

HANDLING QUALITIES FLIGHT TESTING OF THE STRATOSPHERIC OBSERVATORY FOR INFRARED ASTRONOMY (SOFIA)

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1. ABSTRACT

Airborne infrared astronomy has a long successful history, albeit relatively unknown outside of the astronomy community. A major problem with ground based infrared astronomy is the absorption and scatter of infrared energy by water in the atmosphere. Observing the universe from above 40,000 ft puts the observation platform above 99% of the water vapor in the atmosphere, thereby addressing this problem at a fraction of the cost of space based systems. The Stratospheric Observatory For Infrared Astronomy (SOFIA) aircraft is the most ambitious foray into the field of airborne infrared astronomy in history. Using a 747SP (The Boeing Company, Chicago, Illinois) aircraft modified with a 2.5m telescope located in the aft section of the fuselage, the SOFIA endeavors to provide views of the universe never before possible and at a fraction of the cost of space based systems. The modification to the airplane includes moveable doors and aperture that expose the telescope assembly. The telescope assembly is aimed and stabilized using a multitude of on board systems. This modification has the potential to cause aerodynamic anomalies that could induce undesired forces either at the cavity itself or indirectly due to interference with the empennage, both of which could cause handling qualities issues. As a result, an extensive analysis and flight test program was conducted from December 2009 through March 2011. Several methods, including a Lower Order Equivalent Systems analysis and pilot assessment, were used to ascertain the effects of the modification. The SOFIA modification was found to cause no adverse handling qualities effects and the aircraft was cleared for operational use. This paper discusses the history and modification to the aircraft, development of test procedures and analysis, results of testing and analysis, lessons learned for future projects and justification for operational certification.

2. ACRONYMS, ABBREVIATIONS, SYMBOLS

CFD	– computational fluid dynamics
CG	– center of gravity
DER	– Designated Engineering Representative
DLR	– German Aerospace Center
FAA	– Federal Aviation Administration
FAR	– Federal Aviation Regulation
IR	– infrared
KAO	– Kuiper Airborne Observatory
LAT	– large aperture telescope
LOES	– Lower Order Equivalent Systems
NASA	– National Aeronautics and Space Administration
PID	– parameter identification
PUPO	– pull up, push over

SCA	– Shuttle Carrier Aircraft
SHSS	– steady heading sideslip
SOFIA	– Stratospheric Observatory For Infrared Astronomy
TA	– telescope assembly
URD	– upper rigid door
V _{mc}	– minimum controllable airspeed
WUT	– wind up turn

3. INTRODUCTION

Ground based infrared astronomy has always been limited by the distorting effects of water in the atmosphere. One method of solving this problem has been by launching observatories into orbit. While successful, this is a very expensive solution that also does not allow for operational flexibility or maintenance of the telescope and sensors. Fortunately, there is another solution that is more cost effective and flexible. Above 40,000 ft, the top of the altitude band for most airliners, an observer is above 99% of the water vapor in the atmosphere.¹ Hence, a science instrument could collect near-space quality images at this altitude. It was for this reason that airborne infrared astronomy was born.

Infrared light is mostly blocked by atmospheric water at ground level.¹ However, many interesting objects emit mostly infrared (IR) such as newly forming stars; planets; comets; galactic cores; and complex, potentially organic molecules.¹ An airborne based system can be deployed to any given location on Earth at any given time unlike space or ground based systems. If an event is taking place at a specific time and location, for instance an occultation, an airborne platform can be positioned to observe it, whereas satellite and ground based devices cannot. Therefore, it is important to have a capability like the Stratospheric Observatory For Infrared Astronomy (SOFIA) to enable fundamental discoveries about the origins and composition of the universe.

The National Aeronautics and Space Administration (NASA) first made use of aircraft for airborne infrared astronomy from 1965 to 1969 using Convair 990 (General Dynamics, Falls Church, Virginia) and Learjet (Learjet Corporation, now Bombardier Aerospace, Dorval, Quebec, Canada) aircraft to loft small telescopes. The success of these programs led to the development of a dedicated airborne observatory.¹

In 1969 planning started for installation of a 36-inch telescope in a modified Lockheed (Bethesda, Maryland) C-141A. This was the beginning of the Kuiper Airborne Observatory (KAO)², the direct predecessor to SOFIA. The KAO flew the first research flight in 1974. Research was conducted successfully until 1995 making such important discoveries as the rings of Uranus and the atmosphere on Pluto.²

4. THE SOFIA PROGRAM

4.1. Program History

Even at the time when the KAO was making its first flights, initial studies had begun on using a larger platform, but the road to getting SOFIA in the air was not an easy one. The timeline for a few of the major program events is as follows:³

- 1971 – The National Academy of Sciences Decade Survey (Greenstein) Report recommended study of a large airborne telescope.
- 1977 – Boeing delivered a study to NASA Ames (Moffett Field, California) on installing a large aperture telescope (LAT) in a Boeing 747SP aircraft (The Boeing Company, Chicago, Illinois).
- 1983 to 1984 – The success of the Infrared Astronomy Satellite demonstrated a need for further efforts and development of the as yet unnamed program continued.
- 1988 – The Space and Earth Sciences Advisory Committee recommended that SOFIA proceed into definition phase.
- 1990 – Initial set of wind tunnel tests were successfully completed.
- 1992 – IR measurements made of the Shuttle Carrier Aircraft (SCA) engine plumes using IR cameras mounted in a Lear jet were used to alleviate concerns of jet plume IR energy contamination for an aft mounted telescope.
- 1997 – Baseline flight-testing of the aircraft that will come to be known as SOFIA is completed as well as follow on wind-tunnel testing.
- 1998 – 7% wind-tunnel tests completed.
- 2003 – Integration of the telescope assembly (TA) into the aircraft began at L-3 Communications Integrated Systems in Waco, Texas.
- 2007 – The modified SOFIA flew for the first time.
- 2010 – First light and science begins on SOFIA.

4.2. The Observatory

SOFIA is a research observatory mounted in a 747SP (figure 1). The SOFIA observatory is a world-class telescope with a 2.5-meter effective diameter, primary mirror optimized for infrared light. SOFIA will complement ground-based facilities as well as current and future space-based IR missions such as the Spitzer and Herschel space telescopes.¹ The aircraft is based at the Dryden Air Operations Facility (DAOF) at the United States Air Force (USAF) Plant 42 in Palmdale, California. SOFIA operating lifetime is intended to be 20+ years at a flight rate of approximately 150 flights per year. The observatory is available to any qualified astronomer through an extensive application and screening process. SOFIA is funded through a 25-year agreement between NASA in the United States and the German Aerospace Center (DLR) in Germany under a formal memorandum of understanding.¹



Figure 1. SOFIA in flight.

The instrument attached to the collection end of the telescope is interchangeable. There are currently seven instruments built or being built for implementation on SOFIA by various research organizations and universities around the world, and several more in various stages of proposal.

4.3. Airframe

The 747 airframe was chosen in order to maximize available airborne volume in order to allow for the largest possible telescope mirror. The 747SP, SP for Special Performance, is a shortened version of the 747-100. The weight saved by the shortened fuselage permits longer range and increased speed relative to other early 747 configurations.⁴ Due to this higher performance relative to other legacy 747s and lower initial costs than newer 747-400 airframes, the 747SP was ultimately chosen to host SOFIA. The resulting SOFIA aircraft is capable of spending over 6 hours at or above 41,000 ft. The specific SOFIA airframe was originally delivered to Pan Am and titled "Clipper Lindbergh." NASA has retained the name and displayed it in Pan Am script on the nose.

4.4. Telescope

The telescope itself is mounted in the aft portion of the aircraft behind a custom designed pressure bulkhead as shown in figure 2. The primary mirror of the telescope is 2.7 m in diameter with a 2.5-m effective aperture. This is the largest size that will fit in the aircraft without requiring multiple pressure bulkheads and overly invasive control modifications. Each science instrument can be mounted to the telescope in such a way that researchers have access in the pressurized cabin shirtsleeve environment. The pressure bulkhead is the largest installed in an aircraft to date and the TA itself is part of pressure and thermal boundaries.

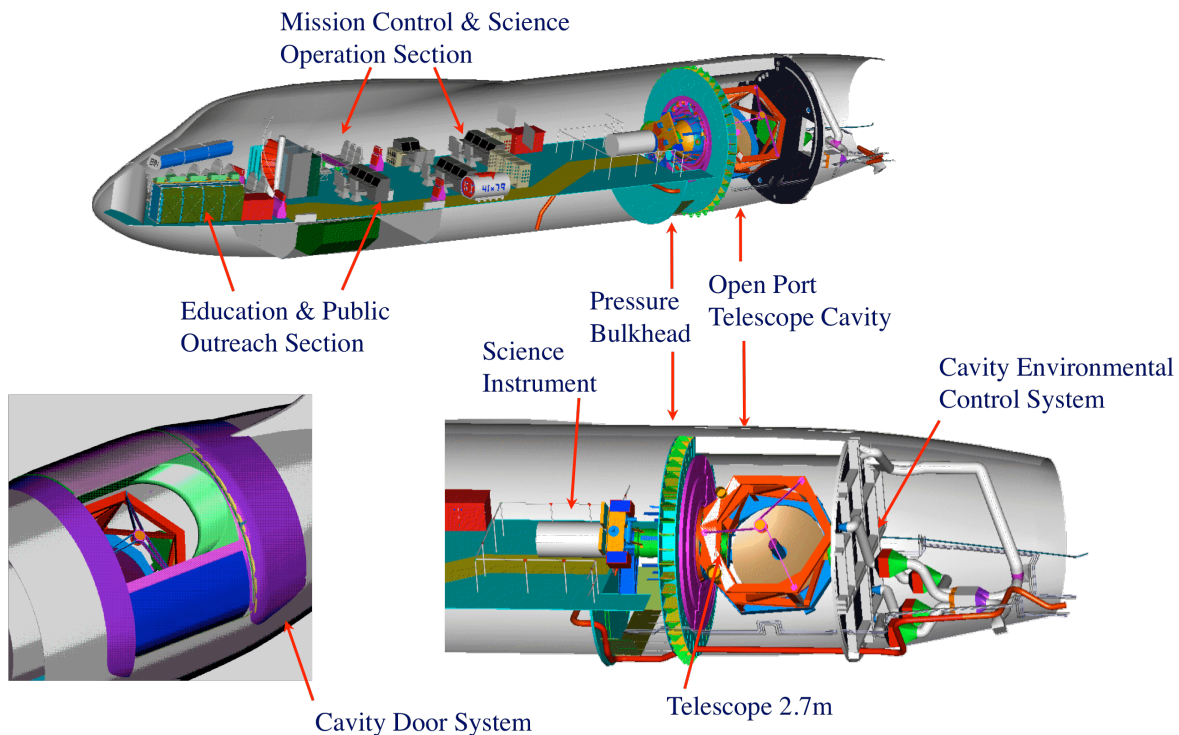


Figure 2. SOFIA fuselage cutaway.

The telescope and detectors cover a wide wavelength range from the near infrared to the sub-millimeter region or a wavelength range of 0.3 to 1,600 microns. Materials generally transparent to visible light are not transparent to IR energy over this range. Hence, observations are made through a 13 ft (3.96 m) square hole in the left upper quarter of the rear fuselage, aft of a new pressure bulkhead. The open cavity exposes the TA to ambient temperatures and airflow induced static torques, dynamic torques, and acoustic noise. Acoustics and the external flow were carefully characterized, and a major factor considered in the design and testing of SOFIA to the extent that a shear layer control device was installed aft of the TA cavity in order to avoid image distortions and unwanted acoustics due to air flow. A sliding door also covers the aperture when the telescope is not in use.

5. TEST PHILOSOPHY AND EXECUTION

The SOFIA modification raised several concerns with regard to handling qualities. First, the open cavity effect on sideslip was a major concern on SOFIA due to the lateral asymmetry created by the open door. In addition, the cavity and open door are located directly in front of the aircraft tail surfaces. Flow disturbances from the modification could cause flow irregularities over the tail surfaces resulting in adverse handling qualities in any axis. Finally, the control cables were rerouted around the pressure bulkhead and telescope assembly; a change that could cause issues with handling qualities. The effects of the modification and moveable cavity opening on aircraft handling qualities were the main focus of the handling qualities envelope expansion testing.

SOFIA is a public asset with the purpose of carrying civilian researchers, observers, and students. Thus, an effort to establish airworthiness was necessary to ensure safety for the crew and observers. It was determined early on that a Federal Aviation Administration (FAA) process was not feasible for SOFIA due to the unique nature of the modification. New FAA standards had been implemented since the construction of the 747SP that would be impossible to meet for an aircraft the age of SOFIA. One reason is simply due to requirements for documentation that no longer exists. Furthermore, the fact that SOFIA is a single aircraft, and there will be no other identical aircraft, drove the need for an alternative certification approach. Certification testing can be taxing on an airframe given that requirements generally take the aircraft to the limits of capability and beyond what is normal for operational flight. The aircraft is by definition a prototype, but at the same time has a required operational life of 20 years. These facts limited the amount of strenuous testing that could be performed, especially where dynamic stability was concerned.

Wind-tunnel modeling and computational fluid dynamics (CFD) predicted that the modification would have no significant effect on aircraft handling qualities. This prediction in combination with aforementioned certification considerations resulted in a decision to utilize a combination of past and present military-specification requirements (see Section 5.3) in order to demonstrate that the modification, in fact, had no appreciable effect on aircraft handling qualities.

The overall goal became to measure the change of critical characteristics between baseline (unmodified 747SP), closed-door, and open-door configurations by establishing equivalence with the baseline aircraft data. The baseline aircraft flight-test data were collected in 1997 prior to the aircraft being modified to the SOFIA configuration. Following modification, flight-test maneuvers were conducted in the closed- and open-door configurations at test conditions, which were selected to mirror points flown in baseline flights. Finally, post flight data analysis

was set up to highlight handling qualities metrics affected by the modification and the extent of the variance between configurations.

5.1. Controls Group Control Room Practices

As mentioned, wind-tunnel and CFD analysis predicted that the modification would have no significant effect on handling qualities. As a result, baseline and closed-door flight-test data could be used as a reference for expected performance during open-door testing. This method proved very successful for providing real-time maneuver clearance throughout envelope expansion testing. Limits for individual open-door test points were chosen based on expected variations from the corresponding closed-door maneuvers. Data were monitored in real time from the control room to ensure these limits were not exceeded; however, the limits were never exercised as the aircraft acted as predicted based on baseline and closed-door flight testing in all cases. In addition to specific predictions, general non-linear responses and undamped oscillations were used as criteria to cease a test point; however, neither of these phenomena were encountered.

5.2. Lower Order Equivalent Systems Analysis

Lower Order Equivalent Systems (LOES) analysis is a method for modeling complex dynamic systems as simpler systems by fitting predefined transfer functions to analyze the frequency content of a maneuver to back out response characteristics of the aircraft. LOES analysis can then be utilized to ascertain dynamic stability characteristics of the aircraft where flight-test data is not available.⁵

LOES analyses are traditionally performed in the frequency domain; however, none of the maneuvers flown had sufficient frequency content. As a result, an analysis method was developed and performed utilizing parameter identification (PID) maneuvers that could be examined in the time domain.⁶

PID doublets were flown for all configurations throughout the operational envelope, and LOES type analyses based on the appropriate military specification (see table 1) was performed. The output of all LOES transfer functions was finally verified with flight data; an example of which can be seen in figure 3.

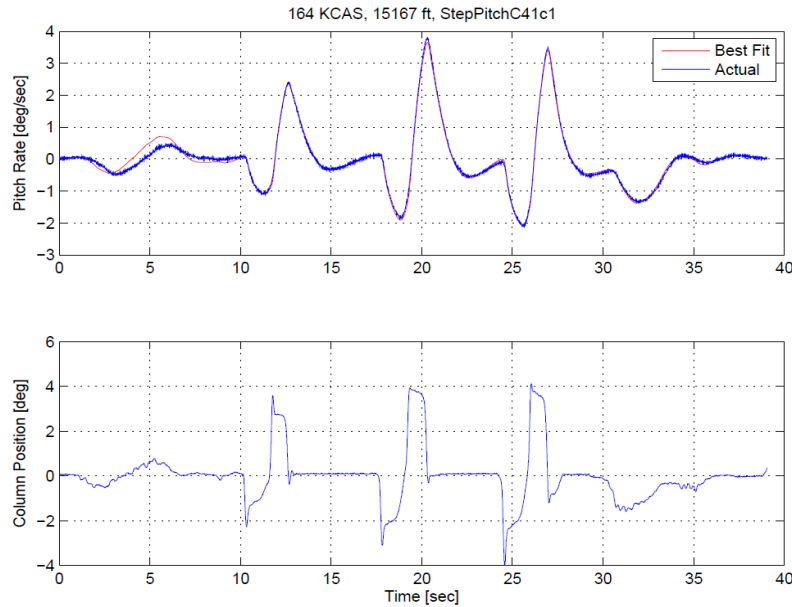


Figure 3. Example LOES output.

The results of the LOES analysis could then be applied to the Federal Aviation Regulation (FAR) certifications (figure 3) and military specifications to show compliance and airworthiness. The analysis was performed on all configurations to demonstrate similarity in aircraft stability and control with the baseline aircraft.

5.3. Airworthiness Determination

Compliance with all certification standards would have required re-flying all certification maneuvers, which was deemed too cost and schedule prohibitive as well as too taxing on a 30-year old airframe. The airworthiness of SOFIA was determined by demonstrating similarity with the baseline configuration using the existing certification standards as guidelines. FAR Part 25⁷ was used as a starting point for airworthiness determination to include advisory circular 24-7A,⁸ which provides guidance on satisfying the requirements. Where FAA standards were not available, applicable military specifications were used. Mil-Spec-8785B⁹ was used to assign quantitative values and analysis techniques to evaluate handling qualities, and is more detailed than FAR Part 25. No existing previously certified aircraft is required to meet a new specification as the older viable aircraft may not be capable of meeting the new standard. As Mil-Spec-8785C post dates the 747SP, it was not used. Mil-Spec-1797¹⁰ was used where other standards did not exist.

The modification had the possibility of effecting compliance with several airworthiness regulations. These regulations were identified, and a test plan was generated cross-referencing each. This created a direct trail for the reasoning behind test points.

Further, FAA Designated Engineering Representatives (DER) were invited to be part of the planning for the modification. The DERs made several suggestions regarding the FAR requirements pertinent to the modification. The test plan was then sent to another FAA DER for review and comment. The DER provided a comprehensive set of comments to the proposed test plan. Most of the comments were applied to an updated test plan that was ultimately flown.

A summary of FAA certification standards addressed can be seen in table 1. Where appropriate, Mil-Spec-8785C and Mil-Spec-1797 standards were used to verify the FAA standard.

Table 1. Certification standards summary.

FAR part	Title	Synopsis	How satisfied
25.143	General	Airplane must be safely controllable and maneuverable during all normally planned maneuvers, configuration changes, critical engine failures, and with critical ice accretion without excessive forces or exceptional piloting skill and free of buffet for a given set of maneuvers.	The fulfillment of this general requirement as compared to a stock 747SP was demonstrated by the normal operations of SOFIA. Minimal controllable airspeed (Vmc) testing was successfully completed to show engine out controllability. Pull up, push over (PUPO)s, wind up turns (WUTs), and steady heading side slips (SHSSs) were executed and verified control force requirements. Buffet boundary testing satisfied the buffet free requirements. Finally, PID results quantified effects of the modification on tail effectiveness for conditions near trim. Original ice accretion testing suffices as wings, tail, and icing prevention are unchanged.
25.145	Longitudinal control	It must be possible to pitch the nose downward so that the acceleration to a given trim speed is prompt.	The Federal Aviation Regulations (FAR) calls out several maneuvers. A subset of these maneuvers was performed per cross-reference with the Designated Engineering Representative (DER). The overall intent was met using PID maneuvers. All door positions were explored. Transients at all test conditions were indiscernible from the stock 747SP. In addition to the FAR comparison, Military specification analysis was performed. All test points flown met level 1 Military specification criteria and agreed well with results from baseline testing.

Table 1. Continued.

FAR part	Title	Synopsis	How satisfied
25.147	Directional and lateral control	It must be possible, with the wings level, to yaw into the operative engine and to safely make a reasonably sudden change in heading of up to 15 degrees in the direction of the critical inoperative engine.	In lieu of original certification maneuvers, demonstration of acceptability of lateral/directional handling qualities was accomplished under a range of operating conditions using a preliminary military specification analyses to show that all handling qualities are level 1. Specifically SHSSs were used to demonstrate that rudder authority was unchanged throughout the envelope.
25.149	Minimum controllable airspeed	Describes the methods used for establishing the minimum control speeds required for the most critical mode of power plant failure with respect to controllability expected in service.	Rudder control effectiveness was determined to be unchanged via PID and SHSSs in all door positions. Hence, original airworthiness is sufficient for stability and control. In addition, Vmc for the airborne takeoff configuration was tested in a manner similar to FARs with the exception that the center of gravity (CG) was not in critical location. Vmc was found during flight test to be 5 to 6 knots below published.
25.161	Trim	The aircraft must be able to be trimmed and hold trim in all configurations and flight phases.	The modified aircraft demonstrated the capability to hold trim in all flight phases and in all portions of the envelope with no deviation from the baseline aircraft. Lateral CG displacement was not tested, however, tail effectiveness is shown to be unchanged hence lateral CG testing is not considered necessary.
25.173 & 25.175	Static longitudinal stability	Defines maneuvers to demonstrate static longitudinal stability and outlines a procedure for compliance.	Stick force per acceleration/deceleration maneuvers were performed closed door. Parameter identification analysis showed that the modification had no effect and the DER concurred that simple operational capability demonstration would satisfy this requirement.

Table 1. Concluded.

FAR part	Title	Synopsis	How satisfied
25.177	Static lateral-directional stability	In straight, steady sideslips, the aileron and rudder control movements must be substantially proportional to the angle of sideslip in a stable sense.	SHSSs were performed for all door configurations throughout the operational envelope, shown to be unchanged from baseline, and thus, meeting this requirement (see Section 5.5).
25.181	Dynamic stability	Any short period oscillations must be heavily damped. Any dutch roll must be positively damped controllable.	LOES analysis of flight test data demonstrated: Short Period Dynamic Stability - The short period mode was shown to fall in the level 1 region based on Mil-Spec-1797. Dutch Roll Mode - The dutch roll mode has been shown to meet the FAA requirement especially with the yaw damper on.
25.237	Wind velocities	A cross component of wind velocity, shown to be safe for takeoff and landing must be established.	SHSSs performed in both directions for all takeoff and landing configurations and demonstrated no change in characteristics with the door open.

5.4. LOES Results

The output of the LOES analysis was applied to the applicable standards as listed in table 1. The results for short period longitudinal dynamic stability can be seen in figure 4. Level 1 and level 2 handling qualities boundaries as defined in Mil-Spec-8785B are depicted. Points for the baseline aircraft, closed door and 100% door open are shown to fall within or on the level 1 handling qualities boundary. The reason for the borderline points is unclear; however, aircraft response is consistent with the conclusion that short period response falls within the level 1 handling qualities boundary. This was also deemed acceptable as this investigation was aimed specifically at identifying a change between configurations, for which these points show no significant difference. Points for intermediate door positions fall within this boundary as well, but were omitted for clarity.

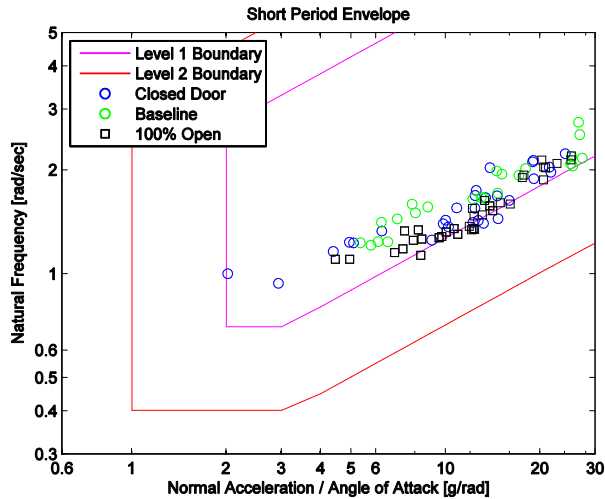


Figure 4. Short period dynamic stability envelope.

LOES analysis was also applied to dutch roll characteristics. The dutch roll mode was shown to meet the FAA requirement, and all door positions compare well with the baseline aircraft as depicted in figure 5. The scatter in the flight data was due partially to the fact that dutch roll mode of jet transport type aircraft tends to be lightly damped. Turbulence also contributes to scatter in the data. LOES analysis indicates a slight improvement in dutch roll damping at higher speeds. There are two potential reasons for this behavior.⁵ One, the LOES analysis is bare airframe response only while all flight testing was conducted with yaw dampers on. Baseline, closed-door and open-door flight-test data used for the LOES analysis was gathered with the yaw dampers on. However, the results of the LOES analysis for all configurations show the bare aircraft response. This demonstrates that the inter-configuration comparison is consistent, but comparison of LOES data to raw flight-test data does not account for the yaw dampers being on in flight. Yaw dampers would compensate some of the bare airframe effects as depicted in the LOES analysis and negate any positive effect on dutch roll characteristics. Two, there could be a slight stabilizing effect of the open door; however, if this is true, the difference is not of practical significance. In the end, review of the raw flight-test data and pilot assessment suggests the door has no appreciable effect.

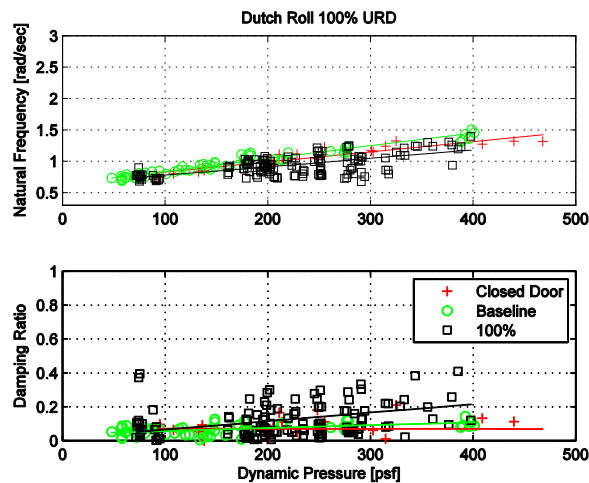


Figure 5. Dutch roll damping results

5.5. Rudder Deflection vs. Sideslip

As stated earlier, open cavity effect on sideslip was a major concern due to the lateral asymmetry created by the open door. This could especially have an effect on crosswind landing capabilities. Multiple sideslip points were flown to full rudder deflection throughout the envelope in the baseline configuration and in all door positions. The data for all points are shown in figure 6. The data clearly depict no appreciable effect of the open door on sideslip angle. Hence, the stock aircraft crosswind limit is preserved.

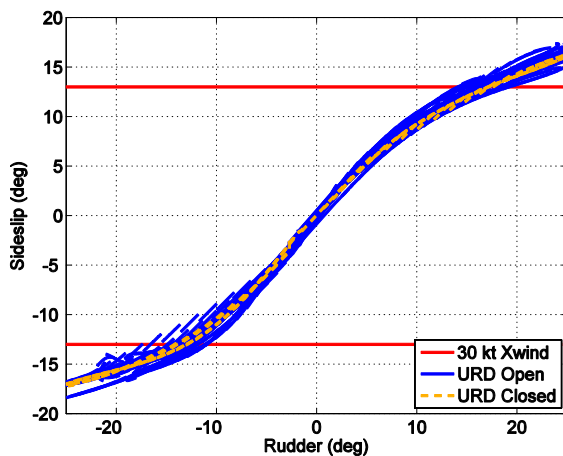


Figure 6. Sideslip versus rudder deflection.

5.6. Qualitative/Pilot Opinion

Pilot comments collected on all flights amounted to the simple consistent comment that the open-door aircraft behaved identically to the closed-door aircraft. More specific, but also common, pilot comments were that during all controls test points forces were normal, oscillations were heavily damped, and control harmony was good. There were a few instances where the pilots noted a possible, minute difference; however, these instances were all shown to be driven by atmospheric turbulence or other non-door related phenomena. Test points including doublets, SHSS, PUPOs, simulated approach to landings, and engine out events were flown throughout the flight envelope and were appropriate.

6. CONCLUSION

The flying qualities flight-testing of SOFIA had several beneficial outcomes. The modification to the SOFIA airframe showed no significant negative handling qualities impacts. Next, two precedents were set. First, the overall scope of the project demonstrated re-establishment of airworthiness through a demonstration of similarity with an earlier configuration. Second, the more specific process using LOES analysis specifically demonstrated similarity of dynamic response.

Again, the exercise of re-establishing the airworthiness of a modified transport aircraft for public use has set a precedent. The program was successfully executed within resource constraints far tighter than would be required for standard aircraft manufacturing and upgrade. In so doing, this procedure has set an example that can be used for future NASA programs in allowing public access to modified aircraft.

The implementation of a simple LOES analysis for verification of airworthiness compliance also sets a precedent. The method provides a simple and accurate means of ascertaining basic aircraft dynamics that has potential application on other NASA aircraft.

Overall, the SOFIA modification was demonstrated to have no appreciable negative effects on the handling qualities of the base 747SP airframe. If anything, the open door created a stabilizing moment that improved dutch roll damping slightly; however, this delta shown in data is so small that it may not be a practical reality. These findings again led to the conclusion by the NASA Dryden Controls Group that SOFIA is cleared for safe operation as an airborne observatory to program defined limits.

7. BIOGRAPHIES

Scott Glaser has a diverse background in flight testing ranging from high angle of attack and wake encounter testing on the F-22 Raptor, to airborne astronomy with the Stratospheric



Observatory for Infrared Astronomy (SOFIA) and envelope expansion on SpaceShipTwo. He has worked for and with a number of noteworthy organizations such as the United States Air Force, the National Aeronautics and Space Administration (NASA), the National Aerospace Training and Research (NASTAR) Center, Lockheed Martin Skunk Works, Scaled Composites, and The Spaceship Company to name a few. He has held positions ranging from

discipline engineer to Director of Flight Dynamics Research, and now provides volunteer service to the aerospace community as President of the Antelope Valley Chapter of SFTE. In addition to engineering, Mr. Glaser is also an accomplished warbird aerobatic pilot and instructor with numerous certifications including Multi-Engine Instrument Instructor and Formation Lead Pilot.

Brian Strovers has been involved in flight testing over a wide range of flight conditions and vehicles from Mach 0.2 to over 9.5 with some notable vehicles such as X-43A, Pegasus launch



vehicle, UAVSAR, X-55A, and of course SOFIA. He has worked with NASA Dryden, Langley, Ames, Johnson, Jet Propulsion Laboratory, Air Force Research Laboratory Wright-Patterson, Boeing Phantom Works, Orbital Sciences Corporation, Lockheed Martin Skunk Works, SAAB Aerospace, and Hamilton Sundstrand. He has performed engineering functions such as design, development test, vehicle analysis, materials, research, and currently resides in the controls and dynamics branch at Dryden Flight Research Center. His extracurricular aviation endeavors include throwing money into

maintaining an old high-performance single engine Cessna and participating in the National Airspace System as an instrument cruise pilot.

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