Planning and Executing Airborne Astronomy Missions for SOFIA

Michael A. K. Gross and Ralph Y. Shuping

*Universities Space Research Association, NASA/Ames Research Center, MS 211-3, Moffett Field, CA 94035 USA*

**Abstract.** SOFIA is a 2.5 meter airborne infrared telescope, mounted in a Boeing 747SP aircraft. Due to the large size of the telescope, only a few degrees of azimuth are available at the telescope bearing. This means the heading of the aircraft is fundamentally associated with the telescope’s observation targets, and the ground track necessary to enable a given mission is highly complex and dependent on the coordinates, duration, and order of observations to be performed. We have designed and implemented a Flight Management Infrastructure (FMI) product in order to plan and execute such missions in the presence of a large number of external constraints (e.g. restricted airspace, international boundaries, elevation limits of the telescope, aircraft performance, winds at altitude, and ambient temperatures). We present an overview of the FMI, including the process, constraints and basic algorithms used to plan and execute SOFIA missions.

1. Introduction

The Flight Management Infrastructure (FMI) product is intended to keep the aircraft from interfering with preplanned observations on the sky. It predicts the ground tracks necessary to execute its mission, and corrects the plan for actual conditions while airborne. To support this, it contains both a planning component that can run on the ground and in the air, and an execution component that runs in the air. The planning component manages a set of ordered observations and optional aircraft repositioning requests. The execution component compares the plan to actual conditions in flight and requests headings (indirectly) from the autopilot.

SOFIA mission planning differs from satellite or ground based observatory planning in a few key areas. Most importantly, the observatory position is a function of observation target history, which prevents observations from being considered as time-slots alone. Assignment of flight dates is also nontrivial — targets cannot be localized on the sky or the observatory will always fly in about the same direction (requiring nearly equivalent dead time to return); this suggests entire flight series should be considered at once, for greater target variety.

Flight planning and execution differs from conventional as well. All conventional aircraft fly from point to point along specified paths on the ground, and “drift” the aircraft to compensate for winds. Typical drift angles (course - heading) exceed 3°, and the worst possible case approaches 30°, so SOFIA cannot necessarily observe in this manner. Expected winds can be planned
for using a weather forecast. Correcting course for unexpected winds can be accomplished by adjusting observation durations, by relocating the aircraft between observations, or by “observation triage” as a last resort. This requires an astronomically-aware airborne monitoring function to compare current conditions to plan. Aircraft capabilities are a strong function of fuel weight, which argues against simple parametrizing by time, in favor of fuel.

2. External Constraints

In addition to the geometrical and practical constraints described above, the SOFIA flight planning problem also has a number of external constraints, all of which prevent a truly automated, or even rigorously sequential, flight planning process. For instance, special use airspace (SUA) incursions may require external approval, and it cannot be known ahead of time whether such approval will be forthcoming in all cases. National airspace boundaries require international agreements. Over-ocean operations are prohibited for safety reasons for the first flights; for later flights, fairly complex fuel reserve constraints are required. Gross takeoff weight has a hard limit of 700,000 pounds, which limits the duration of SOFIA missions.

Some science-driven constraints require interaction with scientists or detailed knowledge of the observations; especially, trading off water vapor overburden estimates with altitude and duration, and for trading off observations against each other.

3. SOFIA FMI

Prior to any particular mission, several iterations of flight planning are performed. This is expected to include fully integrated automated flight planning (Frank, Gross, & Kürklü 2004), routinely. Manual choice of observation (including order) will occur subsequently. Upon execution, replanning might occur if conditions are sufficiently different from assumptions. Figure 1 shows a color-processed screenshot of a simulated flight intended for April, 2008, from Palmdale, CA. Actual conditions for the simulation shown differ from planned only by small timing errors of the order of several seconds between segments and at takeoff.

As mentioned earlier, it is advantageous to consider entire flight series at once, in order to trade observations between flights. The data structure supporting this is shown in Fig. 2.

FMI requires substantial input data in order to accurately predict a flight track and its constraints. Weather forecast time-series are taken from the National Center for Environmental Prediction Global Forecasting System, quadrilinearly interpolated. An alternative is required for dates more than several days in the future, since accurate forecasts are not available then; we use a set of stacked monthly means for 1997–2001 (the last years available) from the European Center for Medium Range Weather Forcasting 40 Year Reanalysis (Uppala et. al. 2005) also quadrilinearly interpolated. Aircraft performance is interpolated from tables generated by Boeing INFLT runs, for cruising, thrust-limited climbs, and descents.
Planning and Executing SOFIA Missions

Figure 1. A sample flight in southern California airspace, executing in a simulated environment. Coastlines and Arizona and Nevada borders are shown as coarsely dotted lines. Planned and actual tracks are shown as solid lines. Since actual conditions never exactly match plans, the remainder of the flight is projected from the current actual location, shown as a dashed line. Offshore polygons are warning zones; others are restricted airspace. The current position and heading is shown as an aircraft glyph, near Santa Barbara, CA.

Figure 2. Structure of a flight series, corresponding to all flights between a given instrument’s installation and its removal.

Planned flight track intersections with special use airspace (SUA) boundaries (including non-US zones, from the US National Imagery and Mapping Agency) are evaluated using a quadtree-based search on the 8000+ SUA boundaries for each flight segment. Observation segments are treated as initial value problems in Cartesian coordinates, others may be boundary or initial problems, as appropriate. Desired headings are calculated during execution from planned (not actual) sky coordinates and actual position; direct steering by the telescope cannot be allowed for safety reasons.
In order to test FMI components and integrate other systems, as well as for training purposes, we use a simulation environment. This includes a medium-fidelity aircraft simulator, an automated pilot simulator, a method to set the time arbitrarily, and a telescope simulator (Brüggenwirth, Gross, Nelbach, & Shuping 2008).

Figure 3. Dataflow within the airborne configuration for early flights. Later flights will have direct connections to the data acquisition system (MCCS), rather than through a proxy.

While airborne, the FMI software components interact with the airborne data acquisition software to acquire the aircraft’s position and attitude. While on the ground, the planner portion of FMI interacts with observers’ planning software and must support multiple simultaneous planning sessions. The airborne configuration is shown in Fig. 3; the ground configuration is similar, except there is no flight executor nor MCCS data (except in testing configurations), and there is a connection to the Observation Planning Database.

4. Conclusion

SOFIA presents a unique flight planning problem due to the nature of astronomical observation. FMI provides a connection between scientific needs of an observatory with the practical constraints of operating an aircraft, without introducing excessive safety considerations or pilot workload, or planner effort.

Acknowledgments. The authors wish to thank the European Center for Medium Range Weather Forecasting for access to their reanalysis data.

References

Brüggenwirth, S., Gross, M. A. K., Nelbach, F. J., & Shuping, R. Y. 2009, in ASP Conf. Ser. XXX, ADASS XVII, ed. J. Lewis, R. Argyle, P. Bunclark, D. Evans, & E. Gonzalez-Solares (San Francisco: ASP), 485
Frank, J., Gross, M. A. K., & Kürklü, E. 2004, in Proc. 16th Conf. on Innovative Applications of Artificial Intelligence, ed. D. L. McGuinness & G. Ferguson (Boston: MIT Press), 828
Uppala, S. M. et al. 2005, Quart. J. R. Meteorol. Soc., 131, 2961