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Erin C Smith*[i], John W. Miles[a], L. Andrew Helton[a], Ravi Sankrit[a], B-G Andersson[a], Eric E. Becklin[a], James M. De Buizer[a], C. Darren Dowell[b], Edward W. Dunham[c], Rolf Güsten[d], Doyal A. Harper[e], Terry L. Herter[f], Luke D. Keller[g], Randolf Klein[a], Alfred Krabbe[h], Sarah Logsdon[j], Pamela M. Marcum[i], Ian S. McLean[j], William T. Reach[a], Matthew J. Richter[k], Thomas L. Roellig[i], Göran Sandell[a], Maureen L. Savage[a], Pasquale Temi[i], William D. Vacca[a], John E. Vaillancourt[a], Jeffrey E. Van Cleve[a], Erick T. Young[a]

[a]Universities Space Research Association, MS 232, Moffett Field, CA 94035, USA [b]Jet Propulsion Laboratory, 4800 Oak Grove Dr, Pasadena, CA 91109, USA [c]Lowell Observatory, 1400 W Mars Hill Rd, Flagstaff, AZ 86001, USA [d]Max Planck Institute for Radio Astronomy, Auf dem Hügel 69, 53121 Bonn, Germany [e]Yerkes Observatory, Univ. of Chicago, 373 W Geneva St, Williams Bay, WI 53191 [f]Department of Astronomy, Cornell University, Ithaca, NY 14853, USA [g]Department of Physics, Ithaca College, Ithaca, NY 14850, USA [h]University of Stuttgart, Pfaffenwaldring 31, 70569 Stuttgart, Germany [i]NASA Ames Research Center, MS 232, Moffett Field, CA 94035, USA [j]Department of Physics and Astronomy, UCLA, CA 90095, USA [k]Department of Physics, University of California, Davis, CA 95616, USA

ABSTRACT

The Stratospheric Observatory for Infrared Astronomy (SOFIA) is the world's largest airborne observatory, featuring a 2.5 meter effective aperture telescope housed in the aft section of a Boeing 747SP aircraft. SOFIA's current instrument suite includes: FORCAST (Faint Object InfraRed CAmera for the SOFIA Telescope), a 5–40 µm dual band imager/grism spectrometer developed at Cornell University; HIPO (High-speed Imaging Photometer for Occultations), a 0.3–1.1µm imager built by Lowell Observatory; GREAT (German Receiver for Astronomy at Terahertz Frequencies), a multichannel heterodyne spectrometer from 60–240 µm, developed by a consortium led by the Max Planck Institute for Radio Astronomy; FLITECAM (First Light Infrared Test Experiment CAMera), a 1–5 µm wide-field imager/grism spectrometer developed at UCLA; FIFI-LS (Far-Infrared Field-Imaging Line Spectrometer), a 42–200 µm IFU grating spectrograph completed by University Stuttgart; and EXES (Echelon-Cross-Echelle Spectrograph), a 5–28 µm high-resolution spectrometer designed at the University of Texas and being completed by UC Davis and NASA Ames Research Center. HAWC+ (High-resolution Airborne Wideband Camera) is a 50–240 µm imager that was originally developed at the University of Chicago as a first-generation instrument (HAWC), and is being upgraded at JPL to add polarimetry and new detectors developed at Goddard Space Flight Center (GSFC). SOFIA will continually update its instrument suite with new instrumentation, technology demonstration experiments and upgrades to the existing instrument suite. This paper details the current instrument capabilities and status, as well as the plans for future instrumentation.

Keywords: Equipment and services, mid infrared, far infrared, imaging systems, infrared astronomy, observatories, spectrometers, telescopes

1. INTRODUCTION

SOFIA, The Stratospheric Observatory for Infrared Astronomy achieved first light in spring 2010 and has been used in science observations in both the northern and southern hemispheres since that time. In February 2014, with the successful completion of commissioning flights for its forth science instrument, FLITECAM, SOFIA achieved its "full operating capability" and shortly thereafter moved officially from phase D (development) to phase E (operations)[1],[2]. As of May 2014 all 6 first generation instruments have been integrated with SOFIA and have been used for science observations.

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SOFIA is an airborne platform consisting of a 747sp modified to house a 2.5 meter IR-optimized telescope in its aft section. By flying at 37,000 to 45,000 feet in the stratosphere, SOFIA operates above 99% of the atmospheric water vapor responsible for obscuring the near-infrared to far-infrared spectrum from ground-based observatories. SOFIA features an instrument suite offering broad and narrow band imaging and mid- and high-resolution spectroscopy in the optical to far-infrared regime, offering wavelength access and capabilities otherwise currently unavailable to astronomers.

SOFIA features 6 first-generation science instruments: HIPO, FLITECAM, FORCAST, EXES, FIFI-LS, and GREAT. Two of these instruments are Principal investigator (PI)-class instruments, GREAT and EXES, two are facility science instruments (FSI), FORCAST and FLITECAM, one, HIPO, is a special purpose science instrument, while FIFI-LS will begin operations as a PI instrument before converting to FSI class in 2015. FSIs are operated entirely by the SOFIA team, including observation planning, maintenance and instrument operation. PI and SSIs involve the SI team in the operation planning and data reduction stages[3].

The SOFIA instrument suite offers imaging and spectroscopy from the visible to sub-millimeter wavelengths. HIPO offers high-speed optical imaging[4],[5],[6],[7]. FLITECAM offers imaging and spectroscopy in the near-infrared. HIPO and FLITECAM can each fly individually or can be co-mounted for simultaneous observations in the 'FLIPO' mode.[8],[9],[10] FORCAST is a dual channel mid-infrared instrument with imaging and moderate resolution grism spectroscopy from 5 to 40 microns.[11],[12],[13],[14] EXES is a high-resolution (R~100,000) instrument for 5-28 micron spectroscopy[15],[16],[17]. FIFI-LS is a dual channel integral field spectrometer for far-IR (42 to 200 micron) observations.[19],[20],[21],[22],[23],[25] GREAT is a dual channel heterodyne instrument allowing extremely high resolution line mapping in a selection of THz frequencies.[26],[27],[28],[29]

A major capability of SOFIA is the ability to access and update its instrument suite. Two efforts are currently underway to expand SOFIA's scientific capability: upGREAT and HAWC+. upGREAT will add dual-color heterodyne arrays (14 and 7 pixels, respectively) to the 1st generation instrument GREAT[30], while HAWC+ will feature far-infrared polarimetry and imaging as well as state-of-the-art bolometer detectors.[31],[32], [33],[34],[35] Future calls for new SOFIA instruments are currently being planned.

All instruments undergo a period of integration checkout, testing and commissioning prior to use in science observations. On SOFIA this involves both ground and airborne operations. In general the in-flight portion of these activities consist of 5-6 flights split over two periods. The results from these commissioning activities are presented following the completion of the final flight series either as a commissioning review, for PSIs and SSIs, or as an acceptance review for FSIs. Results from the commissioning activities are incorporated into the instrument data reduction pipelines and exposure time calculators, as well as the information made available to observers in the call for proposals.

SOFIA operates as a queue observatory, with the majority of time competitively awarded to general investigators (GIs) through yearly calls for proposals. There have been 4 observing calls issued for SOFIA: Early Science featuring observations by GREAT, FORCAST and HIPO; Cycle 1, featuring GREAT, HIPO, FLITECAM and FORCAST; and Cycle 2, featuring all the Cycle 1 instruments plus FIFI-LS and EXES. The Cycle 3 call for Proposals was issued in May 2014 and offers observations from March 1, 2015 to February 29, 2016).[1],[2],[3],[36]

2. HIPO

HIPO (High-speed Imaging Photometer for Occultations; PI: Edward Dunham, Lowell Observatory) is an optical, high-speed, dual channel imager, designed primarily for use in time-resolved observations as well as observatory characterization[4],[5],[6]. HIPO can be installed in two different configurations: co-mounted with the FLITECAM instrument (referred to as the "FLIPO" mode) or mounted alone. When FLITECAM is co-mounted, a dichroic beam splitter is externally mounted in front of the HIPO entrance window, so optical light is transmitted into HIPO, while near-infrared wavelengths are reflected through a periscope-like structure into FLITECAM. When mounted solo, HIPO does not utilize these external optics. Inside the HIPO instrument is another beam splitter, which simultaneously feeds the red and blue imaging CCD channels. Each channel has independent collimating and re-imaging optics and a dedicated 8-position filter wheel at the image pupil. If the highest throughput is desired, the channel beam splitter can also be removed, and either CCD may be fed directly with the SOFIA beam.

HIPO is used for both science observations and observatory engineering and checkout. The red channel features Shack-Hartmann lenslets which allow focus and alignment tests. HIPO also has a pupil-imaging mode, which allows direct measurement of the SOFIA optical axis and secondary mirror location. These measurements can be transferred by HIPO to ground-based alignment facilities in the SOFIA science instrument labs. For science observations, HIPO features a standard set of optical filters (the Johnson and Sloan standard filters) as well as selected narrow band filters. For faint objects an unfiltered mode is also available. HIPO has been used in more than 20 flights. These include multiple flights co-mounted with the FLITECAM instrument (the FLIPO configuration), as well as several solo flights. HIPO has also been used extensively for ground operations and checkout.

3. FLITECAM

FLITECAM (First Light Infrared Test Experiment CAMera; PI: Ian McLean, UCLA) is a 1 to 5 micron instrument featuring a 1024 x1024 InSb detector offering broad and narrow band imaging and grism spectroscopy. FLITECAM can image the entire SOFIA field-of-view (diameter~8') with a pixel scale of 0.475"/pixel. FLITECAM can operate in two modes, either mounted alone, or co-mounted with HIPO, in 'FLIPO' mode. FLITECAM features a dual filter wheel with the standard J, H, K, L, and L filters; narrow band filters and 3 direct-ruled KRS-5 grisms.

Table 1. FLITECAM imaging bands.

Filter	$\lambda_{central}$ (μm)	Δλ (μm)
J	1.25	0.26
H	1.64	0.27
K	2.12	0.35
L	3.55	0.55
L'	3.875	0.60
M	4.87	0.51
Pa-α	1.88	0.02
Pa-$\alpha_{Cont.}$	1.9	0.02
Water Ice	3.05	0.16
PAH	3.3	0.09
L_{narrow}	3.61	0.18
M_{narrow}	4.81	0.15

Table 2. FLITECAM spectroscopy bands.

Grism Mode	λ_{start} (microns)	λ_{end} (microns)
HwideA	1.55	1.828
Klong A	2.27	2.722
LMA	4.395	5.533
JB	1.141	1.385
HwideB	1.675	2.053
LMB	3.303	4.074
HC	1.5	1.718
KwC	1.91	2.276
LMC	2.779	3.399

A dual width cryogenic entrance slit operates just inside the FLITECAM entrance window, yielding 9 spectral bands covering the 1 to 5 micron regime at low resolution (2000>R>1000).[8],[9],[10] FLITECAM has been operated on 12 total flights: 4 engineering flights for observatory checkout and characterization, 6 commissioning flights and 2 science observation flights. As of May 2014 all FLITECAM flights have been executed in the co-mounted, FLIPO mode, limiting long-wavelength (λ >3.5 microns) observations.

4. FORCAST

FORCAST (Faint Object InfraRed CAmera for the SOFIA Telescope; PI: Terry Herter) was developed at Cornell University to function as a dual channel mid-IR (5-40 micron) camera with imaging and grism spectroscopy capabilities. FORCAST uses a pair of 256x256 blocked-impurity band (BiB) detectors— a Si:As BiB detector for λ<25 microns and a Si:Sb BiB detector for λ>25 microns. Both channels have a 3.4' x 3.2' FOV and a 0.768"/pixel plate scale. The two channels can operate simultaneously or individually depending on choice of dichroic settings. FORCAST offers long slit, low resolution grism spectroscopy over its entire wavelength range and high resolution, cross-dispersed spectroscopy from 5-14 microns.[11],[12],[13],[14] FORCAST has been used extensively on SOFIA, including as the first light instrument in 2010 as well as in multiple science observations.

Table 3. FORCAST imaging bands.

Channel	λcentral (μm)	Δλ(μm)
SWC	5.4	0.16
	5.6	0.08
	6.4	0.14
	6.6	0.24
	7.7	0.47
	8.6	0.21
	11.1	0.95
	11.3	0.24
	11.8	0.74
	19.7	5.5
	25.4	1.86
LWC	24.2	2.9
	25.3	1.9
	31.5	5.7
	33.6	1.9
	34.8	3.8
	37.1	3.3

Table 4. FORCAST spectroscopy bands.

Channel	Spectral mode	Grism(s)	λ_{min}-λ_{max} (μm)	λ/Δλ 2.4" slit	λ/Δλ 4.7" slit
SWC	FOR_G063	G1	4.9 – 8.0	180	90
	FOR_XG063	G1×G2	4.9 – 8.0	1200	NA
	FOR_G111	G3	8.4 – 13.7	300	150
	FOR_XG111	G3×G4	8.4 – 13.7	800	NA
LWC	FOR_G227	G5	17.6 – 27.7	140	70
	FOR_G329	G6	28.7 – 37.1	220	110

5. EXES

EXES (Echelon-cross Echelle Spectrograph; PI: Matt Richter, UC Davis) is a high-resolution (up to R~100,000) spectrograph that covers the 4.5 to 28.3 micron regime. EXES uses a Si:As 1024x1024 array on an SB226 mux. EXES uses an echelon cross-dispersed by an echelle grating. In high-resolution mode both the echelon and echelle are used while the echelon is bypassed in the low and medium resolution modes. The echelle is 9 inches by 4.75 inches wide with a groove spacing of 32.6 microns which operates at a blaze angle of either 26.6 degrees or 63.4 degrees. The echelon is 40 in by 4 inches and has a blaze angle of 84.3 degrees and a groove spacing of 7.6 millimeters. The combinations of the echelle and echelon grating settings yield four main modes: high-medium mode—R~50,000 to 100,000 (echelle blaze at ~ 63.4 degrees, echelon cross-dispersed); high-low mode—R~50,000 to 100,000 (echelle blaze at ~ 26.6 degrees, echelon cross dispersed); medium mode—R~5,000 to 20,000 (Echelle blaze at 63.4, no echelon); and low mode—R~1,000-3,000 (echelle blaze at 26.6 degrees) [15],[16],[17]. In all modes, EXES achieves calibration through observation of atmospheric lines. EXES has flown on 2 flights, completing the first half of its commissioning program. During these flights EXES executed a combination of science observations and commissioning activities, and will complete its commissioning in early 2015. EXES has been offered as a PI instrument in Cycle 3.

Table 5. EXES spectroscopy bands

Mode	Echelle blaze	Echelon	λ/Δλ (est)
High-Medium	63.4° (R2)	84.3	50,000-100,000
High-Low	26.6° (R½)	84.3	50,000-100,000
Medium	63.4° (R2)	N/A	5,000–20,000
Low	26.6° (R½)	N/A	1,000–3,000

6. FIFI-LS

FIFI-LS (Far-IR Field Imaging Line Spectrograph; PI: Alfred Krabbe, University of Stuttgart) uses dual channel integral field units to perform imaging spectroscopy in the far-infrared (42-200 microns). FIFI-LS is very similar to the PACS-Spectrometer (detector and optical design), which flew on Herschel, but FIFI-LS has two gratings allowing the independent observation of two spectral lines (one in each channel) simultaneously. Both channels use 16x25 pixels Ge:Ga arrays—the red channel utilizes a stressed array to cover the 105 – 200 micron range with a pixel scale of 12″ per pixel, while the unstressed blue channel covers the 50-125 micron range with a pixel scale of 6″ per pixel. FIFI-LS uses a 15 mirror image slicer to rearrange the FOV into a 25x1 pixel line, which is then fed to the diffraction grating. Both arrays have a 5x5 pixel spatial FOV, with 16 spectral elements for a 5x5x16 data cube with R~ 500 to 2000. FIFI-LS utilizes an internal, cryogenic K-mirror to rotate the FOV to an arbitrary position angle and maintain the position angle throughout the observation.[19],[20],[21],[22],[23],[25],[25]

Table 6. Performance of FIFI-LS at four typical transitions

	Blue Channel		Red Channel	
	[OIII] 51.8μm	[OI] 63.2μm	[OI] 145.5μm	[CII] 157.7μm
λ/Δλ	1100	1400	970	1100
Velocity resolution	270 km/s	210 km/s	310 km/s	270 km/s
Field of View	30″×30″		60″×60″	
Pixel Size	6″		12″	

7. GREAT

GREAT (German REceiver for Astronomy at Terahertz frequencies; PI Rolf Güsten, Max-Planck-Institut für Radioastronomie) is a dual channel high-resolution (up to R=10^8) spectrometer over the 1.25 to 4.7 THz range. GREAT was designed as a modular instrument with a front-end unit consisting of 2 independent, exchangeable dewars with mixers tuned to selected frequency bands. Each channel has an associated local oscillator (LO) tuned to a specific line of interest—the M channel uses 2 LOs, one tuned to the OH line and another tuned to the deuterated hydrogen line. The backends consists of 2 Fast Fourier Transform Spectrometers for each mixer: an XFFTS with bandwiths of 2.5 GHz and 88 kHz operated simultaneously with an AFFTS with a 1.5 GHz bandwith and 212 kHz resolution[26],[27],[28],[29]. The instrument has been in continuous upgrade, making latest technological advancements readily available to the communities (performance figures in Table 7 reflect the instrument status as offered for cycle 3). GREAT has been operated since Early Science on multiple SOFIA flights including a flight series in the southern hemisphere. All 4 channels (L1, L2, M_a, and H channels) have been commissioned, and the team is developing the extension of GREAT into multi-pixel heterodyne arrays: a low-frequency array with 14 pixels that will make mapping of e.g. the [CII] line an order of magnitude more efficient, and a high-frequency array with 7 spatial pixels, centered on the [OI] transition.. The LFA of this upgrade, called upGREAT[30] will be made available in Cycle 4.

Table 7. GREAT frequency channels

Channel	Frequency (THz)	Astronomical lines
L1	1.25 – 1.39	CO(11-10), CO(12-11), OD, SH, H_2D^+, HCN, HCO^+
	1.42 -1.52	CO(13-12), [N II]
L2	1.81 – 1.91	NH_3(3-2), OH($^2\Pi_{1/2}$), CO(16-15), [C II]
Ma	2.49 – 2.56	OH ($^2\Pi_{3/2}$)
Mb	2.675	HD(1-0)
H	4.745	[O I]

8. HAWC+

HAWC (High-resolution Airborne Wideband Camera) is a five-band, far-infrared camera (50-240 µm) developed at the University of Chicago (PI Al Harper). The HAWC+ upgrade, currently under development at JPL (PI Darren Dowell); will add polarimetry, larger detector arrays, and an additional photometric band. Polarimetry is achieved with a wire grid polarizing beamsplitter and a set of cryogenic rotating half-wave plates. HAWC+ detectors are a pair of backshort under grid (BUG) arrays developed at GSFC that utilize superconducting transition-edge sensors and SQUID multiplexers and that simultaneously detect the reflected and transmitted polarization components.[31],[32], [33],[34],[35] HAWC+ will be completed in late 2015, and will be offered to the community in Cycle 4.

Table 8. HAWC+ Imaging bands

Band	$\lambda_{central}$ (µm)	($\Delta\lambda/\lambda$)	FWHM	FOV	Imaging NEFD[a] (Jy/beam $s^{1/2}$)	Min flux density[b] for $\sigma(P)<0.3\%$ (Jy/beam)
A	53	0.17	5.4"	1.4' x 1.7'	0.93	10.7
B	62	0.12	6.4"	2.1' x 2.6'	0.80	9.2
C	89	0.19	9.0"	2.1' x 2.6'	0.79	9.1
D	155	0.22	16’’	3.6' x 4.5'	0.64	7.3
E	216	0.20	22"	4.8' x 6.1'	0.55	6.3

[a]Noise Equivalent Flux Density=flux density detectable w/ SNR=1 (1s integration time)
[b]Assumes 60% observing efficiency.

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