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Adding a Second Spectral Channel to the SOFIA FPI+ Science Instrument

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ABSTRACT

The Stratospheric Observatory for Infrared Astronomy (SOFIA) is a heavily modified Boeing 747SP aircraft, accommodating a 2.7 meter infrared telescope. This airborne observation platform operates at flight altitudes of up to 13.7 km (45,000 ft) and therefore allows a nearly unobstructed view of the visible and infrared universe at wavelengths between 0.3 μm and 1600 μm.
The Focal Plane Imager (FPI+) is SOFIA's main tracking camera. It uses a commercial, off-the-shelf camera with a thermoelectrically cooled EM-CCD. The back-illuminated sensor has a peak quantum efficiency greater than 95% at 550 nm and the dark current is as low as 0.01 e-/pix/sec. Since 2015, the FPI+ has been available to the community as a Facility Science Instrument, and can be used to observe stellar occultations by solar system objects such as dwarf planets, moons, asteroids, and comets, and transits of extra-solar planets.
To date, SOFIA has conducted multi-channel observations of occultations, e.g. the occultation by Pluto in June of 2015 or the occultation by Triton in October 2017, using three instruments, HIPO and FLITECAM at the main instrument flange of the telescope, and the FPI+. This multi-wavelength sampling is important for enabling discrimination of particle sizes and constituents of hazes in the atmosphere of bodies such as Pluto and Triton, and the coma material of comets. Multi-wavelength observations also serve to allow us to place constraints on the chemical compositions of these formations.
After the retirement of the two other instruments, the FPI+ is now SOFIA's only remaining observing tool for occultations. In order to preserve some of the multi-color observing capability of the platform, we here discuss the addition of a second spectral channel to the FPI+. In a first upgrade step, a beamsplitter will split the incoming light and send it to two EMCCD cameras, one working in the "blue", e.g. SLOAN g' band, and the other working in the "red", e.g. SLOAN i' or z' band. In a second upgrade step, the "red" channel could be equipped with a NIR camera in order to provide a wider wavelength separation of the two bands. This will however require a modified dichroic coating on the tertiary (Nasmyth) mirror of the SOFIA telescope.
This paper presents a preliminary design study of the opto-mechanical configuration of the dual channel FPI+.

Keywords: SOFIA, EMCCD, Science Instrument, Multi-Color, Dual Channel, Photometry, Occultation

1. INTRODUCTION

SOFIA is a joint project of the National Aeronautics and Space Administration (NASA) and the German Aerospace Center (DLR). These two agencies are working together to operate this airborne observatory with its 2.5 meter telescope mounted in the rear fuselage of a heavily modified Boeing 747SP aircraft. During its projected lifetime of 20 years, SOFIA is used to study the universe in the infrared and far-infrared spectrum by carrying out astrophysical observations at flight altitudes up to 45,000 feet (13.7 km). SOFIA's mobility is an

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unique feature which makes it ideal to observe localized events like stellar occultations or eclipses.
Currently, SOFIA is in its sixth observing cycle with more than 450 completed flights and with a suite of six science instruments. The home base of this airborne observatory is Palmdale, California but the observatory regularly deploys to Christchurch, New Zealand for observations in the southern hemisphere.

2. CURRENT STATUS OF THE FPI+

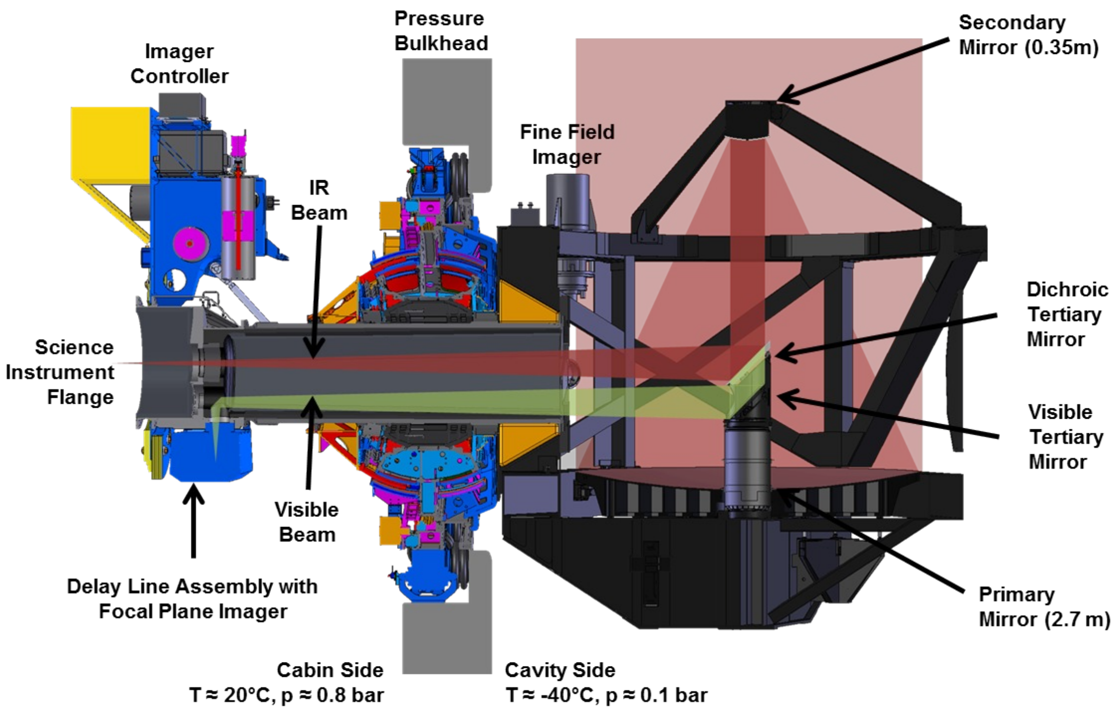

Figure 1. Cut-away CAD view of the SOFIA telescope and the light path through the optical system. Some of the main components are highlighted (illustration M. Wiedemann).

2.1 Optical configuration of the FPI+

The SOFIA telescope is a classical Cassegrain telescope with Nasmyth focus (figure 1). The FPI+ receives light via SOFIA's primary and secondary mirror. Most of the visual light passes the dichroic tertiary mirror M3-1 before it is reflected into the Nasmyth tube by the second tertiary M3-2. A transmission measurement of the dichroic tertiary is displayed in figure 4. The peak transmission is around 550 nm and gradually decreases toward longer wavelengths. The graph illustrates that a significant amount of visual light is not transmitted but rather absorbed or reflected along with the longer, infrared wavelengths. However, in the range between 480 nm to 800 nm where the visual-light CCD cameras are most sensitive, more than 50% of the light is transmitted.
The visual light continues through a set of silver-coated folding mirrors inside the Delay Line Assembly (DLA, figure 2). The first folding mirror is installed inside the Nasmyth tube to reflect the light beam into the DLA. A pair of windows is installed between the Nasmyth tube and the Delay Line Assembly that create the boundary between the stratospheric conditions in the Nasmyth tube and cabin conditions inside the DLA. The folding mirror "2" reflects the light onto the folding mirrors "3" which are installed on a slide to allow for a back focal length adjustment of ±600 mm. This large focus travel is required to compensate for different positions of the secondary mirror, which the "main flange" science instruments use to set their internal foci. An achromat is used to collimate the beam and to focus the pupil (i.e. the secondary mirror) onto the ZEISS lens. Close to the camera is a pellicle beam splitter, which has an 85% transmission and can be used to reflect a reticle into the

light path for camera alignment purposes.
A double carousel filter wheel is located in the collimated light beam. It has twelve positions with 60 mm diameter filters to select a neutral density filter for tracking on bright guide stars or to select different spectral bands. The last optical element in front of the camera is a commercial ZEISS photo lens. It is a Planar T IR lens with a special coating for increased transmission at near-infrared wavelengths, stepped down to f/2.0. The FPI+ camera is a commercial Andor DU-888 camera.*

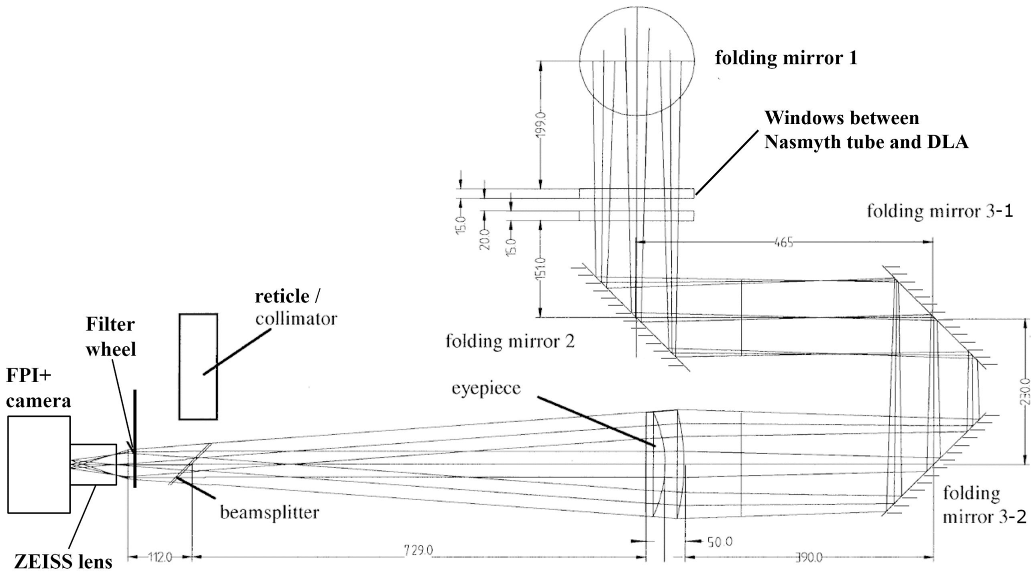

Figure 2. Schematic ray trace of the FPI+ optics from the pick-off mirror in the Nasmyth tube to the FPI+ camera at the end of the Delay Line Assembly (SOFIA design specification SOF-SPE-KT-5100.0.04).

2.2 FPI+ capabilities as a SOFIA facility science instrument

The focal length of the FPI+ is 5210 mm ±600 mm (due to the delay line focus mechanism) which results in a pixel scale of 0.515 arcseconds per pixel (unbinned) ±10% for the 13 μm pixel. The instrument has a square field of view (FOV) of 8.7 arcminutes. The unvignetted FOV is a circular beam of approx. nine arcminutes diameter, centered on the FPI+ sensor. The image quality at visual wavelengths is limited by shear layer seeing across the open door telescope cavity. The fast moving, turbulent air layer inflates the star image size to a FWHM in the range of 3.5 to 4 arcseconds depending on the aircraft flight altitude, the telescope elevation and the exact wavelength.
The double-carousel filter wheel of the FPI+ holds six spectral filters within the wavelength range of 360 nm to 1100 nm. These are five Sloan Digital Sky Survey filters u' g' r' i' z' and a Schott RG1000 near-infrared cut on filter. Table 1 shows the configuration of the FPI+ double filter wheel. The neutral density filters are used to attenuate bright stars if they are used for tracking. The RG1000 filter is used for target acquisition and tracking during twilight. The "OPEN" position is often used as the most sensitive mode of the FPI+. The "Blocked" position is used for taking calibration data (bias frames, dark frames).

The FPI+ is mainly used as a photometer to observe time-domain events in the visible wavelength range, e.g. stellar occultations by solar system objects. To date, this instrument has been used to observe stellar occultations by the dwarf planet Pluto (2011 and 2015), by Neptune's moon Triton and by the next NASA New Horizons fly-by target 2014MU69. Most of these observations have been performed in parallel with other SOFIA science instruments to collect multi-wavelength data.

*This is not the current "Ultra" version but rather its predecessor "iXon 3".

Table 1. FPI+ filter wheel configuration for the two filter wheel carousels.

Carousel 1 Science filters	Carousel 2 Tracking filters
OPEN	OPEN
Sloan u'	ND 1
Sloan g'	ND 2
Sloan r'	ND 3
Sloan i'	Blocked
Sloan z'	Daylight

More stellar occultation observations are planned for the current observing cycle.

2.3 FPI+ as a tracking camera

As the observatory's main tracking camera, the FPI+ is permanently installed and fully integrated into the telescope system. The target acquisition and tracking is routinely used on every SOFIA flight by the Telescope Operators (TO) through the observatory's Mission Controls and Communication System (MCCS). With the FPI+ it is possible to track on targets as faint as visual magnitude 16 during observations without chopping (starring).

3. UPGRADE OF THE FPI+

3.1 Motivation

Multi-wavelength sampling of stellar occultation events is important for enabling discrimination of particle sizes and constituents of hazes in the atmosphere of bodies such as Pluto and Triton, and the coma material of comets. Multi-channel observations also serve to allow us to place constraints on the chemical compositions of these formations.

Atmospheric temperature gradients can mask and be masked by extinction profiles (dust) in monochromatic occultation data. The easiest way to break this duplicity is with multi-wavelength observations.

Two of SOFIA's instruments that have previously been used to observe stellar occultations, HIPO and FLITECAM are being retired and the FPI+ is now the only remaining observing tool for occultations. In order to preserve some of the multi-color observing capability of the platform a second spectral channel could be added to the FPI+.

3.2 Dual channel FPI+ design

A dichroic beam splitter can be installed in the Delay Line Assembly to separate the incoming light beam into a "red" and "blue" channel. The beam splitter would be located close to the camera, in front of the filter wheel. The second camera could be from the same camera series as the current FPI+ camera, making use of known hardware and simplifying this upgrade. The lens in front of the camera and the camera window coatings can be optimized for the respective channel within the visible wavelength spectrum. The "red" channel could also be equipped with a camera that is sensitive to wavelengths up to $\approx$1.6 μm (H band). The thermal emission of the warm fore optics on the cabin side of the aircraft limits the sensitivity of the camera beyond 1.6 μm.

To make full use of this wavelength range at the FPI+ position, SOFIA's dichroic tertiary mirror would need to be modified (see figure 4). The cut-off wavelength of the pass-band would need to be shifted beyond 1650 nm, while maintaining high reflectivity for the longer wavelength infrared light.

The new beam splitter will be mounted on a slide, so it can be moved in and out of the light path. When positioned outside the light path, the current configuration of the FPI+ as a tracking camera and as a single channel photometer will be fully preserved.

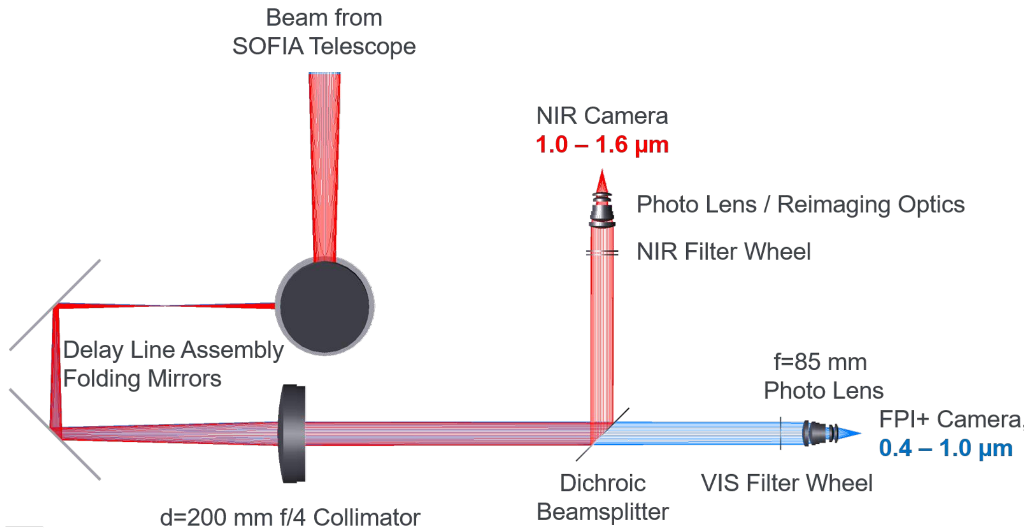

Figure 3. Ray trace of the FPI+ optics from the pick-off mirror in the Nasmyth tube to both of the FPI+ cameras at the end and the side of the DLA. This shows the option with a NIR camera at the second focus.

When the beam splitter is moved into the light path, the FPI+ will operate as a dual channel photometer. Provided that the exposure time for the "blue" channel will be compatible with tracking, FPI+ tracking will also be available in this dual channel mode. The image data of the new "red" or NIR channel will also be provided to the MCCS/tracker system on SOFIA, to enable tracking on the longer wavelength image data.

3.3 NIR camera candidates and selection criteria

Unlike CCDs, near infrared sensors have separate readout electronics for each pixel. There is no option for "on sensor pixel binning" to match the effective pixel size to the optimal sampling frequency of the PSF with the resulting improvement in readout noise. Thus, the pixel size of the detector needs to be matched to the angular

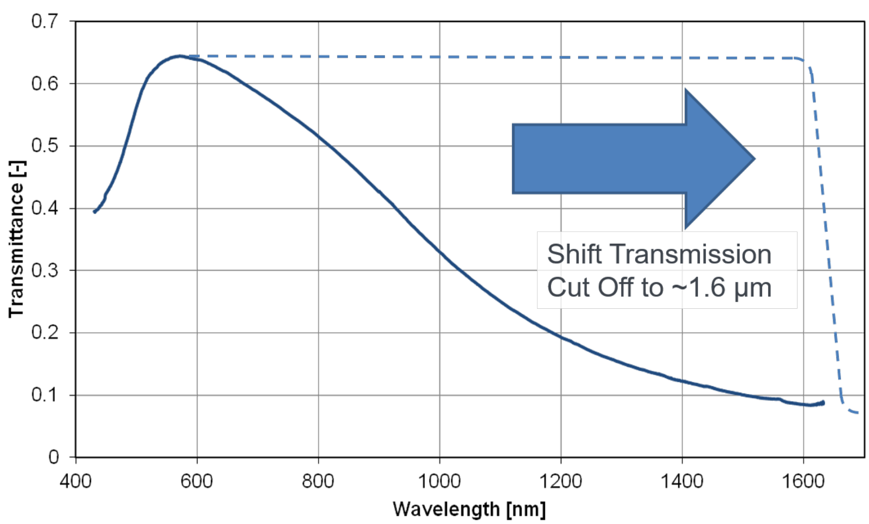

Figure 4. Transmittance of the dichroic tertiary mirror illustrating high transmittance at visible wavelengths and lower transmittance in the infrared. The current FPI+ is sensitive in the wavelength range from 400 nm to 1000 nm where the tertiary mirror lets most of the light pass through (DSI measurement, Wiedemann). Displayed with a dashed line is the shifted transmission to allow NIR imaging at the FPI+ focus.

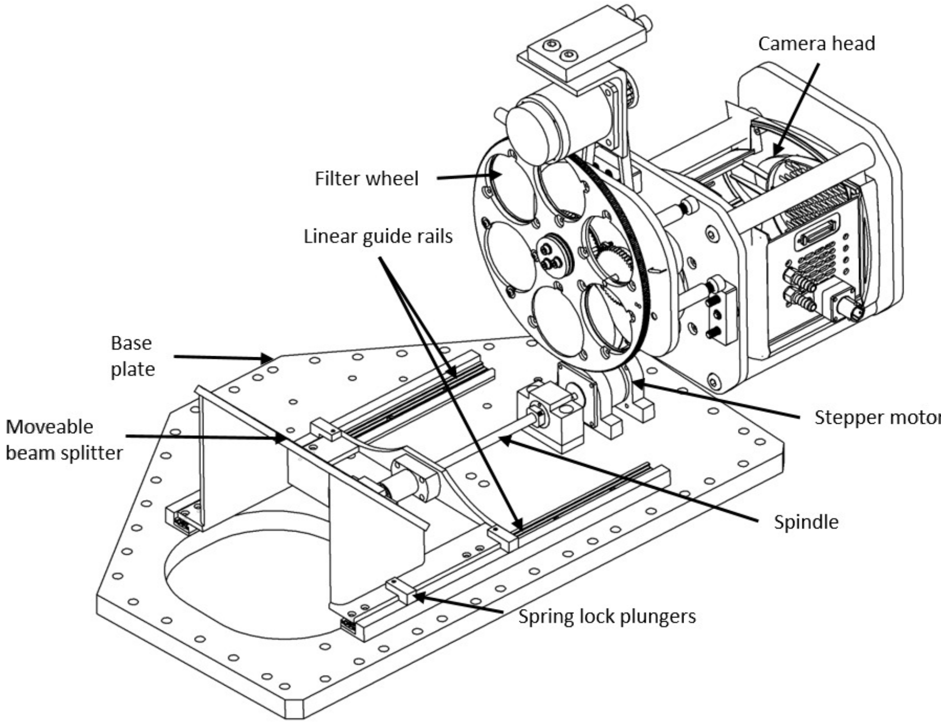

Figure 5. Preliminary design of a retractable beam splitter and the setup for a filter wheel, lens, focuser and second camera. In this view the light from the SOFIA telescope comes from the top and the original FPI+ with its filter wheel and lens is located below the "base plate" (not pictured).[Petri (2017)]

resolution after the chosen reimaging optics.
The image size on SOFIA at visible wavelengths is between 4 and 5.5 arcseconds FWHM. This characteristic improves somewhat at near infrared wavelengths (figure 6).

For roughly 3 arcseconds FWHM at NIR wavelengths, the optimal sampling would be 1.5 arcseconds per pixel. This could be achieved with a large pixel size and a higher focal reduction than in the current FPI+ channel (shorter effective system focal length). Table 2 shows a comparison of available sensors and their pixel properties. The system focal length would have to be achieved with reimaging optics directly in front of the camera since the other SOFIA optics are not to be changed. Among other favorable properties, the Lenoard Saphira APD FPA would offer the biggest pixel size, requiring a reduction of the system focal length to about 3300 mm to achieve 1.5 arcsec/pixel sampling.

Table 2. Available NIR sensors.

Focal Plane Array	Substrate	Pixel Count	Pixel Pitch
Teledyne H1RG	HgCdTe	1024 x 1024	18 μm
Leonardo Saphira APD	HgCdTe	320 x 256	24 μm
Xenics XFPA-1.7-640	InGaAs	640 x 512	20 μm
Princeton Infrared PIRT1280A1-12	InGaAs	1280 x 1024	12 μm
Sofradir SNAKE SW	InGaAs	640 x 512	15 μm

4. EXAMPLE OF MULTI-CHANNEL STELLAR OCCULTATION DATA

The 2015 stellar occultation by the dwarf planet Pluto was observed from SOFIA with three different instruments simultaneously. The resulting light curves of the four different wavelengths are displayed in Bosh et.

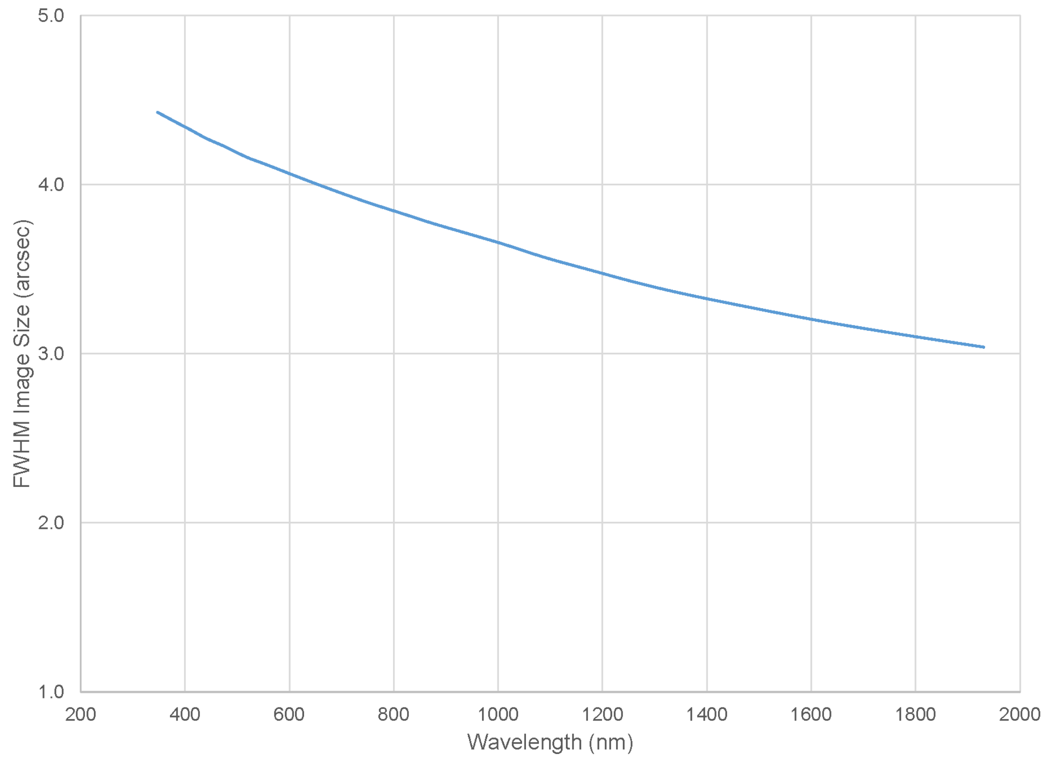

Figure 6. FWHM versus wavelength calculation for SOFIA showing the effect of shear layer turbulence, shear layer unsteady motion, and cavity aero-optical aberrations. This graph has been generated with data from Sutton and Pond,[Sutton, Pond (1998)] adjusted to the average measured image size of 4 arcseconds at 0.65 micron. The image size is calculated to be just above FWHM = 3 at a wavelength of 1.6 μm.

al.[Bosh *et al.* (2018)] The signal at the bottom of the light curve is comprised of the light from the solar system object, Pluto in this case, and light from the occulted star that is refracted in Pluto's atmosphere. The data nicely shows that the amount of refracted light differs depending on the wavelength. The atmospheric models indicate that this is only possible with haze present in Pluto's atmosphere.

These results show the importance of multi-channel photometry for stellar occultation observations. Multi-channel capability is necessary to study particle sizes and aerosol compositions during stellar occultationsby atmospheres, rings, and cometary coma.

Having multiple wavelengths available can make certain events more or less feasible, since the main limitation in occultation science is the SNR resulting from the ratio in brightness of the occulting body to the occulted star. This SNR can vary depending on the color of the objects.

5. SUMMARY AND OUTLOOK

With the retirement of HIPO and FLITECAM, SOFIA looses two instruments that can be used for multi-channel observation of stellar occultation. To preserve this capability, a second channel, either at visible wavelengths or at NIR wavelengths, can be added to the FPI+. Mechanically and optically, this upgrade seems feasible, whereas the NIR option is more challenging. It would involve a newly coated dichroic tertiary mirror for SOFIA as well as a departure from CCD sensors at the FPI position.

First industry contacts are promising that dichroic coatings with the required specification are available and a camera with a suitable NIR detector can be purchased or adapted.

A detailed feasibility study for this upgrade is expected to start later this year.

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