


# Occultations from SOFIA

**Occultations from SOFIA**  
Eliot F. Young(1), Marc W. Buie(1), Michael J. Person(2), Enrico Pfüller(3), Simon Porter(1), Karsten Schindler(3), Jürgen Wolf(3)  
(1) Southwest Research Institute, (2) Massachusetts Institute of Technology, (3) Deutsches SOFIA Institut

### About Occultations

**Why Occultations?**  
An occultation occurs when an object passes in front of a more distant object, so that a solar system body passes in front of a star.



**Fig. 2. Apparent occultation geometry.** The Jupiter or Mars-like (Jupiter) passes in front of distant star and causes shadow across the Earth. Because the star is so distant, the occultation shadow is the shape of the occulting object (shown in atmospheric effect) and that shadow moves across the Earth as the planet passes in front of the star. The sky plane velocity of the occultation shadow is the vector sum of the star's radial velocity and the Earth's orbital velocity.  $\sim 30$  km/s are typical.

Occultations can provide a rich suite of information about the occulting object, such as:

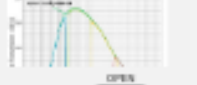
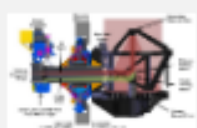
- Its precise location in space.
- Its size (provided stars are known from a satellite, its density).
- Projected shape (from multiple chords obtained from different sites).
- The pressure of an atmosphere from the shape of the light curve. Pluto's atmosphere was discovered from SOFIA's predecessor, the Kuiper Airborne Observatory.
- The temperature, surface wind direction, surface...

OPEN

### SOFIA: Supporting Occultations

**SOFIA: Occultation Specific Observations**  
The instrumentation of SOFIA is primarily for high-resolution infrared spectroscopy (IRS, FPI, LRS and QFPI) plus a coronagraph (C-COR) and the Faint Object Spectrograph (FOS). Each of these instruments can be mounted on the telescope, one at a time. The instrument of choice for occultations is the Faint Object Spectrograph (FOS), which is permanently mounted on SOFIA's main building system. It operates independently of the instrument that is mounted on the main stage. FOS is a 6000 Å camera of high spectral efficiency and a frame transfer camera. It can take precisely timed image sequences at high frame rates which is important for a complete sampling of an occultation light curve with high time resolution.

**Instrumentation for Occultations**




OPEN


### SOFIA: Occultation Mission Results

**Pluto 2015**  
Pluto occulted a bright star on 29 JULY 2015, just two months before the New Horizons spacecraft's flyby. SOFIA was deployed from Christchurch, NZ, to record this event. This occultation represented a new chance to compare ground-based occultations with the "ground truth" provided by the New Horizons radio occultation.

The video below shows the occultation star fading out... there is central flash, and the star's... appearance. Also, the occulted star is the brightest one in the field, located in the bottom of the field and just to the left of center.



Extensive planning was required to enable SOFIA's flight through Pluto's central flash zone. Fig. 3 shows a chronology of meteoric events and the resulting predictions to the months before the event.



OPEN

### How To: Planning SOFIA Occultation Campaigns

**Predictions: Meteoric Star and Object Position**  
The need for precise astrometry, with low error bars, quickly available light curves are essential to successfully observe an occultation on plus a SOFIA flight. Triggering an observation is usually provided by news of astrometric observations of a body of interest to refine its ephemeris. The goal is for astrometric errors to high-precision (e.g. 100  $\mu$ m) and a high-precision (e.g. 100  $\mu$ m) accuracy of 10 mas with respect to the star it will occult. That knowledge into a shadow path uncertainty of 200 km on the Earth. An analysis of sensitivity even small errors... the occultation for telescopes based planets... need to be well-understood.

The positions of the occultation shadow need to be measured at various epochs with respect to the GCR reference frame. This results systematic offsets to the published ephemeris, leading to a model that allows extrapolation of the "true ephemeris" to the event date. An even and more precise position measurements become available in the days leading up to an event, extrapolation errors and thus prediction uncertainties can often be reduced.

Given the value of observing time on SOFIA, there is the expectation that a high-precision, high-probability of achieving its science goals, such as successfully obtaining data from within the central flash zone or position detection of a nearby occultation.

Double stars, variable targets. The possibility of a double star is an additional risk to the occultation prediction. To mitigate the risk of SOFIA successfully being placed in front of two ground truths and thus missing the event, meteorologists must identify high-resolution observations of the target star using selective filters or a nearby occultation event to be sure.

OPEN

ABSTRACT CONTACT AUTHOR PRINT GET POSTER

Eliot F. Young(1), Marc W. Buie(1), Michael J. Person(2), Enrico Pfüller(3), Simon Porter(1), Karsten Schindler(3), Jürgen Wolf(3)

(1) Southwest Research Institute, (2) Massachusetts Institute of Technology, (3) Deutsches SOFIA Institut

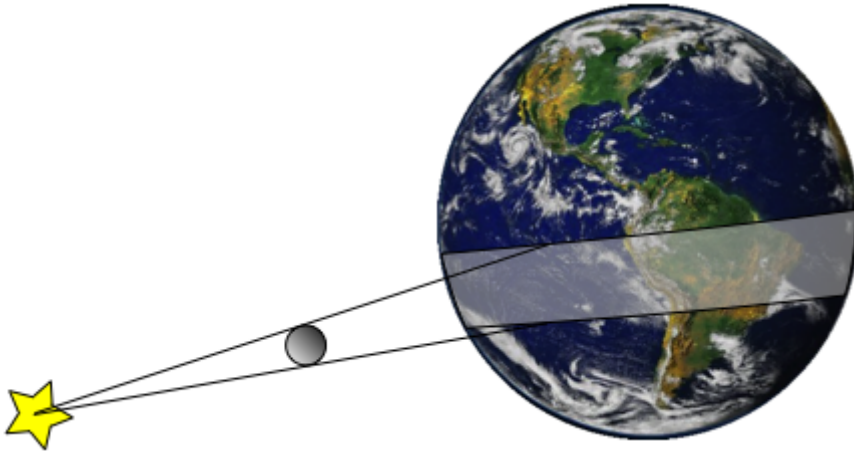
PRESENTED AT:



# ABOUT OCCULTATIONS

## Why Occultations?

An occultation occurs when an object obscures a more distant object, as when a solar system body passes in front of a star.



**Fig. 1** A typical occultation scenario: a solar system object, like Jupiter or Miranda or Quaoar, passes in front of a distant star and casts a shadow across the the Earth. Because the star is so distant, the instantaneous shadow is the shape of the occulting object (minus its atmospheric effects) and that shadow moves across the Earth at a rate that depends on the sky plane velocity of the object. The sky plane velocity is often dominated by parallactic motion due to the Earth's orbit: velocities of  $\sim 20$  km/s are typical.

Occultations can provide a rich suite of information about the occulting object, such as

- Its precise location in space.
- Its size (and if a mass is known from a satellite, its density).
- Projected shapes (from multiple chords obtained from different sites).
- The presence of an atmosphere from the shape of the lightcurve – Pluto's atmosphere was discovered from SOFIA's predecessor, the Kuiper Airborne Observatory.
- The temperature, pressure and density profiles of the atmosphere and the bulk column abundance.
- Gravity waves in the atmosphere.
- Atmospheric constituents, in cases where occultation lightcurves are obtained in diagnostic wavelengths.
- Haze opacities (usually requires two or more wavelengths).
- An atmospheres that is oblate or has a non-circular figure.
- For objects with unknown orbits, the distance and size can be separately determined if diffraction features can be resolved.

## Multi-wavelength Occultations

There are many reasons to observe an occultation in two or more wavelengths simultaneously. We mention three here.

*1. Distinguish aerosol opacity from attenuation due to the vertical temperature structure.* Light from the occulted star can be diminished by (a) refractive effects that spread out the star's rays (e.g., caused by thermal inversions, often called "differential refraction") or (b) by absorption by hazes or aerosols in the atmosphere. A single wavelength cannot separate the two effects, but two wavelengths can, because haze attenuation is wavelength-dependent.

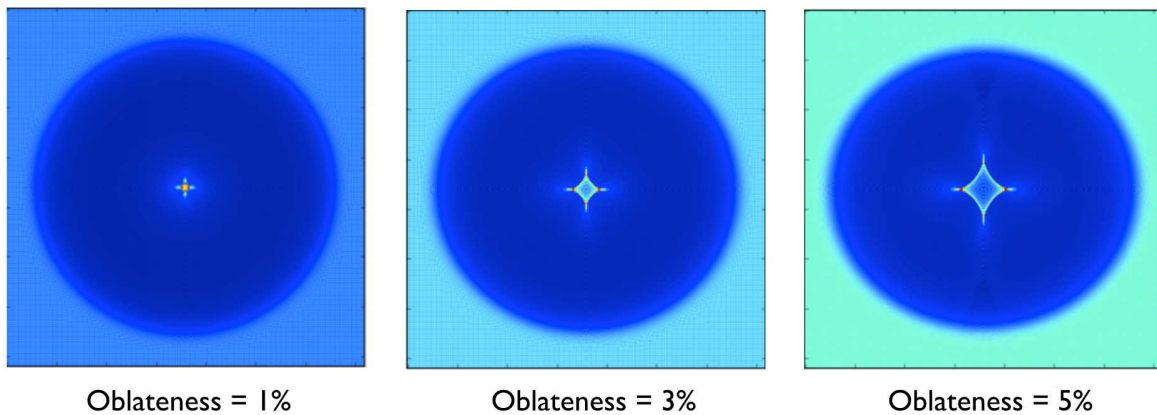
*2. Determine gas constituents in an atmosphere.* Two filters, one in a gas absorption band, one in a transmission window, can resolve the vertical mixing ratio of the gas.

3. *Confirm size of and distance to occulting bodies.* A solid body produces diffraction rings as it passes in front of the source. The width of the first ring is approximately a *Fresnel Scale*, defined as  $F = (\lambda D/2)^{1/2}$ , where  $\lambda$  = wavelength and  $D$  = distance to the occulting object. The overall duration of an occultation depends on the size of the occulter and its distance from the observer, but the extent of the diffraction fringes gives us a separate measure of the distance to the object. Two wavelengths aren't obligatory, but they provide useful confirmation in the form of fringe widths that are proportional to  $\lambda^{1/2}$ .

(See <<https://lesia.obspm.fr/perso/francoise-roques/odks/node4.html> (<<https://lesia.obspm.fr/perso/francoise-roques/odks/node4.html>>)>)

### Central Flashes

Occulters with atmospheres often produce a bright caustic-shaped feature in the center on their shadows. These features are caused by refraction of rays around the limb of the occulter, and the shape of these bright features are extremely sensitive to the shape of the atmosphere.



**Fig. 2** Simulated occultation shadows in the observer's plane with bright caustics in the centers of the shadows. As the oblateness of the occulter varies from 1% (equatorial radius is 1.01 times the polar radius) to 5%, the size of the central caustic changes dramatically.

An observer near the center of the shadow path will see a "central flash" as the bright caustic feature passes by. For an object like Pluto, the extent of the central flash region is several tens of km. The amplitude of the central flash peak is very sensitive to opacity sources, like aerosols, at the altitude from which the central flash rays originate.

### Advantages of an Airborne Platform

SOFIA has advantages as a mobile, airborne occultation observing platform.

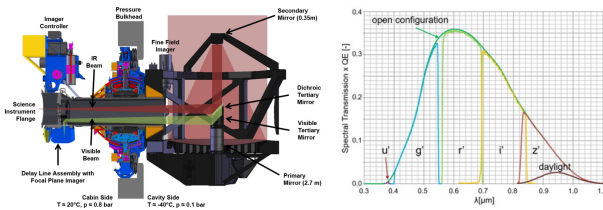
- Results are mostly independent of weather. SOFIA is rarely "clouded out."
- SOFIA can access locations on the Earth over oceans or difficult terrain.
- SOFIA can navigate to be at a precise location at a precise time. For short-duration occultations by small objects (like Arrokoth), this ability is crucial. It also enables central flash observations when ground observers can't get near the shadow's central chord.
- SOFIA can respond to late changes in the shadow path prediction (within a certain range).
- SOFIA's aperture (effectively 2.5 m) is larger than many ground-based telescope's and all portable telescopes.
- SOFIA's Focal Plane Imager Plus (FPI+) is well-suited to occultation observations. It is always available (via a dichroic), it has fast frame rates with virtually no deadtime, high quantum efficiency and low read noise.

# SOFIA: SUPPORTING OCCULTATIONS

## SOFIA: Occultation-Specific Overview

The instrumentation of SOFIA is primarily for high-resolution far-infrared spectroscopy (EXES, FIFI-LS and GREAT) plus a camera for  $\lambda < 30 \mu\text{m}$  (FORCAST). Each of those instruments can be mounted on the telescope, one at a time. The instrument of choice for occultations is the Focal-Plane Imager, FPI+, which is *permanently mounted* as SOFIA's main tracking camera. It operates independently of the science instrument mounted at the main flange. With an EMCCD camera of high quantum efficiency and a frame transfer sensor, it can take practically gapless image sequences at high frame rates which is important for a complete sampling of an occultation light curve with high time resolution.

## Instrumentation for Occultations



**Fig. 3a** (left panel) Cut-away view of the SOFIA telescope with some of its main components and a depiction of the incoming light. The dichroic tertiary mirror reflects the IR light to the instrument flange and transmits most of the VIS light to the Focal Plane Imager.

**Fig. 3b** (right panel) The portion of the incoming signal that is detected by the FPI+ camera in open configuration or with the spectral filters.

The focal length is  $5210 \text{ mm} \pm 600 \text{ mm}$  (due to the delay line focus mechanism) which results in a pixel scale of 0.515 arcseconds per pixel (unbinned)  $\pm 10 \%$  for the  $13 \mu\text{m}$  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 visible 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 and the telescope elevation.

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. The remaining filter positions are used for neutral density filters, blocked and open positions.

FPI+ offers different readout modes, with trade-offs between readout speed and readout noise for the different modes. For a given mode the readout noise per area on the sky can be reduced with pixel binning, where multiple pixels are read out as one pixel. The instrument offers electron multiplication which can increase the signal on the sensor before it is read out. Electron Multiplication can be applied for observations that are read-noise dominated – this results in a virtual reduction of the sensor readout noise. This feature has been used for pure detection observations but not for occultations that aim at sampling the atmosphere of the occulting body due to concerns over the stability of the EM gain over time.

The FPI+ instrument is permanently installed on SOFIA and it is available in parallel to any infrared science instrument at the main flange. Most FPI+ observations can be integrated into the flight plans of any other science instrument as specialized observing leg and therefore do not require a full SOFIA flight. Observations can be performed in parallel with the IR instruments to collect simultaneous datasets at multiple wavelengths.

Currently, there are preparations underway to upgrade the FPI+ with a second near-infrared channel. This would enable dual wavelength observations of stellar occultations which greatly improves the atmospheric research of the occulting bodies.

## SOFIA Logistics

SOFIA's home base is in Palmdale, CA, where standard missions start and land after typically 10 hours of flight. As the azimuth (called cross-elevation XEL on SOFIA) of the telescope's pointing is determined by the flight direction, except for a small range of  $\pm 3$  degrees of telescope movement in XEL, the sample of astronomical objects selected for a mission is setting a rather complicated zig-zag flight path projected on the ground. Another border condition for flight planning is the limited elevation range of the SOFIA telescope (23 to 58 degrees).

SOFIA is stationed at Christchurch, NZ during its annual southern deployment for 8 to 12 weeks in the northern summer.

If the observation of an occultation is embedded in a mission with other astronomical objects, the range around Palmdale (or Christchurch) will be about 2000 to 3000 km. For occultations that occur farther out of Palmdale, a dedicated mission has to be planned. With it, occultation paths up to about 4000 km out of Palmdale can be reached, covering large parts of North America and the Pacific. These missions require a pre-arranged landing site that allows access to the occultation path with a take-off or landing at Palmdale. SOFIA is not allowed to enter Mexican airspace.

# SOFIA: OCCULTATION MISSION RESULTS

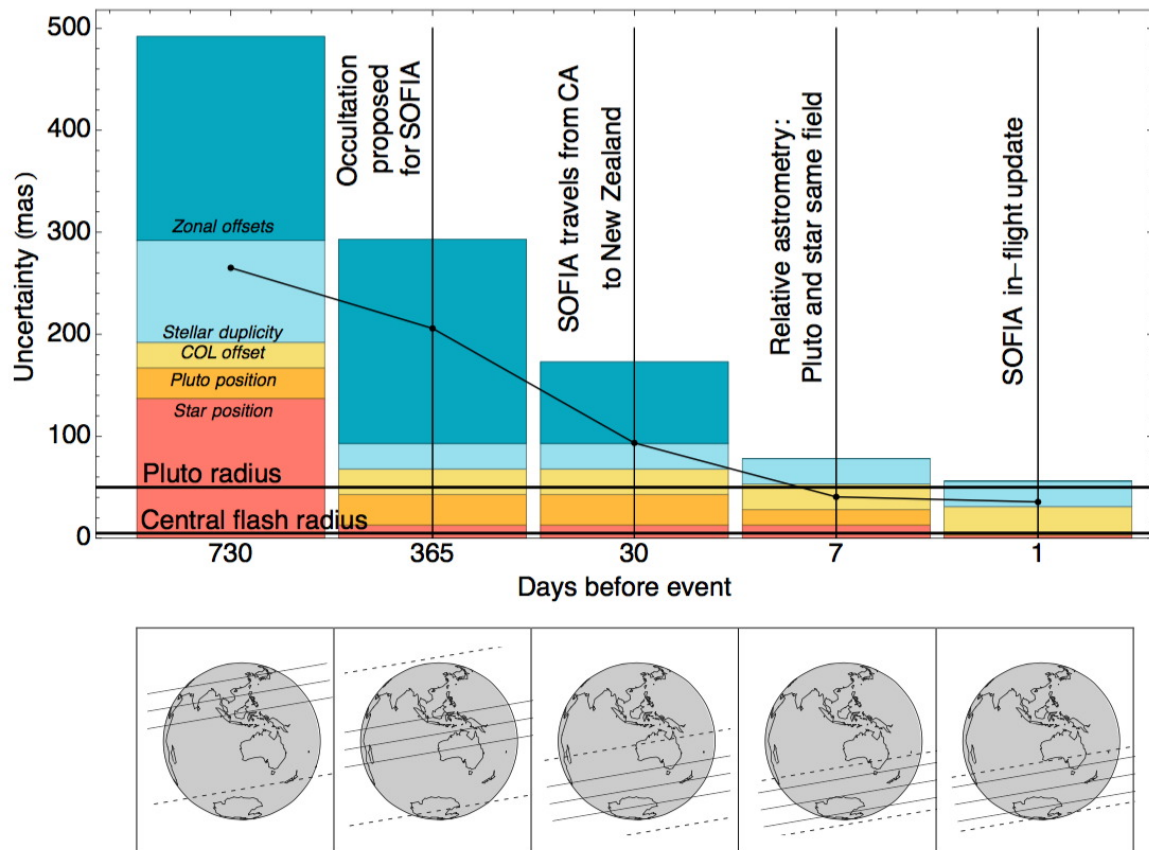
## Pluto 2015

Pluto occulted a bright star on 29-JUN-2015, just two weeks before the New Horizons spacecraft's flyby. SOFIA was deployed from Christchurch, NZ to record this event. This occultation represented a rare chance to compare ground-based occultations with the "ground-truth" provided by the New Horizons radio occultations.

The video below shows the occulted star fading out - then a central flash - and the star's re-emergence. *Hint:* the occulted star is the brightest one in the field, towards the bottom of the field and just to the left of center.

[VIDEO] <https://www.youtube.com/embed/6p5e8ZCpSpY?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0>

Extensive planning was required to enable SOFIA's flight through Pluto's central flash zone. Fig. 4 shows a chronology of astrometric errors and the migrating prediction in the months before the event.

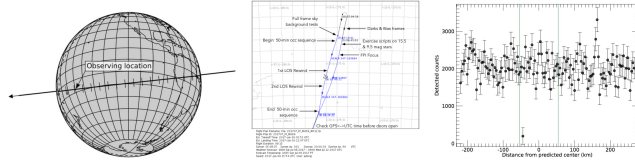


**Fig. 4** Occultation prediction uncertainties in the two years before the event. The stacked bar shows the relative contribution of each type of uncertainty; the connected black points give the sum in quadrature of the ensemble of uncertainties. Also highlighted are the different stages in the prediction as it relates to preparing for an occultation observed with SOFIA. Some uncertainties we can reduce very early in the process - like improving on the star's position and checking for duplicity - while other uncertainties due to zonal issues remain until the same astrometric network can be used to measure Pluto's and the occultation star's positions.

## Arrokoth 2017

The New Horizons spacecraft flew by Arrokoth (2014 MU69) on 1-JAN-2019, but SOFIA acquired the first occultation detection of Arrokoth on 10-JUL-2017. We now know that Arrokoth is a contact binary, 22 x 12 x 6 km in extent. Although its dimensions were not known before the occultation, the largest plausible size (corresponding to a 4% albedo) was 40 km, suggesting that astrometric errors of less than 1 mas were required to have a reasonable chance of being in the shadow at the time of the occultation.

Arrokoth was discovered from Hubble Space Telescope (HST) images, and an additional HST campaign (GO-14627) shortly before the SOFIA flight improved the  $1\text{-}\sigma$  cross-track error to 14 km. SOFIA's flight crew successfully placed the telescope within 1 km and 1 sec of the targeted window.



**Fig. 5a** (left panel) The predicted shadow path for Arrokoth, with SOFIA's chosen intercept point (Fig. 5 of Buie et al. (2020)). Arrokoth's sky plane velocity was 25.0 km/s. The arrowhead shows the direction of the shadow; the ticks represent 30-s intervals.

**Fig. 5b** (middle panel) Part of the SOFIA flight plan, annotated with observing tasks, including the 50-min segment spanning the Arrokoth occultation.

**Fig. 5c** (right panel) The SOFIA/FPI+ lightcurve from Fig. 6 of Buie et al. (2020). The occultation was observed at 20 Hz. Three points showed a dimmed star. The lightcurve in this figure was derived from binned pairs of data frames, so just one low point appears in this 10-Hz lightcurve, corresponding to a chord length of  $\sim 1$  km. *Note:* most of the 44 km distance from the predicted center in this figure has since been attributed to a 2-s timing error in the FITS headers of the HST GO-14267 images. The SNR of this event was degraded by about a factor of 3 by scattered light from the full moon, which was only  $17^\circ$  from the occultation.

# HOW TO: PLANNING SOFIA OCCULTATION CAMPAIGNS

## Predictions: Astrometric Star and Object Positions

*The need for precise astrometry.* With few exceptions, publicly available ephemerides are insufficient to successfully observe an occultation or plan a SOFIA flight. Triggering an observation is usually preceded by years of astrometric observations of a body of interest to refine its ephemeris. The penalty for astrometric errors is high: if a 40 AU-distant TNO, for example, has a 1- $\sigma$  uncertainty of 10 mas with respect to the star it will occult, that translates into a shadow-path uncertainty of 290 km on the Earth. At that level of sensitivity, even small effects - like plate solutions for telescopic focal planes - need to be well characterized.

The positions of the candidate occulter need to be measured at various epochs with respect to the Gaia DR2 reference frame. This reveals systematic offsets to the published ephemeris leading to a model that allows extrapolation of the “true ephemeris” at the event date. As more and more position measurements become available in the days leading up to an event, extrapolation errors and thus prediction uncertainties can often be reduced.

Given the value of observing time on SOFIA, there is the expectation that a flight must have a high probability of achieving its science goals, such as successfully obtaining data from within the central flash zone or positive detection of a small-body occultation.

*Double stars, double targets.* The possibility of a double star is an additional risk to the astrometric prediction. To minimize the risk of SOFIA essentially being placed between two ground tracks and thus missing the event, investigators must attempt high resolution observations of the target star using adaptive optics or speckle interferometry with a large telescope. (This time often needs to be requested around the time a SOFIA proposal is due, i.e. more than a year ahead of the event.)

Many of the larger TNOs are known to be binaries. Any presence of a satellite will cause a periodic shift of the combined center of light, often on the order of the radius of the target. Hubble, AO and ALMA data collected in recent years led to a discovery of numerous satellites and in some cases, have helped to shed light on the geometry of these binary systems. Generally, it remains difficult to have firm information on the satellite’s relative position and brightness, which does affect the primary body’s position on the milliarcsecond level. Often, this risk can only be mitigated by collecting as much data from as many sources as possible ahead of the event.

*Collaborate with SOFIA/DSI to refine predictions.* To support occultations on SOFIA, DSI has developed several Python packages from scratch that support astrometric observations, generate shadow path predictions, allow optimized light curve and event time extraction, and reconstruct and visualize the geometry of an event based on obtained data. The immense amount of preparatory work and required data collection to enable a successful SOFIA mission requires a collaborative effort between investigators and DSI scientists.

## Triggering Occultation Events

Flight planning for a series of missions with a particular instrument starts around two months before the series’ first flight. At that time, an investigator needs to trigger a particular event, either through an approved *target of opportunity proposal* or a request for *director’s discretionary time*. This decision needs to be based on a still-preliminary prediction to allow the project to work out a flight schedule and path that accommodates the general timing needs.

While the cross-track positioning of SOFIA is critical to getting the event and meeting the science goals, along-track positioning of the occultation’s “intercept point” will depend on many variables such as distance to SOFIA’s home base, flight range, operational constraints (must land before dawn, available alternative landing sites, air space constraints), and the other science targets to be observed with the main instrument during the same flight. Integrating an occultation into a regular flight plan becomes a complex optimization problem ensuring that SOFIA is at a precise location at a precise time while using the remaining flight time for other science investigations.

Activating a Target-of-Opportunity proposal requires approval of the particular science case by SOFIA’s Science Mission Operations (SMO). During the weeks leading up to the event, a significant effort is made to update and reduce the uncertainty of the prediction through repeated astrometric observations of the target body, and ideally also through high resolution observation of the target star using suitable large telescopes.

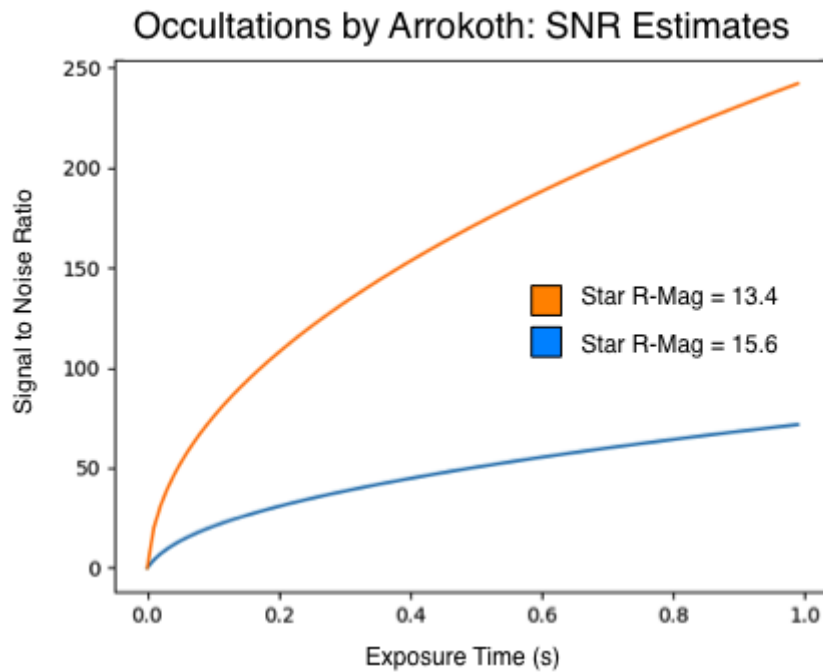
As operational schedules (flight days) of the observatory are usually approved months in advance by the Project Management Board (PMB), occultation observations usually require shuffling of flight days and required personnel. *The PMB needs to review and approve any schedule change one month ahead of the event.* An improved prediction needs to be available at the time of this review, which provides a formal “go/no-go decision.”



During the last month before the event, the team takes any opportunity to improve and verify the prediction. Prediction updates are required 5 days, 72 h, 36 h and 12 h (day of flight) before SOFIA's take-off. The later three relate to flight schedule updates that also incorporate weather forecasts along the planned flight route. It is not unusual that the flight path gets tweaked up until day-of-flight review, or on dedicated occultation missions, even after take-off (as was done with Pluto occultation flights in 2011 and 2015). Shift of the flight's waypoints result in a change of the formal flight schedule that needs to get filed with air traffic authorities. To compensate for any variability in precise take-off time and ground speed due to wind conditions, flights usually incorporate a holding pattern of several minutes before an occultation leg, while SOFIA's flight altitude during the occultation is usually reduced to about 36k – 38k ft to allow the pilots more precise speed variations in denser air to reach a precise point at the exact time.

### Expected SNR at the Required Cadence

Occultation observations are essentially exercises in stellar photometry, with two key differences. First, exposure times are often short in order to resolve a phenomenon of interest (e.g., two samples per atmospheric scale height or the chord length across a small occulter). Cadences of 1 to 10 Hz are common. Second, the photon shot noise from the occulter itself is present throughout the event. For that reason, it is good if the occulted star is brighter than the occulter, or at most a magnitude fainter.



**Fig. 8** Estimated Signal to Noise Ratios (SNRs) with SOFIA/FPI+ for two 2017 occultations by the TNO (and New Horizons target) Arrokoth. One of the stars had an R-magnitude of 13.4, the other, 15.6. The Jupyter notebook used to produce this plot is online:

[www.boulder.swri.edu/~efy/SOFIA/MU69\\_FPI\\_SNR\\_v02.ipynb](http://www.boulder.swri.edu/~efy/SOFIA/MU69_FPI_SNR_v02.ipynb)

# ABSTRACT

Occultations occur when a relatively near object (like Pluto) passes in front and blocks light from a more distant object. These events can be useful in determining an object's size, its precise celestial coordinates, the vertical temperature, pressure and density profiles of its atmosphere, the vertical distribution of aerosols, and in cases where Fresnel fringes can be resolved, the distance to the occulting object.

We are currently in an occultation golden age: the Gaia star catalog provides us with unprecedentedly accurate stellar positions, but these positions will be degraded by stellar proper motions in the years to come. A SOFIA occultation campaign often requires extensive pre-flight observations to determine a very accurate ephemeris for the occulting object, as well as adaptive optics observations of the star itself to make sure it is not double. For objects with sizes of a few 10s of km (like Arrokoth), a milliarsecond error in the object's RA and DEC relative to the occulted star is equivalent to missing the event by more than the width of the shadow path. Other science goals, like observing central flashes, also require that observers be placed within a few 10s of km of the center of the shadow path.

SOFIA is an effective platform from which to observe occultations. It can be deployed with extreme precision to locations where ground-based observations are impossible, as it was for Arrokoth (then 2014 MU69). The permanent guide camera, FPI+, has properties that are well-suited to occultation observations: high quantum efficiency, low read noise and high frame rates. SOFIA's large aperture means that occultations of faint stars may still provide lightcurves with productive signal-to-noise ratios.

We report on a few examples of SOFIA's successful occultation campaigns, including the first occultation detection of Arrokoth and occultations of Triton and Pluto with central flash lightcurve features. We briefly describe where central flash features come from and why they are so sensitive to haze opacity and temperature profiles. Finally, we discuss SOFIA's prospects for upcoming occultations.