4GREAT—A Four-Color Receiver for High-Resolution Airborne Terahertz Spectroscopy

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Abstract—4GREAT is an extension of the German receiver for astronomy at terahertz frequencies (GREAT) operated aboard the Stratospheric Observatory for Infrared Astronomy (SOFIA). The spectrometer comprises four different detector bands and their associated subsystems for simultaneous and fully independent science operation. All detector beams are coaligned on the sky. The frequency bands of 4GREAT cover 491–635, 890–1090, 1240–1525, and 2490–2590 GHz, respectively. This article presents the design and characterization of the instrument, and its in-flight performance. The first light of 4GREAT was on June 2018. It has been offered to the interested SOFIA communities starting with observing cycle 6.

Index Terms—Airborne astronomy, far-infrared astronomy, hot electron bolometers (HEB) mixer, heterodyne spectroscopy, receivers, SIS mixer, submillimeter-wave technology, superconducting devices.

I. INTRODUCTION

SINCE the completion of the Herschel satellite mission [1], the spectrometer German receiver for astronomy at terahertz frequencies (GREAT) [2] onboard the Stratospheric Observatory for Infrared Astronomy (SOFIA) airborne observatory [3] is the only instrument that routinely allows performing the high-resolution spectroscopy of astronomical signals at far-infrared wavelengths. Except in very limited windows ($\lambda > 300 \mu m$), the otherwise opaque terrestrial atmosphere prevents far infrared (FIR) observations from ground-based facilities (see Fig. 1).

Since its first light in 2011, GREAT has collected science data on more than 175 flights. In its early configuration GREAT operated, in parallel, two single-pixel LHe/LN$_2$ cooled cryostats hosting heterodyne detectors in the 1.5 and 1.9 THz frequency bands. In the following years, thanks to the instrument’s modular design, the operation was extended to more and higher frequencies, and by 2015 there was a choice of dual-color observations among four frequency bands [4]. A major upgrade came in 2015 with the addition of the upGREAT low-frequency array [5] (LFA) and later in 2016 with the high-frequency array (HFA) [6]. The LFA consists of two 7-pixel arrays, working in dual polarization mode, to ultimately cover the 1.9–2.5 THz atmospheric windows. The HFA is equipped with a 7-pixel array operating at 4.7 THz in the single polarization.

The addition of the arrays imposed major hardware changes. Because of the parallel operation of both arrays, the instrument was required to expand the intermediate frequency (IF) processor and the digital back end from 2 to 21 channels, each of them with the frequency coverage from 0 to 4 GHz. To facilitate the

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array operation for astronomical observations, a K-mirror working as a beam derotator, was installed as part of the instrument optics system. Finally, the use of closed-cycle coolers required the installation of adequate cooling infrastructure aboard the aircraft. The instrument status as of June 2017 is presented in [6].

With the success of the upGREAT arrays, and considering the enhanced infrastructure of the instrument and cooling capacity of the observatory, the idea of 4GREAT was born. The new instrument should facilitate the operation and scheduling by reducing the number of flight configurations, while further extending SOFIA’s science capabilities. The requirements toward the design of 4GREAT were as follows:

1) To allow for the integration of the GREAT single-pixel units operating in the 1.2–1.5 THz and 2.49–2.52 THz frequency bands [4].
2) To extend the science opportunities to subTHz frequencies, not covered by SOFIA after the cancellation of the CASIMIR project [7].

This article describes the design of the instrument along with its integration, testing, and commissioning onboard the SOFIA observatory. We will show that by making use of the improved performance of today’s dichroic (frequency) filters, up to four frequency bands can be arranged into a single cryostat for simultaneous science operation with coaligned pixels on the sky. The final choice of frequency bands is presented in Table I. For the lower frequency extensions, we gave preference to those frequency regimes that cannot be observed from ground-based facilities, thereby taking unique advantage of the transparent atmosphere at SOFIA’s flight altitude.

To exemplify the new science opportunities, i.e., the absorption line spectroscopy toward the FIR background continuum sources will allow in-depth studies of the galactic interstellar medium with hydrides (many of which have their ground-state transition in the lower 4GREAT bands, as given in Table I); this will be a unique addition to what has commenced so successfully with HIFI/Herschel [8] but now operating up to five frequency bands simultaneously.

The development was launched at the end of 2015, as part of the Ph.D. thesis work of C. Durán [9], [10], and 18 months later 4GREAT (with three of its four channels) was integrated with the GREAT infrastructure. Its first-light flight took place on July 13, 2017, out of Christchurch, New Zealand.

II. 4GREAT DESIGN

The 4GREAT design follows the modularity of the GREAT instrument, as described in detail in [2]. There are the following four clearly distinguishable hardware groups.

1) The 4GREAT receiver cryostat.
2) The local oscillator “upper” unit (LO-U), hosting the 4G-1 and 4G-2 local oscillator (LO) chains and guiding optics, located on top of the optic compartment.
3) The LO “lower” unit (LO-L), hosting the 4G-3 and 4G-4 LO chains and guiding optics, located below the optic compartment.
4) The 4GREAT optics plate (common warm optics).

These four modules are installed in the main instrument frame, along with the common support and control hardware. The latter includes a calibration unit (cold and hot load, with optics), the mixer bias controller, LO synthesizers, readout electronics for temperature sensors, and control for the motorized parts of the optics (grid attenuators, calibration unit, and K-mirror). Fig. 2 shows the disposition of the different modules as mounted to the

| Table I 4GREAT Frequency Coverage |
| --- |
| Channel | Frequency (GHz) | Astrophysical lines of interest (examples) |
| 4G-1 | 491 - 655 | [CH, HD, CH, (13)CH, H2O(1-0-10)], NH2, CO, ArI, HCl, SH, CS, C2S |
| 4G-2 | 890-1090 | (13)CO, HDO, H2O(2-1-21), H2S, OH, NH2, NH3, CS, C2S |
| 4G-3 | 1240 - 1525 | [NII], OD, (13)CO, H2O*, SH, CH, CS |
| 4G-4 | 2490 - 2590 | (18)OH, (16)OH, CO(22-21) |

Note: The usable sky frequency coverage is calculated for an IF center frequency of 6 GHz (SIS) and 1.5 GHz (HEB), respectively. CO transitions are accessible in all bands, the superscript (13) indicates that at least one isotopic transition can be observed. Script (a) denotes that multiple transitions of linear rotors, such as CS, HCN, HNC, HCO+, and SiO can be observed in bands 4G-1–4G-3. In bold we mark molecular ground-state transitions.

Fig. 1. Frequency coverage of the 4GREAT channels, of the upGREAT LFA and HFA arrays, and the ALMA receivers for reference, superimposed on the atmospheric transmission. For SOFIA, the zenith transmission (gray) is calculated for a flight altitude of 13.1 km and 10 µm of residual precipitable water; for the Chajnantor plateau at 5000 m (ALMA, light blue) very best conditions of 200 µm PWV are assumed, although occurring for a few nights per year only. In the lower panels, we zoom-in on the transmission for each of the 4GREAT bands (gray for SOFIA, black for Chajnantour), with a selection of important astrophysical transitions marked (compare with Table I).
Fig. 2. Overview of the main 4GREAT modules mounted in the GREAT structure. Some panels and sidewalls, including cryostat vessel, have been removed for better visualization.

TABLE II
4GREAT MIXER CHARACTERISTICS

| Band | Built by | Technology | RF/IF band (GHz) |
|------|----------|------------|------------------|
| 4G-1 | LERMA    | SIS Nb [12] | 480-640 / 4-8   |
| 4G-2 | SRON     | SIS NbTIN [13] | 960-1120 / 4-8 |
| 4G-3 | KOSMA    | HEB NbTIN [14] | 1200-1600 / 0.1-2.6 |
| 4G-4 | KOSMA    | HEB NbN [15][16] | 2500-2700 / 0.1-3.5 |

Note: (1) The HEB receiver temperature increases with IF; the 3 dB rolloff bandwidth is quoted.

instrument structure. We discuss the individual modules in the following sections.

A. 4GREAT Detectors

The 4GREAT cryostat (see Section II-E) hosts the mixer for each of the four channels, the low-noise amplifiers (LNAs), the isolators, temperature sensors, and the cold part of the optics. All of them are mounted together in a unique structure, named cold tower, made of aluminum (see Fig. 3). The detectors are of different technologies: the 4G-1 and 4G-2 channels utilize superconductor–insulator–superconductor (SIS) mixers, whereas 4G-3 and 4G-4 employ hot electron bolometers (HEBs). All mixers are of double sideband (DSB) response. Table II summarizes the main characteristics of each mixer.

1) SIS Mixers for 4G-1 and 4G-2: The SIS mixers for 4G-1 and 4G-2 are units originally developed for HIFI, the heterodyne instrument [11] onboard the Herschel Space Observatory. They provide an output IF signal that runs from 4 to 8 GHz.

The 4G-1 mixer is the spare flight mixer developed by LERMA in Paris, France, and therefore complies with all the specifications for a HIFI band 1 unit. Mixer noise temperatures lower than 100 K DSB have been reported for operation at 2 K bath temperature [12], a temperature that cannot be provided by the cryocoolers aboard SOFIA. As this good mixer performance is dependent on the actual junction temperature, our mechanical design places the mixer as close as possible to the coldest point of the 4 K stage. The horn is thermally connected to the cold finger by flexible copper straps, reaching an operation temperature of 3.45 K.

Similarly, the 4G-2 mixer is a flight spare mixer of the HIFI band 4, developed by SRON [13]. In 4GREAT, we extend the operation of the mixer well below its design frequency range to provide access to important astrophysical lines (see Table II) while compromising the unit’s noise performance.

Both mixers have their bias network incorporated in the housing, as well as the coil to generate the magnetic field to suppress the Josephson effect, and a heater to temporarily increase the junction temperature and remove the trapped magnetic flux if needed. The connection between each SIS mixer and its respective LNA is by a ferrite isolator, to minimize the effect of standing waves due to the impedance mismatch.

2) HEB Mixers for 4G-3 and 4G-4: Both 4G-3 and 4G-4 detectors were originally developed by the KOSMA group at the Cologne University for the single-pixel cryostats GREAT-L1 and GREAT-M, respectively. The 4G-3 mixer performance and technology are described in [14]. Per Fourier transform spectrometer (FTS) response measurements, the mixer performs between 1.2 and 1.6 THz (3 dB falloff). The mixer includes a corrugated horn clamped to the mixer body. A coaxial SMA connector is used for the IF output and also used to supply
the bias voltage through an external bias \( T \), which is integrated with the LNA. The 4G-4 HEB is fully described in [15] and [16]. It is a novel custom-scaled spline-profile conical feed [17], [18], which was micromachined by Radiometer Physics GmbH (Meckenheim, Germany). The NbN HEB mixer has been optimized to cover the RF band from 2.5 to 2.7 THz. Like 4G-3, the 4G-4 mixer requires an additional biasing module included in the LNA.

### B. Local Oscillators

4GREAT makes use of four fully independent, tunable LO units [19], made up of cascaded multiplication stages and a high frequency power amplifier driver. The chains have been custom manufactured by Virginia Diodes Inc. (Charlottesville, VA, USA). The reference input signal, provided by the external oscillator, is between 10 and 16 GHz with a minimum power of 10 dBm. The four chains are grouped in pairs, in two separated enclosures, due to physical constraints. The 4G-1 and 4G-2 LO chains are lodged in the LO-U, whereas the 4G-3 and 4G-4 LO are in the LO-L. Table III summarizes the LO performance for all four chains.

#### 1) LO “Upper” Unit: The LO-U unit is placed above the optics compartment of the GREAT structure, in front of the 4GREAT cryostat. The wide RF bandwidth of the 4G-1 LO chain, ranging from 495 to 630 GHz, is realized by operating two frequency-shifted driver stages. The resonance of the diplexer that combines the two signals has been tuned to match the strong atmospheric absorption by the ground-state water line (a gap between 550 and 565 GHz). The chain delivers at least 200 \( \mu \)W of output between 2480 and 2620 GHz.

#### 2) LO “Lower” Unit: The LO-L unit is placed in the compartment assigned for the LO source servicing the right-hand side (looking toward the telescope) GREAT cryostat. The optical LO path has to allow for vacuum windows. These windows, made of silicon with an antireflection coating, are identical to the vacuum windows of the cryostat. When in flight, the LO-U is part of the aircraft pressure boundary, whereas the 4G-4 mixer requires an additional biasing module included in the LNA.

#### 3) Reference Synthesizer: The GREAT reference signal box has been upgraded to contain four independent LO reference signals. They are made up of a digitally controllable YIG-based synthesizer and a 30 MHz wide tunable YIG filter. The synthesizer and the bandpass filter can be tuned from 8 to 20 GHz. The YIG filter is used for harmonic filtering, eliminating unwanted harmonics and spurious signals from the synthesizer. It also allows performing a smooth ramp up of the LO reference signal, by slowly tuning the YIG filter to match the requested frequency.

### C. Optics Design

Some of the relevant SOFIA telescope optical characteristics [20] are summarized in Table IV. The nominal telescope focal plane is placed 300 mm behind the science instrument interface flange (toward the cabin). The optical image derotator that has been installed with the upGREAT arrays adds 319.7 mm to the signal path (the K-mirror is located in the optics path common to all channels). This change of the telescope’s effective focal length is compensated by adjusting the position of the telescope’s subreflector.

All 4GREAT channels are designed for an edge taper of 14 dB on the telescope secondary mirror. The optics setup uses only reflective elements except for the dichroic filters and polarization grids needed for the simultaneous operation of the four channels and the comounted upGREAT HFA.

#### 1) Signal-Path Optics: The first optical element in the signal path (see Fig. 4) is a low-pass dichroic filter from QMC (Cardiff, U.K.), used to separate the beams of the HFA and 4GREAT. The dichroic has a cutoff frequency \( \nu_c \) of 3.3 THz, its frequency-dependent transmission varies between 88% and 98% over the 4G operation range. The signal loss in the HFA path is low, as the reflectivity is 97% at the frequency of the [OI] 63 \( \mu \)m fine-structure transition, i.e., the operating frequency of the HFA.

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**Table III**

4GREAT LOCAL OSCILLATORS PERFORMANCE

| Channel | LO BANDWIDTH (GHz) | POWER (\( \mu \)W) | MULT. FACTOR |
|---------|---------------------|-------------------|--------------|
| 4G-1    | 495-550 / 565-630   | 300               | 48           |
| 4G-2    | 850-975 / 990-1085  | 200               | 72           |
| 4G-3    | 1240-1395 / 1425-1525| 40                | 108          |
| 4G-4    | 2480-2620          | 3.5               | 216          |

Note: (1) minimum output power across >95% of the LO bandwidth, as measured by the manufacturer using a bolometric power meter.

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**Table IV**

SOFIA—OPTICAL PARAMETERS WITH GREAT

|                  |                  |
|------------------|------------------|
| Primary diameter | 2500 (2700) mm   |
| Primary focal length | 3200 mm       |
| Secondary diameter | 352 mm        |
| Telescope total focal length | 49141 mm |
| Focal length with K-mirror | 51421 mm |

Note: The clear aperture of the oversized primary mirror is 2500 mm.
Fig. 4. Top: sketch of the signal beam splitting by polarization and frequency-selective dichroics, and the active optical elements in each of the channels of 4GREAT. The upGREAT HFA and 4GREAT are operated simultaneously. In the bottom-left figure, we illustrate the signal (golden) and LO (green and orange) beam propagation, in two levels. A side-view picture of the optics plate is shown at the bottom right.

The dichroic is located in the focal plane of the instrument, attached to the HFA optics plate.

The signal optics for each of the 4GREAT channels are made of the same kind of elements but dimensioned for their respective frequency ranges. Some of these elements are common to two or even all of the channels. The 4G-4 optics have additional components due to their different LO coupling scheme (as shown in the following part).

The next element that the signal encounters, after the first dichroic filter, is an ellipsoidal mirror (named M4), which is common to all four channels. This mirror focuses and deflects the beam to a first wire grid (WG), which separates the signal beam into two polarizations. Each of the new beams, namely horizontal and vertical, are then refocused by active mirrors $M_{3,13}$ and $M_{3,24}$, respectively, which, along with M4, form the first Gaussian beam telescope of each channel. Next, the horizontally and vertically polarized beams are split in frequency by dedicated low-pass dichroic filters $D_{1,3}$ ($\nu_c = 1.1$ THz) and $D_{2,4}$ (1.6 THz), yielding now four independent beams: horizontal-low (4G-1); horizontal-high (4G-3); vertical-low (4G-2); and vertical-high (4G-4). Each individual beam is subsequently reflected to a group of flat/active (F2/M2) mirrors, which provide four degrees of freedom (DOF) for the optical alignment of each beam. The beams then pass their respective LO coupling grids (an interferometric diplexer in the case of 4G-4, placed before the flat/active group) and a polarization cleaning grid, aligned with the respective mixer polarization, before entering the corresponding cryostat vacuum window. Inside the cryostat, the beams pass through an infrared filter located on the 45 K shield before reaching the cold optics.

The cold optics is composed of a focusing mirror (M1), a flat mirror (F1), and a parabolic mirror (M0) in front of the respective detector horn. The pair of M2/M1 mirrors form the second Gaussian beam telescope in the beam path of every channel.

As an example, to illustrate the optic design, Fig. 5 displays the unfolded signal path for channel 4G-3, showing the critical components and the reimaging with the Gaussian telescopes.

2) LO Coupling Optics: The 4G-1, 4G-2, and 4G-3 LO signals are optically combined with their respective sky signals by WGs. The amount of LO and signal power that is coupled to the detectors depends on the polarization angle of the grid with respect to the polarization of the LO and signal beams. Coupling more LO power has a penalty in the receiver temperature, as less signal from the sky is coupled. The 4G-4 channel, due to its relatively low LO power, employs a Martin–Puplett interferometer as a diplexer.

As the power delivered for every chain is not uniform in the frequency, an adjustable optical attenuator has been installed in the beam path of each LO. 4G-2, 4G-3, and 4G-4 use a concentric rotating polarizer (WG). Therefore, the effective angle of the wires of the attenuator with respect to the LO coupling grid defines the amount of coupled power. 4G-1 uses a turntable variable aperture that truncates the LO beam and with this its power.

D. Front-End Cryostat and Closed-Cycle Cooler

The 4GREAT cryostat is an exact copy of those used for the upGREAT LFA and HFA. It has been fabricated by CryoVac GmbH (Troisdorf, Germany) and complies with all specifications on the GREAT vessels to certify airworthiness.

The receiver is cooled by a two-stage closed-cycle pulse tube refrigerator from TransMIT GmbH (Giessen, Germany). The pulse tube cooler provides about 0.8 W of cooling power at 4 K and 10 W at 45 K for the first stage. The pulse tube is connected to its rotary valve by a 0.75 m flexible hose. This
helps to decouple the mechanical vibrations from the valve, located outside the cryovessel, to the pulse tube where the mixers are located. The frequency of the pulse tube is controlled by a three-phase variable frequency drive. The pulse tube stages are mechanically connected to the first and second-stage plates (and their respective shields) through flexible copper braids. The stages are held in position by fiber glass cylindrical structures.

In the outer vacuum walls of the 4GREAT cryostat are vacuum RF windows. The 4G-1 and 4G-2 windows are made of quartz with the antireflection coating, supplied by QMC (Cardiff, U.K.). The 4G-3 and 4G-4 windows, manufactured by Tydex (Saint Petersburg, Russia), are made of silicon with a parylene coating. Each of the 4GREAT channels uses one layer of Zitex G104 [21], cooled to about 45 K, as the infrared filter. Table V summarizes the maximum and minimum window transmission as well as the average across the band of the windows and filter for each band.

The electrical wiring inside the cryostat is done by using phosphor–bronze wires. The capacitive filter networks are used to provide filtering of the dc lines and better thermal isolation. Filters, integrated with D-sub and D-microconnectors are placed on the 300, 45, and 4 K interfaces. The IF output signals are routed using flexible coaxial cables between the LNAs and the interface connectors on the 4 K stage, and semirigid coaxial cables with the stainless steel outer and copper–beryllium inner conductor among the 4, 45, and 300 K stages. The former allows easier servicing of the main components, the latter has been chosen because of its robustness, and to reduce the thermal transfer between stages.

When the receiver is in operation, i.e., mixers and LNAs are powered ON, and LO signal is applied to the mixers, the copper plate temperatures are 43 K for the first stage and 3.9 K for the second stage.

### E. IF Signal Processing

The IF output of each mixer is connected to the LNA. In the case of the SIS channels, 4G-1 and 4G-2, this is performed through ferrite isolators. These channels use cryogenic LNAs from Low Noise Factory (Gothenburg, Sweden), covering an IF band of 4–8 GHz with over 40 dB of gain. They have a noise temperature of only 2 K when cooled below 6 K of the physical temperature.

The 4G-3 and 4G-4 HEB output IF signals are amplified by SiGe cryogenic LNAs C1TFL4 from Cosmic Microwave Technology, USA. The amplifier gain is 35–40 dB and the noise temperature is 4–5 K when measured at 23 K physical temperature. The LNAs were modified by replacing a 5 kΩ resistor used in an external bias network with custom-made coils. These amplifiers define the lower edge of the receivers IF range at 0.2 GHz.

The output of each LNA is routed, as explained above, to the cryostat top plate that accommodates the electrical feedthroughs: bias connectors; temperature sensors; heaters; and IF connectors. Preamplifier bias modules and warm IF amplifiers, with a gain of 30 dB, are enclosed in a case directly mounted on the top plate.

Each of the four IF outputs of the cryostat is connected to an individual module of the IF processor, located in the telescope’s counterweight rack, by a 3 m long flexible coaxial cable. The function of the IF processor is to filter, equalize, and adjust the power to the optimum input level required by the spectrometer. While the channels utilizing the HEB detectors produce the IF output in the 0.2–4 GHz range, the 4G-1 and 4G-2 SIS channels operate from 4–8 GHz. To accommodate any required configuration between the HFA, the LFA, and 4GREAT, the IF processor, built at the Max Planck Institut für Radioastronomie (MPIfR), is therefore composed of 23 modules (21 modules: 0.1–4 GHz; 2 modules: 4–8 GHz) plus their controller. They are internally equipped with a total power detector used by the power autoleveling feature and to characterize the mixer conversion curves during instrument tuning.

Finally, the signals are fed into the MPIfR-built fast FTSs (FFTSSs, [5], [22]), which digitize the signal and calculate the spectral power distribution of the detected signals. The spectrometer offers 11 dual-input independent boards, serving 0.1–4 GHz (of up to 22 HEB output channels), and three single-input boards for the 4–8 GHz SIS bands. The latter achieve this IF coverage by fast input digitizers, which allow using the second Nyquist band in the Fourier transform. Due to this feature, all of the IF processor channels could be designed without a frequency conversion stage. Although programmable to provide up to 64k channels, all of the spectrometer boards are currently configured for operation with 16k spectral channels only to limit the data rate for fast dumping observing modes. A spectral resolution of 244 kHz, corresponding to a velocity resolution of around 0.15 km/s at 492 GHz, the lowest 4G-1 observing frequency, and 0.015 km/s at the 4700 GHz [OI] frequency (HFA), meets all of our science requirements.

### III. 4GREAT Integration and Laboratory Results

4GREAT was integrated and tested using the 4G-1, 4G-2, and 4G-4 detectors in the MPIfR laboratories between late January 2017 and late March 2017. In order to maintain the integrity of the GREAT receiver, still in-flight operation during those months, we decoupled the commissioning of these three units from the later addition of the 4G-3 (former GREAT-L1).
4GREAT was then shipped to the NASA Armstrong Flight Research Center, Palmdale, CA, USA, for integration and alignment with the actual GREAT flight hardware. In the following sections, we describe critical steps in this integration process and present results achieved during this laboratory verification.

A. Alignment of the GREAT Optics

1) LO Coupling and Alignment: The LO optics are designed to provide 4 DOF: tip, tilt, and shift on the vertical and horizontal directions. The alignment and coupling of the LO signal to each channel are optimized by manipulating the adjustable mirrors in this path while inspecting the I–V curve of the respective mixer. During this process, the angle of the LO coupling grid (hence, the LO power at the mixers) is also determined.

2) Signal Beam Alignment: Signal beam alignment is a slow, iterative process. The basic principle is to measure the beam response at two distances along the signal path: from these, we calculate the beam positions in the focal plane (using the standard ABCD matrix method), and derive and apply the necessary changes to the positions of the adjustable warm optics elements. This sequence is performed iteratively until a satisfactory alignment of the optics is achieved. The relative beam positions on the sky can be derived from the measured offsets in the focal plane with the known telescope plate scale of 4\(^{\prime}\)/mm and are later on verified on the sky.

The first signal beam response is measured close to the focal plane using a compact beam measurement wheel [23] installed within the optics compartment of the GREAT structure. A second beam measurement is done in the laboratory with an external two-axis scanner, placed at 3000 mm from the science instrument flange, slightly less than half the distance to the secondary mirror. The measurement target on the scanner consists of a sheet of millimeter-wave absorber material at room temperature with a central hole. Scatter cones with varying free apertures can be mounted inside the hole. Behind the hole, a flat mirror points toward the absorber material floating in a dewar filled with liquid nitrogen.

The beam positions are determined by sweeping vertically and horizontally the target, meanwhile recording the total power counts from each channel. Once this alignment is done, a high-resolution map is taken to check for beam distortions, such as asymmetric beams or coma and sidelobes. Fig. 6 shows the beam maps for two channels of 4GREAT during the alignment phase in the laboratory. Important parameters to evaluate are the instrument coupling to the subreflector and the channels’ co-alignment. The latter is fundamental for making use of the simultaneous scientific capabilities, among the 4GREAT channels and the HFA array.

The final alignment verification in tilt can only be performed with the instrument mounted to the telescope flange by directly moving a test probe across the telescope’s subreflector. In this procedure, the portions of the secondary mirror of the telescope at predefined positions are covered with a small rectangular (8 \times 25 cm) paddle of Eccosorb dipped into liquid nitrogen. Variations in the total power level for the selected channel are then correlated to the positions of the paddle and the illumination of the subreflector can be derived. The final verification of the offsets is done by astronomical measurement on the sky (as shown in the following part).

B. Receiver Characterization

1) Receiver Noise Temperatures: Receiver temperatures \(T_{\text{Rec}}\) of the complete instrument were measured for each channel at different LO frequencies, using the Y-factor method. The optics compartment was evacuated to avoid atmospheric absorption in the measurement, representative for conditions at the flight altitude. The cold load is implemented as an absorber cooled to around 70 K by a Stirling cooler. An external LN\(_2\) load was used to cross-reference the temperature scale of this internal calibration unit. The spectroscopic measurements of \(T_{\text{Rec}}\) across the receiver IF were obtained with the FFTS spectrometer. Fig. 7 displays the representative results for all four channels. The

2 As the instrument is regularly upgraded (inter alia the local oscillator bandwidth coverage and output power are improved, as technology allows), the performance described in this section reflects the receiver status as flown during SOFIA observing cycle 7-I (Nov 2019).
values presented here are on the DSB temperature scale, as measured in the actual 4GREAT flight configuration.

The results show that the receivers perform as expected on the basis of their RF design bands and LO coverage. 4G-1 can be operated with $T_{\text{Rec}}$ of 100–140 K (DSB) over much of the IF and RF bands. The small noise bump at midband is likely due to a mismatch between the mixer and cold amplifier and will be addressed in a future maintenance campaign. As is, science is little affected as the large IF bandwidth does allow shifting the line-of-interest to the sweet spots. At the low-RF band edge, we verified the on-sky operation of the Cl 492 GHz transition with $\sim$150 K (lower side band (LSB) tuned). 4G-2 performs well within its nominal design band (see Table II), with $T_{\text{Rec}}$ $\sim$300–400 K above 1 THz, rising to $\sim$600 K at 950 GHz and below. 4G-3 performs with similar figures as during its operation in the “old” GREAT channel L1, with $T_{\text{Rec}}$ between 1000 and 1200 K across its operational range (typically measured at an IF frequency of 1.2 GHz). The noise performance of 4G-4 depends heavily on the tuning of the Martin–Puplett interferometer (in a tradeoff between the passband width and IF frequency, defined by the science requirements) but DSB temperatures of 3000 K can be achieved. We summarize the performance figures of 4GREAT in Table VI.

At this point, the latest, the interested reader may wonder about the competitive performance of the 4GREAT, with its color-splitting, complicated foreoptics, against a straightforward direct approach with the reflective optics only. As even the first-light version of GREAT split the incoming signal by polarization [2], the answer is given in Table VI: the signal gain of a 4GREAT channel, still based on the 2018 observations of Mars.

We determined the boresight and beam coalignments by direct approach with the reflective optics only. As even the first-light version of GREAT split the incoming signal by polarization [2], the answer is given in Table VI: the signal gain of a 4GREAT channel, still based on the 2018 observations of Mars.

Fig. 8. GREAT instrument in its HFA/4GREAT configuration, mounted to the SOFIA telescope flange. The 4GREAT cryostat can be partly seen on the right-hand side of the central instrument structure. The counterweight rack, with the back-end electronics, is seen on the upper right, and the rack on the left side houses the receiver control electronics.

Table VI 4GREAT Receiver Performance

|       | 4G-1 | 4G-2 | 4G-3 | 4G-4 |
|-------|------|------|------|------|
| RF Bandwidth$^1$ (GHz) | 491-635 | 890-1090 | 1240-1525 | 2490-2590 |
| IF Bandwidth (GHz) | 4-8 | 4-8 | 0.5-2.5 | 0.75-2.25$^2$ |
| $T_{\text{Rec}}$ (DSB) [K] | 100-140 | 300-600 | 1000-1200 | 3000 |

Note: $^1$ The effective bandwidth includes a central gap due to LO features. Also consider atmospheric transmission features. $^2$ The 4G-4 IF bandwidth is limited by the MP diplexer to about 1.5 GHz, centered around any frequency in the range 1.4–2.9 GHz.

and FFTS modules), and no other radiation sources active other than those required for the operation of the receiver. In the flight, with changing environmental conditions slightly worsen stabilities are to be expected. For science operation, we limit the 4GREAT observing modes to the phase times of less than 50 s.

IV. COMMISSIONING AND FIRST LIGHT

The instrument’s scientific commissioning took place in July 2017 during the SOFIA’s fourth southern deployment to Christchurch, New Zealand. In June 2018, the 1.3 THz HEB mixer was transferred from GREAT-L1, bringing 4GREAT to its full capabilities. Fig. 8 shows a picture of the instrument installed onboard the SOFIA.

4GREAT performed well during these verification flights, as did the HFA operating in parallel. The sensitivities were as measured in the lab prior to installation.

We determined the boresight and beam coalignment by scans across and maps of Jupiter (2017) and Mars (2018), the only astronomical targets suitable for our optical verifications. Unfortunately, both planets were rather extended, compared at least with the higher frequency channels of 4GREAT. On July 11th, 2017, Jupiter was extended with a 33.9 $\times$ 36.3′′ disk diameter, while on June 28th, 2018, Mars was extended with a 19.8′′ disk diameter (in June 2017, Mars was a daytime target and therefore not accessible). Because the Martian atmosphere (and hence its spectral intensity distribution) is rather clean and well modeled (compared with Jupiter with strong atmospheric features imprinted to its continuum), the following numbers are based on the 2018 observations of Mars.

1) The HFA central pixel and the four 4GREAT channels are coaligned within a circle of less than 1 arcsec radius. In the flight, we track on the smallest beam requested by the science case, which is 4G-4 or (in most cases) the central pixel of the HFA. The boresight offsets of all pixels relative to the reference pixel are small compared with the beams (see Table VII).

2) The observed beam patterns confirm the diffraction limited optics. The half-power full beam widths $\Theta_{\text{HPFW}}$
TABLE VII
GREAT BEAM PARAMETERS

| Channel | #pixels | $v_{\text{obs}}$ (GHz) | $\Theta_{\text{HPFW}}$ (arcsec) | $\eta_{\text{mb}}$ |
|---------|---------|------------------------|-------------------------------|----------------|
| 4G-1    | 1       | 530                    | 52                            | 0.61           |
| 4G-2    | 1       | 1038                   | 27                            | 0.53           |
| 4G-3    | 1       | 1337                   | 20                            | 0.62           |
| 4G-4    | 1       | 2675                   | 10.5                          | 0.57           |
| HFA     | 7       | 4745                   | 6.3 (13.6)                    | 0.64           |
| LFA-H   | 7       | 1900                   | 14.1 (31.8)                   | 0.65           |
| LFA-V   | 7       | 1900                   |                                | 0.66           |

The half-power full beam width ($\Theta_{\text{HPFW}}$) and main beam coupling efficiency $\eta_{\text{mb}}$ were derived from the observations of Mars at frequency $v_{\text{obs}}$. The figures for the LFA and HFA are from [6] and the numbers in parenthesis describe the pixel spacing in the hexagonal arrays.

presented in Table VII have been derived from cross scans toward Mars, after deconvolving the observed profile from the emission of the Martian disk. An exception is 4G-4, for which the beam is too narrow to perform a reliable deconvolution, within the signal-to-noise of the data. We quote the width as extrapolated from the lower frequencies ($10.5''$).

3) Finally, comparing the observed versus the modeled brightness of Mars [25] we determine the main beam coupling efficiency $\eta_{\text{mb}}$. The relatively low values are consistent with the expected values due to the large central blockage by the tertiary folding mirror in SOFIA’s folded Nasmyth optics.

In the course of these measurements, we verified all the GREAT observing modes, from pointed to raster and on-the-fly observations, chopped and unchopped. 4GREAT performed well, meeting the specifications. In Fig. 9, we present a typical result achieved during the regular science observations of an astronomic target.

V. CONCLUSION

We present the details of the design, construction, and laboratory tests of the 4GREAT receiver. After its successful integration and commissioning in July 2018, the instrument has been made available to the SOFIA user communities with the call for proposals for observing cycle 6.

With the addition of 4GREAT, GREAT is currently composed of three cryostats: the LFA with its dual-polarization 7+7 pixels; the HFA with its 7 pixels single-polarization array; and 4GREAT with four independent single-pixel channels. The three cryostats are grouped in two flight combinations. The first combination, commissioned in June 2017, operates the LFA and HFA simultaneously. In the second combination, the four channels of 4GREAT observe in parallel with the HFA. Fig. 10 illustrates the beam sizes and pixel spacing of this configuration, superposed on an image of the Horsehead nebula.

4GREAT adds new scientific opportunities to the suite of SOFIA instrumentation. Its frequency multiplexing will allow for more efficient use of the precious observing time onboard SOFIA. 4GREAT’s extension to lower frequencies will reopen access to, among others, the ground-state transitions of light hydrides (see Table I) studied so successfully with Herschel/HIFI [11].

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