Invited Paper

Deutsches SOFIA Institut (DSI) at the SOFIA Science Center: Engineering and scientific contributions to the airborne observatory

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ABSTRACT

The Stratospheric Observatory for Infrared Astronomy (SOFIA) is a 2.5 meter infrared telescope built into a Boeing 747SP. In 2014 SOFIA reached its "Full Operational Capability" milestone and nowadays takes off about three times a week to observe the infrared sky from altitudes above most of the atmosphere's water vapor content.

Despite reaching this major milestone, efforts to improve the observatory's performance are continuing in many areas. The team of the Deutsches SOFIA Institut, DSI (German SOFIA Institute) at the SOFIA Science Center in Moffett Field, CA works in several engineering areas to improve the observatory's performance and its efficiency. DSI supports the allocation process of SOFIA's observation time for guest observers, provides and supports two facility science instruments and conducts an observing program of stellar occultations by small objects of the solar system. This paper summarizes results and ongoing work on a spare secondary mirror made of aluminum, the new and improved Focal Plane Imager (FPI+) that has become a facility science instrument, the Field-Imaging Far-Infrared Line Spectrometer (FIFI-LS), new cameras and optics for the Fine Field and Wide Field Imagers (FFI+ and WFI+), real-time astrometric solution of star field images, ground support equipment and astronomical observations.

Keywords: Stratospheric Observatory for Infrared Astronomy, SOFIA, astronomy, CCD, infrared detectors, instrumentation, telescope pointing

1. INTRODUCTION

The Stratospheric Observatory for Infrared Astronomy, SOFIA, is a joint project of the US space agency NASA and the German space agency DLR, which share the project efforts at an 80-to-20 percent ratio. During the development phase of the observatory NASA has provided the Boeing 747SP aircraft and its necessary modifications to accommodate the telescope, and its ground support facilities. The SOFIA telescope with its 2.7 meter physical diameter primary mirror has been developed by a German industry consortium under contract and with funding of the DLR. Now, in the operational phase of the observatory, NASA and DLR continue to share the operational efforts and the observing time at the same ratio. DLR has contracted the German contributions out to the University of Stuttgart, where the Deutsches SOFIA Insistut, DSI, operates as a department of the university's Institute of Space Systems, IRS.

The DSI employs about 30 scientists, engineers and technicians to work on SOFIA in California, USA. Most of them are located at the home base of SOFIA in Palmdale with tasks in the areas of telescope maintenance, telescope operational support and operations engineering. A smaller contingent of DSI, six full time scientists and engineers plus Ph.D. and undergraduate students, works at the SOFIA Science Center located at the NASA Ames Research Center in Moffett Field. Their major projects are in the area of upgrade engineering of the telescope and its subsystems, support and operation of facility type SOFIA instruments and in scientific observations. This paper summarizes recent and ongoing projects of the DSI at the SOFIA Science Center.

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2. THE ROLE OF THE DSI IN THE SMO DIRECTORATE

The DSI is represented in the SOFIA Science Mission Operations (SMO) by the Deputy Director (currently Hans Zinnecker), appointed and funded by Univ. of Stuttgart, who is responsible to support and coordinate the German interests in all SOFIA matters. Equally important, he is also responsible for the scientific productivity of SOFIA on the German side. As such, he is the selection official for the German SOFIA observing proposals, following the recommendation by the German "Time Allocation Committee" (TAC). It is the task of the Deputy Director to search for and select the German TAC members (typically 6-8 people + a chairman). Previous chairmen were M. Grewing (Tübingen), D. Lemke (MPIA Heidelberg), and A. Quirrenbach (LSW, Heidelberg). Typically there are 30 proposals per observing Cycle each year and about 100 hours of observing time available for the German side, split into open time for the German community and guaranteed time for the German instrument teams (GREAT and FIFI-LS).

The SMO deputy director also gives science talks (e.g., Zinnecker, 2013[1]) in the German and US community to attract astronomers to write SOFIA observing proposals (mainly far-infrared). Furthermore, he has been involved in organizing a German SOFIA science workshop at Ringberg castle and a forthcoming SOFIA conference at Asilomar in California. He and the DSI director (Alfred Krabbe) at the Deutsches SOFIA Institut interact closely with USRA management at NASA Ames, e.g., through regular DSI/USRA telecons, and in particular will support the forthcoming NASA senior review of SOFIA. There is a plan to bring SOFIA to the DLR airshow in Cologne in 2017, and perhaps also to Stuttgart Airport.

3. FIELD-IMAGING FAR-INFRARED LINE SPECTROMETER

The Field-Imaging Far-Infrared Line Spectrometer, or FIFI-LS (Klein et al., 2014[2]) was accepted as a facility science instrument (FSI) in the beginning of 2016. With this acceptance, the SOFIA SMO became fully responsible for the operation, maintenance and possible upgrades of the instrument. Within the SMO, these responsibilities are shared between staff from DSI and USRA. DSI provides instrument operators for in flight and laboratory operation and maintenance of the instrument. These operators are responsible for the training of the USRA instrument operators on the German built instrument. Besides the operation of FIFI-LS, the work of DSI at the SOFIA Science Center focuses on instrument upgrades and improvements. This work is divided into three areas: optics, control software (S/W) and procedures.

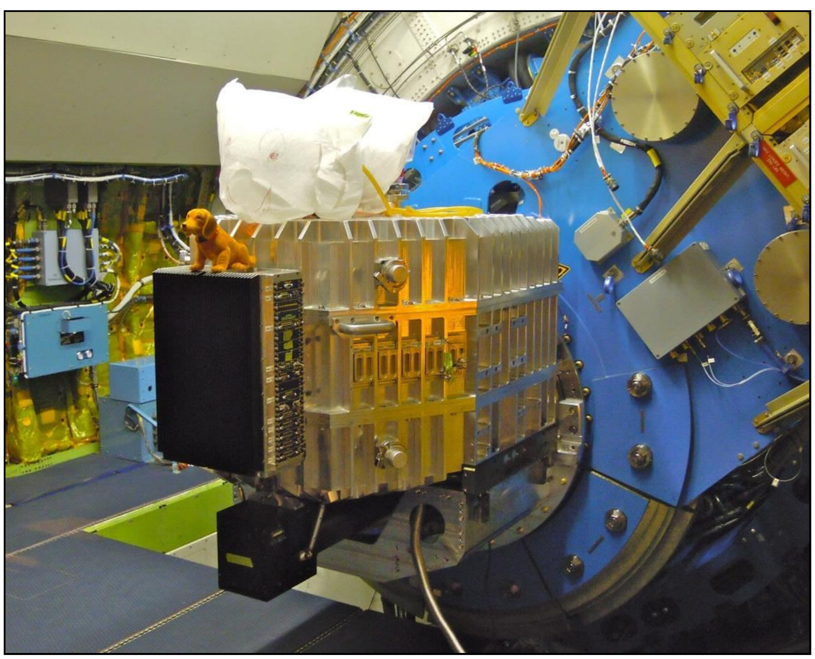

Figure 1. FIFI-LS mounted to the SOFIA telescope.

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Concerning the optics, the work includes research on the implementation of a new entrance filter which has the potential to increase the instruments efficiency at the astronomically important OIII line (51.8 µm) by a factor of ~ 2. The new filter would also allow to extend the accessible range of the instrument down to ~ 45 µm. This would for instance add the capability to observe certain water ice features with FIFI-LS. Additionally, the work in the area of optics includes the investigation of instrumental features. One feature is a spatial ghost in the red channel. This ghost is also shifted significantly in spectral direction and is therefore usually not interfering with line measurements of the instrument. Another known instrument feature is the vignetting of spatial pixels on one side of the field of view in either channel, the reduction of this effect promises to increase the sensitivity of the instrument and simplify the reduction pipeline of the instrument. Zemax ray tracing simulations will be used to determine the root causes of these instrument features and develop effective mitigation strategies.

In the area of the control S/W, the work concentrates on continuous improvements to increase the instrument's reliability, which is already very high with less than 15 minutes lost due to instrument issues on an average flight. Updates of the control S/W will also improve the instrument's efficiency by reducing instrument internal time lags and optimization of the detector readout. Additional observing modes are investigated and will be implemented in the control S/W in close coordination with the colleagues from DSI/USRA in Palmdale and Moffett Field.

It is necessary to recalibrate the instrument boresight and redo the instruments wavelength calibration once before each flight series. Currently the calibration procedures include laboratory measurements taking three to four days and one day for data analysis. These procedures are laid out conservatively to guarantee the accuracy of the instrument's calibration of 10% of a resolution element in wavelength and better than 1.5 arcseconds in the boresight. Further investigation is performed by DSI to reduce the necessary measurement and analysis times while maintaining the accuracy of the calibration.

4. FPI+ AS FACILITY SCIENCE INSTRUMENT

SOFIA's Focal Plane Imager (FPI) is the observatory's main target acquisition and tracking camera. This CCD camera is mounted at the focal point of the visual light beam of the telescope to measure the pointing during every observation. In early 2013, the FPI has been upgraded with a modern, back-illuminated sensor with high quantum efficiency. This makes the FPI+ a very sensitive and versatile imaging photometer for visible wavelengths (see also section 5).

The SOFIA Project Scientist had requested the development of this camera into a facility science instrument to take advantage of its permanent installation on the telescope and make it available to the scientific community (Pfüller et al., 2016[4]). The observing modes and characteristics of the FPI+ instrument are described in a dedicated chapter of the "SOFIA observers handbook." This reference has been created to provide an instrument overview, describe the design, angular resolution, filter suite, imaging sensitivities, and camera performance for scientists who are planning observations with this instrument. For detailed observation planning, the online tools "SOFIA Instrument Time Estimator" (SITE) and "Data Cycle System" (DCS) can be used. The FPI data has been integrated into SITE after several on-sky photometric measurements with all spectral filters were analyzed to determine the relations between target brightness, signal-to-noise ratio, and exposure time (figure 2). The information in the observers handbook and the time estimator should be sufficient for planning viable observations.

The hardware of the tracking camera did not have to be changed for its use as science instrument. However, the software on the camera controller and the control laptop was optimized for the acquisition of science data. During the creation of FITS images additional keywords are added to the image header which are required by the DCS for the storage of science data. Official verification testing of all software is required before a connection to the Mission Control and Communications System (MCCS) on SOFIA is allowed. This connection is needed to send commands to the telescope and to subscribe to observatory housekeeping data. This had to be completed in a laboratory observatory simulator before using the software on the aircraft. All these prerequisites were completed before the call for proposals for observing cycle 4 and the FPI+ was officially offered as a science instrument for observations starting in 2016.

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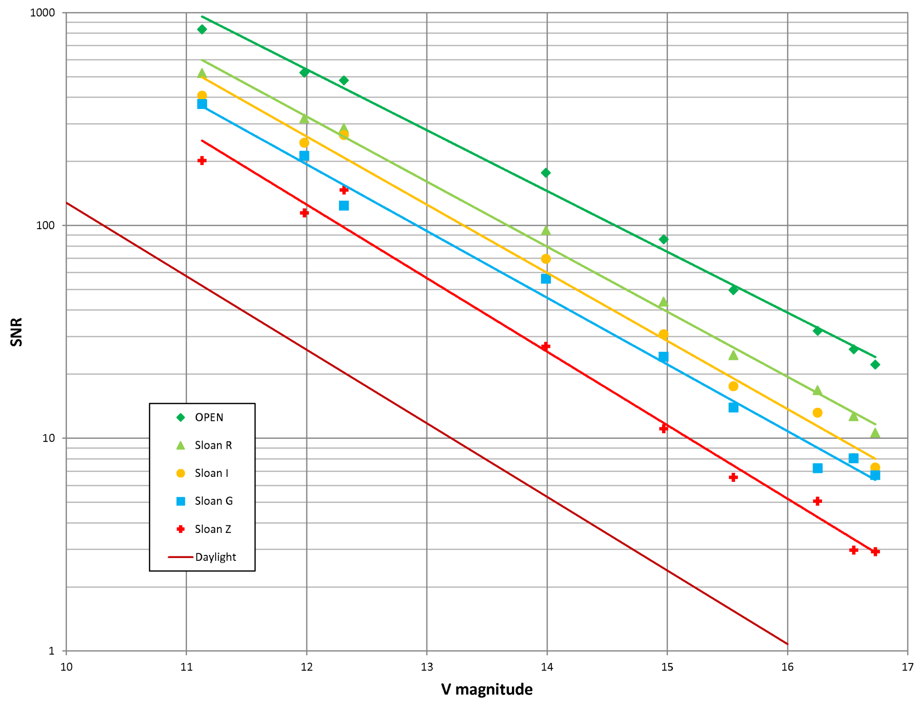

Figure 2. Signal-to-noise ratios (SNR) for point sources imaged with FPI+ at $t_{exp} = 1\,s$. Displayed are the OPEN broadband configuration as well as the spectral Sloan filters g′, r′, i′, and z′ and the DAYLIGHT near-infrared cut-on filter. The fit for the DAYLIGHT filter was extrapolated from brighter stars recorded at a shorter integration time.

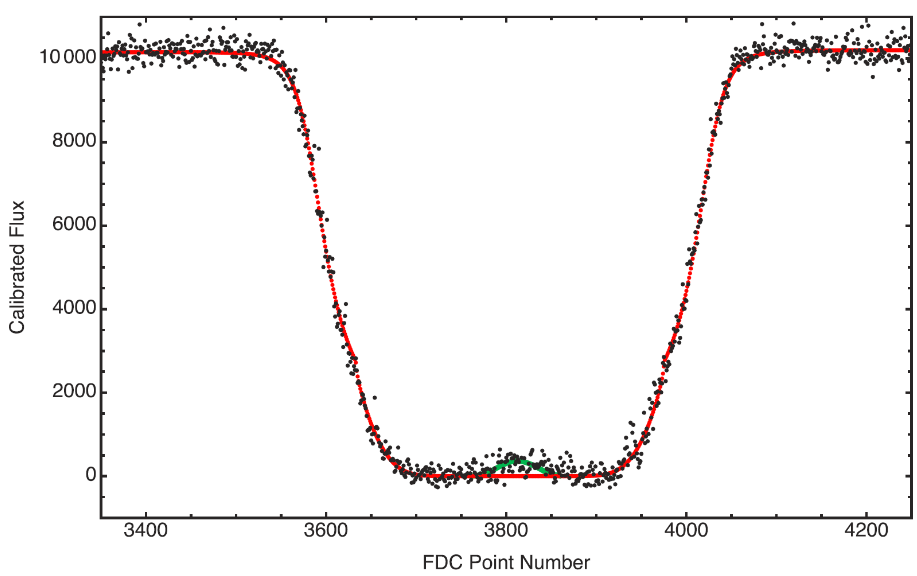

Figure 3. Flux as measured with the FPI+ (at the time called "Fast Diagnostic Camera," FDC) during the time of the stellar occultation in 2011 (black). The red dots represent atmospheric models for Pluto including a "lower atmosphere haze model" and a simple evolute model (green) to account for the ellipticity of Pluto's atmosphere (Person, et al. 2013[3]).

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The FPI+ was used to acquire science data during previous observations, like two stellar occultations by Pluto. The first occultation observation was in June 2011 with the shadow path moving across the Pacific Ocean (scientific results published by Person et al., 2013[3]). The second observation took place during the 2015 southern hemisphere deployment of SOFIA in New Zealand (first results will be published by Bosh et al., 2016[5]). In 2011 the observation (figure 3) was performed together with the instrument HIPO and in 2015 with HIPO and FLITECAM which resulted in four data sets. The infrared FLITECAM light curve, the red and blue channel of HIPO and the FPI+ data set were acquired at the same time. By coincidence the 2015 occultation occurred just two weeks before the NASA New Horizons spacecraft had its closest approach to Pluto. The different data sets are being used to calibrate and complement each other.

5. TARGET ACQUISITION AND TRACKING CAMERAS UPGRADE

SOFIA has three target acquisition and tracking cameras that used identical cameras, but different optics to achieve different fields of view and sensitivities. The cameras did not meet the sensitivity requirements upon commissioning of the SOFIA telescope, due to low quantum efficiency and high dark current of the front-illuminated and un-cooled CCD cameras. The optical properties and achieved sensitivities of the three cameras are summarized in table 1. To improve the sensitivity so the cameras can fulfill the requirements, DSI began upgrading all three cameras with highly sensitive back-illuminated EMCCD cameras (Andor iXon3 888) with multi-stage thermoelectric coolers (Wiedemann et al., 2012[7]).

The upgrade of the SOFIA's main tracking camera, Focal Plane Imager (FPI), was completed in 2013. The FPI+ now achieves about 100× the sensitivity of the original FPI and achieves a limiting magnitude for tracking stars of up to $V = 17$ mag. The FPI receives the visible light that is transmitted by the dichroic tertiary mirror of the SOFIA telescope. It is the only camera of the three that is mounted on the temperature and pressure controlled cabin side of the telescope (as shown in figure 4), which allowed us to use a standard, off-the-shelf iXon3 888 camera.

The Wide Field and Fine Field Imagers (WFI and FFI) are used primarily for target acquisition and for off-axis tracking, if an extended object is observed where no visible guide stars are available in the FPI's field of view. The imagers are mounted to the TA headring and are exposed to stratospheric conditions in flight ($T \approx -40\,°C$, $p \approx 0.1\,atm$). Several modifications to the standard iXon camera were necessary, to operate a camera reliably and safely in this extreme environment. Andor Technology[*] and DSI developed a working prototype for these conditions, which was extensively tested in a thermal vacuum chamber. Its noise values are equal to standard production line cameras of Andor, but at temperatures down to $-62\,°C$ and we are ready to start the production of the flight models (Wiedemann et al., 2016b[8]).

After initially planning to upgrade only the cameras, it is now planned to upgrade the optics of the WFI and FFI as well. The goal is to improve image quality and the focus stability during the cool down phase of the structure, early in flight, without using a focusing mechanism. For the WFI, the goal was to find a commercial lens with a suitable focal length and aperture, with a good image quality and temperature stability. Several candidate lenses were tested for their focus stability in a thermal vacuum chamber and the lens with the best performance was selected: The Canon CN-E 85mm T1.3 L F (Lachenmann et al., 2014[9]). The proposed design of the new WFI+ is shown in figure 5.

The current FFI uses the optical components from a commercial 10-inch Schmidt-Cassegrain telescope and a custom focal reducer. Most of the optical components are made from Borosilicate glass with a coefficient of thermal expansion (CTE) of $3\text{-}7\times10^{-6}$/K. The relatively high CTE in combination with the conical shape of the primary mirror lead to significant defocussing during the transient cool-down phase. The optical design of the new FFI+ is a Riccardi-Honders design from Officina Stellare with the support from DSI (see figure 6). In the new design all optical elements are made from fused silica with a CTE of $\sim 0.55\times10^{-6}$/K. The thermal and optical analyses that were able to reproduce the defocussing issue of the current FFI design show that the new design will show hardly any detectable defocussing, allowing the new FFI+ to achieve better centroiding accuracy over the entire duration of a SOFIA flight.

[*] Andor Technology Ltd., Belfast, UK, http://www.andor.com

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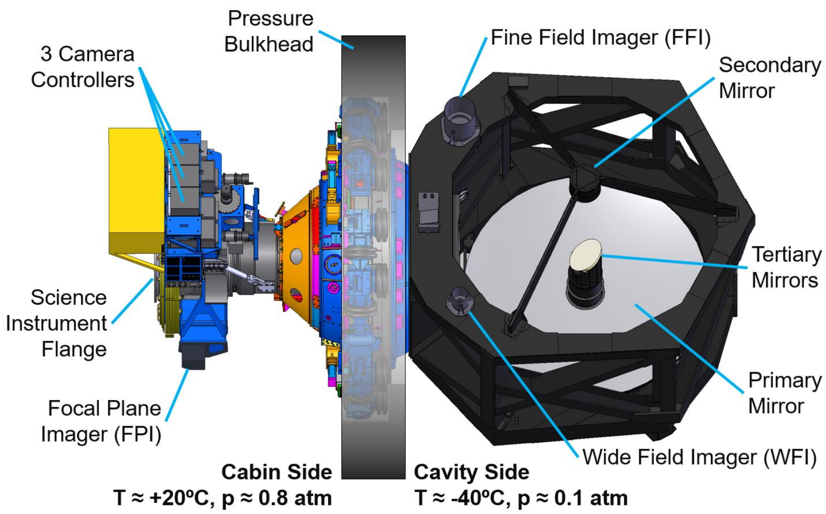

Figure 4. Model of the SOFIA Telescope Assembly (TA) with its three target acquisition and tracking cameras.

Table 1. Overview over the optical specifications and sensitivity requirements of the three SOFIA target acquisition and tracking cameras (data from Wiedemann, 2016a[6]).

	WFI	**FFI**	**FPI**
Field of view	6 deg	67 arcmin	9 arcmin
Pixel FoV	21 arcsec	3.9 arcsec	0.51 arcsec
Focal length	136 mm	733 mm	$\sim$ 5240 mm
Aperture	68 mm	254 mm	2500 mm
Optics	Petzval lens	Schmidt-Cassegrain	SOFIA telescope
Mag limit requirement	11 mag	13 mag	16 mag
Mag limit before upgrade	9.8 mag	11 mag	12 mag*

* Since the upgrade in 2013 the FPI+ achieves a limiting magnitude of V ≈ 17 mag.

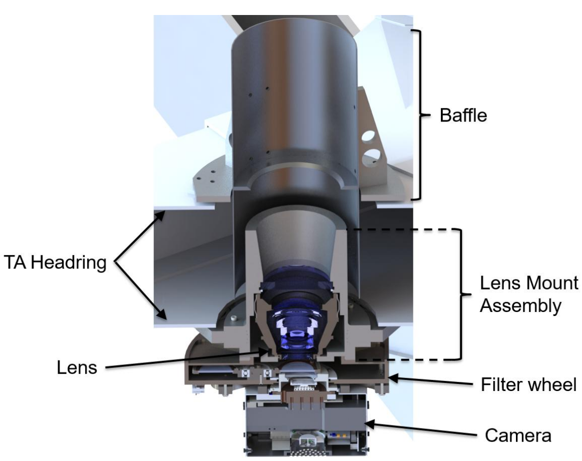

Figure 5. Model of the current WFI+ design.

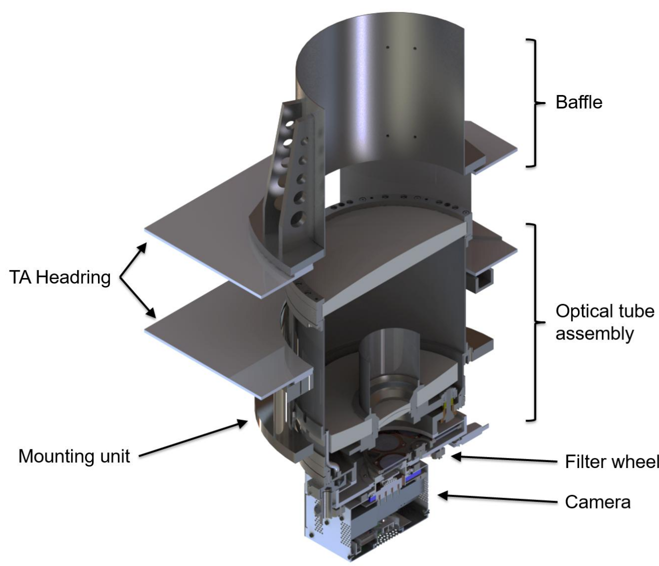

Figure 6. Model of the current FFI+ design.

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With the new optics and cameras, the WFI+ is expected to achieve a limiting magnitude of $V \approx 12.6$ mag and the FFI+ $V \approx 15.0$ mag at $t_{exp} = 2$ s (Wiedemann, 2016a[6]). The design of the WFI+ and FFI+ is complete and manufacturing of optics and the cameras has begun. It is planned to integrate the new imagers during a regular SOFIA maintenance period in 2017.

6. COMPUTER-AIDED STAR PATTERN RECOGNITION ON SOFIA

After SOFIA opens its door to the night sky, the initial telescope pointing is estimated with an accuracy of about 1°; i.e., the desired target is usually not positioned in the field of the FPI+ or FFI. This pointing estimate is calculated from GPS measurements (time, aircraft latitude, and longitude), avionics information (aircraft heading), and inertial gyroscope measurements (telescope attitude). To calibrate the pointing exactly, the telescope operator has to recognize the field in the three tracking cameras and manually identify two stars in an image. Telescope pointing also needs to be verified and refined at the beginning of each flight leg, as gyro drift accumulates without periodic correction through centroid measurements of selected guide stars in FPI+ or FFI images ("tracking").

As automated star pattern recognition (or "plate solving") has become standard practice in astronomic data reduction, we were looking for a tool that could support and potentially automate telescope pointing calibrations. After extensive testing, we have implemented the *astrometry.net* package[10,11] on the telescope operator workstations on-board SOFIA, which provides a very robust, reliable and fast algorithm for blind astrometric image calibration without any a-priori information. The *astrometry.net* package was explicitly developed to run without any human intervention, is distributed as open source under the GNU General Public License, and was developed on Linux with portability in mind. As the algorithm relies entirely on image data, it could be implemented as a stand-alone tool without any need to access observatory housekeeping data or to modify SOFIA's complex Mission Communications and Control System (MCCS). All these features made it the perfect choice for our specific application, although some hurdles had to be overcome to port the code to the Solaris 10 operating system on the MCCS workstations.

SOFIA's Wide Field Imager (WFI) was the prime choice for the task at hand: Its large 6° field, intended to provide context information on the sky, always contains a sufficient number of bright stars that allow for very quick plate solving. Our aim was to support the telescope operator with "live" information on telescope pointing, i.e., a continuous, almost instant feedback that assists with supervision and pointing calibration. The program's run time to solve a WFI image on the MCCS workstations is below 2 s. After demonstrating the code's capabilities in the WFI, plate solving was extended to the Fine Field Imager (FFI) right away, which allows for a similar processing speed given its medium field size (1.12°).

The *astrometry.net* package was deployed on board SOFIA in March 2016, together with a new release of the MCCS workstation GUI (v8.9.0) developed by USRA. A new GUI panel allows continuous solving of WFI images in specified intervals, and immediate solving of a WFI or a FFI image at any time. In addition, it is possible to command a pointing calibration based on the calculated right ascension and declination of the field center, and the field's rotation angle.

The telescope operator can now rely on a computer-aided star pattern recognition algorithm to quickly calibrate telescope pointing based on WFI and FFI images, which is especially advantageous for observations of targets in crowded fields. This new tool could potentially save a significant number of valuable minutes on every SOFIA flight in favor of collecting more science data, further increasing the efficiency of the observatory. Details on the implementation of the *astrometry.net* package on SOFIA can be found in Schindler et al. (2016a)[12].

To simplify the usage of the command line based solver and to speed up processing of narrow fields obtained e.g., with ATUS (see section 8) and the FPI+, a platform independent graphical user interface (GUI) has been developed at DSI on the basis of Python and PyQt4. We plan to make this GUI available to the community on GitHub. The GUI and *astrometry.net* are used among DSI's staff on various computers running Windows, macOS and Ubuntu. The package also finds use to add World Coordinate System (WCS) FITS file header information to Level 2 FPI+ data products.

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7. BACKUP SECONDARY MIRROR

The SOFIA telescope is a Cassegrain design with a convex, hyperbolic secondary mirror (M2). The M2 is 352 mm in diameter, was made from silicon carbide and weighs only 1.9 kg. Given the fact that this material is brittle and the secondary mirror represents a single-point of failure, an inexpensive backup solution with reduced performance was made in 2003/2004 (Erickson et al., 2004[13]). The design of this aluminum 6061 mirror matches the mass, center of gravity, and moments of inertia with those of the SiC mirror. In order to account for the lower specific stiffness of aluminum, the light-weighted structure on the backside was altered, increasing the number of stiffeners in all directions to reduce the free span width of all pockets.

However, during ground tests on the SOFIA telescope in Waco in August 2004, it became apparent that the mirror produced double peaked images with peaks 5 arcsec apart. This was considerably worse than expected. One plausible explanation was that the surface figure was significantly worse at the outskirts area, where it could not be determined with the used measuring machine. Another explanation was that since only two profiles across the surface were measured, by chance they could have been "good" ones, while the rest of the mirror is severely deformed. Or it could be a structural problem due to gravity or temperature gradients which were not addressed during the development phase.

Hence, new FE analyses predicting the gravitational sag and the dynamic behavior were conducted in 2011, which showed that the design of the aluminum mirror was sufficiently stiff and was not accountable for the poor optical performance. It seemed, therefore, desirable to carry out a more careful and complete characterization of the mirror surface in order to find an explanation for the discrepancy between predicted and actual image quality before manufacturing a new one. NANOMEFOS, an at that time newly developed non-contact measurement machine at TNO[†] in the Netherlands, allowed a highly accurate determination of the complete convex hyperbolic surface of the mirror. The measurements showed that one of the mounting bipods used to interface to the Secondary Mirror Mechanism was deformed and caused a significant amount a warp of the mirror surface. However, even without this bipod, the measurement showed a trefoil that was higher than specified and previously measured with the two profiles. Optical simulations with the measured mirror surfaces were able to accurately reproduce the observed double peak images (Lachenmann et al., 2012[14]).

In 2012, DSI thus started the work on procuring a new, more precise aluminum spare mirror, that would allow tracking in the visual spectral range and diffraction limited observations in the mid-wavelength infrared. This was finally achieved in 2015 with the use of a state-of-the art diamond turning machines at TNO, the design change to a new aluminum alloy, and the verification of the diamond turned surface during several stages of the manufacturing. The new mirror (figure 7) shows a surface error of 121 nm RMS and 685 nm peak-to-valley (figure 8). This is about ten times better than the previous aluminum mirror. Hereby, the use of the special aluminum alloy RSA905 was a key element in achieving these results. This material does not have to be heat-treated in order to become hard enough for diamond-turning. This was determined to be the root cause for a previously failed mirror manufacturing attempt. The heat treatment generated too much stress in the light-weighted structure, that could not be reduced enough with additional thermal treatments. Diamond-turning such a blank released the stress and resulted in a deformed surface of several microns.

With the new aluminum mirror, diffraction-limited observations are possible at wavelengths above 3.6 µm and the 80%-encircled energy diameter of less than 1 arcsec is more than sufficient for accurate tracking with the FPI+. The surface roughness was measured to be between 2.2 and 3.5 nm RMS. This results in a total integrated scatter of 0.5% at 633 nm. Table 2 shows a comparison of the nominal SiC M2 and the new backup aluminum M2. Further tests and measurements are planned to determine the dynamic behavior during 20 Hz chopping loads.

[†]Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek, https://www.tno.nl/en

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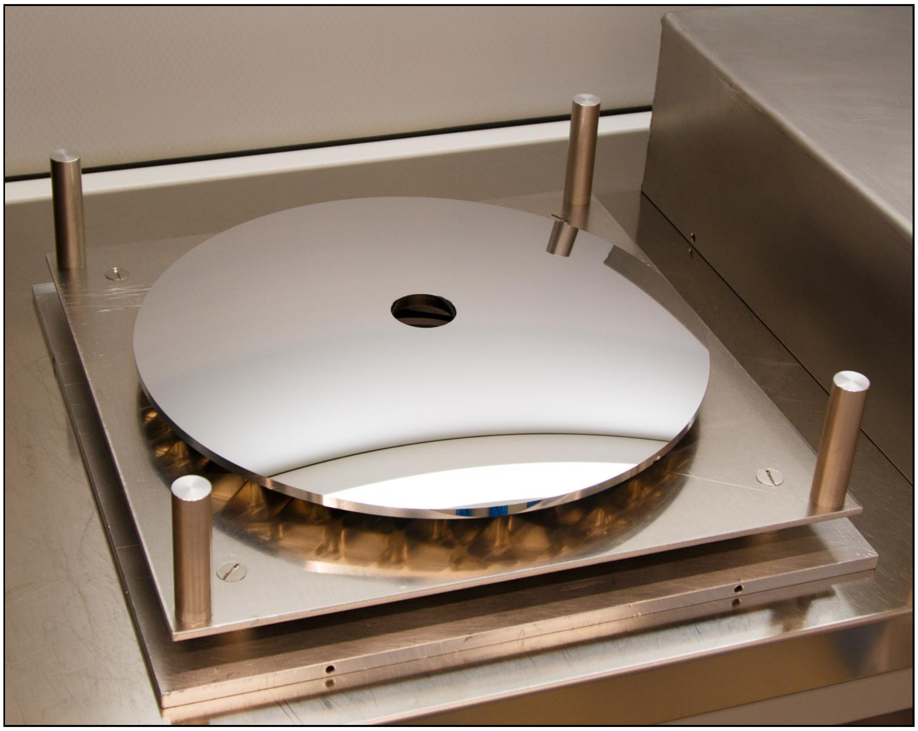

Figure 7. The finished backup aluminum secondary mirror.

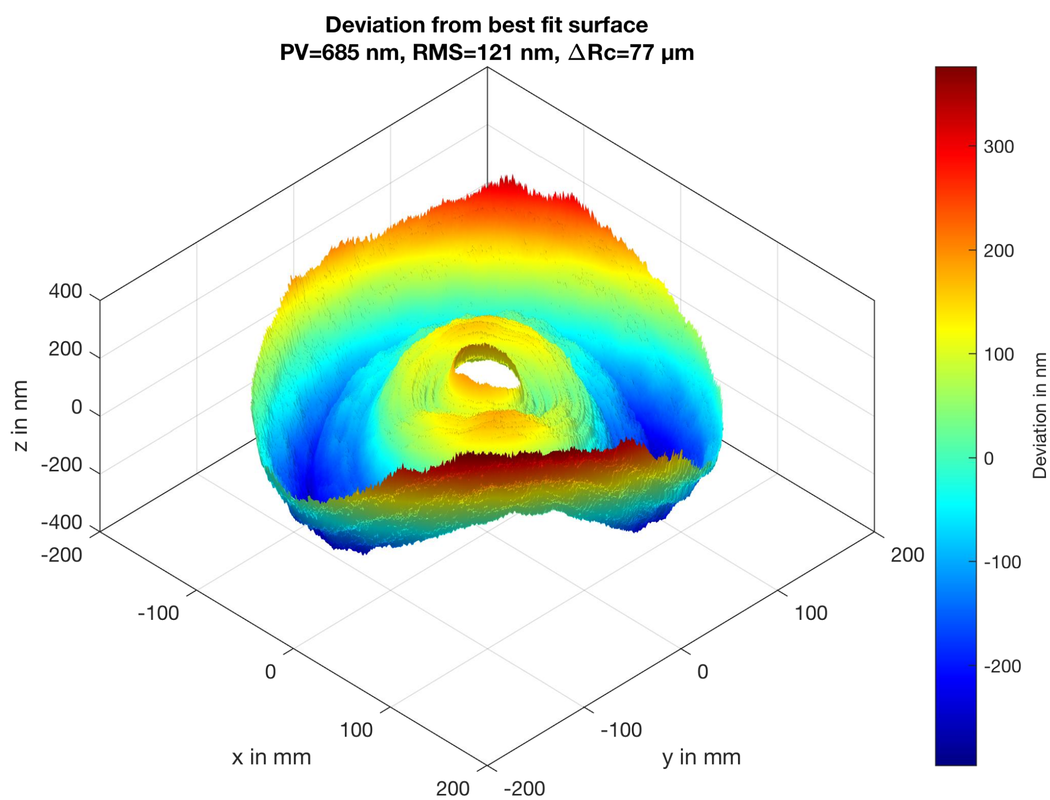

Figure 8. Deviation from best fit: 121 nm RMS, 685 nm PV, $\Delta \mathrm{Rc} = -77.25\,\mu\mathrm{m}$. The surface shows mostly astigmatism and spherical aberration, and only little printthrough of the backside structure.

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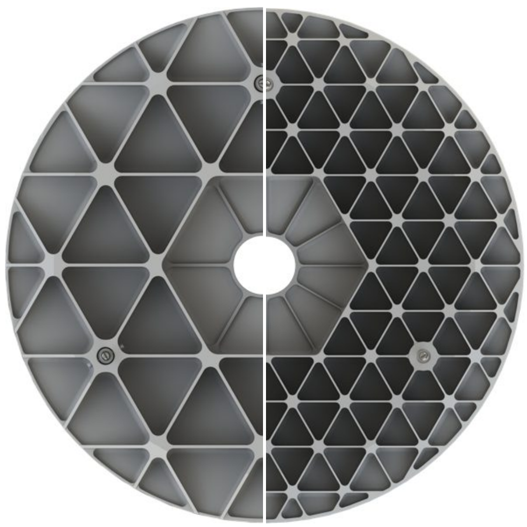
Table 2. Comparison of the SiC and Al secondary mirrors.

	SiC-M2 (as-built)	**Al-M2 (as-built)**
Material	Silicon Carbide	RSA905 Aluminum
Mass	1.967 kg	2.029 kg 76% light-weighted
Curvature radius	-954.13 mm	-954.78 mm
RMS surface error	$\sim$39 nm	121 nm
PV surface error	$\sim$170 nm	685 nm
RMS surface roughness	$\sim$2.6 nm	3.5 nm
TIS @ 633 nm	0.27%	0.5%
Diffraction limited λ	$< 0.7\,\mu$m	$3.6\,\mu$m
Backside structure		

8. THE ASTRONOMICAL TELESCOPE OF THE UNIVERSITY OF STUTTGART (ATUS)

DSI is operating the remotely controlled 0.6 m telescope "ATUS," the *Astronomical Telescope of the University of Stuttgart*[‡], in partnership with the University of Stuttgart's Institute of Space Systems (IRS). Located at Sierra Remote Observatories (SRO) in California's Sierra Nevada about an hour's drive north-east of Fresno, operations commenced in October 2013. A newly designed optical tube assembly, manufactured by Officina Stellare[§] and developed in partnership with DSI, was installed at the observatory in May 2015. During the design phase, emphasis was put on a reliable secondary mirror focusing mechanism, a weight reduction of the primary mirror, and a high mechanical stiffness verified through finite element analysis. The telescope is remotely controlled via internet connection from the SOFIA Science Center in Moffett Field, California and from Stuttgart, Germany, without any personnel on site at the observatory. Seeing conditions are in the range of 1.0 to 1.5 arcsec during summer.

The fully reflective 0.6 m f/7.9 Ritchey-Chrétien telescope is carried by a German equatorial mount made by Astro-Physics (AP3600GTOPE), which allows slew speeds of up to 2.5° per second. A precision encoder system at the polar axis of the mount provides nominal guiding accuracy better than 0.5 arcsec over periods of 20 minutes. Both mirrors are made of the ultra-low expansion glass-ceramics CLEARCERAM-Z HS supplied by

[‡]https://www.dsi.uni-stuttgart.de/forschung/atus.html
[§]Officina Stellare, Sarcedo, Italy, http://www.officinastellare.com

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Ohara. The primary mirror has a conically shaped back to reduce its weight. For focusing, the secondary mirror cell can be moved along the optical axis by a stepper motor linear actuator. The optical tube assembly is a dual carbon fiber truss structure with titanium alloy joints. Figure 9 illustrates the setup at the observatory.

The primary instrument at the Ritchey-Chrétien focus is an Andor iXon DU-888 camera with a back-illuminated EMCCD sensor, combined with a 10-position filter wheel containing a Sloan filter set. This setup closely resembles SOFIA's Focal Plane Imager (FPI+). The camera offers excellent quantum efficiency ($\eta_{\mathrm{Peak}} > 90\%$), high frame rates and virtually gap free imaging thanks to the sensor's frame-transfer architecture. As the camera's thermoelectric cooler achieves sensor temperatures of about 100 K below ambient, the sensor's dark current is extremely low. The main optical telescope is complemented by a piggy-back wide field imager, which consists of a FLI ProLine 4720 CCD camera, a 7-position filter wheel with a Johnson filter set and a commercial 135 mm f/2.8 Canon photo lens that can be remotely focused via an Arduino microcontroller. This setup is very similar to the SOFIA Wide Field Imager (WFI). An 80 mm f/9 guide scope with a QSI 632-ws8 CCD camera, including an 8-position filter wheel with Sloan and narrow-band filters, completes the setup. More details on the design and performance of ATUS can be found in Schindler et al. (2016b).[15]

For the University of Stuttgart, ATUS serves as a training platform for aerospace engineering students towards a basic education in astronomy. It acts as an example of a fully remote controlled complex system and as an instrument for research in engineering and astronomy for M.Sc. and Ph.D. students. For SOFIA, it is used as a test platform to evaluate new hardware (e.g., for wavefront sensing) and software (e.g., the *astrometry.net* plate solver, described in section 6) before its integration on the airborne observatory. In some cases, the telescope is also used to support SOFIA missions by providing preparatory or parallel measurements of a target, or to conduct follow-up observations. ATUS provided valuable inputs for planing and execution of SOFIA observations of, for example, the stellar occultation by Pluto in 2015, the comet C2013 US10 Catalina, and the nova V339 Delphini.

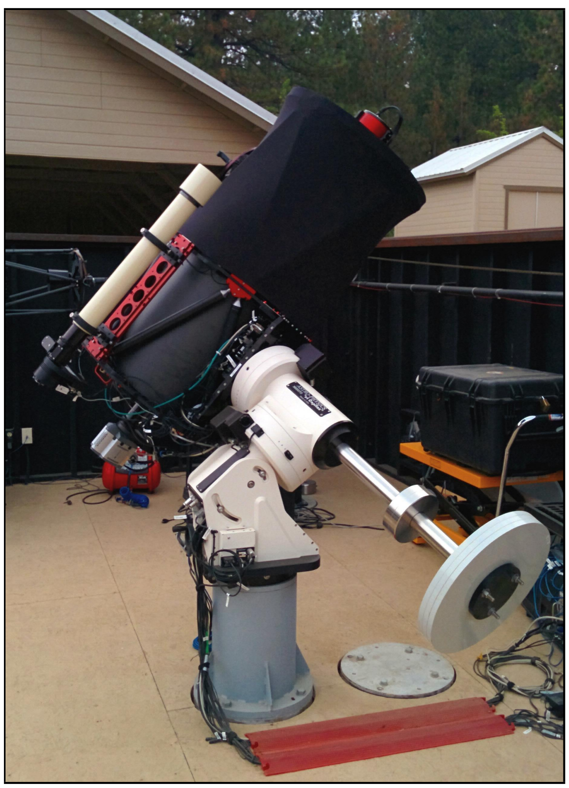

Figure 9. The 0.6 m Astronomical Telescope of the University of Stuttgart (ATUS) at Sierra Remote Observatories, California.

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ATUS will continue to serve as a test platform to evaluate and compare different methods for wavefront sensing; a comparison of Shack-Hartmann wavefront sensor measurements with results from an implementation of Roddier's curvature wavefront sensing technique[16] is in progress. Using ATUS, we also participated in a number of coordinated observing campaigns of predicted stellar occultations by asteroids[17] and trans-Neptunian objects (TNOs). Results from a successful observation of an occultation by TNO (229762) 2007 UK_{126} are summarized in Schindler et al. (2016c).[18]

9. OBSERVATION OF STELLAR OCCULTATIONS ON SOFIA

Our solar system beyond Neptune's orbit is populated with numerous small objects, referred to as trans-Neptunian objects. About 1500 TNOs are known today ranging in size from the most prominent one, Pluto (2370 km diameter), down to a few kilometers. Most diameters have been determined by radiometric methods in the IR/FIR (SPITZER, HERSCHEL) with uncertainties in the ±20% range. Only for Pluto and about 12 other objects have the projected diameters been measured more accurately by stellar occultations. A group of objects lingering between the orbits of Jupiter and Neptune, the Centaurs, are believed to have originated from TNOs. Two of them, Chariklo and Chiron, have recently drawn attention, as stellar occultations have revealed ice rings around them. We have successfully proposed occultation observations with SOFIA that shall add to the sparse knowledge on TNOs and Centaurs by determining more projected diameters and albedos. They have the potential of detecting moons, ice rings and atmospheres. We will use SOFIA's demonstrated capability of measuring occultations (Pluto 2011 & 2015) with the FPI+ to observe up to five events on flight legs of approximately 30 min each in 2017.

10. OUTLOOK

The DSI team at the SOFIA Science Center will complete the upgrade of the telescope's target acquisition and tracking cameras. The manufacturing of components for the new FFI and WFI has begun. Once the optical systems of each imager are complete (expected in early 2017), they will undergo environmental and optical testing, both in the laboratory and on sky. The integration into the observatory is planned in 2017, followed by in-flight tests and verification.

DSI is also planning to evolve the current stand-alone implementation of *astrometry.net* into a new "full frame tracking" mode for SOFIA that would use an entire star pattern, rather than manually selected field stars for centroid tracking in shift and field rotation.

Another task for 2017 is the observation of stellar occultations by trans-Neptunian objects and Centaurs, as approved for the team's observing proposal. The key to success of these observations will be highly precise predictions of shadow paths, precise enough to be able to place SOFIA close to the path's center line. Such predictions require extremely precise astrometry measurements, where the DSI team will rely mostly on their co-investigators with extensive expertise in this area, but hopes to make significant contributions with DSI's own ATUS telescope over time.

Further instrumental work for the SOFIA telescope will include the measurement of surface deformations of the aluminum spare secondary mirror under the dynamic loads of the chopping motion, possibly a spare dichroic tertiary mirror, a second spectral channel or grism for the FPI+, and a wavefront sensor for monitoring the optical performance of the SOFIA telescope. For FIFI-LS an option for larger detector arrays will be considered, that might increase the spatial and spectral coverage of the instrument.

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