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SOFIA Flight Planning and Execution

K. Leppik[1,4], K. Bower[2], C. Kaminski[1], C. Trinh[1], T. Civeit[3] and T. Kilsdonk[2]

[1]USRA SOFIA, NASA Armstrong Flight Research Center
Building 703, Palmdale, 93550, CA

[2]USRA SOFIA, NASA Ames Research Center, N-232, Moffett Field, 94035, CA

[3]Deneb Aerospace, 404 Bryant Street, San Francisco, CA 94107
[4]karina.m.leppik@nasa.gov

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The Stratospheric Observatory for Infrared Astronomy (SOFIA) is NASA's airborne observatory. Observing with SOFIA has different challenges than observing from a ground based, or even space-based observatory. Although pointing SOFIA is similar to pointing an alt/az telescope, positioning the telescope requires not only the telescope assembly but also the aircraft. SOFIA's telescope assembly can move in altitude nominally between 20° and 60°. Since the telescope is pointed out the left side of a modified Boeing 747, the azimuth is determined by the aircraft heading. As a result, observing plans become the basis for a flight plan, and the science observation and aircraft operations are intrinsically linked. This paper will discuss flight planning and execution on this unique observatory.

Keywords: SOFIA, airborne astronomy, flight planning, flight execution, infrared astronomy.

1. Introduction

The Stratospheric Observatory for Infrared Astronomy (SOFIA) is NASA's airborne observatory, a 2.5 meter telescope placed in a modified Boeing 747-SP (Young *et al.*, 2012; Ennico *et al.*, 2018). Planning and executing observations from an airborne platform has different challenges than observing from a ground based, or even space- based observatory. Since SOFIA is in constant motion during observations, planning an observation requires constantly updating the relative position of the object and telescope. It is possible for the observatory to travel to a latitude where objects become visible, or conversely are no longer visible. While this can be a challenge, it can also be used to SOFIA's advantage to observe a wider range of objects.

Pointing SOFIA is similar to point an altazimuth telescope. However, positioning the telescope requires not only the telescope assembly but also the aircraft. SOFIA's telescope assembly can move in altitude between 20° and 60° out the left side of the aircraft. The telescope azimuth is the aircraft heading minus 90°. As a result, observing plans become the basis for a flight plan, and the science observation and aircraft operations are intrinsically linked. Before and during flight, the aircraft and telescope systems are constantly monitored and adjusted in real-time to ensure that the telescope is positioned correctly for the planned observations to occur.

One distinctive aspect of SOFIA is that it is not limited to objects visible from any specific location on the Earth. Unlike any ground based telescope, SOFIA has the ability to observe objects anywhere on the celestial sphere by relocating. SOFIA can also put itself right under the path of an occultation, making these events observable with a world-class telescope. SOFIA has relocated to locations other than its base of operations at Palmdale, California to take advantage of these capabilities, including being based on Christchurch, New Zealand for many weeks each year.

2. Scheduling Observations with SOFIA

The process of observing with SOFIA starts with a call for proposals for a specific cycle, or year of observations. The call for proposals includes what instruments will be available in that cycle. Instruments offered in cycle 7 which begins in 2019 are: Echelon-Cross-Echelle Spectrograph (EXES), a mid-infrared high-resolution spectrograph (Richter *et al.*, 2010, 2018); Far Infrared Field-Imaging Line Spectrometer (FIFI-LS), an integral-field far-infrared spectrometer (Klein *et al.*, 2014; Fischer *et al.*, 2018; Colditz *et al.*, 2018); Faint Object InfraRed Camera for the SOFIA Telescope (FORCAST), a mid-infrared camera and grism spectrometer (Herter *et al.*, 2012, 2018); Focal Plane Imager (FPI+) a visible light focal plane imager (Pfüller *et al.*, 2016, 2018); German Receiver for Astronomy at Terahertz Frequencies (GREAT), a heterodyne spectrometer including the seven-beam receiver array upGREAT and 4GREAT (Heyminck *et al.*, 2012; Risacher *et al.*, 2016a,b, 2018); High-resolution Airborne Wideband Camera + Polarimeter (HAWC+), a far-IR camera and polarimeter (Harper *et al.*, 2018). More details on SOFIA's science instrument suite are in this volume (Ennico *et al.*, 2018). All of the submitted projects for a cycle go through a scientific peer review process. Accepted projects are granted an award of observatory time and a priority relative to other projects, and then refined into observation plans.

Once a cycle's worth of projects has been determined, the instrument schedule for the year can be set. Objects specified in each project are grouped together by the instrument, and this group of objects to be observed by a single instrument is called a "target pool." The best object availability during the year for each instrument is determined, and an instrument schedule for the cycle is set. Each group of flight using one instrument is called a series; a typical series is 6–12 flight over 2–3 weeks. Between each series, it takes a few days to remove an instrument from the aircraft and install another one. With a target pool, series dates and instruments selected, observations can be grouped into individual flight plans. While some aspects of flight planning and determining an instrument schedule are able to be solved by computer software, the fine details need to be done by a human.

2.1. *Software for scheduling and flight planning*

A new automated scheduling system has been developed to generate SOFIA's long-term and short-term operational schedules (Civeit *et al.*, 2017). The complex SOFIA scheduling problem has been decomposed into two sub-problems that can be handled by dedicated solvers:

- A Long-Term Scheduler (LTS) that generates yearlong schedules using global optimization. The LTS assigns instruments and maintenance activities to weeks, and it provides observation candidates for the individual flights. As the exact flight date, actual aircraft position and observation time cannot be known in advance, the LTS generates partially ordered/specified sequences of observations allotted to time windows (i.e. least commitment scheduler) and makes relevant approximations to generate realistic schedules.
- A Short-Term Scheduler (STS) that generates and simulates the individual flights is given by the instrument schedule. The STS combines the selection of feasible observations returned by the LTS and schedules all the science activities, calibration activities, and maneuvers required to satisfy all flight constraints and requirements. The STS also takes weather data into account to ensure a realistic execution of the flight schedules. For each flight, the STS evaluates multiple departure times (five minutes time step) and flight routes, which in general corresponds to 5–20 million schedules being generated and evaluated.

The automated framework has been gradually integrated to the science operations procedures over the last observing cycles. In addition to the flight schedules, the software output products include scheduling reports and statistics that the operator can review. Computation time wise, the LTS/STS performances allow an observing cycle consisting of about 100 flights equally distributed on five instruments (20 flights per instrument) to be fully generated in about five hours.

In addition to the automated scheduling system, operators can manually create and edit flight plans using the Flight Management Infrastructure (FMI). The FMI contains six architectural elements:

- an accurate geometry and dynamics engine (called the "leg constructor"), to implement the

construction and propagation of flight legs and the bookkeeping necessary to communicate the results,
- a weather package, to estimate realistic wind, temperature and water vapor throughout a flight under construction,
- a special-use-airspace package to parse airspace, communicate to the display, and identify projected incursions,
- a flight planner module that uses the leg constructor to construct flight plans, both prior to and during a flight,
- a flight executor module that compares a flight plan to actual conditions in flight, and implements simple "canned" replanning functions, and
- an observation package to interact with the Observation Planning Database (DCS) to provide a pool of observing targets and for the storage of flight planning data products.

The FMI is hosted in the SOFIA Science Center (SSC) for planning and simulation purposes, and on the SOFIA aircraft workstations for execution and replanning. It consists of a C++ server which performs the flight leg computations, and a Java client which allows for geographical display and editing of the flight plan, as well as display of special use airspace boundaries and weather data.

2.2. *Flight planning*

The flight planning process starts three months before the start of a series. At this time, the parameters of the flight series are set: flight dates, target pool, additional constraints and requirements, and science priorities. With this information, the science flight planner (SFP) uses the output of the STS and assembles draft flight plans. These draft flight plans are reviewed by the instrument scientist and revised as needed until four weeks before the start of the series when they are reviewed by the mission operations team. Mission operations reviews the flight plans for executability, and are further revised by the SFP before the plans are released in their post-review state two weeks before the start of the series. These post-review flight plans are used by the instrument scientist, mission operations and flight operations for flight preparation.

A SOFIA flight lasts 10 h, with science observations starting after sunset at an aircraft altitude of 39,000 feet and ending before sunrise at an aircraft altitude of 43,000 feet. Each flight plan has a unique shape and character driven by the 3–10 observations included in the flight. In order to avoid confusion with aircraft altitude, the telescope altitude is referred to as "elevation." The telescope elevation is set by the telescope assembly which by design has a range of 20–60° (Kärcher *et al.*, 2016), and the coarse telescope azimuth is set by the direction the aircraft is flying. The telescope assembly can move a few degrees in each direction, so fine adjustments are possible if the aircraft heading is slightly off or the aircraft experiences turbulence. Since the telescope is positioned on the port side of the fuselage, the azimuth of the telescope is the aircraft's true heading $-90°$.

Creating viable flight plans with the FMI is as much of a craft as it is a science. Unlike other telescopes where it is possible to view any number of objects from a list at any given time, observing on SOFIA is highly choreographed and modifying the objects to be observed on a given flight is not possible after the flight plans have been created and reviewed. SOFIA is constrained by the duration of flight, the changing location of the aircraft, Air Traffic Control constraints, restricted airspaces, landing location, and individual limitations that may exist for specific objects such as timing or order of observations. In order to piece together flight plans that allow for SOFIA to land at its point of origin, the entire target pool needs to be evaluated together to determine what objects are in pieces of the sky so that there is a heading balance of the aircraft during each flight.

Many flights from Palmdale either travel over the Pacific Ocean (Fig. 1) or remain over the continental United States and Canada. Airspace restrictions discourage flight plans that cross the coast many times in a flight, and SOFIA is not permitted to fly over Mexico.

Unlike all other aircraft, SOFIA's flight plans are not determined by a ground track but are instead only dictated by the aircraft heading for each object observed, so aircraft drift due to winds needs to be taken into account. As flight plans are developed, a weather model with average winds for that date are used. The day before the flight, actual weather forecasts become available and each flight plan is revisited to maintain a flight plan that meets its science objectives and does not violate any flight rules such as restricted airspace incursions or flight duration limits. Updating each flight plan with actual weather the day before flight and the day of

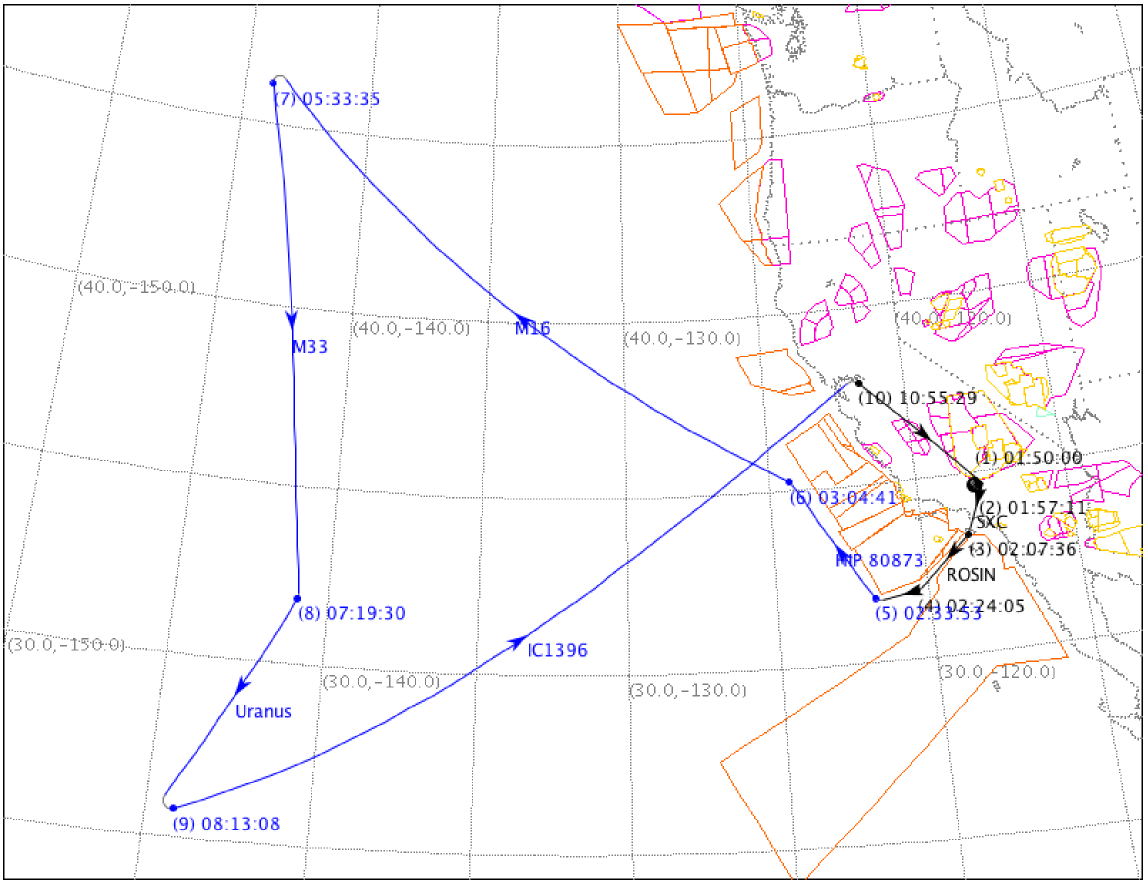

Fig. 1. Example flight plan over the Pacific Ocean. The yellow, magenta and orange areas are different types or restricted airspaces. Each observation leg of the flight is in blue, and non-observation legs, including climb legs and arrival legs, are in black. This figure is from the FMI software, and also shows leg name, number and time at the start of each leg.

flight is crucial for flight execution. Figure 2 shows a typical post-review flight plan over the continental U.S. using the weather model in red. This is the flight plan that would be used for flight preparations. In blue is the same flight plan with predicted winds. This figure illustrates how the difference in winds significantly changed the ground track, particularly towards the end of the flight.

Since SOFIA observes each object for a specific duration, a stronger headwind than expected would shorten the ground track, while a stronger tailwind would lengthen the ground track. In this example, the winds moved the ground track into Mexico (which isn't allowed), and through restricted airspaces. Additionally, the change in ground track may have modified the telescope elevation to approach an elevation limit. The SFP needs to modify the flight plan using the actual winds to correct all issues that the change in wind created. To do this, the SFP may modify the direction of dead legs (legs on which no science observations are planned), change the durations of the legs such that the science is not affected, modify the takeoff time or, in rare cases, reorder the observations. Post-review plans are less than 10 h in duration so that the SFP has the ability to extend legs as needed when the weather is updated. Restricted airspace availability is also more accurately known the day of flight, so some airspaces become available to use and others may close. Once the flight plan is modified to account for these updates, it is distributed for flight operations planning. Flight operations develops an aviation-standard flight plan that uses straight lines to approximate our route to file with the Federal Aviation Administration (FAA) and load onto the aircraft for the pilots to follow. Mission operations or science operations may modify their observation plan to account for slight changes in leg durations or telescope elevation or field rotation. The weather and winds are updated twice: the day before flight and the morning of the flight; the latter becoming the final plan used in flight.

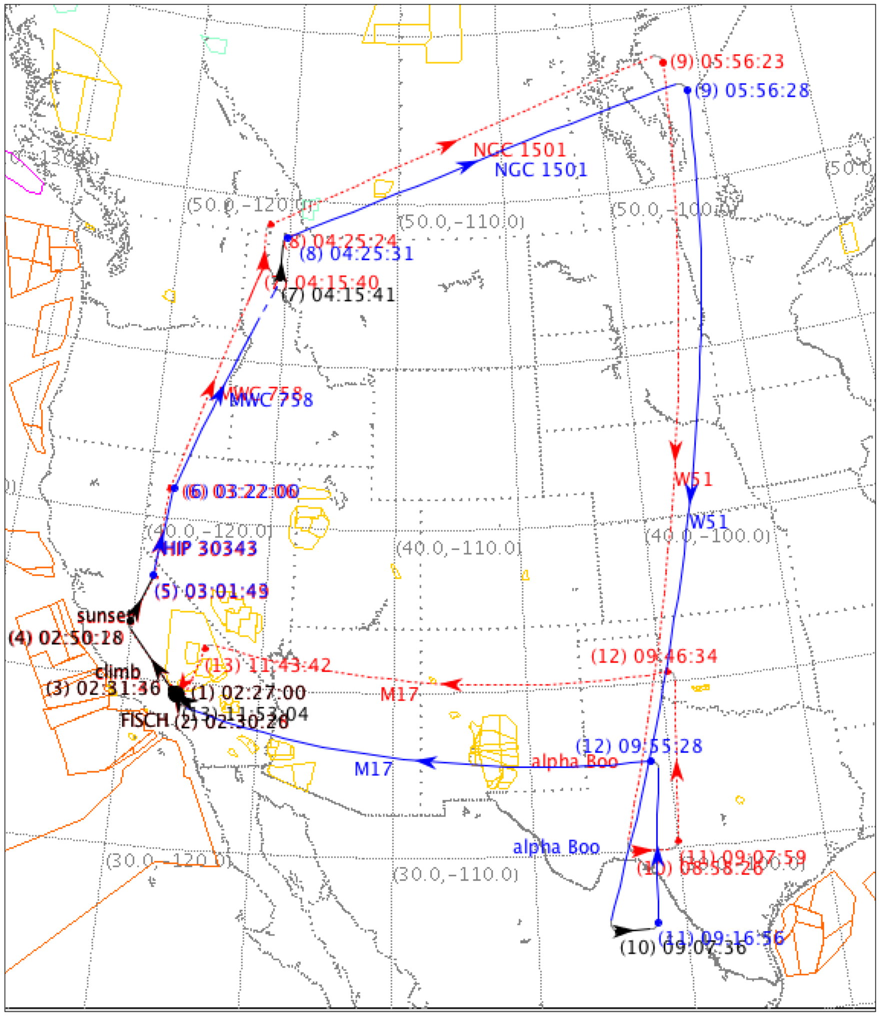

Fig. 2. Flight plan using weather model (red) and updated with the predicted winds 12 hours before flight (blue and black). The updated winds moved the telescope elevation towards its limits (shown by a dotted line just before point 7) and moved the projected ground track at the end of the flight into Mexico and through restricted airspaces (yellow areas).

3. Where are the Objects?

3.1. *Typical concentrations of IR objects*

Astronomical objects viewed from the Earth are seen in the regions of the sky based upon their location in the universe. Objects within our solar system are usually found in the ecliptic plane; most stars within our galaxy are in the galactic plane; nearby stars and distant galaxies are in all directions. The ecliptic and galactic planes are both visible in the South from SOFIA's home base in California. Infrared objects that SOFIA users often want to observe tend to occur in three regions: in the ecliptic plane, near the galactic center, and near the Orion nebula — all of these regions are in the south and often at low elevations when viewed from California (Fig. 3).

3.2. *Using time choices to capture objects in different parts of the sky*

Utilizing all available flight time for observations requires a balanced range of aircraft headings so that SOFIA is able to land at its point of origin. Most objects in each target pool are in the south, which dictate a westerly heading for SOFIA. However, a southerly object will appear first in the southeast as it rises, in the south at maximum elevation, then in the southwest as it sets. By scheduling observations during an object rising and setting periods, a southerly object uses a southwest route followed by a northwest route, requiring less net eastbound travel time to return to SOFIA's home base.

Circumpolar objects in the north dictate eastbound travel, and become very valuable objects in

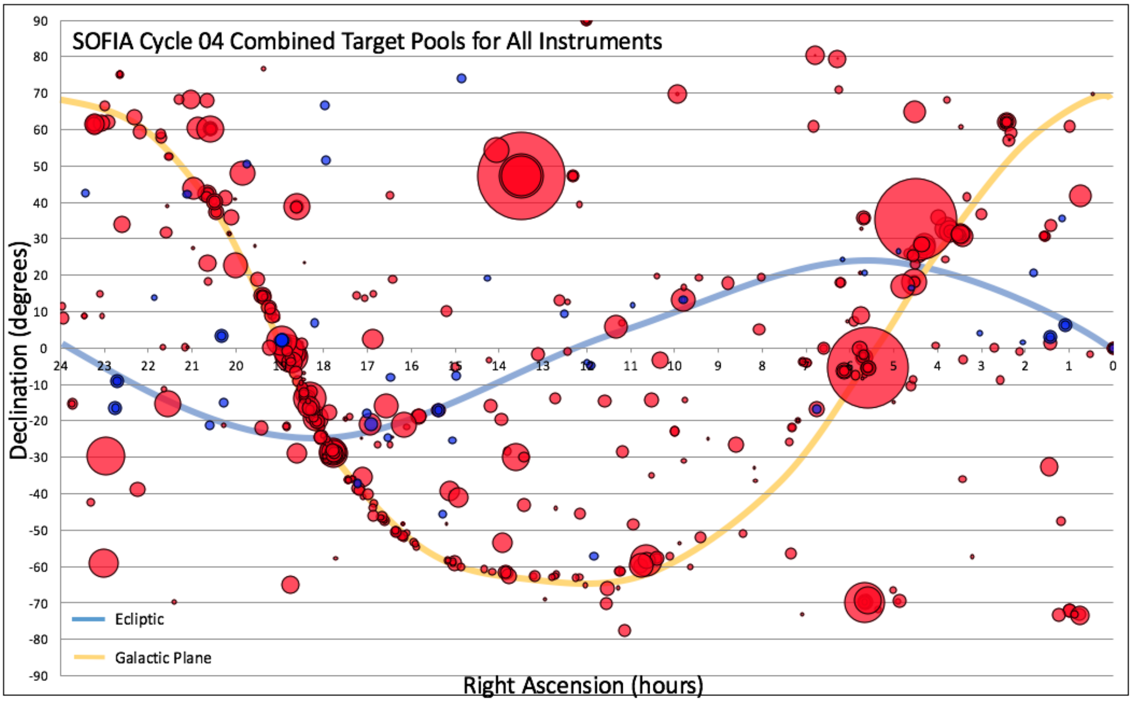

Fig. 3. The location of the objects selected for observation in SOFIA's fourth year of operations. The diameter indicates amount of time awarded, and the blue objects are calibrators. The yellow line highlights the galactic plane and the blue line the ecliptic.

flight planning. While it is common for middle priority objects near the galactic center to get excluded so that higher priority objects in the same region will be observed, high declination northern objects are very likely to be included in flight plans. Middle declination objects rise in the east (southbound for SOFIA) and set in the west (northbound). It is common for setting objects to be scheduled early in a flight and rising objects late in a flight, allowing SOFIA to travel north early and south late. Skewing flight plans to the north of our origin in Palmdale is desirable since the air tends to be drier at higher latitudes, and SOFIA is restricted from flying over Mexico.

3.3. *Inherent flexibilities*

Since not all flight time is used for science observations, there is always some time that is heading flexible. There are three types of legs within a flight plan that provide heading flexibility: arrival and departure, telescope set-up, and calibrators. The first and last half hour of each flight is for departure and arrival (climbing and descending). Since the telescope is not in use during these times, these legs can be planned in almost any direction. The second half hour of each flight is used for telescope set-up, with objects chosen from a very broad variety of visible stars. Stars for these legs are frequently selected once a flight plan is complete and a desired heading is known. Many flights also contain a calibrator that can be chosen from a modest list, and it is common for one of those calibrators to allow the aircraft to travel in a desired direction. Combined, these flexible legs allow for about a 15% imbalance in the target pool. Despite such flexibilities, it is common for SOFIA to have insufficient objects scattered around the sky to provide complete heading balance and fully utilize the entire flight duration for science observing. Figure 4 is an example of the impact of the lack of balanced target pools.

3.4. *Constraints on objects*

Some objects have special requirements that constrain the opportunities to observe them. Timing constraints are introduced by fleeting events or periodic events. Fleeting events, such as comets, supernovae can only be usefully observed in limited absolute time range. Periodic events, such as moons orbiting planets, extrasolar planet transits, and cyclical variable stars can only be observed during certain periods in their cycles, which might be only

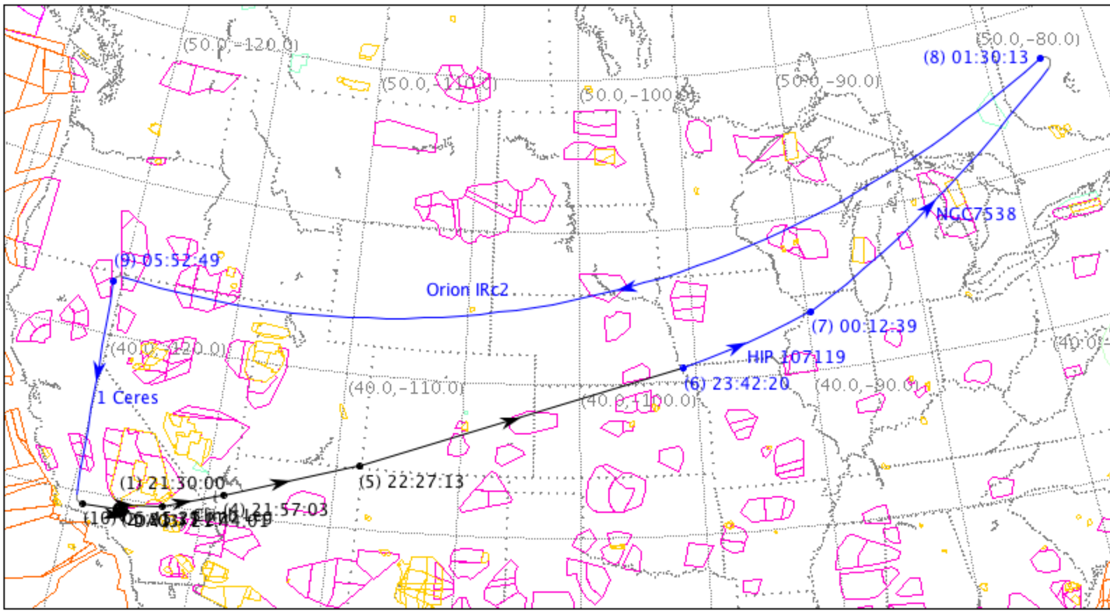

Fig. 4. An example flight plan that uses northern objects and dead legs (in black) to balance out a long observation on Orion, a southern object.

minutes or hours long in a cycle that lasts days or years (Angerhausen, 2018). For these events, the specific date and time of the observation in a flight plan is crucial.

Some objects challenge the sensitivities of SOFIA's instrumentation and must be observed only under ideal conditions of the sky: high aircraft altitude (for low water vapor burden) and high telescope elevations (for low atmospheric extinction). Conversely, many infrared objects that are bright to the instrument are dim to the tracking abilities of the telescope, so SOFIA commonly utilizes visible brighter stars in the close region of the object. If no such bright neighbors exist for a given object, then SOFIA relies upon other methods of tracking that often apply additional constraints to the observation. For example, wider field tracking scopes are available, but are less linked to the optical path of the telescope, so the telescope must be very stable; this precludes observations during the initial cooling of the telescope (first 1–3 h of flight).

Background light can also affect the success of an observation and is considered during flight planning. This most commonly happens during twilight, but can also happen when the Earth's moon is within five or ten degrees of the object (depending on moon phase), or when a bright planet such as Jupiter or Saturn is within a degree of the object.

Some spectrographic observations will be overwhelmed by signal from the Earth's atmosphere unless there is sufficient Doppler shifting to isolate the signal peaks from the background peaks. Objects within our solar system need to be carefully assessed for Doppler shifting at the date of the proposed observation. This can occur, but is less common, for more distant objects that routinely have large Doppler shifts.

Some objects must be observed with specific relationships to other observations. Some objects require that a calibrator observation occur immediately before, after, or on the same flight as the observation. If the goal of an observation is to look for changes over long or short periods of time, then these objects will need to be revisited at specific time intervals. For example: a variable star may be observed every few months for many years; a planet may be observed a few hours or days apart to view different longitudes of that planet, or a planet may be observed over many days to capture the same longitude repeatedly.

3.5. *Instrument calibration requirements*

Many instruments require an initial calibration observation to properly align the final light path to the detector (boresight). With instruments that are blind on the ground, this observation must be the first object viewed in a flight series, and might be chosen from a short list of options. Calibrators are typically large solar system objects including asteroids or planets, or IR bright standard stars. When no suitable objects are available early in the night for this purpose, an alternate object needs to be used, the flight shortened to observe a calibrator early in flight but later in the night, or the timing of when the instrument is used or moved so that there is a suitable calibrator available. Some instruments require a single calibrator for the series, others require a calibrator observation on each flight, while some others require calibrators depending upon the observation modes in that series or flight.

4. Flight Execution

A successful flight starts with teams on the ground preparing the flight plan, aircraft, telescope assembly, mission systems and science instrument in a highly choreographed dance. On the morning of a flight, the aircraft undergoes a preflight inspection to ensure that it is safe and ready to fly. The SFP completes the science plan weather update, and distributes it to flight operations for final preparation. The telescope assembly, telescope cavity and other components are inspected by the ground support team to ensure they are ready and safe for flight. After these initial activities, there are other preparations that happen at specific times relative to the takeoff time (T-0):

T-5 hours:

- Mission systems are started on the aircraft.
- Files specific for this flight are installed on the aircraft.

T-4 hours:

- Mission operations verify mission systems are functioning properly and set up for the flight.
- Flight operations has the flight plan ready to file with the FAA.

T-3 hours:

- Aircraft and mission preflight checks are complete.
- Flight crew arrives.

T-2.5 hours:

- Science instrument cryogens are topped off, if needed.
- Telescope balanced.
- Crew briefing, attended by primary and secondary aircrew, aircraft operations.

T-2 hours:

- Mission brief, attended by all personnel flying, and ground representatives for each system.

T-1 hour

- Aircraft doors closed.
- Crew complete final preparations for takeoff.

A typical flight will have anywhere from 12–30 people on board: the primary aircrew (pilots and flight engineer), secondary aircrew (mission directors and flight safety technicians), the mission crew (telescope operators, instrument operators, instrument scientists), and guests (astronomers, teachers, media, etc.). Prior to flight, each person on board has completed his or her own preparations for flight and attended the mission briefing. At the mission briefing, the flight plan is reviewed along with the weather, planned science observations and the status of each system so that the entire crew is familiar with what will be happening during the flight and if any last-minute modifications need to be made. The mission brief also serves as a handoff from the daytime crew to the flight crew.

After take-off, SOFIA climbs to an initial altitude of 35,000–37,000 feet. The door is opened to expose the telescope to the atmosphere and start cooling it to ambient temperature, and mission crew verify whether the mission systems, telescope, and science instrument are ready for observations. During the first observation leg for telescope set up, the telescope is pointed at a visible star and the telescope operators initialize its set up for that night's observations. The science instrument team may run test scripts for observing modes, check their pointing, or take calibration images during this time.

Following the set up leg is a series of 3–10 observation legs according to the specific flight plan. At the start of each leg, the pilots maneuver the aircraft in consultation with the mission director so that SOFIA is pointing in the right direction and the telescope operators can prepare the telescope for the observation. Once the telescope is pointed, tracking started, and the specific parameters for the observation mode are set up, the science team starts taking data. The aircraft climbs during the flight, up to 45,000 feet, as conditions allow: the aircraft becomes lighter as it burns fuel, and air temperatures change with location.

In order for science to continue without interruption, all systems are monitored and some things require continuous attention and small adjustments. Most notably, keeping the telescope centered is crucial for pointing at an object. The telescope can track up to ±3° from center in nearly orthogonal axes of elevation (el), cross-elevation (xel) and ROF. In practice, the mission crew limits the range of each axis to ±2° so that a small bit of unforeseen turbulence won't disrupt our observations. Ideally, the telescope is centered in all three axes (Fig. 5), but with a moving telescope tracking on a moving object, they are all constantly moving. When tracking, the telescope assembly constantly tweaks the elevation, keeping the telescope centered in elevation. Since the aircraft is flying a specific heading, the xel of the telescope slowly moves left or right. As the xel moves away from the center, the mission director and pilots adjust the aircraft heading one degree at a time resulting in a curved flight path. Heading adjustments of one degree at a time are small enough that they do not impact the observation. The planned versus actual flight path is constantly monitored in conjunction with the telescope xel axis, to strike a balance between staying close to our filed flight route and keeping the telescope centered (Fig. 6). The third axis, ROF, is also constantly adjusted by the telescope assembly to keep it centered. Since it can only rotate up to three degrees, when a limit is approached, the science observations pause to allow the telescope to adjust the ROF.

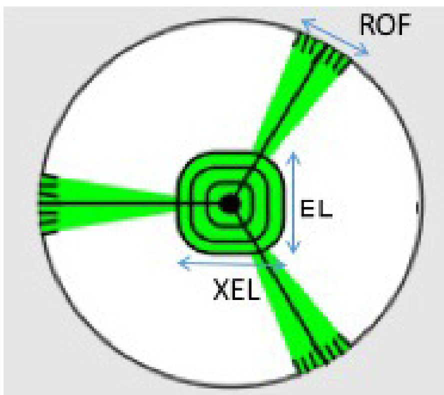

Fig. 5. Cartoon display of the telescope position in three axes: elevation (up/down), cross elevation (left/right), and rotation of field (ROF) (clockwise/counter-clockwise). The black dot at the center shows the center of the telescope, and the limits of each axis are in green. The telescope can move up to ±3° in each of these axes while tracking on an astronomical object.

The non-orthogonality of elevation, cross-elevation and ROF due to the offset of the primary mirror from the spherical bearing that acts as the

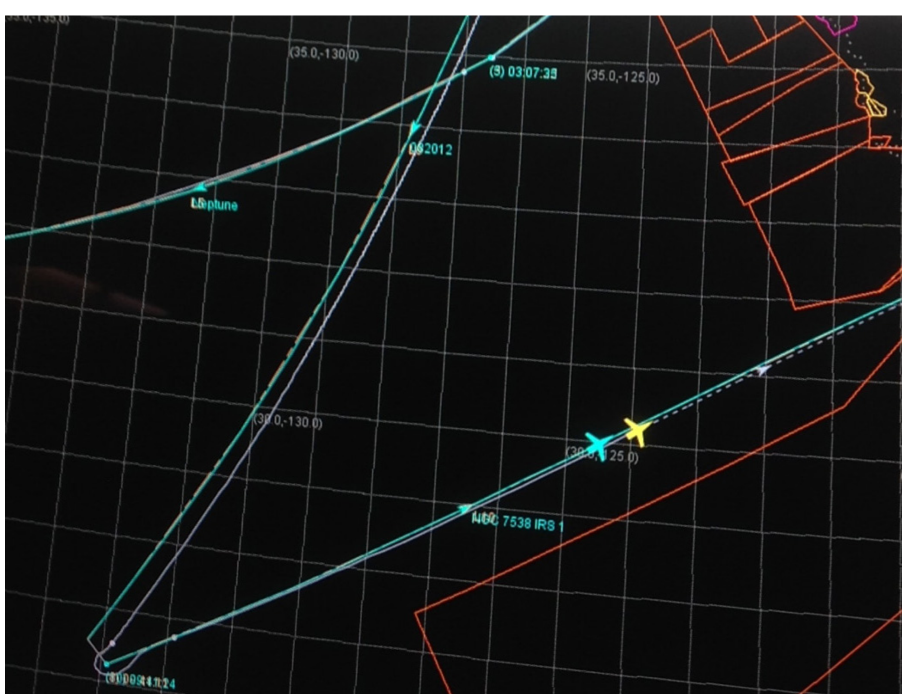

Fig. 6. Planned versus actual flight path. The blue line and blue aircraft icon are the planned path and location; the yellow aircraft icon is the actual location with a white line behind it showing the actual flight path and a dotted line in front showing a projected track.

center of rotation allows some subtle fine-tuning when approaching the limits of any one axis. As the elevation increases, the ROF adjusts which also changes the xel. Conversely, adjusting the xel changes the ROF and the elevation. Each ROF adjustment also move the elevation and the xel of the telescope, so ROF adjustments are sometimes done in conjunction with heading changes. Having these axes intertwined can be used to our advantage during an observation to keep the telescope or aircraft away from other limits. The telescope assembly can only move in elevation between 20° and 60°; if the telescope approaches the edge of its observing elevation range, adjusting the xel may keep the telescope away from these limits long enough to complete an observation. If the telescope is not near a limit but the aircraft is drifting away from the planned ground track, the xel may be biased to one side, affecting the elevation and ROF, but keeping the aircraft within an acceptable distance of our planned route.

Once the science objectives for the flight have been completed, the mission crew prepares the mission systems for landing: the telescope is parked and braked, the science instrument is put into a safe configuration, the door closed and all items in the cabin secured for landing. With all of the mission systems ready for landing, the pilots can descend and land the aircraft.

5. Taking SOFIA Worldwide

One of SOFIA's unique capabilities is that the telescope can, in principle, be positioned anywhere around the globe. This opens up opportunities to observe the entire celestial sphere with SOFIA.

Each austral winter since 2015, SOFIA operations have been based out of Christchurch, New Zealand for several weeks of the year. This allows SOFIA to observe a different part of the celestial sphere compared to flights from Palmdale, CA in each observation cycle. Two or three science instruments are taken to Christchurch each year, and a temporary SOFIA Operations Center (SOC) is set up at the United States Antarctic Program facilities at the Christchurch International Airport.

With a temporary remote SOC, the SOFIA team is capable of conducting identical processes as at the regular base of operations. However, each environment provides its own unique challenges. In Palmdale, weather is rarely a factor for operations; but cold temperatures, precipitation, and fog during winter in Christchurch may hinder regular operations. Flight plans are also slightly different than in

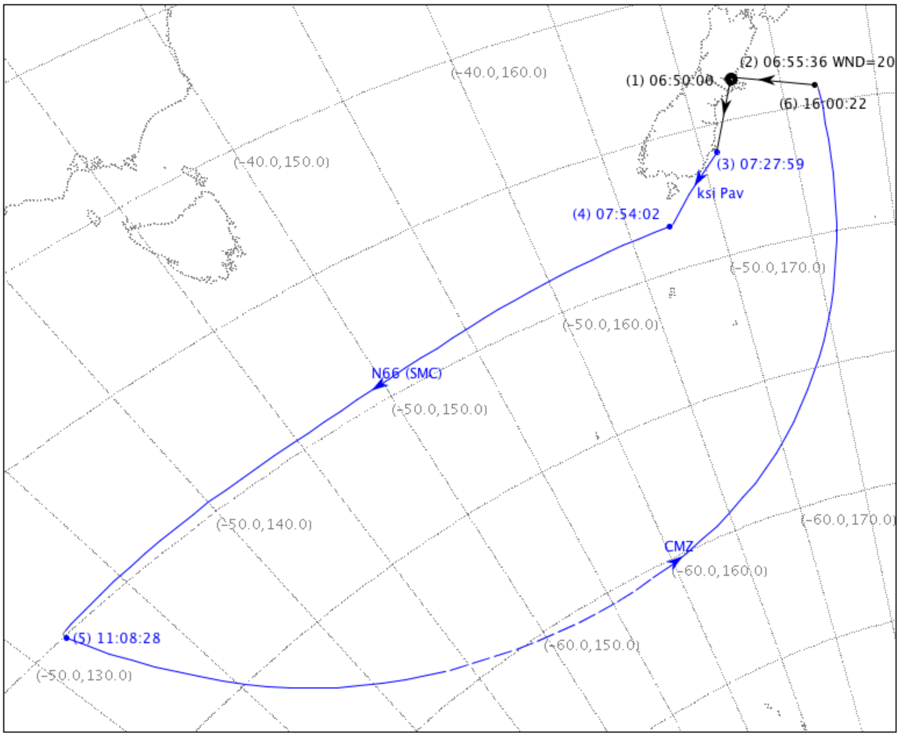

Fig. 7. Flight plan from New Zealand. The entire flight is spent observing two high value objects: the Small Magellanic Cloud (SMC) and the Central Molecular Zone (CMZ) near the Galactic Center.

Palmdale to account for weather in Christchurch possibly preventing an on-time takeoff or landing after a flight. Robust plans to divert to an airport other than Christchurch are developed for each flight. As of 2018, SOFIA has only needed to divert once to Auckland.

Although the weather on the ground in Christchurch is more eventful than in Palmdale, the weather at altitude is ideal for airborne astronomy. During winter, the tropopause is typically much lower in altitude, resulting in drier air surrounding SOFIA during flights from Christchurch. These conditions improve the atmospheric transmission of infrared radiation and increase the overall sensitivity of the science instruments. Additionally, the target-rich center of the Galaxy is higher in the sky, reducing airmass and thus improving the signal-to-noise ratio even further. While it is sometimes difficult to find objects in the target pool to complement the Galactic Center from Palmdale, it is possible to have a flight from Christchurch in the winter that observes high-value objects in the center of the Galaxy and the Magellanic clouds for the entire flight (Fig. 7). Despite the challenges of relocating the SOC to New Zealand, the resulting science data is very valuable.

6. Occultations and Other Special Events

On occasion, SOFIA will observe occultations or other special events like a supernova, comet or near-Earth asteroid. SOFIA is unique in that it is the only major (3-m class) observatory that can change its location to be at a specific place for a specific observation. Without this capability, there may not otherwise be a world-class telescope and instrumentation at the right location to observe these celestial events. For objects that are not visible from Palmdale, SOFIA may relocate for a short period of time to observe that part of the sky. Unlike typical celestial objects, observing a fleeting event that is specific in time and place, like an occultation, requires planning and preparation that is a little different from regular science observations.

6.1. *Shorter, smaller deployments*

SOFIA also operates for shorter periods of time from other locations. Short deployments allow SOFIA to observe special events that are localized in time and/or space. For these short, special purpose deployments, the entire SOC does not need to be relocated. However, SOFIA does need to have the required resources to ensure that the aircraft and installed science instrument are ready for each flight from the remote location; this includes cryogens for the science instrument and equipment needed for pre-flight and post-flight inspections and operations. Flight plans and flight preparation are completed as much as possible prior to leaving Palmdale.

In 2017, SOFIA operated from Daytona Beach, Florida for a week to observe an occultation by Neptune's moon, Triton. This occultation was occurring over the Atlantic Ocean, beyond the reach of SOFIA in Palmdale. However, from Florida the occultation event was well within reach. The flight plans were created and vetted prior to the deployment, so only last-minute changes due to weather and modification of the projected occultation path were needed. SOFIA flew three science flights from Florida: a regular science flight, the occultation flight, and a third science flight which landed back in Palmdale, CA (Fig. 8).

6.2. *Occultation flight planning*

SOFIA has observed four occultations through 2017, with additional ones planned for 2018. Flight plans for occultations differ from regular observation flight plans: most notably they may be dedicated to a single observation. However, they frequently include observing the occultation object earlier in the flight, and may include other objects following the event if they fit into the plan without affecting the occultation observation itself.

Being at the exact location (typically within two nautical miles) at a specific time (typically within 20 seconds) while using a quickly moving aircraft (about 600 kts) is key for an occultation flight. As a result, occultation flight plans incorporate various features that will allow SOFIA to fine tune the timing in flight and stay on the planned ground track. Timing is critical: if SOFIA is off of the planned timing, the ground track will slowly deviate from the planned ground track as SOFIA follows a celestial object through the sky. For occultation flights, long dead legs and flexible timing "trombone legs" are built in to ensure SOFIA stays on the planned ground track (Fig. 9). Trombone legs are short legs immediately prior to the occultation object that are parallel and anti-parallel to the observation leg. Trombone legs can be lengthened

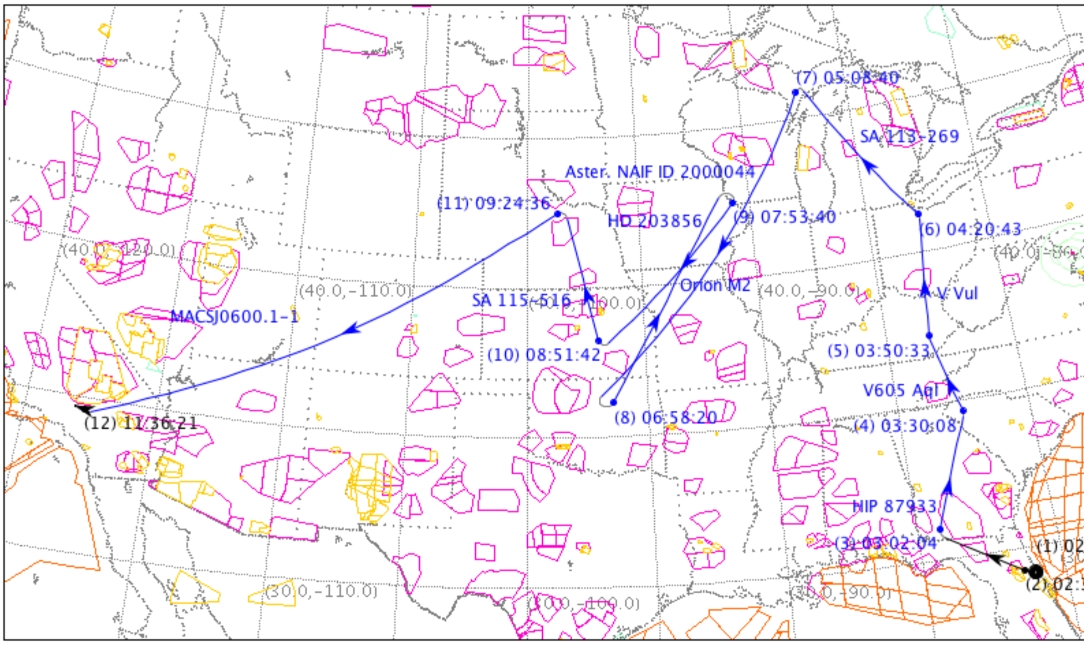

Fig. 8. Ferry flight plan from Florida to Palmdale.

or shortened as needed to arrive at the start of the occultation leg at a specific time. Dead legs within the flight plan can also make up for unforeseen circumstances such as a late takeoff, air traffic considerations, and significant deviations from the forecasted wind. In some cases, such as the 2015 Pluto occultation, the last prediction for the event location was not available until after takeoff. In such cases, the flight plan needs to include significant dead legs that can be modified to change SOFIA's location later in the flight.

Occultation flights are planned to stay at a lower altitude. This gives the flight crew the ability to change the ground speed slightly, up to 35 kt, allowing for slow, small timing changes as necessary. Since occultations are frequently photometric objects, only the relative brightness is needed for a successful observation. Thus, the increased noise

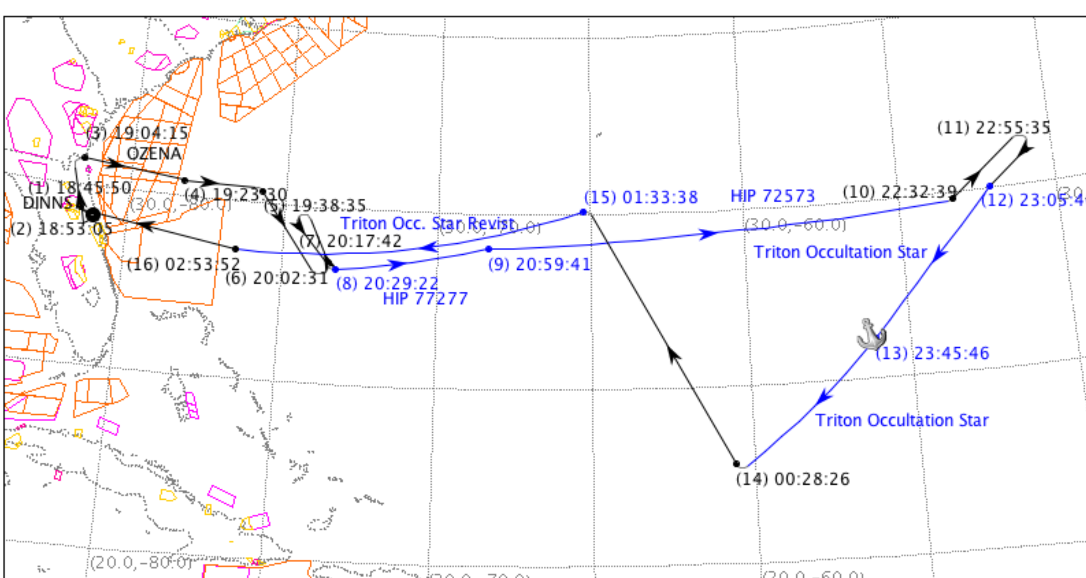

Fig. 9. Occultation of Triton flight plan from Florida. The occultation event location is marked by an anchor. Note the timing trombones towards the start of the flight which allow for large timing modification and a second set of timing trombones just prior to the occultation observation leg.

that may result from a lower altitude is less detrimental than missing the event all together.

6.3. *Occultation flight execution*

Each occultation flight is unique, and a flight plan that will get SOFIA to the position of the occultation at the right time is only as good as its execution. The flight crew, mission crew and science team work together prior to the flight to ensure that everyone knows how the flight plan will be executed, and importantly how to communicate among the teams to react to real-time conditions. Although the flight plan has features built in to make large-scale changes to timing and location, once the occultation observation has started, 45–60 min before the occultation event, the flight crew needs to make small real-time adjustments that do not affect the observation. To counteract deviations left/right of our desired ground track, the mission director can bias the xel of the telescope by up to two degrees. To counteract small timing discrepancies, SOFIA's ground speed can be changed only slightly, about 0.5%. Neither of these small adjustments can make large changes, but they can be just enough to ensure that SOFIA is as accurate as possible in location and timing.

In 2015, SOFIA observed an occultation of Pluto that coincided with the *New Horizons* mission (Stern & Spencer, 2003) to the dwarf planet (Pasachoff *et al.*, 2017). One of the challenges of this flight was that the prediction of where the occultation centerline would be changed by hundreds of miles even a few days before the event. The final predicted location could not be determined until after SOFIA had taken off, so the team created a flight plan that would be able to withstand a significant change in location. The team also had plans in place for receiving the updated location in flight and ensuring that the flight plan could be modified, and these changes accurately communicated to the entire team and air traffic control. The location prediction received in flight differed from the preflight location by just over 400 nautical miles, or about 45 min of fight time (Fig. 10). With limited time, the on-board science flight planner, mission director, and navigator modified the flight plan to turn SOFIA north earlier than planned and intercept the new occultation location. As Pluto passed in front of the star, a visibly significant difference in

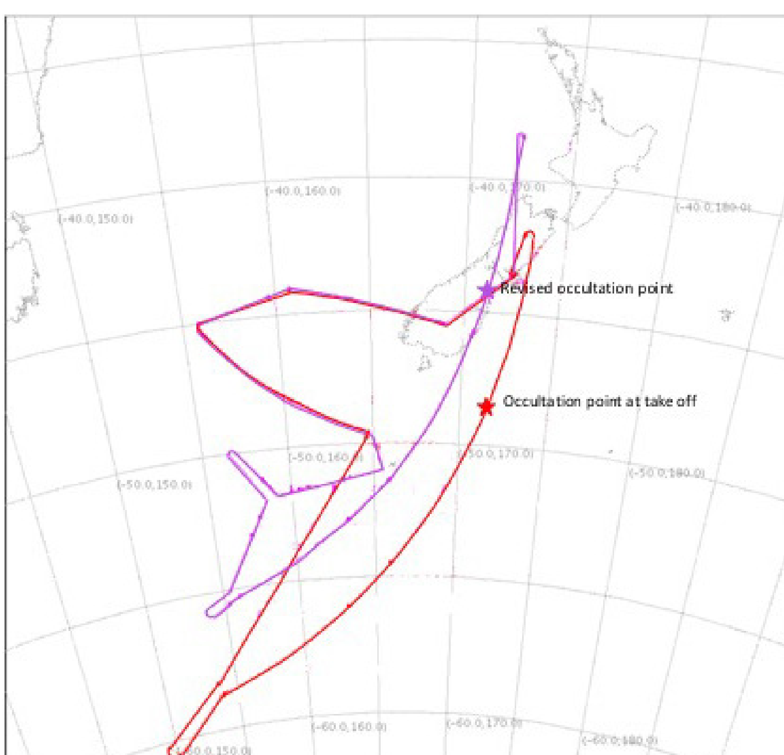

Fig. 10. The planned route of the Pluto occultation flight at takeoff time (red line) and the actual route of flight (purple line). The red star marks the occultation point at takeoff and the purple star marks the actual occultation point where the event was observed from SOFIA.

brightness was observed and the flight team knew immediately that the observation had been successful. Further data reduction indicated that SOFIA had indeed been on the centerline of the occultation path.

The MU69 occultation in 2017 in support of the *New Horizons* mission was SOFIA's most challenging task to date, and it was executed to a high degree of accuracy. MU69 is a very small body — at the time estimated to be a single body under 30 km wide — and located more than 6.5 billion km from the Earth in the Kuiper Belt. As a result, the center of the occultation path was very narrow in both space and time: SOFIA's margin of error for the center of the occultation path was 1 nautical mile and 1.5–3 seconds. One advantage for this flight's execution was that the final location update occurred prior to takeoff, so there were no in-flight adjustments needed to the flight plan. The flight crew utilized all the available tools to be at the right place at the designated time, and later analysis of the planned versus actual aircraft location showed that SOFIA was only 4.5 wingspans away from the requested position at the requested time. SOFIA's observation of MU69 suggests that this object may be binary (NASA, 2017). *New Horizons* is scheduled to fly by MU69 in January of 2019 for a closer look at this small and distant object.

6.4. *Special events*

SOFIA has the capability of responding to special events that require a quick response time, such as a supernova. In 2015, V5668 Sgr (Nova Sgr 2015 #2) was discovered, and a request to observe it with SOFIA was made (Gehrz *et al.*, 2015). Within a few days, an existing flight plan was modified to observe the supernova. Although the requested observation did not require an instrument change, it is possible to change instruments for such an observation, or even travel to another location if the object is not visible from SOFIA's current location. All of these changes will change SOFIA's planned schedule, so the opportunity cost for a last-minute special observation is weighed against the scientific merit of the proposed observation.

7. Conclusion

NASA's SOFIA is a unique telescope with unique capabilities. Planning and executing observations with SOFIA is unlike any other telescope, and requires detailed and specific planning, teamwork, and adjustments to events in real time. SOFIA can be taken anywhere on the Earth to observe objects at any declination, and time-specific events. This capability enables observations are unlike those possible from any other telescope on the ground or space such as high-precision occultations that can empower and enrich the observations made by other observatories and enable new kinds of science.

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