SOFIA
Stratospheric Observatory For Infrared Astronomy

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Outline

• Heritage & History
• Level 1 Requirements
• Top Level Overview of the Observatory
• Development Challenges
• Highlight Photos
The Great Observatories

- Mt Wilson
- Mt Palomar
- Keck (Hawaii)
Hubble
Hubble Discoveries
HISTORY OF SOFIA

1965-1985

- **1965-1969** First use of NASA aircraft for infrared (IR) astronomy (CV-990 & Lear Jet)
- **1969** Planning started for installation of 36-inch telescope in a CV-990
- **1969** First astronomy community interest in a Boeing 747
- **1971** National Academy of Sciences (NAS) Decade Survey (Greenstein) Report recommended study of Large Airborne Telescope (LAT)
- **1974** First research flight of Kuiper Airborne Observatory; Initial studies on larger system
- **1983-1984** Success of Infrared Astronomy Satellite (IRAS) shows need for follow-up/exploitation
- **1984** "Stratospheric Observatory For Infrared Astronomy (SOFIA) Preliminary Feasibility Study" report issued (10th KAO Anniversary)
- **1985** SOFIA study funding provided – partnership with Germany started
HISTORY OF SOFIA

1986

• **JANUARY**  Ames Research Center (ARC) establishes SOFIA Study Office
• **JANUARY**  Challenger accident
• **MAY**  SOFIA technology workshop at Ames;
• **MAY-NOVEMBER**  Boeing-Military Aircraft Company Phase I Study; Confirms feasibility of installing a 2.5 meter telescope in a 747SP
• **JULY**  Draft of the Memorandum of Understanding (MOU) for Telescope System study established with Germany
• **OCTOBER**  Ames in-house Conceptual System study begins
• **NOVEMBER**  Collaborative agreement made with DFVLR (Deutsche Forschungsanstalt für Luft und Raumfahrt)
• **NOVEMBER**  German Phase A Telescope System studies kickoff

1987

• **FEBRUARY**  Telescope System Phase A Study midterm review at ARC
• **FEBRUARY-SEPTEMBER**  Boeing-MAC Phase II Study
• **MAY**  German Phase A studies completed
• **JULY**  SOFIA concept review held at ARC
• **SEPTEMBER**  Ames Conceptual System study finished; SOFIA "Phase A System Concept Description" (The Red Book) published
1988

- **JUNE** Space and Earth Sciences Advisory Committee (SESAC) recommends that SOFIA proceed into definition phase
- **JUNE** – Began planning for wind tunnel tests
- **OCTOBER** Phase B (Definition Study) kickoff for Aircraft System at Ames
- **OCTOBER** Phase B (Definition Study) kickoff for Telescope Assembly at Zeiss

1989

- **JANUARY** Telescope fixed at 2.5 meters by NASA HQ/DFVLR agreement
- **FEBRUARY** Wind tunnel model design complete and fabrication begins
- **MAY** Project Definition Review completed at ARC; Found SOFIA well planned and defined and approved the project to proceed into the development phase contingent on a successful completion of wind tunnel test
- **JUNE** Draft MOU for development & operations phases reviewed by Ames & DLR
- **JULY** Non-Advocate Cost Review successfully completed, Affirmation of project readiness for 1991 start; FRG listed as responsible for telescope assembly
- **JULY** Definition studies completed by NASA
- **SEPTEMBER** Telescope and Aircraft System Phase B final reviews are completed and reports published
- **OCTOBER** Boeing re-organizes; No longer interested in "one-off" mods like SOFIA
- **NOVEMBER** Berlin wall falls; Reunification of East and West Germany considered
HISTORY OF SOFIA

1990

- **MARCH** SOFIA I wind tunnel model tests start
- **MAY** DARA budget cuts begin
- **JUNE** Non-Advocate Review is held for SOFIA in accordance with the agency's new start-gate policy; SOFIA deemed ready to proceed to development again and recommended for 1992 start
- **JUNE** Preliminary engineering study of SOFIA Ground Support Facility
- **JUNE** Aircraft System modification procurement activities underway, Source Evaluation Board (S.E.B.) established
- **JULY** Wind tunnel tests successfully completed; A low drag passive shear layer control device derived that exceeds performance expectations
- **OCTOBER** Reunification of Germany, requires reduction of German government agencies' budgets

1991

- **NAS Decade Survey (Bahcall) Report** recommends SOFIA as the top priority moderate new missions for NASA
- **MAY** With the realization of DARA budget cuts, SOFIA plans FY92 to prepare for an all U.S. program with optional help from DARA in FY94
- **MAY** Aircraft Modification Contractors road trip to find companies w/interest/capability to perform the SOFIA aircraft modification
- **JULY - SEPT** In-house descope studies, to reduce total cost; 5 cases considered, one considers an aft cavity location to reduce aircraft modification costs
- **OCTOBER** Aft cavity location adopted as new baseline for the Aircraft System
HISTORY OF SOFIA

1992

- **JANUARY** IR measurements made of the Shuttle Carrier Aircraft (SCA) engine plumes using IR cameras mounted in Lear jet
- **DECEMBER** Final reports of Aircraft Systems NRA concur with Ames in-house study regarding feasibility and cost savings for the aft cavity configuration

1993

- **JUNE** ARC Code R agrees to de-mothball 14 ft wind tunnel for SOFIA test; Test entry planned for 1994
- **AUGUST** Headquarters OSS proposes SOFIA as an FY95 new start to Administration/Comptroller

1994-1995

- SOFIA New Start approved
- Headquarters mandates Privatization concept:
  - “Government owned, contractor operated”
  - “Better-Faster-Cheaper”
- Procurement proceeds for development & operations phase
  - Science organization prime - Government work packages

1996

- **December** - SEB process complete - NASA [contract awarded](#) to USRA-UAL-Chrysler Tech Team
- **December** - DLR [awards contract](#) to team of MAN-G, MAN-T, & KT
The Org structure for majority of the development phase
Major Components of SOFIA

Observatory

Science and Mission Operations Center

Science Instruments
HISTORY OF SOFIA

Milestones

• 1997
  – System requirement reviews completed (2)
  – Baseline Flight test completed
  – SOFIA V Wind Tunnel test completed

• 1998
  – TA PDR completed
  – AS PDR completed

• 1999
  – Schedule slips
  – 3% S&C wind tunnel tests completed

• 2000
  – TA CDR completed
  – AS CDR completed
  – Schedule continues to slip

• 2001
  – TA ground I&T begins
  – September 11 attack - impacts US airlines
HISTORY OF SOFIA

Contract Milestones

• 2002
  – TA ground testing & Project Final Review completed
  – TA shipped to Waco September 2002

• 2003
  – TA integration into aircraft begins
  – Columbia accident
  – UAL departs SOFIA program under bankruptcy protection (9/11)

• 2004
  – TA functional, SI mounted, First Light August 2004
  – Aircraft Proof pressure test completed
  – DSI selected in Germany to support SOFIA Ops

• 2005
  – Push for flight leads to multiple mishaps then work stoppage
  – Mod audit conducted
  – Per ICSMR recommendations Re-baseline & new approach begins
HISTORY OF SOFIA

Contract Milestones

• 2006
  – SOFIA Budget zeroed for FY07 budget
  – SORT commissioned to consider options for future
  – GVT conducted on aircraft in June per IMS established 8/2005
  – HQ dropped requirement for FAA certification (Public Use)
  – Budget rebaselined & program office transferred to Dryden
  – Flight Readiness Review started in Oct

• 2007
  – Airworthiness Flight Safety Review Board on 15 Mar 07
  – First Flight on 26 Apr 07
  – Ferry Flight of SOFIA to Dryden 31 May 07
  – Begin Phase 1 flights (door closed envelope expansion) Sep 25 07?
Heritage

- Kuiper Airborne Observatory is the direct Predecessor to SOFIA
  - Modified C-141 with 36” Diameter Telescope
  - Flew w/open port cavity 1974-1995
  - Cavity in forward fuselage
  - Porous fence was primary Shear Layer Control device
  - Aft Ramp augmentation based on SOFIA development wind tunnel test results was implemented in 1993
    - Flow attachment significantly improved
    - Internal Cabin noise significantly reduced for Open cavity flight
    - Cavity Environment significantly improved
    - Allowed fence position to be lowered from 30° to 10°
    - Reduced drag - improved flight performance
Kuiper Airborne Observatory (KAO)

1974-1995
Lockheed C-300
(Modified C-141)
36” Telescope

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KAO Aft Ramp - Passive Flow Fairing

- Installed in 1993
- Developed from wind tunnel test data and research performed during initial development of the SOFIA Shear Layer Control System
- KAO design represents a compromise due to existing OML & cavity door constraint
KAO Aft Ramp - Passive Flow Fairing

- Designed to stabilize the shear layer re-attachment downstream of the open cavity.
- Enabled KAO to fly with the cavity fence at 10° instead of 30°
- Reduced Shear layer thickness
- Significant improvements in “Seeing”
- Reduced cavity aero-acoustics
- Reduced structural fatigue in and around cavity
- Pilot noticed improvements in open door flight
SOFIA - Airborne Astronomy Size Comparison

**SOFIA** - OPERATIONAL 2001
AIRCRAFT - BOEING 747SP
MAXIMUM GROSS WEIGHT - 703,000 lb
TELESCOPE APERTURE - 98 in. diam (2.5 m)

**KAO** - OPERATIONAL 1975
AIRCRAFT - LOCKHEED C-141A
MAXIMUM GROSS WEIGHT - 320,000 lb
TELESCOPE APERTURE - 36 in. diam (0.91 m)

**LEARJET OBSERVATORY** - OPERATIONAL 1965
AIRCRAFT - LEARJET, MODEL 24
MAXIMUM GROSS WEIGHT - 15,000 lb
TELESCOPE APERTURE - 11.8 in. diam (0.3 m)

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**SOFIA - Requirements/Specifications**

- Wavelength Range: 0.3 - 1600 microns
- Unvignetted elevation range: 20° to 60° above the horizon
- Configuration: Instrument Access in Cabin
- Telescope effective Aperture Diameter: 2.5 meters
- Time at ≥ 41,000 feet ≥ 6 hours
- Observing hours per year: ≥ 960
- Lifetime: ≥ 20 years
- PI Teams per year capability: ≥ 40
- Education Goals: NASA OSS Guidelines
- Airworthiness: FAR FAA Certification
- IR functional capabilities: chopping, nodding, & scanning
- Image quality: 80% encircled energy within 1.5 arcsec at visible wavelength
- Image stability at focal plane: 0.2 arcsec rms

Combined to 80% encircled energy within 5.3 arcsec diameter image size at First Science Flight, improving to 1.6 arcsec within 3 years.
Pressurized Cabin- containing mission equipment, the science instrument, the flight crew, the observatory crew, and the scientists

Open Port cavity- containing telescope

New pressure bulkhead
Airborne Observatory Layout
2.5 Meter effective aperture

- Aircraft Size
- Large 2.7 Meter Primary Mirror
- “Fast” Mirror to fit within aircraft
  - Drives alignment/stiffness requirements
Telescope Optical Layout

Focal Plane

Focal Plane Imager

Primary Mirror M1

M2

M3-1

M3-2
2.5 Meter effective aperture
Major Telescope Components

- **Primary Mirror M1**
- **M2**
- **M3-1**
- **M3-2**

**Major Telescope Components:**
- Science Instrument
- Counter Weight
- Hydraulic System
- Motors
- Brakes
- Bearing Sphere
- Forward Bulkhead
- Focal Plane Imager
- Vibration Isolation
- Cameras
Telescope pre-ship integration
Configuration: Instrument Access in Cabin

Cabin Side
- Shirt Sleeve Environment

Cavity Side
- Open to Atmosphere
  (0.18 atm - -40°C)

Pressure Bulkhead
- Thermal & Pressure Boundary

Forward
New Pressure Bulkhead
Bulkhead Simulator for TA Integration
• Unvignetted Elevation Range (20° - 60°)

Large Structural Opening
Cavity Door System

- Upper Rigid Door Drive
- Aperture
- Inflatable Seal
- Door Snubbers
- Seal Inflation System
- Aircraft Forward Direction
- Lower Flexible Door (LFD)
- Upper Rigid Door (URD)
Technical Challenges

- Open Port cavity
  - Final Verification pending completion of Flight Tests
  - Influence on aircraft Stability & Control
- Acoustic Issues
  - Resonance
  - Structural Fatigue
  - Environment for Telescope Performance
- Drag (aircraft performance)

Structural Modification

- Strength
- Stiffness
- Transition to unmodified areas
Technical Challenges

- Thermal Environment
  - Systems exposure
  - Science performance

- Cavity Door
  - Accommodate fuselage deformation
  - Track Telescope motion
  - Drive system safety
    - Lightweight Primary Mirror
    - Rotational Isolation System
      - KAO used air bearing but this technology does not scale well…
SOFIA Wind Tunnel Testing Overview

7% Scale Tests
- SOFIA I - March 1990 to July 1990 - Forward Cavity configuration
- SOFIA II - June 1994 to August 1994 - Aft Cavity configuration
- SOFIA III - February 1995 - SP only - Aperture Geometry - TA loads
- SOFIA IV - Sept 1995 to Dec 1995 Door design space evaluation
- SOFIA V - November 1997
  - Adjustment of Boundary Layer profile to match Baseline Flight tests
  - Verification of Final Partial External Door (PED) Design
  - Measurement of loads on Final Telescope design (pointing performance)
  - Measurement of loads for use in PED design

3% Scale Tests
Stability & Control - measure aero-coefficients between baseline 747-SP and SOFIA and provide substantiation for reduced flight test program
- Low Speed Tests - University of Washington Kirsten Wind Tunnel
- High Speed Tests - Boeing Transonic Wind Tunnel
  - November 1998
SOFIA 7% model in Ames 14ft Transonic Wind Tunnel

Primarily used to development shear layer control design technology and to determine cavity acoustic environment and resultant loads on Telescope.
SOFIA CFD Predictions

- Example of CFD flow over the mod
• Stab & Control
• Negligible change in drag and pitching moment
• No other F&Ms affected
Objectives

- Per all Test and Analyses completed, data indicates Objectives will be met
  - Minimal impact on Stability & Control of Aircraft
  - Robust - Non resonating cavity (structural/safety)
  - “Quiet” cavity for optimum TA pointing performance
  - Minimize drag to maintain Aircraft performance
  - Optimize Aero-Optic performance “seeing” for short wave length image quality performance

- Flight Testing is remaining step to Verify
Summary

- SOFIA SLC development began with KAO heritage
- Open port cavity/SLC issues identified early (1980’s) as risk areas
  - Risk reduction activities were planned & completed accordingly
- Eight Separate Wind Tunnel Test Series Completed
  - Results Indicate:
    - Shear layer control implementation will provide quiet well behaved cavity acoustic environment
    - Stability & Control of aircraft will be essentially unaffected
- Multiple CFD and other analyses completed
  - Results concur with wind tunnel tests and provide additional data
- Multiple Independent Reviews Concur with approach
  - Latest NESC review extensively examined test and analysis data and planned program approach and recommend proceeding to flight test
- **All data indicates that SOFIA will fly like an unmodified 747-SP**
Telescope arrival in Waco- Sept 2002
Unloading Telescope Pieces
Inside aircraft just before SUA installation

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Primary Mirror Installation
7/15/03
Telescope inside Aircraft Cavity
SOFIA Stratospheric Observatory for Infrared Astronomy

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Inside the aircraft - Fall 2003
First Light
August 2004
Roll out from paint hangar September 2006
First Flight
Ferry to Dryden
Questions?