Pointing the SOFIA Telescope

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\textbf{Abstract.} SOFIA is an airborne, gyroscopically stabilized 2.5m infrared telescope, mounted to a spherical bearing. Unlike its predecessors, SOFIA will work in absolute coordinates, despite its continually changing position and attitude. In order to manage this, SOFIA must relate equatorial and telescope coordinates using a combination of avionics data and star identification, manage field rotation and track sky images. We describe the algorithms and systems required to acquire and maintain the equatorial reference frame, relate it to tracking imagers and the science instrument, set up the oscillating secondary mirror, and aggregate pointings into relocatable nods and dithers.

1. SOFIA Telescope-Pointing Architecture

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\textbf{Figure 1.} The telescope-pointing systems on the SOFIA aircraft.

The SOFIA pointing architecture is shown in Fig. 1. The Telescope Assembly (TA) keeps track of its attitude using gyroscopes corrected by tracking imagers, but is unaware of sky coordinates. The Science Instrument (SI) is responsible for science data acquisition. Avionics provide aircraft location and attitude necessary to initialize sky coordinates. The Mission Communications & Control System (MCCS) correlates gyroscopes with sky coordinates and translates pointing building blocks between coordinate systems.

2. Coordinate Systems

The TA describes its attitude as a 3 degree-of-freedom (DOF) rotation from the telescope reference frame (TARF) to various coordinate systems mechanically attached to the telescope. The MCCS translates these to external coordinates, and accounts for the optical path. The TA is far from rigid and orthogonal; thus many intermediate coordinate systems are established. Directly-observable

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MCCS coordinate systems are Equatorial (ERF) and grid coordinates for the three tracking imagers and the Science Instrument (SIRF). Key internal coordinate systems are the telescope and inertial references (TARF and IRF) with IRF derived from a set of gyroscopes. The MCCS distributes positions in all coordinates for real-time monitoring, FITS headers, and archiving.

3. Establishing Equatorial Coordinates

The MCCS uses a 2-3 stage approach to relate ERF to IRF, to \( \leq 1'' \):

1. Rough-estimate (\( \sim 1° \)) ERF coordinates from avionics-reported aircraft position and attitude and the TA’s IRF and airframe attitudes.
2. Fine-tune using field recognition (PIXY; Yoshida 2000) on the Wide Field Imager (WFI; 6° FOV).
3. Optionally, refine further using a 2DOF correction, based upon two Focal Plane Imager (FPI; 0.57''/pixels) acquisitions several degrees apart.

The operator monitors IRF \( \rightarrow \) ERF with an overlay of calculated positions of stars on imagers against sky images (see Fig. 2), and executes the 2DOF refinement when mismatch drifts too large.

4. Simple Pointing and Tracking

The TA can be pointed in any directly observable coordinate system. Areas of Interest (AOIs) can be defined on imagers; the TA continually calculates AOI centroids. This provides stability feedback to the TA, necessary because gyroscopes are not sufficient to maintain pointing over hours. A centroiding AOI can be attached to a position of interest; when activated, the TA keeps the image fixed at the desired position, by modifying IRF to cancel its motions inferred from the AOI. The AOI need not coincide with the point of interest.

5. Chopping

A chop is a high-frequency square-wave oscillation of the secondary mirror (SMA), synchronized electronically with imager acquisition to subtract sky background. Only the FPI and SI observe chopped images; other imagers do not share the optical path with the telescope. A given FPI or SI pixel has two ERF coordinates since any images taken are a superposition of two images with different centers; the MCCS publishes both for key positions. For pointing commands, positions can be modified by chop beam designation. The SMA is commanded by a 2D center offset, amplitude, and position angle, and a coordinate system. SMA state is propagated through telescope motions by keeping its specification constant in the coordinate system specified. A “3-point” chop is also supported; this includes a pause at an intermediate point (labelled “0”).

6. Nodding and Dithering

A nod is a low-frequency motion of the whole telescope, usually relating to an accompanying chop, to remove instrument backgrounds. Nods are defined in
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Figure 2. Typical telescope setup for a single data acquisition. Two AOIs are defined on the WFI (left) to monitor rotation. A third is defined on the FPI (right) to monitor transverse drift. Computed positions are superposed (for both chopped beams on the FPI), along with their names. Mismatch represents several arcseconds of drift in absolute pointing; depending on the precision required, a realignment may be necessary. Data shown is sky simulation (Brüggenwirth, Gross, Nelbach, & Shuping 2009) with a thermal dark current model. The FPI is at 20°C and the WFI is at −40°C.

Figure 3. Graphical description of nodding (left) and dithering (right). Nods are specified in the same manner as chops, so they can be matched unconditionally, without direct connections. The center position (“Nod X”) is optional, and can be used to match a 3-point chop, which includes the center position as well. A formulation based upon circular lists of relative pointings is used for dithers – all positions are understood to be relative to the first.

the same manner as chops, without direct coupling, and are propagated through telescope motions identically. Dithers are a generalization of nods to arbitrary-length sequences, intended to image the same star on several different imager pixels, in order to remove outliers such as cosmic ray hits or hot pixels. The first position in a dither is considered to be a “reference,” with all other positions defined relative to it, for relocatability on the sky. Chops, nods, and dithers have no direct coupling and can therefore be mixed and matched in any combination.
7. Managing Field Rotation

TA motion is significantly constrained by clearance to the airframe. Thus, azimuth is mostly controlled by turning the aircraft (Gross & Shuping 2009). Rotation against the sky can be held constant as the aircraft rotates up to 5.6°. As this rotation nears its limit, the telescope is periodically “rewound” manually to a new rotation angle, between data acquisitions. During rewind, all building blocks are held constant in the coordinate systems in which they were defined.

8. Key Design Points and Tests

In order to minimize development risk for the MCCS, several critical design features have been included. Pointing building blocks do not depend directly on each other and state derives strictly from the TA, allowing for independent development, testing, and operational use. Much attention has been given to abstraction and simplification, to aid in development of testing procedures. Each building block has a realistic operational “scenario,” defining detailed inputs, operator commands, user-visible outputs, and intermediate calculations.

Coordinate systems present special problems, and are notoriously difficult to orient correctly and keep that way; to that end, regression tests include:

- Diurnal rotation rate measurements with zero aircraft speed.
- A “home position” at the equator on the vernal equinox, with northbound heading and zero speed (enables manual calculations).
- Modifying each coordinate parameter individually.
- Composite tests (verifies calculations are in the correct order).
- Corner cases (identifies quadrant problems).
- Complete-system tests pointing to specific stars, using synthetic images.

Some tests violate TA physical limits; these are evaluated against a simulator (Brüggenwirth, Gross, Nelbach, & Shuping 2009).

9. Conclusion

Placing a telescope on a moving platform, while still desiring to point in absolute coordinates, presents a difficult challenge for software development. Eventual success of the SOFIA platform in this regard depends upon careful abstraction and testing strategies for pointing the telescope.

References

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