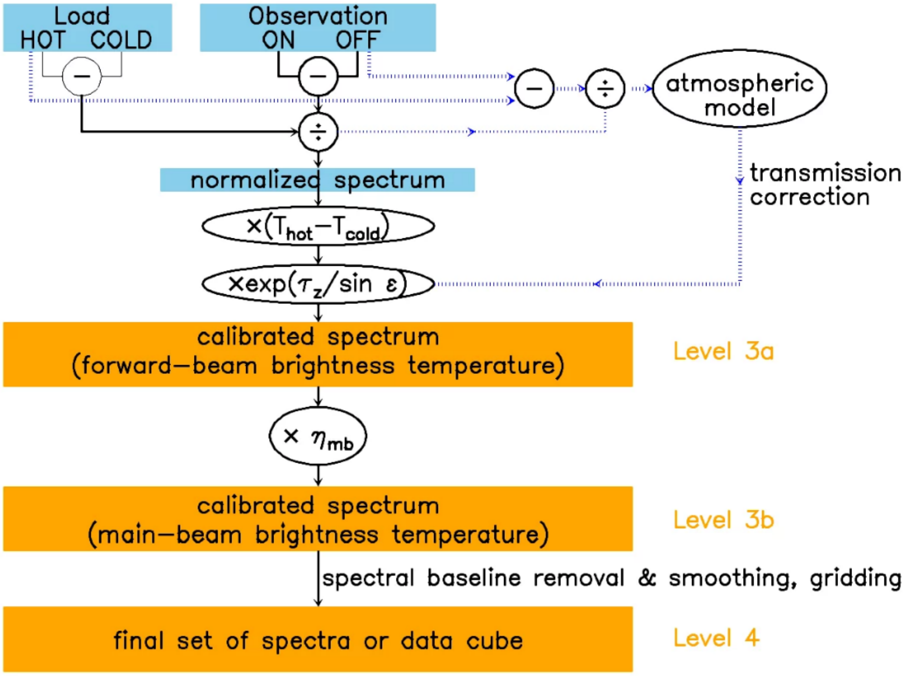


Figure 13 *Data reduction scheme for GREAT; figure taken from the GREAT website.*

An observation always consists of on- and off-source observations (achieved by the chopping secondary mirror in Beam Switching mode, or by moving the telescope to a reference position in Total Power mode (see also Section 2.5.1), interrupted roughly every five minutes by a hot- and cold-load observation. In this case, "hot" means ambient temperature and "cold" means a low temperature such as LN_2 or the temperature of a Peltier-cooled cold load. Subtracting the off- from the on-source spectra removes any telescope and atmospheric background emission as well as the receiver temperature equivalent brightness. The ON-OFF-difference is still in arbitrary units (counts) and needs to be calibrated onto the physical intensity scale (antenna temperature) by applying the receiver gain (i.e., conversion from counts to intensity). This is done by observing a hot- and a cold-load of known temperature and dividing the ON-OFF-difference (in counts) by the hot-cold-difference (in counts) and normalizing the result to the (Rayleigh-Jeans-corrected) hot-cold-temperature difference.

This simple scheme ignores the fact that the receiver optics coupling to the hot- and cold-load may be modulated in frequency, in particular by the window of the evacuated cold-load unit. This effect was ignored until March 2021. For observations starting March 5th, 2021, a new scheme was introduced: the frequency dependent coupling to the hot- (essentially constant) and cold-load (window modulated) was determined in the laboratory and the resulting coupling variations were stored as frequency dependent effective load-temperatures (RJ-corrected) in a look-up table for each GREAT receiver channel across its reception bandwidth. These look-up tables now store the raw data FITS headers and are properly applied in the calculation of the gain-factors derived from the hot-cold-difference measurement, thus taking the variation of the optical coupling to the calibration loads into account.

The atmospheric transmission in the GREAT passbands is highly variable with frequency, water vapor (which depends on the altitude), and zenith angle. It can vary over the duration of an observation. Standard atmospheric calibration is performed using the 12-layer AM Atmospheric model (Paine 2022). The steps to obtain an estimation of the atmospheric transmission are as follow: (i) make use of AM to estimate the atmospheric opacity as a function of frequency for a given altitude and line of sight, parameterized by atmospheric parameters such as the precipitable water vapor (PWV) and the ambient temperature; (ii) using the thus determined PWV as a start value, fit the atmospheric model to the observed SKY-HOT, to determine the best-fit -value; and (iii) correct for the attenuation of the astronomical signal using the model opacities calculated with the best-matching parameters. The intermediate results of this procedure are stored in the first Level 3 data product (Section 4.1.2.1). The transmission gets applied to the hot-cold load calibrated spectra resulting in flux and telluric corrected spectra calibrated to the forward-beam brightness temperature scale (T_A^*). The blue dotted arrows in Figure 13 illustrate this procedure. These spectra are the first Level 3 data product of a GREAT data release. The second Level 3 data product contains the spectra scaled to the main-beam brightness temperature T_{MB} (see Section 3.1). The spectra get further processed, including baseline removal, averaging, smoothing, re-gridding, etc., to arrive at the Level 4 data product as detailed below (Section 4.2.2).

4.2.1 Kalibrate – implementing the calibration and atmospheric correction

The proprietary tool *kalibrate* is software developed by the GREAT team at the University of Cologne for the atmospheric transmission fitting of submm- and FIR-data specifically at SOFIA. The software takes the raw data counts from the backends and writes CLASS spectra in antenna temperature (processing the data to Level 3). The software is written in a combination of C++, Python, and Fortran. It supports all observing modes of the GREAT instrument. One critical element of the calibration routine is the application of the atmospheric model. *Kalibrate* stores an internal atmospheric model generated from the AM code (Paine 2022). This model is used to fit the PWV-value to match the measured Off-HOT spectra from which the atmospheric transmission can be determined. *Kalibrate* has a number of options for how the atmospheric calibration can be applied. It can be fitted commonly across an array (LFA/HFA), or it can be applied individually to single pixels. There are additional options where the atmospheric model can be fitted to one pixel, after which this fit to the transmission is applied to the rest of the pixels in the array.

Once the atmospheric model fit is applied to correct for the atmospheric transmission, the data and its ancillary products are written to a CLASS-file as the Level 3 data product.

4.2.2 From Level 3 to Level 4 data products

The next step in the data reduction is processing the output of *kalibrate* i.e., the original unsplit `*Tant.great`-file (see Section 4.1.2), to create spectra scaled to the T_{MB} temperature. The CLASS-script doing that for the original unsplit data file should be part of the Level 3 and Level 4 ancillary files. In general, these scripts find the source spectra and then loop through them to scale the spectra by $B_{\mathrm{eff}}/F_{\mathrm{eff}}$ to go from T_A^* to T_{MB}. In CLASS that is achieved by the command `modify  beam_eff`. The beam efficiencies are hardcoded into the script (often called `Convert-Tant-to-Tmb.class`), while the forward efficiency is part of the meta-data in the `Tant.great`-file. The output of this first processing step is the original unsplit `*Tmb.great`-file mentioned in Section 4.1.2. This is still a Level 3 data product.

The next step is to create the Level 4 data product by averaging the T_{MB}-spectra to the final data product, which could be one or several individual spectra or a data cube. As for any data reduction of heterodyne single dish spectra, this includes:

- Subtracting a baseline with the CLASS command `base`. Typically, the baseline is an order 1 polynomial, but could also be of different orders. Windows to exclude spectral features from determining the baseline are defined in the process.
- Re-binning of the data typically with the CLASS command `smooth box` or `resample` to the desired spectral resolution.

The choice of parameters for the baseline subtraction and how much to re-bin the data was informed by the main science goal for the proposed observation. Spectral features other than the main goal may not show up in the reduced Level 4 data product. If the data are to be re-examined for other spectral features or purposes, these settings should be reviewed and possibly changed to achieve other goals.

This step and possibly plotting the data is done by a second CLASS-script, which should also be part of the ancillary files. The scaling to the T_{MB}-scale and the processing to Level 4 could also be comprised in one CLASS-script.

4.2.2.1 Single Spectra

For a single pointing or other projects where the results are only separate spectra, the CLASS-script selects all the spectra of one frequency (and one position or, for the array receivers, one pixel) and applies `average` to the data. The resulting single spectra get saved in a CLASS-file and possibly plotted.

For 4GREAT projects, especially absorption studies, the spectra are written out with the continuum level added back to the baseline reduced data. The added back continuum levels are hardcoded into the scripts. The continuum levels are determined in uncontaminated velocity intervals for each sub-scan. The final values are median values clipping physically unreasonable values. The determination of the continuum level is not part of the scripts.

4.2.2.2 Maps/Data Cubes

For any mapping project regardless of the observing mode, the source T_{MB}-spectra get compiled, re-gridded, and convolved in CLASS with the `table`- and `xy_map`-commands after setting the beam size, which is the parameter that controls the re-gridding and convolution. From the `xy_map`-documentation: “The convolution kernel is a Gaussian of size one-third the telescope beamwidth, the convolution being computed on a limited support (large enough to ensure excellent accuracy).”

For the FEEDBACK legacy program (Program ID: 07_0077), the data cubes were created by the SOFIA Science Center, not the GREAT Team, and the scripts used for that are not included among the ancillary files. In 2023 or 2024, the FEEDBACK Team together with the GREAT Team may produce better Level 4 data cubes using sophisticated algorithms to suppress mapping artifacts.

4.3 DATA ANALYSIS AND VISUALIZATION TUTORIALS AND SOFTWARE

4.3.1 GILDAS

GILDAS (https://www.iram.fr/IRAMFR/GILDAS/) is software developed by IRAM for processing radio to sub-mm data. GILDAS can be used for plotting and analyzing GREAT data. Much of the GREAT data reduction was made using CLASS, a submodule of GILDAS. Archival Level 3 and 4 data are provided as CLASS-files typically with extensions .great or .lmv. CLASS-scripts provided with the Level 3 and 4 data can help guide data analysis and serve as examples. The IRAM group has supported GREAT-specific extension to the GILDAS header block etc., which are now part of the standard distribution.

Cookbooks:

- A SOFIA cookbook showing how to load a GREAT spectrum into CLASS and complete a basic baseline subtraction: https://github.com/SOFIAObservatory/Recipes/blob/master/GREAT-Class_primer.ipynb
- "Understanding GREAT data products" presented by Juan Luis Verbena (University of Cologne) at SOFIA School on Friday, February 4, 2022, video: https://youtu.be/Sg3tlLMGH5Q
- CLASS Data Reduction example presented in a ipython notebook from the talk: https://github.com/KOSMAsubmm/GREAT_data_reduction_notebook/blob/main/GREAT_data_reduction_notebook.ipynb

4.3.2 Python

Python is a high-level general purpose programming language commonly used in astronomy for data reduction, analysis, and visualization. Various python packages such as astropy and jdaviz can be used to analyze and visualize GREAT data.
Cookbooks:

- Inspection of the data structure and header information. Plotting spectra, visualizing image slices, producing moment maps, and extracting spectra
iPython notebook: https://github.com/SOFIAObservatory/Recipes/blob/master/GREAT-data-inspection.ipynb
- Re-project other astronomical data to the pixel map of GREAT data for better comparison of the data
iPython notebook: https://github.com/SOFIAObservatory/Recipes/blob/master/GREAT-reproject-data-to-GREAT-resolution.ipynb
- Visualizing data cubes in 2D and 3D using the python/jdaviz tool Cubeviz and glue
iPython notebook:
https://github.com/SOFIAObservatory/Recipes/blob/master/GREAT_Cubeviz.ipynb

4.3.3 DS9 (https://sites.google.com/cfa.harvard.edu/saoimageds9)

DS9 is astronomical data visualization software and is well suited for viewing maps and data cubes that are FITS -formatted files.

4.3.4 SOSPEX (https://github.com/darioflute/sospex)

SOSPEX is a SOFIA data cube visualization and analysis tool by Dario Fadda capable of opening GREAT data cubes in the FITS-file format.

4.3.5 CARTA (https://cartavis.org)

CARTA is the Cube Analysis and Rendering tool for Astronomy and can be used to visualize and do basic analysis on GREAT data cubes in the FITS-file format.

You can find a video tutorial on visualizing GREAT data in CARTA here:
https://youtu.be/UFL_2kfFtmw

5. SCIENTIFIC RESULTS

The two SOFIA Legacy Projects executed with the GREAT instrument contain a significant amount of GREAT data. This section contains an overview of the two projects and the data collected for them.

5.1 FEEDBACK: RADIATIVE AND MECHANICAL FEEDBACK IN REGIONS OF MASSIVE STAR FORMATION

- Principal Investigators: *A.G.G.M. Tielens (University Leiden) and N. Schneider (University Cologne)*
- Plan ID: 07_0077
- FEEDBACK Team website: https://feedback.astro.umd.edu/index.html

Publications:

- FEEDBACK: a SOFIA Legacy Program to Study Stellar Feedback in Regions of Massive Star Formation: Schneider, N. et al. (2020), PASP 2020, 132, 104301
  DOI: 10.1088/1538-3873/aba840
- Stellar feedback and triggered star formation in the prototypical bubble RCW 120: Luisi, M. et al. (2021), Science Advances, 7, 15
  DOI: 10.1126/sciadv.abe9511
- SOFIA FEEDBACK Survey: Exploring the Dynamics of the Stellar Wind-Driven Shell of RCW 49: Tiwari, M. et al. (2021), ApJ, 914, 117
  DOI: 10.3847/1538-4357/abf6ce
- FEEDBACK from the NGC 7538 H II region: Beuther H. et al. (2022), A&A, 659, A77
  DOI: 10.1051/0004-6361/202142689
- Self-absorption in [C II], ^{12}CO, and H I in RCW120. Building up a geometrical and physical model of the region: Kabanovic, S. et al. (2022), A&A 659, A36
  DOI: 10.1051/0004-6361/202142575
- Ionized carbon as a tracer of the assembly of interstellar clouds: Schneider, N. et al. (2023), Nature Astronomy,
  DOI: 10.1038/s41550-023-01901-5

FEEDBACK is a SOFIA Legacy Project that took full advantage of the efficient mapping capabilities and high spectral resolution of the upGREAT instrument on SOFIA to create large scale [CII] 1.9 THz and [OI] 4.7 THz maps of 11 Galactic star forming regions[3]. These lines are prominent collisionally excited cooling transitions in the interstellar medium FEEDBACK focused primarily on the [CII] 1.9 THz line, which traces singly ionized carbon across ionized, neutral, and molecular gas. The aim of these observations was to study the interaction of massive stars with their environment in a sample of sources that span a broad range in stellar characteristics, from single OB stars to small groups of O stars, to rich young stellar clusters, to mini starburst, and to quantify the mechanical energy injection and radiative heating efficiency in regions dominated by different processes (stellar winds, thermal expansion, and radiation pressure). The large (~100 to

[3] This summary of the project is based on, and links to, the team's website. It reflects the status of the project in early 2023.

~1500 arcmin^2) [CII] maps with high spatial (14") and spectral (sub-km s^{-1}) resolution, together with the [OI] 4.7 THz line that was observed in parallel, provide an outstanding dataset for the community.

The source selection was based on numerous factors such as star formation activity, morphology, dynamic driving mechanisms, and evolutionary stage. The full sample allows systematic study of the effects of parameters like cluster size, stellar wind activity, FUV photon leakage from compact HII regions, evolutionary stage (the expansion time may evolve along the sequence Orion, M17, NGC 7538, diamond ring in Cyg X), sculpting of pillars, spires, and bright rim clouds (M16, NGC 7538), driving mechanism (thermal expansion, stellar wind, radiation pressure: RCW 120, RCW 49, RCW 79), environmental effects (isolated O stars such as RCW 120 vs. clusters), converging flows and impact of nearby OB association (Cyg X), mini starburst activity (NGC 6334), starburst activity fueled by the converging flows where spiral arm meets the central bar (W43), compact versus dispersed star formation (RCW 49, NGC 6334) and small versus large scale filamentary structure (W40, RCW36, NGC 6334, Cyg X). While one goal of this program is to understand the individual factors involved in the feedback of massive stars on their environment, three large, complex regions (NGC 6334, W43, Cyg X) were specifically included in the sample, as the concerted action of multiple, nearly simultaneous regions of massive star formation in close proximity will be key to understanding observations of massive star forming complexes in external galaxies. Table 10 lists all sources with the planned and achieved map sizes.

Table 10: List of sources and their achieved and planned map sizes.

Source	Observed Tiles	Planned Tiles
RCW120	4.00	4
Cygnus X	18.00	18
M16	11.25	12
M17	8.44	13
NGC6334	5.76	16
NGC7538	4.00	4
RCW36	1.86	4
RCW49	6.40	12
RCW79	9.00	9
W40	8.67	12
W43	12.00	12

The maps are made of square tiles (7.26' × 7.26'), each observed in the Total Power Array OTF mode. Each tile was covered four times, once in x-direction, once in y-direction, and then again in x- and y-direction but offset by 36.2" in the negative scan x- and y-directions (positive RA and negative Dec for unrotated maps). One coverage in one direction fully samples the tile in [CII].

All four coverages are needed to fully sample the tile in [OI]. Table 10 lists all sources with their planned size expressed as number of planned tiles and how many of these tiles were observed in the end. A tile observed for a quarter of what was planned means it was fully covered once in [CII]. For example, M16 had 12 tiles planned. Only 11.25 were observed. Thus, the [CII] map looks fully observed, but the last tile with only a quarter of the integration time will be about twice as noisy as the other tiles in that map. The respective [OI] map will have some holes in the last tile.

Each map had one reference position to which the Total Power observations were referenced. For some maps, the reference position was measured against another reference position further away, if there was an indication of contamination from emission at the first reference position. A so-called CAL (for calibration) position inside the map area was observed at the beginning of each observing leg to be able to cross calibrate observations taken between different observing legs and flights. An observing leg is the section of an observing flight assigned to observe a particular source for a particular program. For FEEDBACK the observing legs were typically between one to two hours long. One full tile took about 50 minutes to observe. It was no problem to stop the observation in the middle of one tile at the end of an observing leg and continue the tile at the next observing opportunity.

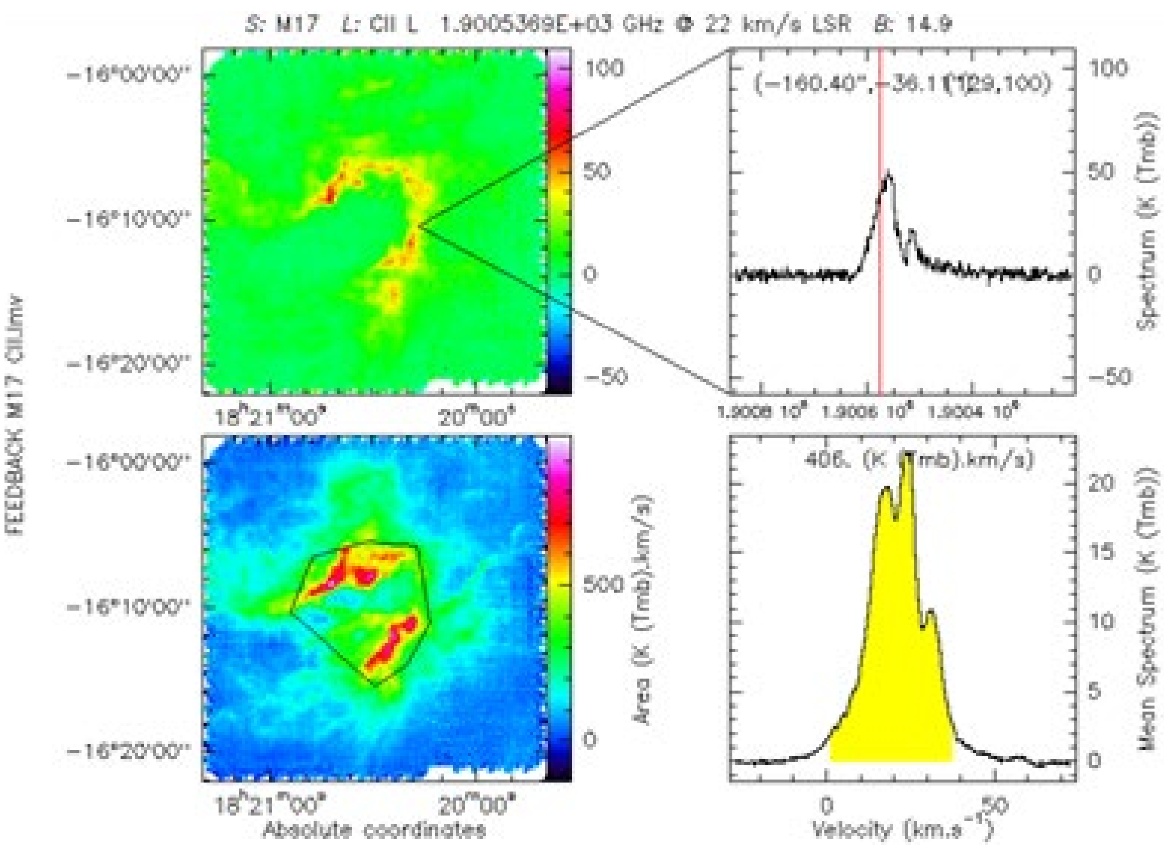


Figure 14 *Preview of the [CII] data cube for M17. Details are in the text.*

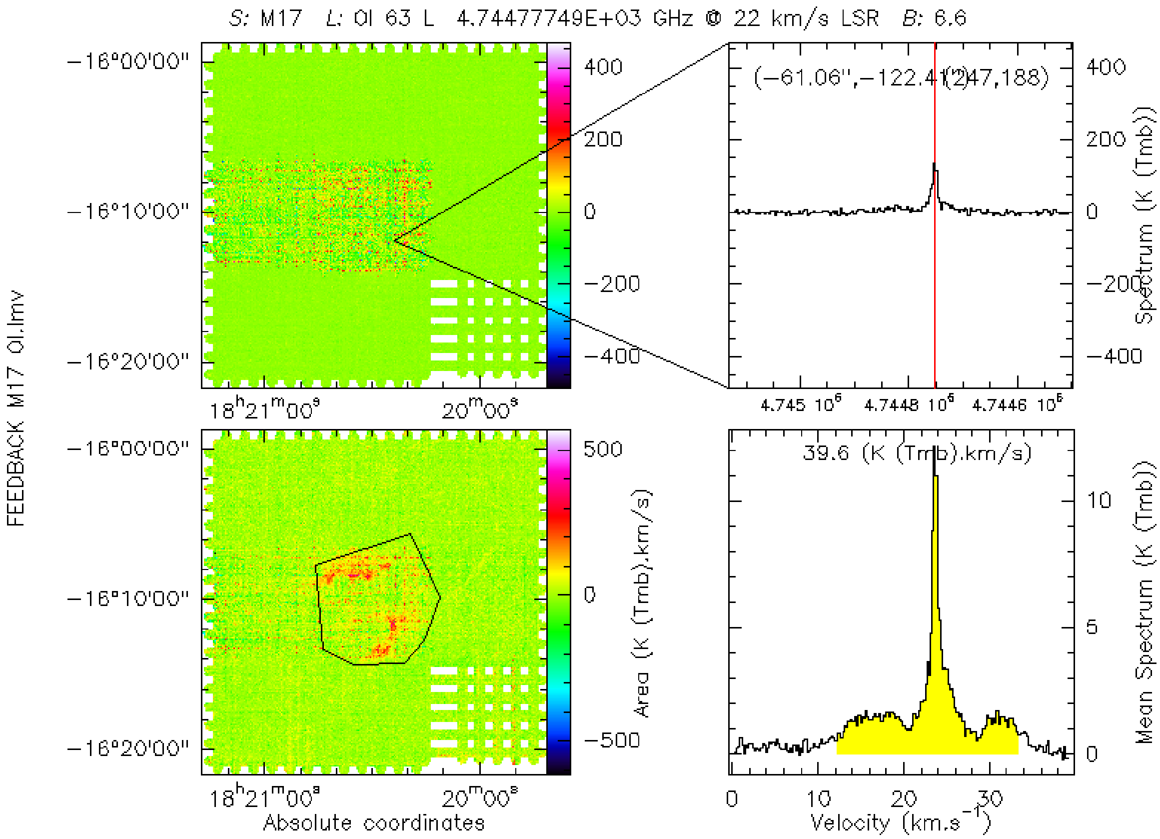


Figure 15 *Preview of the [OI]63 µm data cube for M17. Details are in the text.*

Figure 14 and Figure 15 show the previews of the [CII] and [OI] data cubes available at IRSA for M17. For each data cube, the panels represent (clockwise from the lower left):

- The integrated line flux integrated over the velocity range marked in yellow in the lower right panel.
- The velocity slice through the cube at the velocity marked in red in the upper right panel.
- The spectrum at the position marked in the upper left panel.
- The spectrum integrated over the polygon marked in the lower left panel.

The currently (early 2023) archived Level 4 data cubes for the FEEDBACK program were created by the SOFIA Science Center, not the GREAT Team. The Level 3 T_{MB}-spectra provided by the GREAT Team were compiled, re-gridded, and convolved in CLASS with the `table`- and `xy_map`-commands with a beam size of 14.1" for the [CII] maps and 6.3" for [OI] maps. The FEEDBACK Team together with the GREAT Team are working on improving the final results and plan to publish these within the next two years.

5.2 HYGAL: CHARACTERIZING THE GALACTIC INTERSTELLAR MEDIUM WITH HYDRIDES

- Principal Investigators: *David Neufeld (Johns Hopkins University) and Peter Schilke (University Cologne)*
- Plan ID: 08_0038

Publications:

- HyGAL: Characterizing the Galactic Interstellar Medium with Observations of Hydrides and Other Small Molecules. I. Survey Description and a First Look Toward W3(OH), W3 IRS5, and NGC 7538 IRS1, Jacob A. et al. (2022), ApJ 930, 141
  DOI: 10.3847/1538-4357/ac5409
- HyGAL: Characterizing the Galactic ISM with observations of hydrides and other small molecules. II. The absorption line survey with the IRAM 30 m telescope, Kim W.-J. et al. (2023), A&A 670, A111
  DOI: 10.1051/0004-6361/202244849

HyGAL is a SOFIA Legacy Project that took full advantage of the capability of the GREAT instrument to observe up to five frequency bands simultaneously. By line-of-sight absorption-line spectroscopy towards 24 background terahertz continuum sources widely distributed within the Galactic plane, the program obtained spectra of six hydride molecules (OH^+, H_2O^+, ArH^+, SH, OH, and CH) and two key atomic constituents (C^+ and O) within the diffuse ISM. Studies with Herschel demonstrated the unique value of specific hydride molecules as quantitative diagnostic probes of the H_2 fraction, the cosmic-ray ionization rate, or of "warm chemistry" associated with the dissipation of interstellar turbulence in regions of elevated temperature or ion-neutral drift. These observations were conducted to address these questions:

- What is the distribution function of H_2 fraction in the ISM?
- How does the density of low-energy cosmic rays vary within the Galaxy?
- What is the nature of interstellar turbulence (e.g., typical shear or shock velocities), and what mechanisms lead to its dissipation?

Table 11: Details for all the transitions observed for the HyGal project.

Species	Transition	Frequency (GHz)	Setup	Receiver
H_2O^+	1_{10}–1_{01} J=3/2–3/2	607.2258	#1	4GREAT CH1 LSB[a]
ArH^+	J=1–0	617.5252	#1	4GREAT CH1 USB[a]
OH^+	N_J=1_2 –0_1	971.8038	#1	4GREAT CH2
SH	$^2\Pi_{3/2}$ J = 5/2 – 3/2	1382.9086 [b], 1383.2397 [b]	#1	4GREAT CH3
OH	$^2\Pi_{3/2}$ J = $5/2^-$ – $3/2^+$	2514.3167 [b]	#1	4GREAT CH4
CH	N_J = $2_{3/2}^-$ – $1_{1/2}^+$	2006.7991 [b]	#2a	LFA
C^+	$^2P_{3/2}$ – $^2P_{1/2}$	1900.5372	#2b	LFA
O	$^3P_1$– $^3P_2$	4744.7775	All	HFA

[a] LSB = "lower side band"; USB = "upper side band",

[b] Frequency of the strongest hyperfine component: additional components are at 971.8053 and 971.9192 GHz (OH^+); 1382.9041, 1382.9153, 1383.2350 and 1382.2463 GHz (SH); 2514.2987 and 2514.3532 GHz (OH); and 2006.7489 and 2006.7626 GHz (CH)

Table 11 lists all the species and transitions targeted by this Legacy Project. Table 12 lists all the background sources that were observed. The columns represent the setups detailed in Table 11. The percentages list how much of the planned time was achieved for each source and setup. Empty cells indicate that the source was not observed in this setup in this program.

Table 12: Percentage of the planned time for each source and receiver setup that was achieved.

Source	Setup #1	Setup #2a	Setup #2b
HGAL284.015-0.86-1	100%		
HGAL285.26-0.05	30%		
G291.579-00.431	100%		
IRAS 12326-6245	30%		
G328.307+0.423	100%		
IRAS 16060-5146	100%	100%	
IRAS 16164-5046	100%		
IRAS 16352-4721	100%		
IRAS 16547-4247	100%		
NGC 6334 I	100%	100%	100%
G357.558-00.321	60%	85%	85%
HGAL0.55-0.85	70%	58%	58%
G09.622+0.19		100%	100%
G10.47+0.03	50%	100%	100%
G19.61-0.23	70%	100%	100%
G29.96 -0.02	100%	100%	100%
G31.41+0.3	100%		
W43 MM1	100%	100%	100%
G32.80+0.19	100%	100%	100%
G45.07+0.13	100%	100%	100%
DR21	50%	100%	100%
NGC 7538 IRS 1	100%	100%	100%
W3 IRS 5	65%	100%	100%
W3(OH)	100%	100%	100%

Figure 16 shows two example spectra using the same preview plots as can be found in the IRSA archive. The source, transition, and sideband are identified in the text at the top of the plots together with other details like source coordinates, system temperature, source velocity, and spectral resolution in km/s.

The observations are complemented by the legacy team with ancillary observations of non-hydride molecules with ground-based observatories like the IRAM 30m telescope (see Kim et al. 2023).

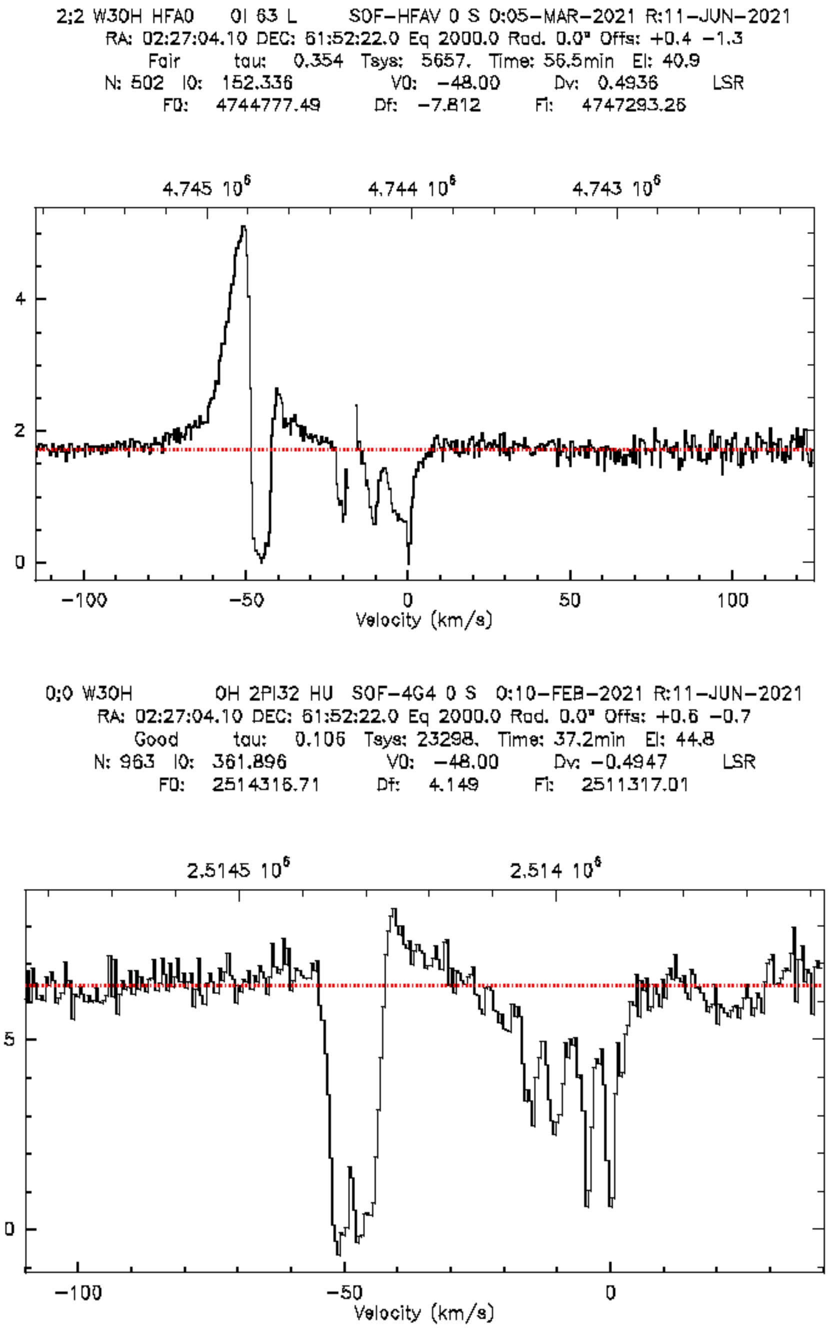


Figure 16 *Previews of the [OI]63 µm (Top) and OH (Bottom) spectra of W3(OH)*

6. REFERENCES

- Büchel, D., et al. 2015, IEEE Transactions on Terahertz Science and Technology, 5, 207
- Crowe, T. W. et al., 2011, Proc. 22nd Intl. Symp. Space THz Techn, 11, 209
- Downes, D. 1989, Lecture Notes in Physics, 333, 351
- Durán, C. A., et al. 2020, IEEE Transactions on Terahertz Science and Technology, 11, 194
- Guan, X., et al. 2012, A&A, 542, L4
- Heyminck, S., et al. 2012, A&A, 542, L1
- Klein, B., et al. 2012, A&A, 542, L3
- Kutner, M. L., & Ulich, B. L. 1981, ApJ, 250, 341
- Paine, 2022, Submillimeter Array Technical Memo #152 version 12.2
- Pütz, P., et al. 2012, A&A, 542, L2
- Richter, H., et al. 2015, IEEE Transactions on Terahertz Science and Technology, 5, 539
- Risacher, C., et al. 2016, A&A, 595, 34
- Risacher, C., et al. 2016, IEEE Transactions on Terahertz Science and Technology, 6, 199
- Risacher, C., et al. 2018, Journal of Astronomical Instrumentation, 7, 1840014
- Schieder, R. & Kramer, C., 2001, A&A 373, 746
- Wilson Th. L. et al. (2009), Springer, ISBN 978-3-540-85121-9

APPENDIX

A. Level 1 FITS-header

The standards column lists the origin of each of the keywords in the FITS header.

- **FITS** - The FITS Standard as defined by the FITS Support Office at NASA/GSFC.
- **AIPS** - Radio astronomy-specific keywords defined in NRAO AIPS and discussed in AIPS memo 117. Note that CLASS adopts many of the FITS keywords used by AIPS.
- **CLASS** - Keywords from the GILDAS CLASS header or variable transferred from CLASS to the FITS header when the Level 4 .FITS-files are generated. Note that there is not always a one-to-one correspondence between the name of a FITS Keyword and what it is called in CLASS. The name of the CLASS variable in the keyword description is provided when it is known.
- **DCS** - Keywords generated by the Data Cycle System (DCS). Detailed in the DCS ICD DCS_SI_01.
- **KOSMA** - Keywords generated internally by the GREAT instrument Kosma software. Many of these keywords also have equivalent CLASS variables. The name of the CLASS variable in the keyword description is provided when it is known.

The Level 1 FITS-files only use the Primary extension and header.

Notes about the GREAT Level 1 FITS headers:

- Many of these keywords refer to the position of the telescope, GREAT arrays, aircraft, etc., in various reference frames (e.g., SIRF, TARF, etc.). Descriptions for every keyword have been provided, when possible, but this is not an exhaustive documentation of the SOFIA and GREAT position reference frames. Please refer to the documentation on these various reference frames for more information.
- "Active" pixel or array refers to the pixel (e.g., LFAV0) or array that the data stored in this FITS-file is recorded from. Each Level 1 FITS-file only records data from one pixel of a given GREAT array/channel.
- "Reference" array/channel refers to the array/channel used as a reference frame that the "Active" pixel coordinates or reference frame is compared to. This is the primary array/channel of scientific interest. It is used for mapping specifications. Reference and Active can both be the same (e.g., a Level 1 FITS-file with LFAV0 data and the LFAV being chosen as the primary array).

Keyword	Description	Standard
SIMPLE = T / file does conform to FITS standard	Denotes if this header conforms to the FITS Standard. T means true. F means false.	FITS
BITPIX = 32 / number of bits per data pixel	Bits per data value. The value 32 indicates the data format is 32-bit two's complement binary integers.	FITS
NAXIS = 4 / number of data axes	The number of axes in the associated data array. While this extension has 4 axes, this is a 1D spectrum where only the first axis has a length > 1.	FITS
NAXIS1 = 16384 / length of data axis 1	The data array size of axis 1.	FITS
NAXIS2 = 1 / length of data axis 2	The data array size of axis 2.	FITS

Keyword	Description	Standard
NAXIS3 = 1 / length of data axis 3	The data array size of axis 3.	FITS
NAXIS4 = 1 / length of data axis 4	The data array size of axis 4.	FITS
EXTEND = T / FITS dataset may contain extensions	Boolean denoting if this fits file can have multiple extensions. T=True and F=False. This example FITS file only has one extension, despite equaling T here.	FITS
COMMENT FITS (Flexible Image Transport System) format is defined in 'Astronomy	Comment about the FITS file.	FITS
COMMENT and Astrophysics', volume 376, page 359; bibcode: 2001A&A...376..359H	Comment about the FITS file.	FITS
BZERO = 2147483648 / offset data range to that of unsigned long	Since FITS format does not support native unsigned integers, this is the offset to convert the signed integers in the data to unsigned integers. Here it converts a 32-bit signed int into an unsigned int.	FITS
BSCALE = 1 / default scaling factor	Floating point value that sets the scaling of the data to a physical value. Here 1 means the data are stored as unsigned integers.	FITS
NEEDZERO= F / FLAG FOR NEED OF ZERO/COMB	Flag for need of zero/comb measurement. Used for frequency calibration.	Kosma
FITSVERS= '3.3 ' / KOSMA_CONTROL FITS VERSION/SUBVERSION	KOSMA_CONTROL's FITS version number	Kosma
LONGSTRN= 'OGIP 1.0' / The HEASARC Long String Convention may be used.	Signals the possible presence of long strings in the HDU.	FITS
COMMENT This FITS file may contain long string keyword values that are	Keyword used to make comments in the FITS header.	FITS
COMMENT continued over multiple keywords. The HEASARC convention uses the &	...	...
COMMENT character at the end of each substring which is then continued	...	...
COMMENT on the next keyword which has the name CONTINUE.	...	...
DATASRC = 'ASTRO ' / Data Source	Type of data (e.g., astronomical observation, calibration, etc.). Here ASTRO = astronomical observation. CLASS variable: SOFIA%DATASRC.	DCS
OBSTYPE = 'OBJECT ' / Observation type	Observation type. Here OBJECT means Astronomical Object (almost always the case).	DCS
SRCTYPE = 'UNKNOWN ' / Source type	Needed for reduction of split spectra for some SOFIA instruments. Not used for GREAT, hence UNKNOWN.	DCS
KWDICT = 'DCS_SI_01_F' / SOFIA Keyword dictionary version, DCS ICD rev.	Reference for the DCS ICD version used when this file was generated.	DCS
OBS_ID = '2021-08-09_GR_F768_HFAV_PX06_S_039431_009' / SOFIA Observation Identi	Name of this data file. CLASS variable: SOFIA%OBS_ID.	DCS
OBSERVAT= 'SOFIA ' / OBSERVATORY NAME	Name of observatory.	DCS
PLANID = '09_0189 ' / OBSERVING PLAN ID	ID of the observing plan which contains all the associated AORs. CLASS variable: SOFIA%PLANID.	DCS
AOT_ID = 'singlepoint_chopped.sh_-f_inpar_singlepoint_chopped_SGRB2_M_1953'	Astronomical Observation Template (AOT) ID. The AOT defines the type of observation requested.	DCS
AOR_ID = '09_0189_1' / Astronomical Observation Request Identifier	Astronomical Observation Request (AOR) ID. The AOR defines the requested set of parameters for a unique observation within an observing plan.	DCS
PROCSTAT= 'LEVEL_1 ' / Processing status	Status of processing applied to this data (Level 0 to 4).	DCS
HEADSTAT= 'MODIFIED' / Header status	Status of the FITS header during post-processing. MODIFIED means the headers have changed but are not fully corrected.	DCS

Keyword	Description	Standard
DEPLOY = 'PPT ' / Site deployment	Location of the SOFIA deployment. This is the aircraft base of operations. Here PPT means Papeete, French Polynesia.	DCS
MISSN-ID= '2021-08-09_GR_F768' / Mission ID	SOFIA Mission ID. Specifies date, instrument (GR=GREAT), and flight number. CLASS variable: SOFIA%MISSION_ID.	DCS
FLIGHTLG= 8 / Flight leg	SOFIA flight leg ID for the observation.	DCS
MCCSMODE= 'great_standard' / MCCS SI Mode (MCCS_SI_04)	MCCS science instrument mode. Here it is the standard mode for GREAT.	DCS
ORIGIN = 'GREAT - MPIfR/KOSMA' / Origin of FITS file	Organization whose software generated this file. In this case, this FITS file was generated with the GREAT MPIfR/KOSMA software.	FITS
OPERATOR= 'Emily ' / Telescope operator	Name of telescope operator(s). CLASS variable: SOFIA%OPERATOR.	DCS
DATE-OBS= '2021-08-09T09:58:05' / UTC Date of exposure start	Date of exposure start in UTC. CLASS variable: GEN%CDOBS.	FITS
TAMBSOFI= 241.8 / Temperature of ambient, SOFIA [K]	Ambient temperature of SOFIA in Kelvin. CLASS variable: CAL%TAMB.	DCS
TEMPPRI1= -31.35 / Temperature of primary mirror, 1 [C]	Temperature of the telescope's primary mirror in Celsius. First reading. CLASS variable: SOFIA%TEMPRI1.	DCS
TEMPPRI2= -32.55 / Temperature of primary mirror, 2 [C]	Temperature of the telescope's primary mirror in Celsius. Second reading.	DCS
TEMPPRI3= -31.55 / Temperature of primary mirror, 3 [C]	Temperature of the telescope's primary mirror in Celsius. Third reading.	DCS
TEMPSEC1= -36.55 / Temperature of secondary mirror, 1 [C]	Temperature of the telescope's secondary mirror in Celsius.	DCS
TRACKANG= -10.7041 / Aircraft track angle [degrees]	Aircraft track angle at start of observation in degrees.	DCS
AIRSPEED= 468.812 / True aircraft airspeed [knots]	True aircraft air speed at start of observation in knots.	DCS
GRDSPEED= 461.703 / Aircraft ground speed [knots]	Aircraft ground speed in knots at start of observation. CLASS variable: SOFIA%GNDSPEED.	DCS
AIRTEMP = -65.5 / SOFIA Air Temp [C]	Air temperature in Celsius outside of aircraft.	DCS
AIRPRESS= 121.2342 / SOFIA Air Press [Torr]	Air pressure in Torr outside of aircraft.	DCS
PRESSALT= 13263.3588 / PRESSURE ALTITUDE [m]	Aircraft pressure altitude in meters.	DCS
GPS_ALT = 13802.01456 / GPS ALTITUDE [m]	Aircraft altitude measured from GPS in meters. CLASS variable: CAL%ALTI.	DCS
HEADING = -16.5303 / Aircraft true heading [degree]	Aircraft heading in degrees. CLASS variable: SOFIA%HEADING.	DCS
TELCONF = 'UNKNOWN ' / Telescope configuration	Telescope configuration (e.g. mirrors, correctors, light paths, etc.).	DCS
TELRA = 17.7905 / SI Boresight RA (ICRS J2000)	Right Ascension position of the science instrument boresight on the sky in J2000 decimal degrees. CLASS variable: POS%LAM.	DCS
TELDEC = -28.3961 / SI Boresight Dec (ICRS J2000)	Declination position of the science instrument boresight on the sky in J2000 decimal degrees. CLASS variable: POS%BET.	DCS
TELEQUI = 'j2000 ' / Equinox of ERF coords (RA/Dec/VPA)	Equinox for above RA and Dec. Here it is J2000.	DCS
LASTREW = '2021-08-09T09:54:53.853Z' / Time of last rewind (UTC)	UTC time of the last telescope rewind.	DCS
TELVPA = 139.553 / SI Boresight VPA (ICRS J2000)	Vertical Position Angle (degrees East of North in J2000): position angle of the focal plane’s y-axis as projected on the sky.	DCS
TELLOS = 1.22088 / Telescope LOS at observation [degrees]	Telescope fine-drive position in degrees rotating the telescope around the line of sight.	DCS
TELEL = 39.499 / Telescope elevation [degrees]	Telescope elevation above the horizon in degrees at start of observation. CLASS variable: GEN%EL.	DCS
TELXEL = 0.162519 / Total telescope cross elevation [degrees]	Telescope cross-elevation angle in degrees.	DCS
FOCUS_ST= -696.195 / Telescope focus [microns], start of obs	Telescope focus position in microns at the start of the observation.	DCS

Keyword	Description	Standard
FOCUS_EN= -696.195 / Telescope focus [microns], end of obs	Telescope focus position in microns Theat the end of the observation.	DCS
WVZ_STA = 50.754 / Water vapor, zenith [microns], start of obs	The integrated precipitable water vapor to the zenith at the start of the observation from a 60 second running average.	DCS
WVZ_END = 51.185 / Water vapor, zenithn [microns], end of obs	The integrated precipitable water vapor to the zenith at the end of the observation from a 60 second running average.	DCS
LAT_STA = -22.4933 / Aircraft latitude, start of obs [degree]	Aircraft latitude in degrees at start of observation.	DCS
LAT_END = -22.4218 / Aircraft latitude, end of obs [degree]	Aircraft latitude in degrees at end of observation. CLASS variable: CAL%GEOLAT.	DCS
LON_STA = -144.4 / Aircraft longitude, start of obs [degree]	Aircraft longitude in degrees at start of observation. CLASS variable: CAL%GEOLONG.	DCS
LON_END = -144.415 / Aircraft longitude, end of obs [degree]	Aircraft longitude in degrees at end of observation.	DCS
ALTI_STA= 43007. / Aircraft pressure altitude, start of obs [ft]	Aircraft pressure altitude in feet at start of observations in feet.	DCS
ALTI_END= 43006. / Aircraft pressure altitude, end of obs [ft]	Aircraft pressure altitude in feet at end of observations in feet.	DCS
TSC-STAT= 'STAB_INERTIAL_ONGOING' / TASCU Status at observation end	Status of the Telescope Assembly Servo Control Unit (TASCU) at end of observation.	DCS
FBC-STAT= 'FBC_ON ' / FBC Status at observation end	Flexible Body Compensation (FBS) status at end of observation.	DCS
OBSRA = 17.789 / RA - requested [Hours]	The Right Ascension in hours requested by the observation.	DCS
OBSDEC = -28.385 / Dec - requested [Degrees]	The Declination in degrees requested by the observation.	DCS
EQUINOX = 2000. / Coordinate equinox for OBSRA and OBSDEC	Coordinate equinox for OBSRA and OBSDEC. Here it is J2000.	FITS
ZA_START= 50.501 / Zenith angle, start of obs	Telescope zenith angle at the start of the observation in degrees.	DCS
ZA_END = 50.6771 / Zenith angle, end of obs	Telescope zenith angle in degrees at the end of the observation.	DCS
TRACMODE= 'OFFSET ' / SOFIA tracking mode	The SOFIA tracking mode.	DCS
CHPSYM = '2_point_symmetric' / Chopping symmetry [SYM, ASYM]	Chopping symmetry (symmetric vs. asymmetric).	DCS
CHOPPING= T / Chopping flag	Chopping flag (T if observation uses chopping, F if not).	DCS
NODDING = F / Nodding flag	Nodding flag (T if observation uses nodding, F if not).	DCS
MAPPING = F / Mapping flag	Mapping flag (T if observation is a map, F if not).	DCS
SCANNING= F / Scanning flag	Scanning flag (T if observation uses scanning such for an OTF map, F if not).	DCS
TRACERR = F / Tracking error flag [Y/N]	Tracking error flag (T if there were any telescope tracking errors during observation, F if not).	DCS
INSTRUME= 'GREAT ' / Instrument	Name of instrument used to acquire the scientific data. CLASS variable: SOFIA%INSTRUME.	FITS
DATATYPE= 'SPECTRAL' / Data type	Type of data (IMAGE, SPECTRAL, etc.)	DCS
INSTCFG = 'DUAL_CHANNEL' / Instru	Instrument configuration description. Here GREAT is always configured as a dual channel spectrograph. CLASS variable: SOFIA%INSTCFG.	DCS
FRONTEND= 'HFAV_PX06' / Name of frontend device	Name of instrument front end. Here it is for the HFA. CLASS variable: SOFIA%FRONTEND.	DCS
BACKEND = 'HFAV_PX06_S' / Name of backend device	Name of instrument backend. Here it is for the HFA. CLASS variable: SOFIA%BACKEND.	DCS
SPECTRAL= 'NONE ' / spectral element(s) in use	Spectral elements in use. Here set to NONE.	DCS
TSYS = -9999. / System temperature	System temperature in units of Kelvin. CLASS variable: GEN%TSYS.	CLASS
VELDEF = 'LSR ' / VELDEF	Velocity definition and frame (here LSR=Local Standard of Rest). CLASS variable: SPE%VTYPE.	DCS

Keyword	Description	Standard
VFRAME = 76.224 / VELOCITY OF TELESCOPE [km/s]	The velocity of the reference frame with respect to the observer in km s^{-1}.	DCS
CHPFREQ = 1. / Chop frequency (SOFIA)	Requested chop frequency in Hz (note this is different from the actual chop frequency which is stored in the keyword CHOPFREQ). CLASS variable: SOFIA%SCHPFRQ.	DCS
CHPPROF = '2-POINT ' / Chopping profile: 2 or 3 point	Chopping profile. Can be 2 or 3 point.	DCS
CHPAMP1 = 80. / Chop amplitude 1	Chop amplitude to chop position 1 in arcsec. CLASS variable: SOFIA%CHPAMP1.	DCS
CHPAMP2 = 0. / Chop amplitude 2	Chop amplitude to chop position 2 in arcsec.	DCS
CHPANGLE= 240. / Calculated angle in the sky coord sys reference	Angle of the chop throw relative to the sky coordinate reference frame in degrees. CLASS variable: SOFIA%CHPANGLE.	DCS
CHPTIP = 0. / Calculated tip in the sky coord sys reference f	Calculated chop tip in the sky coordinates reference frame in arcsec.	DCS
CHPTILT = 0. / Calculated tilt in the sky coord sys reference	Calculated chop tilt in the sky coordinates reference frame in arcsec.	DCS
CHPPHASE= 0 / Chop phase	Chop phase in milliseconds.	DCS
NODTIME = 0. / Nod time	Nod time in seconds.	DCS
NODN = 1. / Nod cycles	Number of nod cycles.	DCS
NODSETL = 0. / Nod settle time	Nod settle time in seconds.	DCS
NODAMP = 80. / Nod amplitude on sky	Nod amplitude on the sky in arcsec	DCS
NODBEAM = 'a ' / Current nod beam position	Current nod beam position (A or B).	DCS
NODPATT = 'ABAB ' / Nodding pattern, one cycle	Nod pattern for a single cycle. Typically, A is the science target.	DCS
NODCRSYS= 'erf ' / Coordinate system for Nod angle	Coordinate system for the nod angle.	DCS
CHPCRSYS= 'erf ' / MCCS Coordinate system for sky tip, tilt and an	Coordinate system for the sky tip, tilt, and angle.	DCS
NODANGLE= 240. / Nod angle	Nod angle, clockwise from y-axis defined by NODCRSYS in degrees.	DCS
MAPCRSYS= 'J2000 ' / Coordinate system for mapping/scanning	Coordinate system that the observation mapping and scanning are defined in. Here it is set to J2000 coordinates.	DCS
MAPNXPOS= 0 / Number of map positions in X	Number of map positions (readouts) in the X direction.	DCS
MAPNYPOS= 0 / Number of map positions in Y	Number of map positions in the Y direction.	DCS
MAPINTX = 0. / Mapping step interval in X	Map step interval in X direction in arcmin.	DCS
MAPINTY = 0. / Mapping step interval in Y	Map step interval in Y direction in arcmin.	DCS
SPECTEL1= 'GRE_HFA ' / First spectral element in use	First spectral element in use. For GREAT it is the primary frequency or reference array. Here it is the GREAT HFA	DCS
SPECTEL2= 'NONE ' / Second spectral element in use	Second spectral element in use. For GREAT, it is set to NONE.	DCS
SIBS_X = 0 / SI Boresight (x) - as returned by MCCS	For GREAT, X direction location of SI boresight in the focal plane in millimeters.	DCS
SIBS_Y = 0 / SI Boresight (y) - as returned by MCCS	For GREAT, Y direction location of SI boresight in the focal plane in millimeters.	DCS
LRANGE = 'UNKNOWN ' / Spectral Line Range	This keyword was never implemented.	DCS
LPRIOR = 'UNKNOWN ' / Spectral Line Priorities	This keyword was never implemented.	DCS

Keyword	Description	Standard
LGOALRES= 'UNKNOWN ' / Spectral Line Goal Resolution	This keyword was never implemented.	DCS
SCANNUM = 39431 / SCAN NUMBER	Scan number. CLASS variable: GEN%SCAN.	CLASS
DATE = '2021-08-09T09:58:05' / Date Observed	Date the FITS file was generated.	FITS
UTCSTART= '09:58:05' / UTC of exposure start	Start time of observation in UTC. CLASS variable: GEN%UT.	DCS
UTCEND = '09:58:35' / UTC of exposure end	End time of observation in UTC.	DCS
TELESCOP= 'SOFIA ' / OBSERVATORY NAME	Name of telescope. Here it specifies the telescope is SOFIA.	FITS
CREATOR = 'AFFTS_server_06 (kosma_control)' / CREATOR OF FITS FILE	Name and version of the software that created this FITS file.	DCS
NUMSPEC = 21 / NUMBER OF ACTIVE SPECTROMETERS	Number of active spectrometers (pixels) processed by the backends. Here the LFAH, LFAV, and HFA have 7 pixels each for a total of 21.	Kosma
NAMESPEC= 'SOF-HFAV_6_S' / SPECTROMETER NAME	Spectrometer name. Same as keyword BACKEND. CLASS variable: GEN%TELES.	DCS
LATITUDE= -22.491289 / TELESCOPE LATITUDE	Geographic latitude for telescope in degrees. CLASS variable: CAL%GEOLAT.	Kosma
LONGITUD= 144.4007 / TELESCOPE LONGITUDE	Geographic longitude for telescope in degrees. CLASS variable: CAL%GEOLONG.	Kosma
SITEALT = 13802.03 / TELESCOPE ALTITUDE [m]	Telescope altitude in meters averaged for all spectra.	Kosma
OBSERVER= 'YokoParitKyle' / OBSERVER	Name of observer(s). CLASS variable: SOFIA%OBSERVER.	FITS
PI_NAME = 'Giesen_Thomas' / Name of the Principal Investigator	Name of the project's principal investigator.	Kosma
INSTMODE= 'BSA ' / OBSERVING MODE	Instrument observing mode. Here BSA means Beam Switch A.	DCS
SOBSMODE= 'ON ' / OBSERVING SUB MODE	Observing sub mode indicating scan type (e.g., ON, OFF, HOT, SKY, etc.).	Kosma
DATAQUAL= 0 / QUALITY INFORMATION	Quality check information. Not used for GREAT. CLASS variable: GEN%QUAL.	DCS
LST-OBS = '21:32:57' / OBSERVE LST	Local Sidereal Time of observation. CLASS variable: GEN%ST.	DCS
LLOADSN = 39430 / LAST LOAD SCAN NUMBER	Scan number of the last load. CLASS variable: SOFIA%LAST_LOAD.	Kosma
LFRCASN = 3471 / LAST FREQUENCY CALIB SCAN NUMBER	Scan number of the last frequency calibration.	Kosma
LSKYSN = 39336 / LAST SKY MEAS SCAN NUMBER	Scan number of the last sky measurement.	Kosma
AZIMUTH = 250.98025 / AZIMUTH	Telescope azimuth at start of observation in degrees. CLASS variable: GEN%AZ.	CLASS
ELEVATIO= 39.495743 / ELEVATION	Telescope elevation at start of observation in degrees.	CLASS
NODWAIT = 0.02 / BLANKING TIME [s]	Blanking time in seconds.	Kosma
BCKLEN = 0.005 / BCK SINGLE SCAN TIME [s]	Backend single scan time in seconds.	Kosma
BLANK = 0 / BLANKING VALUE	Null value when writing data to FITS file.	Kosma
DATAMIN = 0. / MINIMUM DATA VALUE	Minimum value in the data.	FITS
DATAMAX = 65535. / MAXIMUM DATA VALUE	Maximum value in the data. CLASS variable: SPE%BAD.	FITS
CTYPE1 = 'PIXEL ' / QUANTITY OF 1 AXIS	Coordinates of axis 1. Here it is pixels.	FITS
SUBX = 0. / SUBREFLECTOR X	This keyword was never implemented. The value given here is a default value.	Kosma
SUBY = 0. / SUBREFLECTOR Y	This keyword was never implemented. The value given here is a default value.	Kosma
SUBZ = -3100. / SUBREFLECTOR Z	This keyword was never implemented. The value given here is a default value.	Kosma

Keyword	Description	Standard
SUBI = 0.005 / SUBREFLECTOR I	This keyword was never implemented. The value given here is a default value.	Kosma
SUBJ = -0.3 / SUBREFLECTOR J	This keyword was never implemented. The value given here is a default value.	Kosma
SUBK = 0. / SUBREFLECTOR K	This keyword was never implemented. The value given here is a default value.	Kosma
OBJECT = 'SGRB2_M ' / SOURCE NAME	Name of the science target observed. CLASS variable: POS%SOURC.	FITS
COORDSYS= 'J2000 ' / COORD SYS ON	Coordinate system epoch used for the observations. CLASS variable: POS%EPOCH.	CLASS
LAMBDA = 266.8354 / OBS LAM ON	Longitude of source in degrees. Here it is the Right Ascension.	Kosma
BETA = -28.385 / OBS BET ON	Latitude of source in degrees. Here it is the Declination.	Kosma
COSYDEL = 'J2000 ' / COORD SYS DEL	Requested map offset coordinate system. Here it is J2000 coordinates.	Kosma
LAMDEL = 0. / OBS LAM DEL	Requested map offset lambda (RA) in arcsec.	Kosma
BETDEL = 0. / OBS BET DEL	Requested map offset beta (Dec) in arcsec.	Kosma
OTADEL = 'Y ' / OBSERVE TRUE ANGLE DEL (Y/N)	Are LAMDEL and BETDEL specified as true angular distances on the sky, and not the difference in sky-coordinate values?	Kosma
COSYOFF = 'J2000 ' / COORD SYS OFF	Coordinate system (epoch) that LAMOFF and BETOFF are in. Here it is J2000 coordinates.	Kosma
LAMOFF = 0. / OBS LAM OFF	Offset in LAMBDA in radians. The average observed longitude (RA) on the sky is LAMBDA + LAMOFF. CLASS variable: POS%LAMOF.	CLASS
BETOFF = 0. / OBS BET OFF	Offset in BETA in radians. The average observed latitude (Dec.) on the sky is BETA + BETOFF. CLASS variable: POS%BETOF.	CLASS
CHOPANGL= 30. / POSITION ANGLE FOR SKY CHOPPER	Calculated position angle (CCW from North) for the chopping in degrees in the sky reference frame.	DCS
RDLNGTH = 0.79872 / CHOPPER PHASE TIME LENGTH	Time in one chopper phase in seconds. This is the time at a position (ON or OFF) for a chopped observation.	DCS
CHOPAMP = 80. / SKY CHOPPER AMPLITUDE	Measured sky chop amplitude on the sky in arcsec. Same as keyword CHPAMP1. CLASS variable: SOFIA%CHPAMP1.	DCS
CHOPFREQ= 0.626 / SKY CHOPPER FREQUENCY	Measured (actual) sky chop frequency in Hz. Note that this is not the same as the requested chop frequency stored in keyword CHPFREQ. CLASS variable: SOFIA%SCHPFRQ.	DCS
CHOPCOOR= 'J2000 ' / SKY CHOPPER COORD SYSTEM	Sky coordinate system (epoch) for chopper.	DCS
BORESYS = 'SIRF ' / BORE SITE SYSTEM	Boresight coordinate system. Here it is the Science Instrument Reference Frame (SIRF).	DCS
LINE = 'OI_63_L ' / LINE NAME	Name of spectral line the receiver is tuned to. Here it is the [OI] 63 micron line. The L denotes the Lower Sideband was used (U would denote the Upper Sideband). CLASS variable: SPE%LINE.	CLASS
RESTFREQ= 4744777.49 / REST FREQUENCY (MHz)	Rest frequency of the spectral line the signal sideband is tuned to in MHz. CLASS variable: SPE%RESTF.	CLASS
OBSFREQ = 4743571.255675 / SKY FREQUENCY (MHz)	The observed frequency of the reference pixel along the frequency axis in MHz.	DCS
LOFREQ = 4744971. / LO FREQUENCY (MHz)	Local oscillator frequency in MHz.	Kosma
IMAGFREQ= 4746370.744325 / IMAGE FREQUENCY (SKY) (MHz)	The image sideband rest frequency corresponding to the rest frequency of the signal band (RESTFREQ) in MHz. CLASS variable: SPE%IMAGE.	CLASS
SYNTH = 0. / SYNTHESIZER FREQUENCY (MHz)	Frequency in MHz of the synthesizer used to drive the solid-state multiplier chains that make up the LFA LOs.	Kosma
NUMCHAN = 16384 / NUMBER OF BACKEND CHANNELS	Number of GREAT backend channels. CLASS variable: SPE%NCHAN.	Kosma

Keyword	Description	Standard
BANDWID = 3500. / BANDWIDTH (MHz) OF THE BACKEND	Total bandwidth of the GREAT backend in MHz.	Kosma
CREFPIX = 8191. / REFERENCE CHANNEL	Reference channel for the GREAT backend. CLASS variable: SPE%RCHAN.	Kosma
CMBBOTPX= -9999. / LOWEST CHANNEL SPIKE IN COMB	Lowest channel spike in comb fit. Not used since the LFA never switched to photonic LOs.	Kosma
CMBTOPPX= -9999. / HIGHEST CHANNEL SPIKE IN COMB	Highest channel spike in comb fit. Not used since the LFA never switched to photonic LOs.	Kosma
STARTREF= 8191. / START OF REFERENCE SEARCH	Start channel for the last comb spike center search. Not used since the LFA never switched to photonic LOs.	Kosma
FREQRES = -0.244141 / FREQUENCY RESOLUTION	Frequency resolution in MHz. CLASS variable: SPE%VOFF.	CLASS
FREQOFFS= -600.255675 / FREQUENCY OFFSET	Frequency offset in MHz. CLASS variable: SPE%FREQ_OFF.	CLASS
VELRES = 0.0154296471041759 / VELOCITY RESOLUTION	Velocity resolution of the data in km s^{-1}. It is defined as -c*(FREQRES/RESTFREQ). CLASS variable: SPE%VRES.	CLASS
FREQSWAM= 0. / FREQUENCY SWITCH AMPLITUDE	Frequency switch amplitude of the LO in MHz. Also called the frequency throw. Not used here.	Kosma
BEFF = 0.6 / BEAM EFFICIENCY	Beam efficiency. See definition in Section 3.1. CLASS variable: CAL%BEEFF.	Kosma
FOEFF = 0.95 / FORWARD EFFICIENCY	Forward efficiency. See definition in Section 3.1. CLASS variable: CAL%FOEFF.	Kosma
GAINIMAG= 0.5 / GAIN IMAG	Ratio of signal to image band gain. Here the ratio is 0.5 since both sidebands are weighted equally. CLASS variable: CAL%GAINI.	CLASS
RVSYS = 64.	Radial velocity of the source minus the radial velocity of the telescope in km s^{-1}. CLASS variable: SPE%VOFF.	DCS
REFPOSX = -3.713 / REF POS TEL OFFSET X [arcsec]	Reference position on the sky for the boresight (on which the telescope tracks) projected onto the instrument focal plane in X in arcsec.	Kosma
REFPOSY = 18.2392 / REF POS TEL OFFSET Y [arcsec]	Reference position on the sky for the boresight (on which the telescope tracks) projected onto the instrument focal plane in Y in arcsec.	Kosma
REFRXDX = 1.8651 / REFERENCE PIXEL OFFSET X [arcsec]	Reference position pixel offset in X in arcsec on the sky for the telescope boresight projected into the instrument focal plane.	Kosma
REFRXDY = -4.7044 / REFERENCE PIXEL OFFSET Y [arcsec]	Reference position pixel offset in Y in arcsec on the sky for the telescope boresight projected into the instrument focal plane.	Kosma
ACTELAXX= 0. / ACT INSTRUMENT ELEV AXIS X [arcsec]	Offset of active array elevation axis in X, converted from mm to arcsec using ACTFOCLEN.	Kosma
ACTELAXY= 0. / ACT INSTRUMENT ELEV AXIS Y [arcsec]	Offset of active array elevation axis in Y, converted from mm to arcsec using ACTFOCLEN.	Kosma
HIERARCH ACTROTAXX = 4.4260696599 / ACT INSTRUMENT ROTATOR AXIS X [arcsec]	Offset of active array rotator axis in X, converted from mm to arcsec using ACTFOCLEN.	Kosma
HIERARCH ACTROTAXY = 18.7620814514 / ACT INSTRUMENT ROTATOR AXIS Y [arcsec]	Offset of active array rotator axis in Y, converted from mm to arcsec using ACTFOCLEN.	Kosma
REFELAXX= 0. / REF INSTRUMENT ELEV AXIS X [arcsec]	Offset of reference array elevation axis in X, converted from mm to arcsec using FOCALLEN.	Kosma
REFELAXY= 0. / REF INSTRUMENT ELEV AXIS Y [arcsec]	Offset of reference array elevation axis in Y, converted from mm to arcsec using FOCALLEN.	Kosma
HIERARCH REFROTAXX = 4.4261 / REF INSTRUMENT ROTATOR AXIS X [arcsec]	Offset of reference array rotator axis in X, converted from mm to arcsec using FOCALLEN.	Kosma
HIERARCH REFROTAXY = 18.7621 / REF INSTRUMENT ROTATOR AXIS Y [arcsec]	Offset of reference array rotator axis in Y, converted from mm to arcsec using FOCALLEN.	Kosma
PIXOFFX = 5.27946402088755 / ACT PIX OFFSET FROM REF X [arcsec]	Offset in X in arcsec of the active pixel position from the tracking reference position, converted to sky coordinates.	Kosma
PIXOFFY = -13.1837245865117 / ACT PIX OFFSET FROM REF Y [arcsec]	Offset in Y in arcsec of the active pixel position from the tracking reference position, converted to sky coordinates.	Kosma

Keyword	Description	Standard
SIGNRXDX= -1. / SIGN BETWEEM INSTR-FLANGE FP X AND 1ST MAPPING	Sign for instrument focal plane to sky coordinate conversion in X.	Kosma
SIGNRXDY= 1. / SIGN BETWEEN INSTR-FLANGE FP Y AND 2nd MAPPING	Sign for instrument focal plane to sky coordinate conversion in Y.	Kosma
FOCALLEN= 51868.3 / FOCAL LENGTH [mm] of reference instrument	Focal length of reference array in mm. Used to convert linear to angular scale (determining plate scale).	Kosma
HIERARCH ACTFOCLEN = 51868.304611863 / FOCAL LENGTH [mm] of active instrument	Focal length of active array in mm. Used to convert linear to angular scale (determining plate scale).	Kosma
POSANGLE= 180. / POSITION ANGLE OF ARRAY [deg]	Requested position angle (CCW from North) in degrees for array rotation on sky.	DCS
BEAMANG = -34.4189 / REAL BEAM ROTATOR ANGLE [deg]	Commanded rotator angle.	Kosma
ANGLEDIF= -0.4229 / DIFFERENCE TO CMD ANGLE [deg]	Difference between commanded and actual rotator angle. Negative sign added for consistency with old data.	Kosma
ACTANGIM= 40. / ACT INSTRUMENT MOUNT FLANGE ANGLE [deg]	Instrument mounting flange angle of the active array in degrees.	Kosma
REFANGIM= 40. / REF INSTRUMENT MOUNT FLANGE ANGLE [deg]	Instrument mounting flange angle of reference array in degrees.	Kosma
ACTTILT = 6.025 / ACT ARRAY TILT ANGLE [deg]	Active array (for this pixel) tilt angle in degrees.	Kosma
REFTILT = 6.025 / REF ARRAY TILT ANGLE [deg]	Reference array tilt angle in degrees.	Kosma
VPATEL = 99.5561 / VERTICAL POSITION ANGLE TEL [deg]	Position angle (CW from North) in degrees of the vertical (positive elevation) of the telescope to the celestial north direction.	Kosma
RXDX = 7.0467164756 / PIXEL OFFSET X [arcsec]	Offset of active array pixel in arcsec in the x direction in the internal instrument mounting flange coordinates (u, v). CLASS variable: SOFIA%RXDX.	Kosma
RXDY = 8.5180963266 / PIXEL OFFSET Y [arcsec]	Offset of active array pixel in arcsec in the y direction in the internal instrument mounting flange coordinates (u, v). CLASS variable: SOFIA%RXDY.	Kosma
THOT = 297.399 / HOT LOAD TEMP [K]	Temperature of the hot load in Kelvin. CLASS variable: CAL%TCHOP.	Kosma
TCOLD = 68.361 / COLD LOAD TEMP [K]	Temperature of the cold load in Kelvin. CLASS variable: CAL%TCOLD.	Kosma
TAMB = 241.8 / AMBIENT TEMPERATURE [K]	Ambient temperature of SOFIA in Kelvin. Same as keyword TAMBSOIF. CLASS variable: CAL%TAMB.	DCS
HIERARCH NLOADTEMP = 0 / NUMBER OF LOAD TEMPERATURE POINTS	Number of load temperature points.	Kosma
TAMBLOAD= 297.438 / LOAD AMBIENT TEMPERATURE [K]	Load ambient temperature in Kelvin.	Kosma
FAMBLOAD= 0. / LOAD AMBIENT FILLING FACTOR	Load ambient filling factor.	Kosma
TEMP_OUT= 207.65 / SKY TEMPERATURE [K]	Static air temperature outside of aircraft in Kelvin.	DCS
PAMB = 121.2342 / AMBIENT PRESSURE [Torr]	Ambient pressure in Torr.	Kosma
HAMB = 0.1 / AMBIENT HUMIDITY [0..1]	Ambient humidity in fractional units.	Kosma
FILENAME= '039431_010_HFAV_PX06_S.fits' / Name of	Name of the host file.	DCS
EXPTIME = 13.77 / REAL INTEGRATION TIME [s]	Total effective on-source exposure time in seconds.	DCS
SPECTIME= 30. / SPECIFIED INTEGRATION TIME [s]	Specified integration time in seconds.	Kosma
SCAN = 39431	Scan number. Same as keyword SCANNUM. CLASS keyword: GEN%SCAN.	CLASS

Keyword	Description	Standard
HISTORY	These comments under the HISTORY keyword document changes made during post-processing, when the headers are checked before the file is ingested into the SOIFA archive.	FITS
HISTORY Headers updated by knishiki, 2021-08-11T09:54:30	Who ran header_checker and when the headers were updated during post-processing.	FITS
HISTORY FILENAME: /home/greatuser/data_fits_temp/039431_010_HFAV_PX06_S.fits -	The keyword FILENAME was modified in post-processing with the before value shown.	FITS
HISTORY > 039431_010_HFAV_PX06_S.fits	The value of keyword FILENAME after it was updated during post-processing.	FITS
HISTORY INSTCFG: HFAV_PX00 DLR_HFA_QCL-LO__AAO HFAV_PX04 DLR_HFA_QCL-LO__AAO -	The keyword INSTCFG was modified in post-processing with the before value shown.	FITS
HISTORY > DUAL_CHANNEL	New value of keyword INSTCFG after it was updated during post-processing.	FITS
HISTORY scan: None -> 39431	New keyword SCAN and value added during post-processing.	FITS
HISTORY	Blank.	FITS
FILEREV = 1 / 2021-08-11T18:42:46Z	File revision identifier. Marks if and when file was changed during post-processing. Changes are documented under the HISTORY keywords above.	DCS
END	Marks the end of the header	FITS

B. LEVEL 4 FITS-HEADER FOR A DATA CUBE

Level 4 data cube FITS-files only use the Primary extension and header.

Keyword	Description	Standard
SIMPLE = T / conforms to FITS standard	Denotes if this header conforms to the FITS Standard. T means true. F means false.	FITS
BITPIX = -64 / array data type	Bits per data value. The value -64 indicates the data format is IEEE double-precision floating point.	FITS
NAXIS = 3 / number of array dimensions	The number of axes in the associated data array. Here 3 indicates this file stores a data cube.	FITS
NAXIS1 = 42	The data array size of axis 1.	FITS
NAXIS2 = 36	The data array size of axis 2.	FITS
NAXIS3 = 60	The data array size of axis 3.	FITS
DATAMIN = -0.4665024757385E+01 /	Maximum value in the data. CLASS variable: SPE%BAD.	FITS
DATAMAX = 0.3893236875534E+01 /	Minimum value in the data.	FITS
BUNIT = 'K (Ta*) ' /	Physical units of the data. Here K (Ta*) indicates the data units are the forward-beam brightness temperature in Kelvin.	FITS
CTYPE1 = 'RA---GLS ' /	Coordinates of axis 1. Here it is WCS astrometry in units of Right Ascension with the Global Sinusoidal projection on the sky.	FITS
CRVAL1 = 0.1857207400000E+03 /	Value at the reference pixel for axis 1.	FITS
CDELT1 = -0.2222222306912E-02 /	Increment of the coordinate at the reference pixel for axis 1. Here it is the partial derivative of the Right Ascension with respect to the pixel index evaluated at the reference pixel.	FITS
CRPIX1 = 0.2265164054288E+02 /	Location of the reference pixel for axis 1 in pixel index coordinates.	FITS
CROTA1 = 0.0000000000000E+00 /	The amount of rotation done to another coordinate system for axis 1. Here there is no rotation.	FITS

Keyword	Description	Standard
CTYPE2 = 'DEC--GLS ' /	Coordinates of axis 2. Here it is WCS astrometry in units of Right Ascension with the Global Sinusoidal projection on the sky.	FITS
CRVAL2 = 0.1582431400000E+02 /	Value at the reference pixel for axis 2.	FITS
CDELT2 = 0.2222222306912E-02 /	Increment of the coordinate at the reference pixel for axis 2. Here it is the partial derivative of the Declination with respect to the pixel index evaluated at the reference pixel.	FITS
CRPIX2 = 0.1835993867838E+02 /	Location of the reference pixel for axis 2 in pixel index coordinates.	FITS
CROTA2 = 0.0000000000000E+00 /	The amount of rotation done to another coordinate system for axis 2. Here there is no rotation.	FITS
CTYPE3 = 'VRAD ' /	Coordinates of axis 3. Here VRAD denotes radio velocity which is $c(\nu_0-\nu)/\nu_0$ in units of m s^{-1}.	FITS
CRVAL3 = 0.1566800048828E+07 /	Value at the reference pixel for axis 3.	FITS
CDELT3 = -0.4953862667084E+04 /	Increment of the coordinate at the reference pixel for axis 3. Here it is the partial derivative of the velocity with respect to the pixel index evaluated at the reference pixel.	FITS
CRPIX3 = 0.2739970016479E+02 /	Location of the reference pixel for axis 3 in pixel index coordinates.	FITS
CROTA3 = 0.0000000000000E+00 /	The amount of rotation done to another coordinate system for axis 3. Here there is no rotation.	FITS
CUNIT3 = 'm/s '	Physical units for axis 3. Here axis 3 is the spectral axis of the data cube and is units of velocity in m s^{-1}.	FITS
OBJECT = 'NGC4321 '	Name of the science target observed. CLASS Variable: POS%SOURC.	FITS
RA = 0.1857207400000E+03 / Right Ascension	Requested Right Ascension in decimal degrees.	DCS
DEC = 0.1582431400000E+02 / Declination	Requested Declination in decimal degrees.	DCS
EQUINOX = 0.2000000000000E+04 /	Coordinate equinox for RA and DEC. Here it is J2000.	FITS
LINE = 'CII_U '	Name of spectral line the receiver is tuned to. Here it is the [CII] 158 micron line. The U denotes the Upper Sideband was used (L would denote the Lower Sideband). CLASS variable: SPE%LINE.	CLASS
ALTRPIX = 0.2739970016479E+02 /	Alternative keyword for the velocity axis (axis 3) reference pixel. Has the same value as CRPIX3.	AIPS
ALTRVAL = 0.1890604157437E+13 /	Frequency at the velocity axis (axis 3) reference pixel in Hz.	AIPS
RESTFREQ= 1900536.9	Rest frequency of the spectral line the signal sideband is tuned to in MHz. CLASS variable: SPE%RESTF.	CLASS
VELO-LSR= 0.1566800048828E+07 /	Source velocity in m s^{-1} in the Local Standard of Rest frame. Same as CRVAL3.	CLASS
VELREF = 257 /	Used to denote the velocity reference in the AIPS-convention. A value of 256 indicates radio velocity and +1 to 257 indicates kinematic units of LSR (as opposed to +2 for barycentric or +3 for topocentric).	AIPS
SPECSYS = 'LSRK ' /	Reference frame for the spectral coordinate axis (axis 3). Here it is the Kinematic Local Standard of Rest.	FITS
BMAJ = 0.4444444706465E-02 /	Beam major axis FWHM in degrees.	AIPS
BMIN = 0.4444444706465E-02 /	Beam minor axis FWHM in degrees.	AIPS
BPA = 0.0000000000000E+00 /	Beam position angle in degrees.	AIPS
ORIGIN = 'GILDAS Consortium ' /	Organization whose software generated this file. In this case, this FITS file was generated with GILDAS/CLASS.	FITS
DATE = '2020-04-23T18:51:20.842' / Date written	Date the FITS file was generated.	FITS
MISSN-ID= '2019-12-13_GR_F648'	SOFIA Mission ID. Specifies date, instrument (GR=GREAT), and flight number. CLASS variable: SOFIA%MISSION_ID.	DCS

Keyword	Description	Standard
ASSC_MSN= '2019-12-13_GR_F648'	List of all Mission IDs used to generate this file. Here only one Mission ID was used.	DCS
EXPTIME = 39663.6793975832	Total effective on-source exposure time in seconds. CLASS variable: GEN%TIME.	DCS
TELEL = 30.34357084592806	Telescope elevation above the horizon in degrees averaged for all spectra in this file. CLASS variable: GEN%EL.	DCS
AZIMUTH = 93.67162127723502	Telescope Azimuth in degrees averaged for all spectra in this file. CLASS variable: GEN%AZ.	DCS
LST-OBS = '07:43:46'	Local Sidereal Time of observation averaged for all spectra in this file. CLASS variable: GEN%ST.	DCS
VELDEF = 'RADI-LSR'	Velocity definition and frame. First 4 characters give the velocity definition (here RADI=RADIO) and the last three give the reference frame (here LSR=Local Standard of Rest). CLASS variable: SPE%VTYPE.	AIPS
IMAGFREQ= 1897521.5139036	The image sideband rest frequency corresponding to the rest frequency of the signal band (RESTFREQ) in MHz. CLASS variable: SPE%IMAGE.	CLASS
ASSC_FRQ= 1900536.9	List of all frequencies combined and used to generate this file. Here only one frequency was used.	DCS
RVSYS = 1566.8000488281	Radial velocity of the source minus the radial velocity of the telescope in km s^{-1}. CLASS variable: SPE%VOFF.	DCS
VELRES = -0.038702052086592	Velocity resolution of the data in km s^{-1}. It is defined as -c*(FREQRES/RESTFREQ). CLASS variable: SPE%VRES.	CLASS
FREQRES = 0.24410000443459	Frequency resolution in MHz. CLASS variable: SPE%VOFF.	CLASS
FREQOFFS= 500.000468	Frequency offset in MHz. CLASS variable: SPE%FREQ_OFF.	CLASS
CHPANGLE= 240.0	Angle of the orientation of the chop throw for Beam Switch observations. Measured counter-clockwise from the north in degrees. CLASS variable: SOFIA%CHPANGLE.	DCS
CHPAMP1 = 150.0	Amplitude of the chop throw in arcsec. CLASS variable: SOFIA%CHPAMP1.	DCS
CHPFREQ = 1.0	Chop frequency in Hz. CLASS variable: SOFIA%SCHPFRQ.	DCS
BACKEND = 'LFAH_PX00_S'	Name of instrument backend. Here it is for the GREAT LFA. CLASS variable: SOFIA%BACKEND.	DCS
FRONTEND= 'LFAH_PX00'	Name of instrument front end. Here it is for the GREAT LFA. CLASS variable: SOFIA%FRONTEND.	DCS
HEADING = -178.18699645996	Aircraft heading in degrees. CLASS variable: SOFIA%HEADING.	DCS
GRDSPEED= 827.40399169922	Aircraft ground speed in knots. CLASS variable: SOFIA%GNDSPEED.	DCS
TEMPSEC1= 239.39999389648	Temperature of the telescope's secondary mirror in Kelvin. CLASS variable: SOFIA%TEMPSEC1.	DCS
TEMPPRI1= 0.0	Temperature of the telescope's primary mirror in Kelvin. CLASS variable: SOFIA%TEMPRI1. (Here sensor wasn't working.)	DCS
TAMBSOFI= 247.19999694824	Ambient temperature of SOFIA in Kelvin. CLASS variable: SOFIA%TAMB_SOFI.	DCS
LAMBDA = 3.241438402240299	Longitude of source in radians. Here it is the Right Ascension. Same as the keyword RA but in radians instead of degrees. CLASS variable: POS%LAM.	CLASS
LAMOFF = -1.1028850303511E-05	Offset in LAMBDA in radians. The average observed longitude (RA) on the sky is LAMBDA + LAMOFF. CLASS variable: POS%LAMOF.	CLASS
BETA = 0.27618638116943	Latitude of source in radians. Here it is the Declination. Same as the keyword DEC but in radians instead of degrees. CLASS variable: POS%BET.	CLASS
BETOFF = -4.9911427577569E-06	Offset in BETA in radians. The average observed latitude (Dec.) on the sky is BETA + BETOFF. CLASS variable: POS%BETOF.	CLASS
UTCSTART= '09:28:45'	Start time of observation in UTC. CLASS variable: GEN%UT.	DCS
UTCEND = '10:20:21'	End time of observation in UTC.	DCS
DATE-OBS= '2019-12-13T09:28:45'	Date of exposure start in UTC. CLASS variable: GEN%CDOBS.	FITS
CDOBS = '13-DEC-2019'	Date of observation in alternative format. CLASS variable: GEN%CDOBS.	CLASS
INSTRUME= 'GREAT '	Name of instrument used to acquire the scientific data. CLASS variable: SOFIA%INSTRUME.	FITS

Keyword	Description	Standard
LAT_STA = 38.96303939686687	Aircraft latitude at start of observation in degrees. CLASS variable: CAL%GEOLAT.	DCS
LON_STA = 108.1305867362924	Aircraft longitude at start of observation in degrees. CLASS variable: CAL%GEOLONG.	DCS
OPERATOR= 'Sabrina/Adriana/Tzitlaly'	Name of telescope operator(s). CLASS variable: SOFIA%OPERATOR. CLASS variable: SOFIA%OBSERVER.	DCS
OBSERVER= 'Yoko/Slawa'	Name of observer(s). CLASS variable: SOFIA%OBSERVER.	FITS
DATASRC = 'ASTRO '	Type of data (e.g. astronomical observation, calibration, etc.). Here ASTRO = astronomical observation. CLASS variable: SOFIA%DATASRC.	DCS
PLANID = '07_0126 '	Observing plan ID. The ID assigned to each project per observing cycle. CLASS variable: SOFIA%PLANID.	DCS
AOR_ID = '07_0126_46'	Astronomical Observation Request (AOR) ID.	DCS
ASSC_AOR= '07_0126_46'	List of all AOR IDs used to generate this file. Here only one AOR was used.	DCS
CLS_IDX = 39763.0	Scan number from CLASS. CLASS variable: GEN%SCAN.	CLASS
SPECTEL1= 'GRE_LFA '	First spectral element. Denotes the channel for the Primary Frequency chosen by the PI. Here it is the GREAT LFA.	DCS
SPECTEL2= 'NONE '	Second spectral element. Here there is none.	DCS
INSTCFG = 'DUAL_CHANNEL'	Instrument configuration description. Here GREAT is always configured as a dual channel spectrograph. CLASS variable: SOFIA%INSTCFG.	DCS
OBS_ID = 'Cycle7_GR_OT_07_0126_ABolatto_NGC4321_CII.lmv.fits'	Name of this data file. CLASS variable: SOFIA%OBS_ID.	DCS
FILENAME= 'Cycle7_GR_OT_07_0126_ABolatto_NGC4321_CII.lmv.fits'	Name of the host file. In this case it is the same as OBS_ID.	DCS
TELRA = 12.38134053956152	Average telescope Right Ascension position in J2000 decimal degrees. Calculated from LAMBDA + LAMOFF and converted to degrees.	DCS
TELDEC = 15.8240280285848	Average telescope Declination position in J2000 decimal degrees. Calculated from BETA + BETOFF and converted to degrees.	DCS
OBSTYPE = 'OBJECT '	Observation type. Here OBJECT means Astronomical Object (almost always the case).	DCS
PROCSTAT= 'LEVEL_4 '	Status of processing applied to this data (Level 0 to 4).	DCS
N_SPEC = 42896.0	Number of GREAT spectra used in file.	DCS
END	Marks the end of the header	FITS

C. Level 4 FITS-header for single spectra

Level 4 FITs-files for single spectra have multiple headers: the primary header and one or more headers for each extension holding the individual spectra.

Primary header:

Keyword	Description	Standard
SIMPLE = T / conforms to FITS standard	Denotes if this header conforms to the FITS Standard. T means true. F means false.	FITS
BITPIX = 8 / array data type	Bits per data value. The value 8 indicates the data format is single byte (8 bits) unsigned integers.	FITS
NAXIS = 0 / number of array dimensions	The number of axes in the associated data array. Here 0 indicates this is the primary header with no associated data.	FITS
EXTEND = T	Boolean denoting if this fits file can have multiple extensions. T=True and F=False.	FITS
MISSN-ID= '2021-02-09_GR_F695'	SOFIA Mission ID. Specifies date, instrument (GR=GREAT), and flight number. CLASS variable: SOFIA%MISSION_ID.	DCS
ASSC_MSN= '2021-02-09_GR_F695'	List of all Mission IDs used to generate this file. Here only one Mission ID was used.	DCS
EXPTIME = 3690.360122680753	Total effective on-source exposure time in seconds. CLASS variable: GEN%TIME.	DCS

Keyword	Description	Standard
TELEL = 30.00879461418219	Telescope elevation above the horizon in degrees averaged for all spectra in this file. CLASS variable: GEN%EL.	DCS
AZIMUTH = 332.4228492597371	Telescope Azimuth in degrees averaged for all spectra in this file. CLASS variable: GEN%AZ.	DCS
LST-OBS = '05:32:49'	Local Sidereal Time of observation averaged for all spectra in this file. CLASS variable: GEN%ST.	DCS
VELDEF = 'RADI-LSR'	Velocity definition and frame. First 4 characters give the velocity definition (here RADI=RADIO) and the last three give the reference frame (here LSR=Local Standard of Rest). CLASS variable: SPE%VTYPE.	AIPS
IMAGFREQ= 1380250.552819	The image sideband rest frequency corresponding to the rest frequency of the signal band (RESTFREQ) in MHz. CLASS variable: SPE%IMAGE.	CLASS
RESTFREQ= 1383250.0	Rest frequency of the spectral line the signal sideband is tuned to in MHz. CLASS variable: SPE%RESTF.	CLASS
ASSC_FRQ= 1383250.0	List of all frequencies combined and used to generate this file. Here only one frequency was used.	DCS
RVSYS = -60.0	Radial velocity of the source minus the radial velocity of the telescope in km s^{-1}. CLASS variable: SPE%VOFF.	DCS
VELRES = -0.052894152700901	Velocity resolution of the data in km s^{-1}. It is defined as -c*(FREQRES/RESTFREQ).	CLASS
FREQRES = 0.24410000443459	Frequency resolution in MHz. CLASS variable: SPE%VOFF.	CLASS
LINE = 'SH_U '	Name of spectral line the receiver is tuned to. Here it is a line for the SH molecule. The U denotes the Upper Sideband was used (L would denote the Lower Sideband). CLASS variable: SPE%LINE.	CLASS
FREQOFFS= 499.999674	Frequency offset in MHz. CLASS variable: SPE%FREQ_OFF.	CLASS
CHPANGLE= 240.0	Angle of the orientation of the chop throw for Beam Switch observations. Measured counter-clockwise from the north in degrees. CLASS variable: SOFIA%CHPANGLE.	DCS
CHPAMP1 = 150.0	Amplitude of the chop throw in arcsec. CLASS variable: SOFIA%CHPAMP1.	DCS
CHPFREQ = 1.0	Chop frequency in Hz. CLASS variable: SOFIA%SCHPFRQ.	DCS
BACKEND = '4G3_PX00_S'	Name of instrument backend. Here it is for 4GREAT 4G3. CLASS variable: SOFIA%BACKEND.	DCS
FRONTEND= '4G3_PX00'	Name of instrument front end. Here it is for 4GREAT 4G3. CLASS variable: SOFIA%FRONTEND.	DCS
HEADING = 58.692401885986	Aircraft heading in degrees. CLASS variable: SOFIA%HEADING.	DCS
GRDSPEED= 842.61712646484	Aircraft ground speed in knots. CLASS variable: SOFIA%GNDSPEED.	DCS
TEMPSEC1= 241.62222290039	Temperature of the telescope's secondary mirror in Celsius. CLASS variable: SOFIA%TEMPSEC1.	DCS
TEMPPRI1= 0.0	Temperature of the telescope's primary mirror in Celsius. CLASS variable: SOFIA%TEMPRI1.	DCS
TAMBSOFI= 240.60000610352	Ambient temperature of SOFIA in Kelvin. CLASS variable: SOFIA%TAMB_SOFI.	DCS
LAMBDA = 6.0814048252968	Longitude of source in radians. Here it is the Right Ascension. CLASS variable: POS%LAM.	CLASS
LAMOFF = 1.38308437000425E-05	Offset in LAMBDA in radians. The average observed longitude (RA) on the sky is LAMBDA + LAMOFF. CLASS variable: POS%LAMOF.	CLASS
BETA = 1.0728523902178	Latitude of source in radians. Here it is the Declination. CLASS variable: POS%BET.	CLASS
BETOFF = 8.27995324509476E-08	Offset in BETA in radians. The average observed latitude (Dec.) on the sky is BETA + BETOFF. CLASS variable: POS%BETOF.	CLASS
OBJECT = 'NGC7538_IRS1'	Name of the science target observed. CLASS Variable: POS%SOURC.	FITS
UTCSTART= '21:42:40'	Start time of observation in UTC. CLASS variable: GEN%UT.	DCS
UTCEND = '23:41:07'	End time of observation in UTC.	DCS
DATE-OBS= '2021-02-09T21:42:40'	Date of exposure start in UTC. CLASS variable: GEN%CDOBS.	FITS

Keyword	Description	Standard
CDOBS = '09-FEB-2021'	Date of observation in alternative format. CLASS variable: GEN%CDOBS.	CLASS
INSTRUME= 'GREAT '	Name of instrument used to acquire the scientific data. CLASS variable: SOFIA%INSTRUME.	FITS
LAT_STA = 47.56996050746267	Aircraft latitude at start of observation in degrees. CLASS variable: CAL%GEOLAT.	DCS
LON_STA = 11.70693241963433	Aircraft longitude at start of observation in degrees. CLASS variable: CAL%GEOLONG.	DCS
OPERATOR= 'SA '	Name of telescope operator(s). CLASS variable: SOFIA%OBSERVER.	DCS
OBSERVER= 'CB '	Name of observer(s). CLASS variable: SOFIA%OBSERVER.	FITS
DATASRC = 'ASTRO '	Type of data (e.g. astronomical observation, calibration, etc.). Here ASTRO = astronomical observation. CLASS variable: SOFIA%DATASRC.	DCS
PLANID = '08_0038 '	Observing plan ID. The ID assigned to each project per observing cycle. CLASS variable: SOFIA%PLANID.	DCS
AOR_ID = '08_0038_24'	Astronomical Observation Request (AOR) ID.	DCS
ASSC_AOR= '08_0038_24'	List of all AOR IDs used to generate this file. Here only one AOR was used.	DCS
CLS_IDX = 14.0	Scan number from CLASS. CLASS variable: GEN%SCAN.	CLASS
SPECTEL1= 'GRE_4G3 '	First spectral element. Denotes the channel for the Primary Frequency chosen by the PI. Here it is for 4GREAT 4G3.	DCS
SPECTEL2= 'NONE '	Second spectral element. Here there is none.	DCS
INSTCFG = 'DUAL_CHANNEL'	Instrument configuration description. Here GREAT is always configured as a dual channel spectrograph. CLASS variable: SOFIA%INSTCFG.	DCS
OBS_ID = 'Cycle8_GR_OT_08_0038_DNeufeld_NGC7538_SH.great.fits'	Name of this data file. CLASS variable: SOFIA%OBS_ID.	DCS
FILENAME= 'Cycle8_GR_OT_08_0038_DNeufeld_NGC7538_SH.great.fits'	Name of the host file. In this case it is the same as OBS_ID.	DCS
TELRA = 23.22930816326476	Average telescope Right Ascension position in J2000 decimal degrees. Calculated from LAMBDA + LAMOFF and converted to degrees.	DCS
TELDEC = 61.46991874406619	Average telescope Declination position in J2000 decimal degrees. Calculated from BETA + BETOFF and converted to degrees.	DCS
OBSTYPE = 'OBJECT '	Observation type. Here OBJECT means Astronomical Object (almost always the case).	DCS
PROCSTAT= 'LEVEL_4 '	Status of processing applied to this data (Level 0 to 4).	DCS
N_SPEC = 268.0	Number of GREAT spectra used in file.	DCS
END	Marks the end of the header	FITS

Extension 1 header:

Keyword	Description	Standard
XTENSION= 'IMAGE ' / Image extension	Name of extension type. Here it is the type IMAGE.	FITS
BITPIX = -64 / array data type	Bits per data value. The value -64 indicates the data format is IEEE double-precision floating point.	FITS
NAXIS = 4 / number of array dimensions	The number of axes in the associated data array. While this extension has 4 axes, this is a 1D spectrum and only the first axis has a length > 1.	FITS
NAXIS1 = 1820	The data array size of axis 1.	FITS
NAXIS2 = 1	The data array size of axis 2.	FITS

Keyword	Description	Standard
NAXIS3 = 1	The data array size of axis 3.	FITS
NAXIS4 = 1	The data array size of axis 4.	FITS
PCOUNT = 0 / number of parameters	Number of parameters in a group. For IMAGE type extensions, this is always set to 0.	FITS
GCOUNT = 1 / number of groups	Number of groups in this extension. For IMAGE type extensions, this is always set to 1.	FITS
DATAMIN = -0.172078323364E+001 /	Maximum value in the data.	FITS
DATAMAX = 0.262954368591E+002 /	Minimum value in the data. CLASS variable: SPE%BAD.	FITS
BUNIT = 'K ' /	Physical units of the data. Here K indicates the data units are the main beam (T_{MB}) temperature in Kelvin.	FITS
CTYPE1 = 'FREQ ' /	Coordinates of axis 1. Here this is the spectral axis in units of Hz.	FITS
CRVAL1 = 0.000000000000E+000 / Offset frequency	Value at the reference pixel for axis 1.	FITS
CDELT1 = 0.219690012932E+007 / Frequency resolution	Increment of the coordinate at the reference pixel for axis 1. Here it is the frequency resolution in units of Hz.	FITS
CRPIX1 = 0.682962158203E+003 /	Location of the reference pixel for axis 1 in pixel index coordinates.	FITS
CTYPE2 = 'RA---GLS' /	Coordinates of axis 2. Here it is WCS astrometry in units of Right Ascension with the Global Sinusoidal projection on the sky.	FITS
EQUINOX = 0.200000000000E+004 /	Coordinate equinox for RA and DEC. Here it is J2000.	FITS
CRVAL2 = 0.348438830000E+003 /	Value at the reference pixel for axis 2.	FITS
CDELT2 = 0.784545704047E-003 /	Increment of the coordinate at the reference pixel for axis 2. Here it is the partial derivative of the Right Ascension with respect to the pixel index evaluated at the reference pixel.	FITS
CRPIX2 = 0.000000000000E+000 /	Location of the reference pixel for axis 2 in pixel index coordinates.	FITS
CTYPE3 = 'DEC--GLS' /	Coordinates of axis 2. Here it is WCS astrometry in units of Right Ascension with the Global Sinusoidal projection on the sky.	FITS
CRVAL3 = 0.614699140000E+002 /	Value at the reference pixel for axis 3.	FITS
CDELT3 = -0.282943691485E-005 /	Increment of the coordinate at the reference pixel for axis 3. Here it is the partial derivative of the Declination with respect to the pixel index evaluated at the reference pixel.	FITS
CRPIX3 = 0.000000000000E+000 /	Location of the reference pixel for axis 3 in pixel index coordinates.	FITS
CTYPE4 = 'STOKES ' /	Coordinates of axis 4. Here STOKES denotes this axis is for polarization.	FITS
CRVAL4 = 1.0000000000000 /	Value at the reference pixel for axis 4	FITS
CDELT4 = 1.0000000000000 /	Increment of the coordinate at the reference pixel for axis 4.	FITS
CRPIX4 = 0.0000000000000 /	Location of the reference pixel for axis 4 in pixel index coordinates.	FITS
TELESCOP= 'SOF-4G3_0_S ' /	Name of telescope. Here it specifies the telescope is SOFIA and the primary frequency for this project is 4GREAT 4G3.	FITS
OBJECT = 'NGC7538_IRS1' /	Name of the science target observed. CLASS Variable: POS%SOURC.	FITS
LINE = 'SH_U ' / Line name	Name of spectral line the receiver is tuned to. Here it is a line for the SH molecule. The U denotes the Upper Sideband was used (L would denote the Lower Sideband). CLASS variable: SPE%LINE.	CLASS
RESTFREQ= 0.138325000000E+013 / Rest frequency	Rest frequency of the spectral line the signal sideband is tuned to in Hz. CLASS variable: SPE%RESTF.	FITS
VELO-LSR= -0.600000000000E+005 / Velocity of reference channel	Source velocity in m s^{-1} in the Local Standard of Rest frame.	CLASS
DELTAV = -0.476047366858E+003 / Velocity spacing of channels	Velocity spacing between pixels in m s^{-1}. Same information as CDELT1 but with Hz converted to m s^{-1}.	CLASS

Keyword	Description	Standard
IMAGFREQ= 0.138025055312E+013 / Image frequency	The image sideband rest frequency corresponding to the rest frequency of the signal band (RESTFREQ) in Hz. Class variable: SPE%IMAGE.	CLASS
TSYS = 0.426809472656E+004 / System temperature	System temperature in units of Kelvin. CLASS variable: GEN%TSYS.	CLASS
OBSTIME = 0.184518005371E+004 / Integration time	Effective integration time in seconds.	CLASS
SCAN-NUM= 0.100000000000E+001 / Scan number	Scan number. CLASS variable: GEN%SCAN.	CLASS
TAU-ATM = 0.846915841103E-001 / Atmospheric opacity	Atmospheric opacity.	CLASS
GAINIMAG= 0.500000000000E+000 / Image sideband gain ratio	Ratio of signal to image band gain. Here the ratio is 0.5 since both sidebands are weighted equally. CLASS variable: CAL%GAINI.	CLASS
BEAMEFF = 0.699999988079E+000 / Beam efficiency	Beam efficiency. See definition in Section 3.1. CLASS variable: CAL%BEEFF	Kosma
FORWEFF = 0.970000028610E+000 / Image sideband gain ratio	Forward efficiency. See definition in Section 3.1. CLASS variable: CAL%FOEFF. NOTE the FITS header description here is incorrect.	Kosma
ORIGIN = 'CLASS-Grenoble ' /	Organization whose software generated this file. In this case, this FITS file was generated with GILDAS/CLASS.	FITS
DATE = '2021-07-03T00:00:00.000' / Date written	Date the FITS file was generated.	FITS
TIMESYS = 'UTC ' /	Name of time system used. Here it is UTC.	FITS
DATE-OBS= '2021-02-09T23:40:18.000' / Date observed	Date of exposure start in UTC. CLASS variable: GEN%CDOBS.	FITS
DATE-RED= '2021-06-11T00:00:00.000' / Date reduced	Date the data were reduced in UTC.	CLASS
ELEVATIO= 0.300444448758E+002 / Telescope elevation	Telescope elevation at start of observation in degrees. CLASS variable: GEN%EL.	CLASS
AZIMUTH = 0.000000000000E+000 / Telescope azimuth	Telescope azimuth at start of observation in degrees. CLASS variable: GEN%AZ.	CLASS
UT = ' 23:40:18.000' / Universal time at start	Universal time of the start of the observation. CLASS variable: GEN%UT.	CLASS
LST = ' 05:32:50.000' / Sideral time at start	Sideral time of the start of the observation. CLASS variable: GEN%ST.	CLASS
END	Marks the end of the header	FITS

D. Background Subtraction

Because the sky is so bright in the infrared (IR) relative to astronomical sources, how observations are made in the IR is considerably different from how they are made in the optical and the near infrared. Any raw image or spectrum of a region in the IR is overwhelmed by this sky background emission. Different techniques have been developed to subtract any background emission to remove the background and detect astronomical sources. Heterodyne spectroscopy makes a virtue of necessity and uses the background as a reference source. Thus, what is referred to as background in this appendix is typically called “reference” in the heterodyne literature and the main body of this document. However, the methods for the subtractions for direct detection and heterodyne instruments are the same. They are:

- **Chopping:** On SOFIA, the oversized primary mirror and the moveable secondary mirror allowed switching at a frequency of a few Hertz between two positions on the sky, one containing the source, and the other nearby blank sky. This technique typically allowed a very good subtraction of the sky background. The separation between the two positions was limited to 6 to 10 arcminutes depending on the direction in telescope coordinates.

  There are two ways chopping was set up on SOFIA. They differ in how the two chop positions were set up relative to the instrument's boresight (which is close to the optical axis of the telescope). See Figure 17.

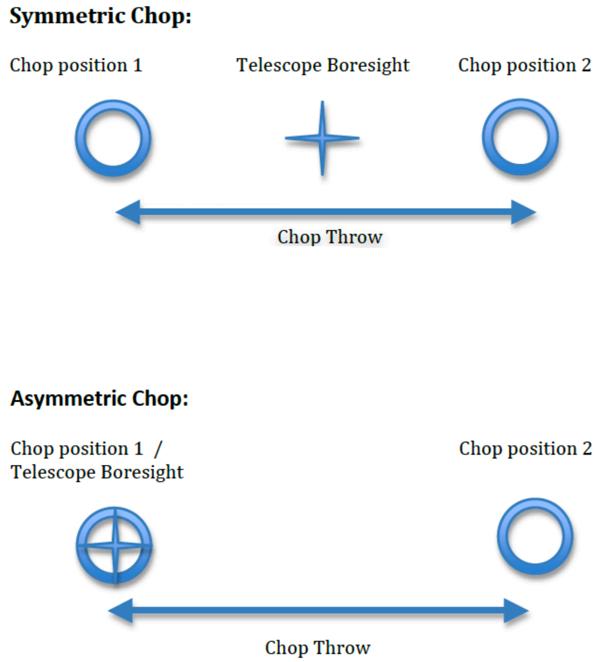


Figure 17 *Symmetric and Asymmetric Chopping*

- **Symmetric Chop:** The telescope boresight is in the middle between the two chop positions. Due to the coma of the telescope beam increasing with distance from the optical axis, the image quality in both chop positions is affected.
- **Coma:** Off-axis beams are affected by coma. On the SOFIA telescope the coma amounts to 1" beam distortion per 1' away from the telescope boresight. Whether coma affects the image quality or spatial resolution depends on the beam size, total chop throw[4] (separation of chop positions), and chop mode. For GREAT, only observations at the highest frequencies may be affected if large chop throws had to be used.
- **Asymmetric Chop (not used by GREAT):** One of the chop positions coincides with the telescope boresight. This position is not affected by coma, while the other chop position suffers from coma.

[4] Chop amplitude is half of the total chop throw.

- **Nodding:** While the sky background is subtracted very well by chopping, the telescope background does not completely vanish, because the optical path through the telescope and used area of the primary mirror differs between the source and the sky observation. Typically, the residual telescope background needs to be measured repeatedly by moving the telescope somewhat and then back again on timescales of minutes.

If **symmetric chopping** is feasible, the telescope nods so that the source appears in one of the two chopping positions on each nod as illustrated below. This is known as Nod Match Chop or Double Beam Switch (Figure 18).

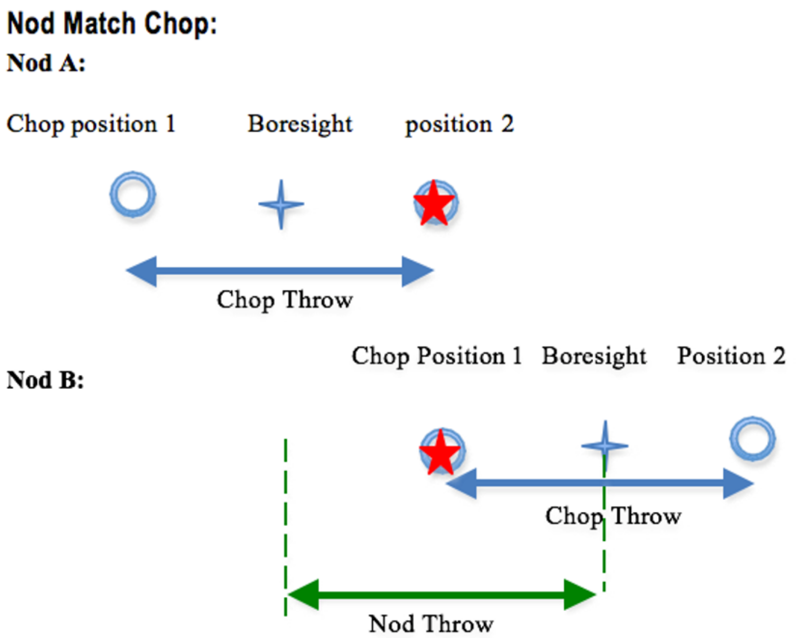


Figure 18 *Nod Match Chop or Double Beam Switch*

This method allows observation of the source in both parts of the nod cycle. The residual telescope emission subtracts because the source signal and the residual telescope emission appear with different signs in the difference signal.

Total Power/Intensity: For extended objects where chopping may not have been feasible due to the limit for the chop throw, Total Power observations were an alternative method to observe a reference position and allow background subtraction. The telescope was moved back and forth between the source and a sky position clean of emission on timescales of up to a minute.
Any observation can be done in Total Power mode. For a single point, the telescope would spend the same amount of time in the source and the reference position just as for chopping. For mapping observations, a number of on-positions can be observed in one On-Off observing cycle as done for On-the-Fly maps.

To spend less time slewing the telescope and have similar atmospheric conditions, the reference position was typically chosen less than 1 degree away from the source. If there was still extended emission at that source or emission was suspected at the reference position, this reference position (often called "near-off" for this purpose) was observed relative to an even further away reference position (often called "far-off"). The emission observed at the near-off position (if any) could then be added back to the observation to recover all the source emission.