SOFIA Quick Guide
Instrument Capabilities & Science Cases
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**SOFIA Quick Guide**

**Instrument Capabilities & Science Cases**

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Further Information

[www.sofia.usra.edu/science](http://www.sofia.usra.edu/science)

SOFIA Help Desk

[sofia_help@sofia.usra.edu](mailto:sofia_help@sofia.usra.edu)

January 2021

Cover image based on Surveying the Giant H II Regions of the Milky Way with SOFIA. I, WS1A, Lim et al., 2019. (NASA/SOFIA/James De Buizer, Wangji Lim; NASA/JPL-Caltech)
Infrared Astronomy

The Stratospheric Observatory for Infrared Astronomy (SOFIA) is an airborne observatory operating at altitudes of 35,000–45,000 ft, above 99% of the Earth’s atmospheric water vapor. Infrared observations allow for the direct measurement of the physical properties of ionized gas ($T \approx 10^4$ K), neutral atomic gas, and warm ($T \approx 100-500$K) molecular gas without obstruction by dust attenuation as with traditional UV and optical diagnostics. In particular, more than half of all the light emitted from stars is absorbed by dust and re-emitted in the infrared.

The SOFIA Observatory

A suite of instruments with coverages ranging from 0.36–612 µm are available for imaging, spectroscopic, and polarimetric observations. Together, the SOFIA instruments bridge the gap between the radio telescope Atacama Large Millimeter Array (ALMA; 300–9600 µm) and the James Webb Space Telescope (JWST; 0.6–28 µm) to be launched in 2021. This Quick Guide provides the technical specifications for each available instrument, along with examples of astronomical observations obtained with each.
The SOFIA Telescope

Mounted onboard an extensively modified Boeing 747SP aircraft, the 2.5m class Cassegrain telescope with Nasmyth focus is the largest telescope ever integrated into an aircraft. It provides an unvignetted field-of-view (FOV) of 8 arcmin to the science instruments. A 45° gold coated dichroic mirror allows transmission of optical wavelengths that are redirected to a visible Nasmyth focus where it feeds the Focal Plane Imager (FPI), with an 8' circular FOV. Two other guiding cameras are attached to the front ring of the telescope and provide guide fields of 6° x 6° and 67' x 67' FOV, respectively.

Image Quality

The telescope is subject to both the stratospheric environment — pressures of 0.2 bar and temperatures of −40°C — and the aircraft’s vibrations and motions. It is inertially stabilized by electronic fiber optic gyroscopes and feedback from the FPI, moved by magnetic torquers around a 1.2m diameter spherical pressurized oil bearing.

The diffraction limit of a telescope defines its maximum achievable resolution, and the Point Spread Function (PSF) delivered by SOFIA is highly wavelength dependent. For wavelengths longer than ~30 µm, the system is diffraction limited. For shorter wavelengths, the PSF is dominated by a combination of diffraction, jitter, optical aberrations, and defocus. Other factors that degrade image quality include turbulence and cavity seeing.

Pointing accuracy astrometry software is used to identify the stars in the field of the Focal Plane Imager (FPI+), then determine the position of the instrument boresight pixel on the FPI+. Image stability is maintained by the Flexible Body Compensation system, which uses high-sampled accelerometer measurements to estimate the jitter and compensate it at frequencies of up to 50 Hz. The uncertainty in the astrometric position is about 0.2 arcseconds.

Calculated PSF of SOFIA (black line) and in-flight PSF data measurements by SOFIA science instruments (blue diamonds). The PSF Full Width at Half Maximum (FWHM) starts around 3.5 arcsec at short wavelengths and asymptotes to diffraction limits at longer wavelengths. (Graf et al.)
### System Characteristics

<table>
<thead>
<tr>
<th>Nominal Operational Wavelength Range</th>
<th>0.3 to 1600 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Mirror Diameter</td>
<td>2.7 meters</td>
</tr>
<tr>
<td>Effective Aperture Diameter</td>
<td>2.5 meters</td>
</tr>
<tr>
<td>Optical Configuration</td>
<td>Bent Cassegrain with chopping secondary mirror and flat folding tertiary</td>
</tr>
<tr>
<td>System f-ratio</td>
<td>19.6</td>
</tr>
<tr>
<td>Primary Mirror f-ratio</td>
<td>1.28</td>
</tr>
<tr>
<td>Telescope Elevation Range**</td>
<td>23 to 57 degrees (approx.)</td>
</tr>
<tr>
<td>Field-of-View Diameter**</td>
<td>8 arcmin</td>
</tr>
</tbody>
</table>

**Nominal Operational Wavelength Range**: 0.3 to 1600 µm

**Primary Mirror Diameter**: 2.7 meters

**Effective Aperture Diameter**: 2.5 meters

**Optical Configuration**: Bent Cassegrain with chopping secondary mirror and flat folding tertiary

**System f-ratio**: 19.6

**Primary Mirror f-ratio**: 1.28

**Telescope Elevation Range**: 23 to 57 degrees (approx.)

**Field-of-View Diameter**: 8 arcmin

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### Science Instruments

<table>
<thead>
<tr>
<th>Name</th>
<th>Principal Investigator</th>
<th>Description</th>
<th>Wavelength Range Resolving Power R=(\lambda/\Delta\lambda)</th>
<th>Field of View Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXES</td>
<td>Matthew Richter, UC Davis</td>
<td>Mid-IR Echelle Spectrometer</td>
<td>4.5 – 28.3 µm R = 1,000 – 10³</td>
<td>1° – 180° slit lengths 1024x1024 Si:As</td>
</tr>
<tr>
<td>FIFI-LS</td>
<td>Alfred Krabbe, DSI</td>
<td>Far-IR Imaging Grating Spectrometer Facility Instrument</td>
<td>51 – 200 µm R = 600 – 2,000</td>
<td>30° x 30° (Blue) 60° x 60° (Red) 2x(16x25) Ge:Ga</td>
</tr>
<tr>
<td>FORCAST</td>
<td>Terry Herter, Cornell University</td>
<td>Mid-IR Camera &amp; Grism Spectrometer Facility Instrument</td>
<td>5 – 40 µm R = 100 – 300</td>
<td>3.2’ x 3.2’ 2x(256x256) Si:As, Si:Sb</td>
</tr>
<tr>
<td>GREAT</td>
<td>Jürgen Stutzki, University of Cologne</td>
<td>Far-IR Heterodyne Spectrometer</td>
<td>63 – 612 µm R = 10⁹ – 10⁸</td>
<td>diffraction limited heterodyne receiver</td>
</tr>
<tr>
<td>HAWC+</td>
<td>Charles Dowell, JPL</td>
<td>Far-IR Bolometer Camera &amp; Polarimeter Facility Instrument</td>
<td>50 – 240 µm Δ(\lambda) = 9 – 43 µm</td>
<td>from 1.4’ x 1.7’ (53 µm) to 4.8’ x 6.1’ (214 µm) 3x(32x40) bolometer</td>
</tr>
<tr>
<td>FPI+</td>
<td>Jürgen Wolf, DSI</td>
<td>Focal Plane Imager Facility Instrument</td>
<td>0.36 – 1.10 µm R = 0.9 – 29.0</td>
<td>8.7’ x 8.7’ 1024x1024 CCD</td>
</tr>
</tbody>
</table>

**EXES**: Matthew Richter, UC Davis

**FIFI-LS**: Alfred Krabbe, DSI

**FORCAST**: Terry Herter, Cornell University

**GREAT**: Jürgen Stutzki, University of Cologne

**HAWC+**: Charles Dowell, JPL

**FPI+**: Jürgen Wolf, DSI

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* Estimated value ** Unvignetted
EXES: Echelon-Cross-Echelle Spectrograph
Principal Investigator Class, High Res, Mid-Infrared Spectrograph

Principal Investigator: Matthew J. Richter, University of California Davis

Spectrally Resolved H$_2$O Absorption Lines

On its second commissioning flight, EXES generated a high resolution spectrum (R=80,000, 4 km/s) revealing gas phase H$_2$O lines toward the massive Young Stellar Object AFGL 2591. Shown in the figure below are the spectrum of AFGL 2591 (black trace), telluric standard (red trace), and the residual after telluric and baseline correction (top). The transition near 6.115 μm is that of absorption by para-H$_2$O in the ground state, Doppler shifted by ~40 km/s from the deep telluric feature at the time of the observations. The EXES observations resolve the H$_2$O lines for the first time. The line width of 15 km/s locates the gas at the base of the molecular outflow. (Indriolo et al., 2015, ApJL, 802, 14.)

Venus Spectral Maps

EXES observed Venus with high spectral resolution at 7.2 μm, simultaneously probing the amount of water and (semi) heavy water in its clouds. Relating the D/H ratio to clouds, temperature, global position, and seasons helps to constrain the microphysical models of water-loss used to study the evolution of Venus's atmosphere. Preliminary results show a surprising spatial uniformity to the D/H ratio. Ratio to the CO$_2$ strength allows us to cancel, to first order, the effects associated with the calibration, the geometry, and atmospheric parameters. (Tsang, et al., in prep)
Specifications

EXES features an array dimension of 1024x1024 and a pixel size of 0.2 arcsec. High resolution is provided by an echelon (a coarsely-ruled, steeply-blazed, aluminum reflection grating) along with an echelle grating to cross-disperse the spectrum.

The echelon can be bypassed so that the echelle acts as the sole dispersive element, resulting in single order spectra at medium or low resolution depending on the incident angle.

The available configurations are Low (low resolution), Medium (medium resolution), HIGH_MED, and HIGH_LOW. Configurations are called HIGH_MED if the cross disperser echelle angle is 35-65° and HIGH_LOW for angles between 10-25°. The shorter slits in HIGH_LOW allow for more orders to be packed onto the array, thus increasing the instantaneous wavelength coverage while maintaining the same high spectral resolution as the HIGH_MED configuration.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Slit Length</th>
<th>Spectral Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>25”–180”</td>
<td>1,000–3,000</td>
</tr>
<tr>
<td>Medium</td>
<td>5,000–20,000</td>
<td></td>
</tr>
<tr>
<td>HIGH_MED</td>
<td>1.5”–45”</td>
<td>50,000–100,000</td>
</tr>
<tr>
<td>HIGH_LOW</td>
<td>1”–12”</td>
<td></td>
</tr>
</tbody>
</table>

In the Medium and Low configurations the slit lengths vary from 25” to 180” depending on the number of rows to be read.

Above: Sensitivities for point (top) and extended (bottom) sources, assuming nominal conditions.

Left: Raw 2D spectra without nod-subtraction to highlight the sky emission lines (dark). Possessing the same spectral resolution, HIGH_LOW has a larger spectral coverage at the expense of a shorter slit.
Cat’s Eye Nebula: [OIII] 52 µm

The FIFI-LS [O III] 52 µm spectral map of the Planetary Nebula NGC 6543 (the Cat’s Eye Nebula) traces the location of the ionized gas. Shifts in the central wavelength correspond to velocity gradients that are present across the nebula. Each pixel in the 5x5 map corresponds to about 6000 AU at the ~1 kpc distance of NGC 6543. The FIFI-LS field of view is shown superimposed on an image obtained with the Nordic Optical Telescope. (FIFI-LS Team)

Orion Nebula: [OI] 146 µm

The Orion Nebula was mapped by FIFI-LS at 146 µm to study the physical conditions of its atomic and molecular gas. The far infrared continuum (logarithmic scale) is shown peaking at the Becklin-Neugebauer object, but also clearly shows the Orion Bar and a similar structure to the north-east (left). Additionally, the [OI] line emission tracing the photon-dominated regions around the Trapezium stars where the star’s UV radiation irradiates the surrounding molecular cloud (right). (FIFI-LS Team)
Specifications

FIFI-LS is an integral field, far-infrared spectrometer consisting of two independent grating spectrometers. Each spectrometer has a detector consisting of 400 pixels of Gallium-doped Germanium photoconductors. The projection onto the sky of the 5x5-pixel FOVs of the blue channel and the red channel is nearly concentric (10” offset), but the angular coverage differs. The spectral resolution channels vary between 500 and 2000, depending on the observed wavelength, with higher values reached towards the long wavelength ends of each spectrom-

<table>
<thead>
<tr>
<th>Channel</th>
<th>Field of View</th>
<th>Pixel Size</th>
<th>λ Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue</td>
<td>30” x 30”</td>
<td>6” x 6”</td>
<td>51–120 µm</td>
</tr>
<tr>
<td>Red</td>
<td>1’ x 1’</td>
<td>12” x 12”</td>
<td>115–200 µm</td>
</tr>
</tbody>
</table>

Channel Parameters

Data Cube

- The integral field unit for each channel consists of 15 specialized mirrors to slice the two dimensional 5x5 pixel FOV into five slices that are each five pixels long, which are then reorganized along a one dimensional line (25x1 pixel), forming the spectrometer entrance slit. The diffraction grating disperses the incoming light, which reaches the 16x25 pixel detector array. The result is a “data cube” with 5x5 spatial pixels and 16 pixels in the spectral dimension.

Minimum Detectable Line Flux

<table>
<thead>
<tr>
<th>Wavelength (µm)</th>
<th>MDLF (10^{-17} W m^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>1.0</td>
</tr>
<tr>
<td>60</td>
<td>0.5</td>
</tr>
<tr>
<td>90</td>
<td>0.2</td>
</tr>
<tr>
<td>120</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Minimum Detectable Continuum Flux

<table>
<thead>
<tr>
<th>Wavelength (µm)</th>
<th>MDCF (Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>10</td>
</tr>
<tr>
<td>60</td>
<td>5</td>
</tr>
<tr>
<td>90</td>
<td>2</td>
</tr>
<tr>
<td>120</td>
<td>1</td>
</tr>
</tbody>
</table>

Predicted Sensitivity for SNR = 4 in 900 s

- The instantaneous spectral coverage and spectral resolution can be calculated using the velocity width and resolution.

Left: The integral field unit for each channel consists of 15 specialized mirrors to slice the two dimensional 5x5 pixel FOV into five slices that are each five pixels long, which are then reorganized along a one dimensional line (25x1 pixel), forming the spectrometer entrance slit. The diffraction grating disperses the incoming light, which reaches the 16x25 pixel detector array. The result is a “data cube” with 5x5 spatial pixels and 16 pixels in the spectral dimension.
PAH Tracing at 11.2 µm

FORCAST has been used to collect 11.1 µm data of NGC 7023 (top left) which was then combined with FLITECAM 3.3 µm data and Spitzer/IRAC 8.0 µm data (top right) to yield a plot of the 11.2/3.3 µm flux ratio revealing the PAH size distribution (bottom). FORCAST observations provide higher angular resolution than Spitzer which thereby enables the PAH size distribution to be traced through the ratio of 11.2 µm emission to the SOFIA/FLITECAM 3.3 µm data.

The famous reflection nebula NGC 7023 was observed with FORCAST in order to better understand the photochemical evolution of polycyclic aromatic hydrocarbons (PAHs) resulting from illumination by the nearby star HD 200775. Similarities to the H₂ flux (contours) indicate that the smallest PAH molecules lie on the surface of the PDR. (Croiset et al. 2016, A&A, 590, A26.)

Grism Coverage from 5–37 µm

The early temporal development of the classical nova V339 Delphini was observed using FORCAST grisms, which provide coverage from 5–40 µm at low spectral resolution (R ~ 140–300). These data revealed a full suite of hydrogen recombination lines, the analysis of which indicated that the ejecta were still at very high density (n_e > 10^{13} cm⁻³) and that the hydrogen lines were optically thick. (Gehrz et al. 2015, ApJ, 812, 132.)
Specifications
The short wavelength channel (SWC) and long wavelength channel (LWC) can be used individually or together for simultaneous imaging of the same field of view. For grism observations, either channel may be used independently.

Imaging
The point spread function (PSF) in FORCAST images is consistent with the telescope’s diffraction limit convolved with the 1.3” rms jitter. In dual channel mode, a dichroic is used to split the beam into the SWC and LWC, decreasing the throughput of the system by 40-85% relative to the single channel mode.

Spectroscopy
FORCAST grisms provide coverage from 5–40 μm. Blazed diffraction gratings are used in transmission and stacked with blocking filters to prevent order contamination. Two long slits (2.4"x191", 4.7"x191") are available.

Grism Details

<table>
<thead>
<tr>
<th>Grism</th>
<th>Coverage (μm)</th>
<th>R (λ/Δλ) α</th>
<th>R (λ/Δλ) β</th>
</tr>
</thead>
<tbody>
<tr>
<td>G063</td>
<td>4.9–8.0</td>
<td>120/180</td>
<td></td>
</tr>
<tr>
<td>G111</td>
<td>8.4–13.7</td>
<td>130/260</td>
<td></td>
</tr>
<tr>
<td>G227</td>
<td>17.6–27.7</td>
<td>110/120</td>
<td></td>
</tr>
<tr>
<td>G329</td>
<td>28.7–37.1</td>
<td>160</td>
<td></td>
</tr>
</tbody>
</table>

* For the 4.7"x191" and the 2.4"x191" slits, respectively.
* The resolution of the long, narrow-slit modes is dependent on (and varies slightly with) the in-flight IQ.

Filter Parameters

<table>
<thead>
<tr>
<th>SWC Filters</th>
<th>LWC Filters</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ_{eff} (μm)</td>
<td>Δλ (μm)</td>
</tr>
<tr>
<td>5.4</td>
<td>0.16</td>
</tr>
<tr>
<td>5.6</td>
<td>0.08</td>
</tr>
<tr>
<td>6.4</td>
<td>0.14</td>
</tr>
<tr>
<td>6.6</td>
<td>0.24</td>
</tr>
<tr>
<td>7.7</td>
<td>0.47</td>
</tr>
<tr>
<td>8.8</td>
<td>0.41</td>
</tr>
<tr>
<td>11.1</td>
<td>0.95</td>
</tr>
<tr>
<td>11.2</td>
<td>2.7</td>
</tr>
<tr>
<td>11.3</td>
<td>0.24</td>
</tr>
<tr>
<td>11.8</td>
<td>0.74</td>
</tr>
<tr>
<td>19.7</td>
<td>5.5</td>
</tr>
<tr>
<td>25.4</td>
<td>1.86</td>
</tr>
</tbody>
</table>

A subset of these will be chosen each cycle as the nominal set.

Continuum point source sensitivities for single and dual channel modes. Values are for S/N = 4 in 900 s under nominal conditions. Investigators are encouraged to use the SOFIA Integration Time Calculator (SITE) for their calculations.

FORCAST Sensitivity

Grism continuum point source sensitivities for both wide and narrow long slits overlaid on an atmospheric transmission model (light blue). Values are for S/N = 4 in 900 s under nominal conditions.
FPI+: Focal Plane Imager Plus
Fast Frame Rate Optical Photometer

Principal Investigator: Jürgen Wolf, DSI

Pluto Stellar Occultation
The 2015 stellar occultation by Pluto of a background star with an r-band of magnitude ~12 was captured by FPI+ as a light curve, showing the decreased signal (in magnitudes) during the event. The central flash in the middle of the light curve confirms the precise position of SOFIA on the centerline of the shadow path, allowing for analysis of the upper atmosphere. This results in a best-fit value for the occultation half-light radius of 1288±1 km (i.e., the radius in the atmosphere at which the occultation light curve drops to half its original flux due to refraction). (Bosh et al. 2016, submitted.)

C2013 US10 Catalina Coma
FPI+ produced an I-band image of Comet C2013 US10 Catalina as part of a combined infrared and visual observation. The comet’s coma is nicely visible in comparison to the more compact stars toward the bottom of the image. (C.E. Woodward et al.)
Specifications

FPI+ is the upgrade to FPI with a science grade CCD. More than 50% of the light detected onboard SOFIA between 480 nm and 800 nm is transmitted to FPI+, the range at which the camera is most sensitive. The CCD sensor is an e2v CCD 201-20 1024x1024 pixel frame transfer EMCCD with the specifications given in the Optical Properties table (right).

Six spectral filters are available, including five Sloan Digital Sky Survey filters u', g', r', i', z' and a Schott RG1000 near-IR cut-on (Daylight) filter. The Sloan u' filter has a very low throughput (~0.5%) because other optical elements in the FPI+ light path are nearly opaque at this wavelength. There are an additional three neutral density (ND) filters that can be used to attenuate bright stars.

The filters are installed in a double-carousel filter wheel with six positions in each carousel, a list of which is given in the Filter Suite table (right). Filters from Carousel 1 and Carousel 2 can be combined freely with a few exceptions.

### Optical Properties

<table>
<thead>
<tr>
<th>Field of View</th>
<th>λ Range</th>
<th>Plate Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.7' x 8.7'</td>
<td>360–1100 nm</td>
<td>0.51&quot; per pixel</td>
</tr>
</tbody>
</table>

### Filter Suite

<table>
<thead>
<tr>
<th>Carousel 1</th>
<th>Carousel 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPEN</td>
<td>OPEN</td>
</tr>
<tr>
<td>Sloan u'</td>
<td>ND 1</td>
</tr>
<tr>
<td>Sloan g'</td>
<td>ND 2</td>
</tr>
<tr>
<td>Sloan r'</td>
<td>ND 3</td>
</tr>
<tr>
<td>Sloan i'</td>
<td>Daylight</td>
</tr>
<tr>
<td>Sloan z'</td>
<td>Blocked</td>
</tr>
</tbody>
</table>

### Filter Throughput

Plot of the optical efficiency for five spectral filters and the OPEN FPI+ configuration. The plot includes the calculated SOFIA telescope throughput, the instrument quantum efficiency, and the measured filter spectral response.

### Sensitivity

Signal to Noise Ratio for point sources imaged unbinned with FPI+ at t_\text{EXP} = 1 sec. Displayed is the OPEN configuration as well as the spectral Sloan filters u, g, r, i, z, and the daylight NIR cut-on filter.
GREAT: German REceiver for Astronomy at Terahertz Frequencies
Principal Investigator Class, Far-Infrared, Multi-Pixel Spectrometer

Principal Investigator: Jürgen Stutzki, University of Cologne

Horsehead Nebula Velocity Resolved Map
A velocity resolved map of the iconic Horsehead Nebula in the [C II] 158 μm line was obtained by the upGREAT Low Frequency Array (LFA). The [CII] line is one of the strongest cooling lines in the interstellar medium, and here it traces the photodissociation region illuminated by the O9.5V star Sigma Orionis. The integrated intensity image is shown in the figure to the right. The 12'x17' map, encompassing the nebula and the underlying cloud ridge, was obtained in just over 4 hours of observation on a single flight. The angular resolution of the map is 15.1" and the velocity resolution is 0.19 km/s (R > 10⁶). These remarkably efficient observations were made possible by an increase in the sensitivity of the upGREAT detectors with the use of fourteen independent detectors of the LFA, and the increased mapping speed facilitated by SOFIA’s inertially stable platform.

Planetary Nebula NGC 7027
Spatial scans made by the GREAT spectrometer’s H-channel receiver enabled the production of a spectral map and integrated spectrum for Planetary Nebula NGC 7027 in the [OI] 63 μm line. The effective angular resolution is indicated by the gray circle. The high-resolution spectrum displays the characteristic shape for an expanding, optically thin shell. The complex line structure shows that the expanding nebula has multiple components moving at different velocities. (GREAT Consortium)
Specifications

GREAT supports the following Astronomical Observing Templates (AOTs): Single Point, Raster Map, On-the-Fly map, On-the-Fly Array map, and On-the-Fly Honeycomb map. Each AOT is run in either of two observing modes: Total Power or Beam Switching.

Observing Modes

**Total Power:** The telescope moves between a target and a nearby emission-free reference position.

**Beam Switching:** The secondary mirror chops between the source and a nearby reference position at a rate of ~1–2.5 Hz. The telescope nods between these positions at a slower rate than when chopping.

4GREAT has four single-pixel channels that observe the same position on the sky simultaneously. Their central frequencies are 0.43, 1.00, 1.37, and 2.54 THz. The GREAT instrument uses eXtended bandwidth Fast Fourier Transform Spectrometers (XFFTS) as backends. Each XFFTS has a bandwidth of 4 GHz and 16,384 channels with a frequency resolution of 244 kHz. At the [CII] line frequency of 1.9 THz, this corresponds to a channel spacing of ~0.04 km/s.

GREAT can be run with the configurations upGREAT LFA with upGREAT HFA or 4GREAT with upGREAT HFA.

<table>
<thead>
<tr>
<th>Channels</th>
<th>Frequency Range [THz]</th>
<th>$T_{\text{rec}}$ Double Sideband</th>
<th>FWHM</th>
<th>Astronomical Lines of Interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>upGREAT HFA</td>
<td>4.7447 +/- 100 km/s</td>
<td>1250 K</td>
<td>6&quot;</td>
<td>[OII]</td>
</tr>
<tr>
<td>upGREAT LFA-H</td>
<td>1.835–2.007</td>
<td>1000 K</td>
<td>15&quot;</td>
<td>[CII], CO, OH$^2\pi_{3/2}$</td>
</tr>
<tr>
<td>upGREAT LFA-V</td>
<td>1.835–2.007 2.060–2.065</td>
<td>1000 K</td>
<td>15&quot;</td>
<td>[OII], [CII], CO, OH$^2\pi_{3/2}$</td>
</tr>
<tr>
<td>4GREAT</td>
<td>2.490–2.590</td>
<td>3300 K</td>
<td>12&quot;</td>
<td>OH$^2\pi_{3/2}$, $^{18}$OH$^2\pi_{3/2}$</td>
</tr>
<tr>
<td></td>
<td>1.240–1.395 1.427–1.525</td>
<td>1100 K</td>
<td>19&quot;</td>
<td>[NIII], CO, OD, HCN, SH, H$_2$D$^+$</td>
</tr>
<tr>
<td></td>
<td>0.890–0.984 0.990–1.092</td>
<td>&gt;600 K, 300 K</td>
<td>25&quot;</td>
<td>CO, CS</td>
</tr>
<tr>
<td></td>
<td>0.491–0.555 0.560–0.635</td>
<td>&lt;150 K</td>
<td>50&quot;</td>
<td>NH$_3$, [CI], CO, CH</td>
</tr>
</tbody>
</table>

A generalized hexagonal pattern of the LFA and HFA. The spacing between pixels, $r$, is slightly more than two beam widths at ~31.7” for LFA and 13.8” for HFA.
HAWC+: High-resolution Airborne Wideband Camera Plus

Facility Class, Far-Infrared Camera and Polarimeter

Principal Investigator: C. Darren Dowell, Jet Propulsion Laboratory

Star Forming Region W3

The structure of the far-infrared polarization in the W3 star forming region, as observed by HAWC+ at a wavelength of 89 μm. Each line segment represents the orientation of polarization at that location overlaid on an image of the total intensity at the same wavelength. Vectors represent the electric field direction. For clarity, only one-quarter of the polarization measurements are shown and the line segments are set to a fixed length. The polarization is caused by the partially oriented radiation from elongated dust grains that are aligned with the magnetic field in the cloud. (HAWC+ Team)

Star Forming Region Orion

HAWC+ performed polarization measurements at 89 μm to capture the structure of the magnetic field in the Orion star forming region. Each line segment represents the orientation of the magnetic field at that location, overlaid on an image of the total intensity at the same wavelength. The total intensity image has a pixel scale of 1.5 arcsec per pixel and the polarization results were smoothed to a scale of 8 arcsec per pixel to produce statistically independent vectors in this HAWC+ observing band. For clarity, the line segments are set to a fixed length. (HAWC+ Team)
Specifications

HAWC+ offers both total intensity imaging and imaging polarimetry in five bands ranging from 50 to 240 μm. Nod match chop observing mode is used for imaging polarimetry and a number of efficient scan modes are available for total intensity imaging.

For all observing modes, a wire grid reflects one component of linear polarization and transmits the orthogonal component to two comounted detector arrays. A single detector array provides a field of view (FOV) of 32x40 pixels for imaging polarimetry and the two detectors combined yield a 64x40 pixel FOV for total intensity imaging. The detectors are designed to deliver background-limited observations with high quantum efficiency for all the HAWC+ continuum bands.

Instrument Parameters for Bands A–E

<table>
<thead>
<tr>
<th>Band/ Wavelength</th>
<th>Δλ</th>
<th>Angular Resolution</th>
<th>Total Intensity FOV (arcmin)</th>
<th>Polarization FOV (arcmin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A / 53 μm</td>
<td>8.70</td>
<td>4.85&quot; FWHM</td>
<td>2.8 x 1.7</td>
<td>1.4 x 1.7</td>
</tr>
<tr>
<td>B / 63 μm</td>
<td>8.90</td>
<td>10.5&quot; FWHM</td>
<td>4.2 x 2.7</td>
<td>2.1 x 2.7</td>
</tr>
<tr>
<td>C / 89 μm</td>
<td>17.00</td>
<td>7.8&quot; FWHM</td>
<td>4.2 x 2.7</td>
<td>2.1 x 2.7</td>
</tr>
<tr>
<td>D / 154 μm</td>
<td>34.00</td>
<td>13.6&quot; FWHM</td>
<td>7.4 x 4.6</td>
<td>3.7 x 4.6</td>
</tr>
<tr>
<td>E / 214 μm</td>
<td>44.00</td>
<td>18.2&quot; FWHM</td>
<td>8.4 x 6.2</td>
<td>4.2 x 6.2</td>
</tr>
</tbody>
</table>

*Band B (63 μm) will be offered as shared-risk during Cycle 9.

Predicted Performance for Continuum Imaging and Polarimetry

<table>
<thead>
<tr>
<th>Instrument Parameter</th>
<th>Band A</th>
<th>Band B'</th>
<th>Band C</th>
<th>Band D</th>
<th>Band E</th>
</tr>
</thead>
<tbody>
<tr>
<td>NESB</td>
<td>18.8</td>
<td>11.4</td>
<td>6.3</td>
<td>1.6</td>
<td>0.8</td>
</tr>
<tr>
<td>MDCF</td>
<td>250</td>
<td>400</td>
<td>300</td>
<td>260</td>
<td>230</td>
</tr>
<tr>
<td>Mapping Speed</td>
<td>0.0027</td>
<td>0.0290</td>
<td>0.029</td>
<td>1.10</td>
<td>7.0</td>
</tr>
<tr>
<td>MDCPF</td>
<td>80</td>
<td>150.0</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>MIPF</td>
<td>28,000</td>
<td>17,000</td>
<td>6,000</td>
<td>2,000</td>
<td>1,300</td>
</tr>
</tbody>
</table>

*Sensitivity estimates in units of the Minimum Detectable Continuum Flux (MDCF) into a single beam. Values take into account all expected overheads. For polarization, the plotted data show the polarized intensity p x I, where p is the fractional polarization.

Footprint for total intensity imaging observations using the 64x40 pixel array in Band E. A 32x40 pixel FOV is available for imaging polarimetry observations.

For more detailed information, see the Observer’s Handbook: www.sofia.usra.edu/latest-Observers-Handbook
Proposal Resources

SOFIA offers the following tools and documentation to facilitate the proposal process. These resources are available at: https://www.sofia.usra.edu/science/proposing-observing

Core Documentation

The Call for Proposals (CfP) solicits observing proposals from the U.S. and international astronomy communities. The document describes how to prepare and submit proposals, including details on how proposals will be evaluated, and formally establishes the policies and rules governing SOFIA operations for the relevant cycle.

The Observer’s Handbook is the primary technical reference for astronomers who wish to submit a proposal in response to the CfP, providing detailed information about the instruments and observing modes that will be available for observations during the relevant cycle.

Proposal Submission Tools

All SOFIA proposals are prepared and submitted using the Unified SOFIA Proposal and Observation Tool (USPOT). USPOT contains many built-in features to help with planning observations, such as the Target Visibility tool that can be used to determine which time of year the target is most visible from the take-off location of SOFIA. The USPOT Manual guides users through the procedures for submitting proposals for SOFIA, with specific instructions for each instrument.

The observatory provides additional tools to aid in the proposal submission process.

Estimations of exposure times for each instrument can be made using the SOFIA Instrument Time Estimator (SITE), a web-based tool that provides total integration time or S/N for a given instrument, filter(s), source type (point, extended, emission line), and water vapor overburden.

The atmospheric transmission as a function of wavelength may be obtained using the online tool ATRAN. The use of ATRAN is necessary for planning SOFIA high-resolution spectroscopic observations.

The observatory hosts webinars and in-person workshops prior to the start of each observing cycle to guide users through using these resources to submit proposals. Sign up for the e-Newsletter and check the SOFIA website for announcements of upcoming events.

Above: USPOT visualization of the Orion Nebula with the FORCAST field of view (FOV) overlaid on an archival WISE Band 1 image. Shown are the FPI+ FOV (yellow circle), FPI+ guide stars (yellow crosses), FORCAST dithers on-source (red boxes), and FORCAST asymmetric chopped dithers off-source (green boxes). Chopping on- and off-source is an observing technique used to remove background emission from the sky. While the WISE image is heavily saturated, FORCAST has a dynamic frame rate that prevents these saturation effects.
Data Resources

The following tools and documentation are available for utilizing and analyzing SOFIA data. These resources are available at https://www.sofia.usra.edu/science/data and on GitHub.

Public Archival Data
The SOFIA Science Center provides raw and calibrated data for the entire instrument suite. The level of data processing ranges from corrections for instrument artifacts, to flux calibrated and telluric corrected data, to maps and mosaics. These data are publicly available for further exploration after their exclusive use periods expire.

The observatory has transitioned from storing data in the SOFIA Data Cycle System (DCS) to the IPAC Infrared Science Archive (IRSA), which has become the primary data archive. Access the SOFIA webpage on IPAC at https://irsa.ipac.caltech.edu/Missions/sofia.html

Custom Software
Detailed data analysis can be accomplished by using custom software provided by the observatory.

Data cubes are three-dimensional matrices with two spatial axes (right ascension and declination) and a wavelength axis. The FLUXER tool can be used to fit the continuum and estimate line strengths in final data cubes. Furthermore, the SOFIA SPectral EXplorer (SOSPEX) allows users to probe spectral cubes produced by the data reduction pipeline.

Data analysis tutorials are available to guide new and experienced users through performing aperture photometry, emission line analysis, custom spectral extraction, finding sample data sets, and other common data analysis objectives using SOFIA processed data.

The SOFIA SPectral EXplorer (SOSPEX) tool analyzing FIFI-LS spectral data cubes produced from C+ observations of the starburst galaxy, M82.