SOFIA

Stratospheric Observatory For Infrared Astronomy

Nans Kunz, NASA Ames Research Center
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National Aeronautics and Space Administration
Ames Research Center

Outline

SOFIA Stratospheric Observatory for Infrared Astronomy

- Heritage & History
- Level 1 Requirements
- Top Level Overview of the Observatory
- Development Challenges
- Highlight Photos

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The Great Observatories

SOFIA Stratospheric Observatory for Infrared Astronomy

- Mt Wilson
- Palomar
- Keck

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Hubble

SOFIA Stratospheric Observatory for Infrared Astronomy

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Hubble Discoveries

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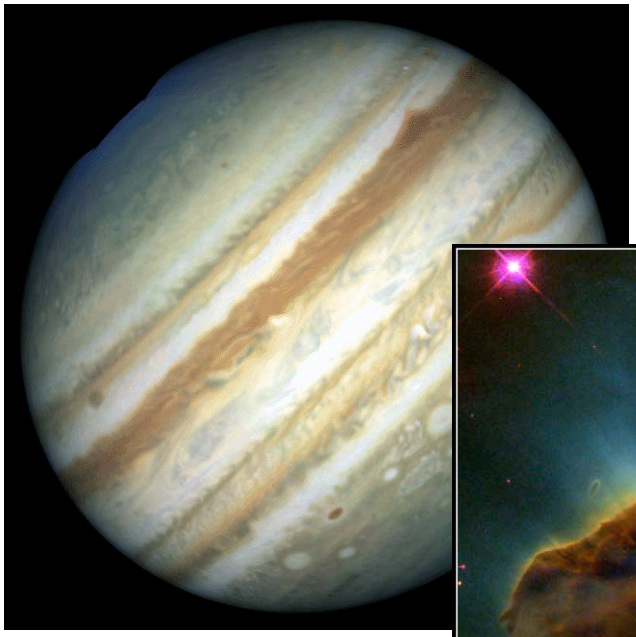

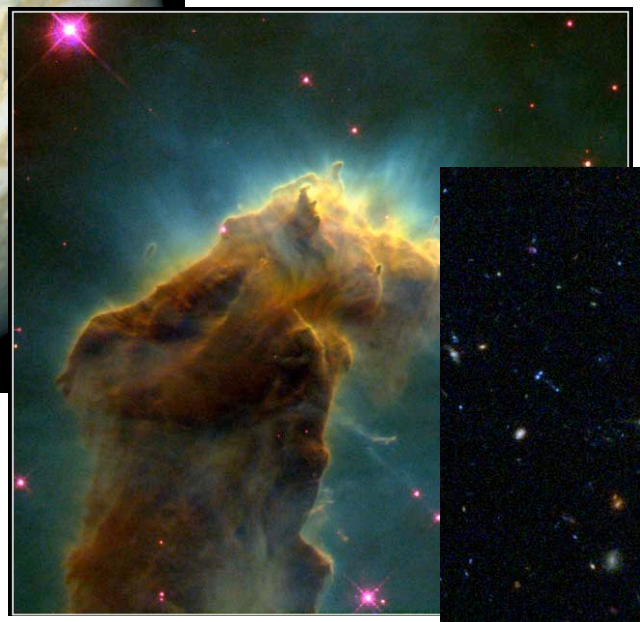

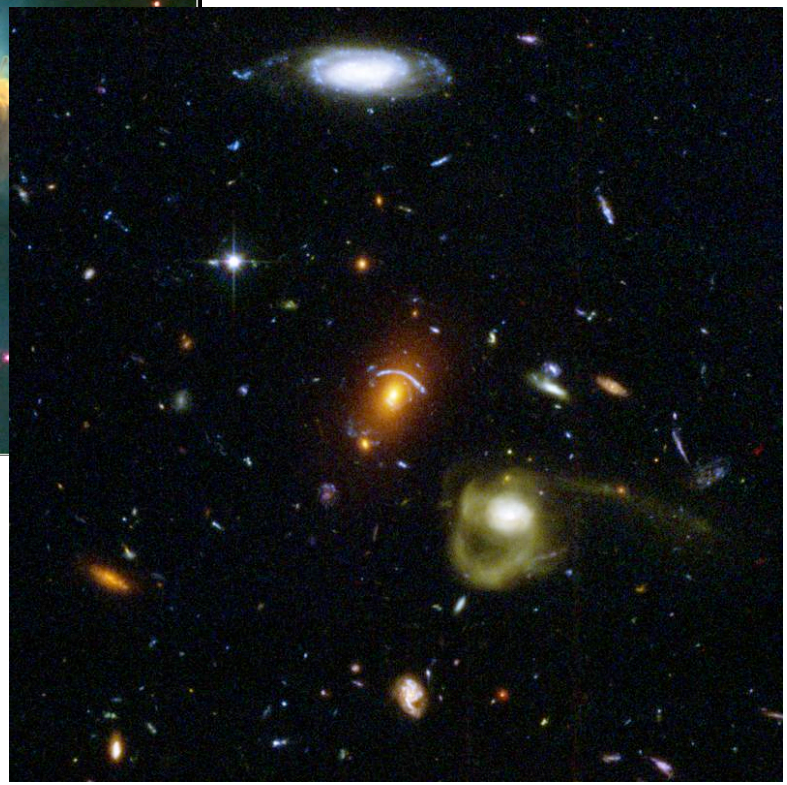

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HISTORY OF SOFIA

SOFIA Stratospheric Observatory for Infrared Astronomy

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
- **1977** Boeing delivered a study for a LAT in a Boeing 747SP
- **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

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HISTORY OF SOFIA

SOFIA Stratospheric Observatory for Infrared Astronomy

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

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HISTORY OF SOFIA

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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

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HISTORY OF SOFIA

SOFIA Stratospheric Observatory for Infrared Astronomy

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

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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

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SOFIA Stratospheric Observatory for Infrared Astronomy

The Org structure for majority of the development phase

NASA — Project Sponsorship, Fiscal Control and Review

DLR — Project Co-Sponsorship, Telescope Provider, Oversight of German Instrument and Subcontracts

USRA — US Instruments and Subcontract Science Support, Operations

MAN TECHNOLOGIE, KAYSER-THREDE — Telescope Assembly

NASA

L3 Communications Integrated Systems

Sterling Federal Systems — Mission Control, Software, Network and Web Support

Astronomical Society of the Pacific

SETI INSTITUTE — Education & Public Outreach

University of California — Instruments, Mirror Cleaning, Science Support

UNITED — Aircraft Operation and Maintenance

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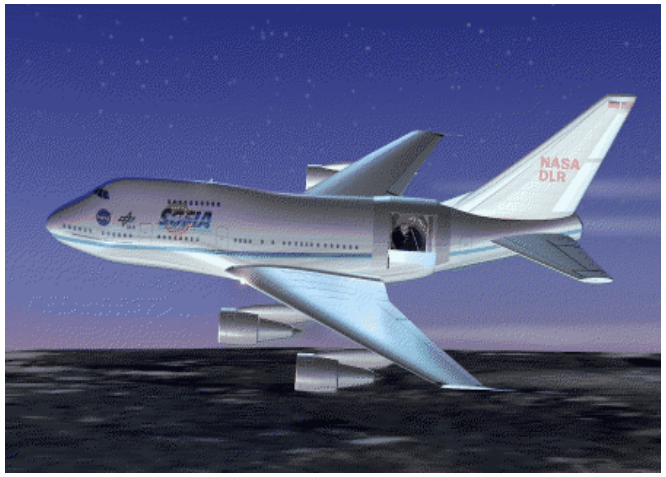
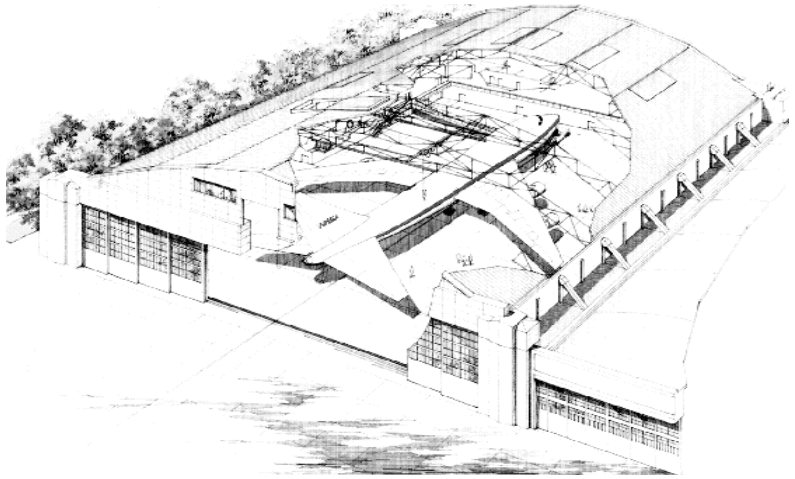
Major Components of SOFIA

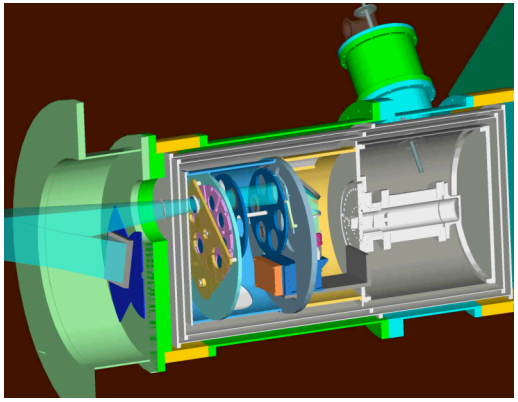
SOFIA Stratospheric Observatory for Infrared Astronomy

Observatory





Science and Mission Operations Center



Science Instruments

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HISTORY OF SOFIA

SOFIA Stratospheric Observatory for Infrared Astronomy

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

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SOFIA Stratospheric Observatory for Infrared Astronomy

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 recommedations Re-baseline & new approach begins

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HISTORY OF SOFIA

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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 25 Apr 07?
  - Ferry Flight of SOFIA to Dryden end of May
  - Begin Phase 1 flights (door closed envelope expansion)

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Heritage

SOFIA Stratospheric Observatory for Infrared Astronomy

- 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

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Kuiper Airborne Observatory (KAO)

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1974-1995

Lockheed C-300
(Modified C-141)

36” Telescope

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KAO Aft Ramp - Passive Flow Fairing

SOFIA Stratospheric Observatory for Infrared Astronomy

- 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

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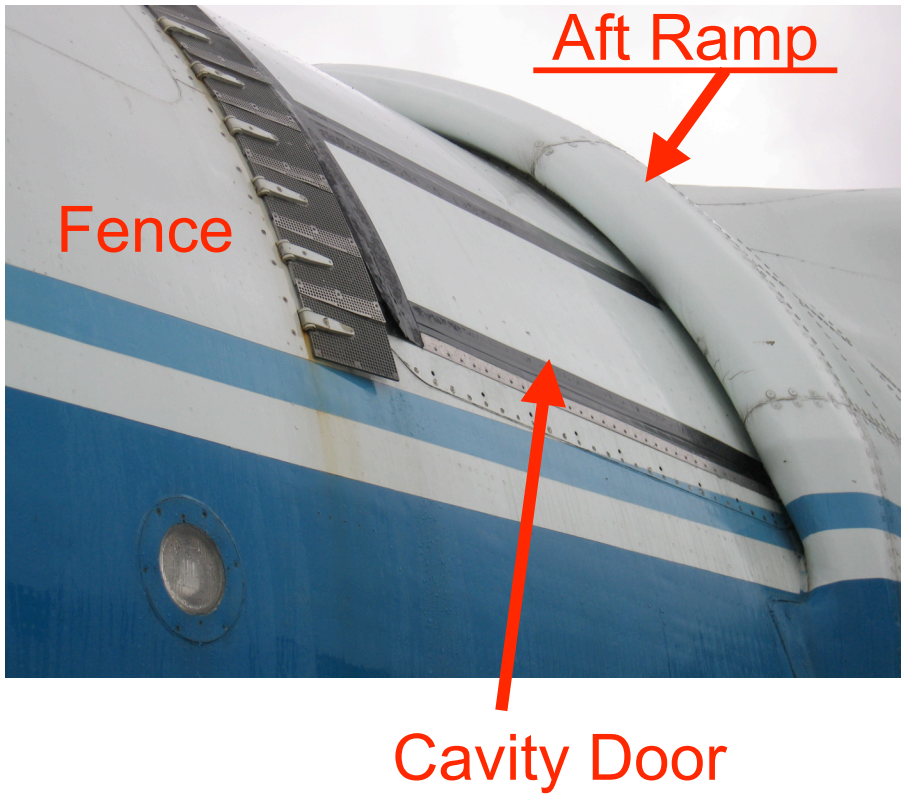
KAO Aft Ramp - Passive Flow Fairing

SOFIA Stratospheric Observatory for Infrared Astronomy



- 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

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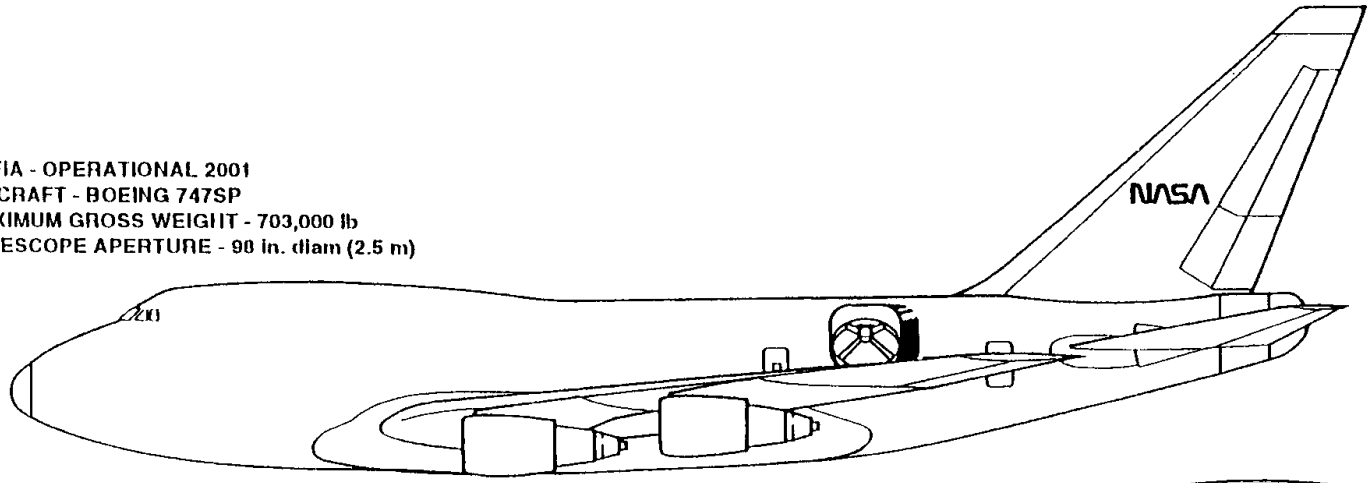
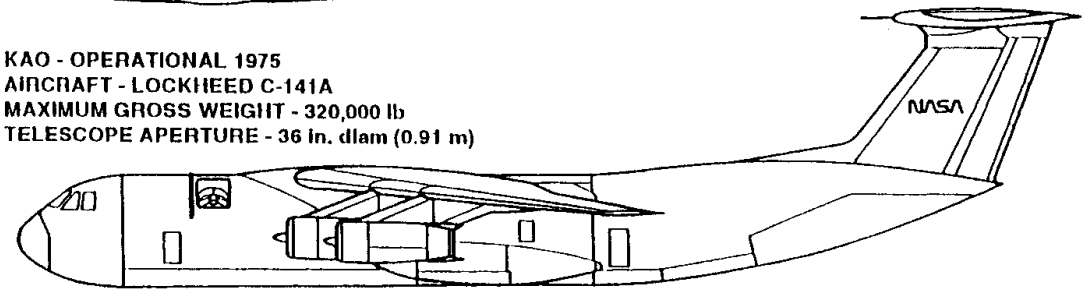
SOFIA - Airborne Astronomy Size Comparison

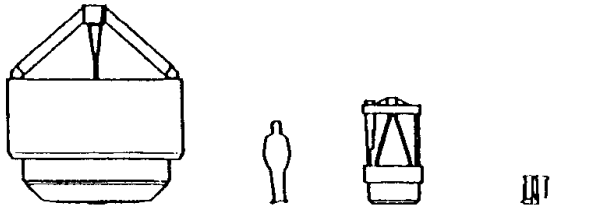
SOFIA Stratospheric Observatory for Infrared Astronomy

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)



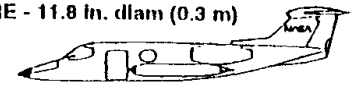


SOFIA

KAO

LEARJET

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

SOFIA Stratospheric Observatory for Infrared Astronomy

- 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.

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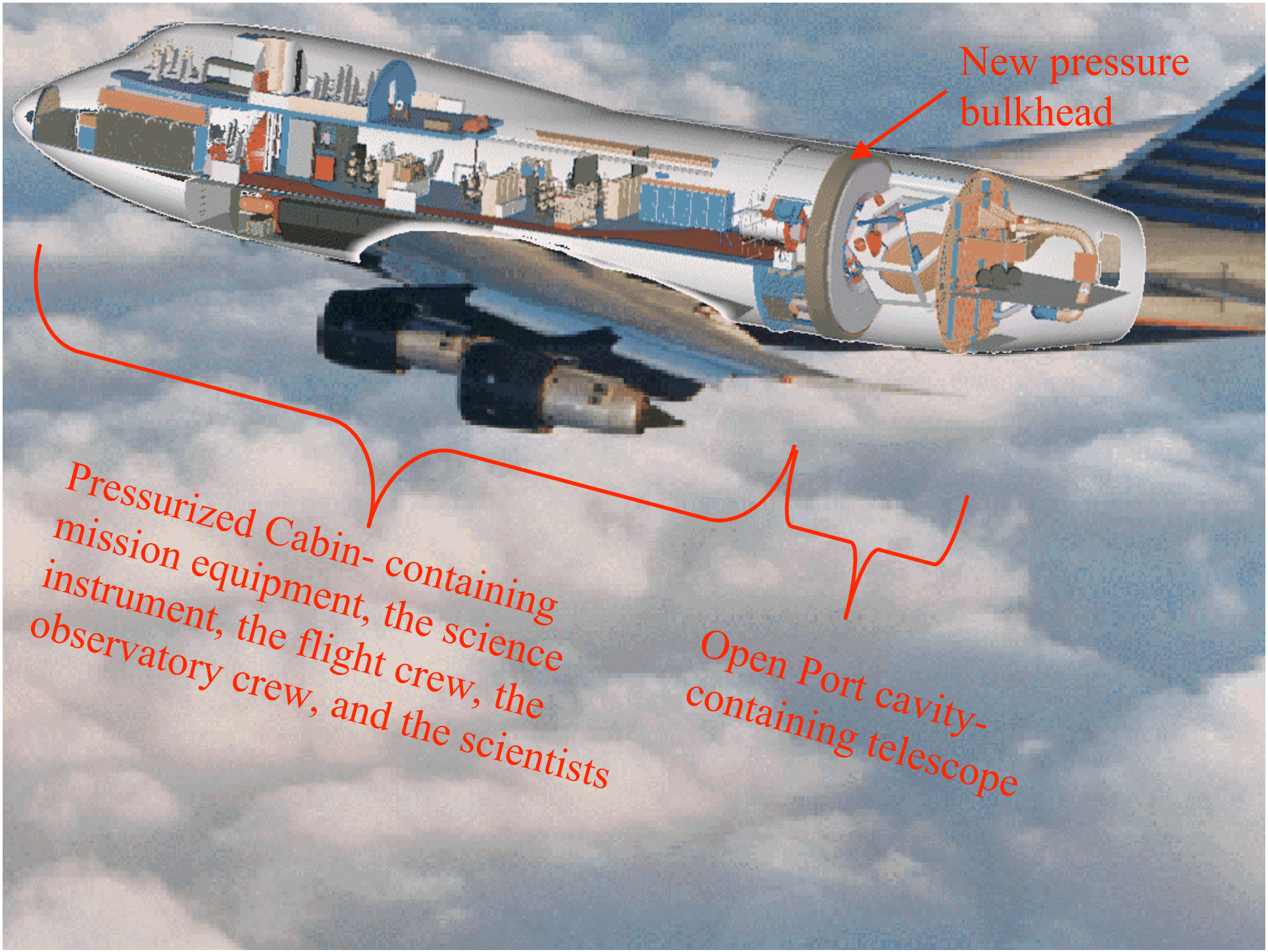
SOFIA
Location of future cavity opening


New pressure bulkhead
Pressurized Cabin- containing mission equipment, the science instrument, the flight crew, the observatory crew, and the scientists
Open Port cavity- containing telescope

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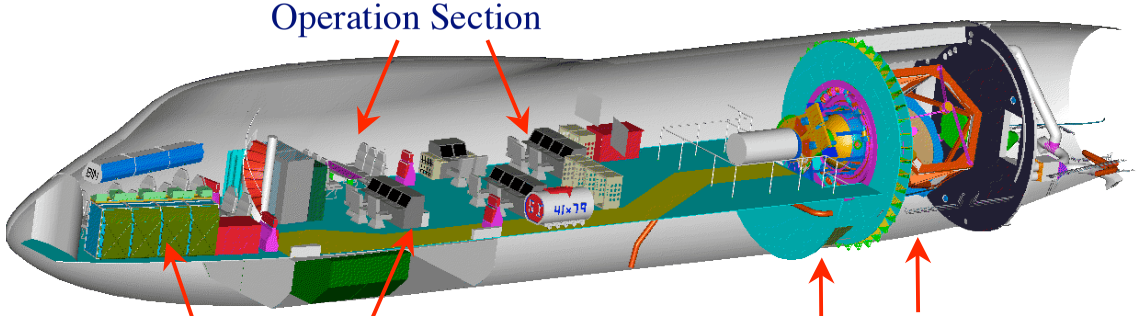
Airborne Observatory Layout

SOFIA Stratospheric Observatory for Infrared Astronomy



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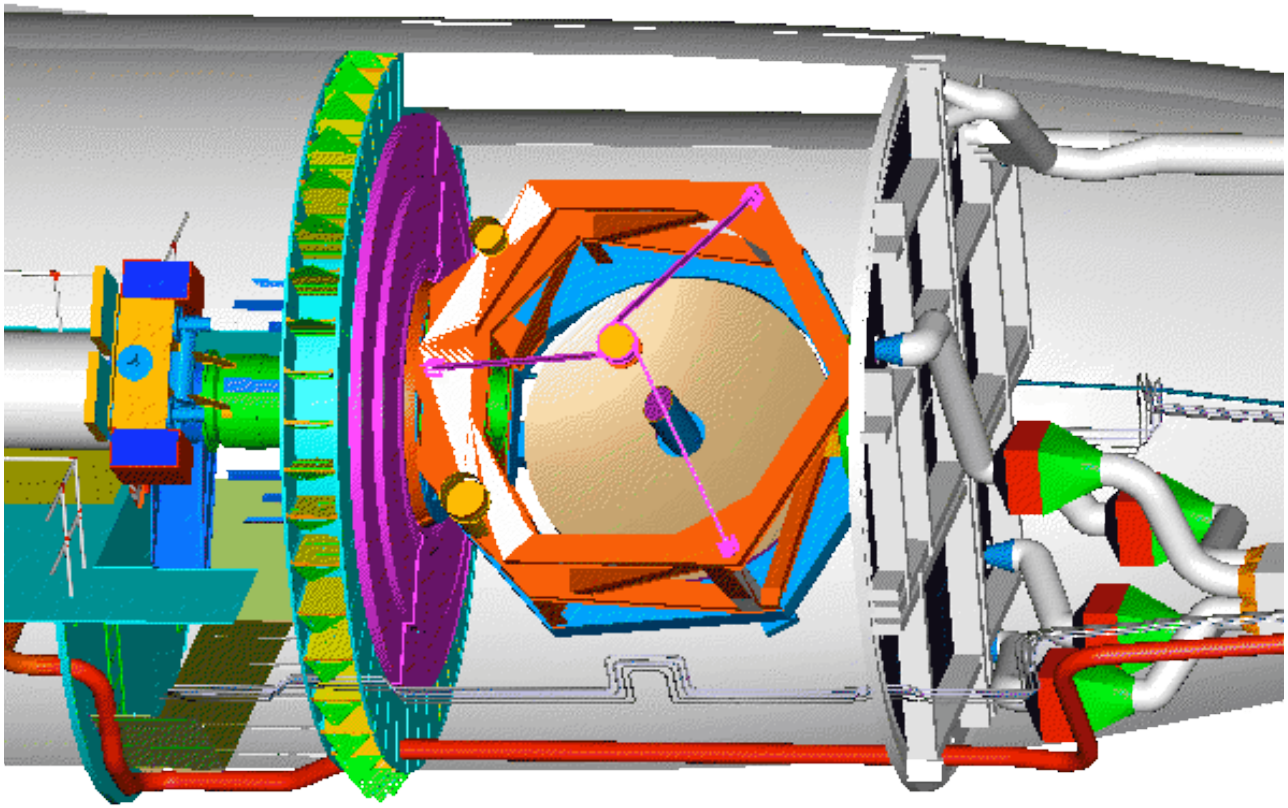
2.5 Meter effective aperture

SOFIA Stratospheric Observatory for Infrared Astronomy

- Aircraft Size
- Large 2.7 Meter Primary Mirror
- "Fast" Mirror to fit within aircraft
  - Drives alignment/stiffness requirements



Telescope Size is Maximum that can fit Available Volume

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Telescope Optical Layout

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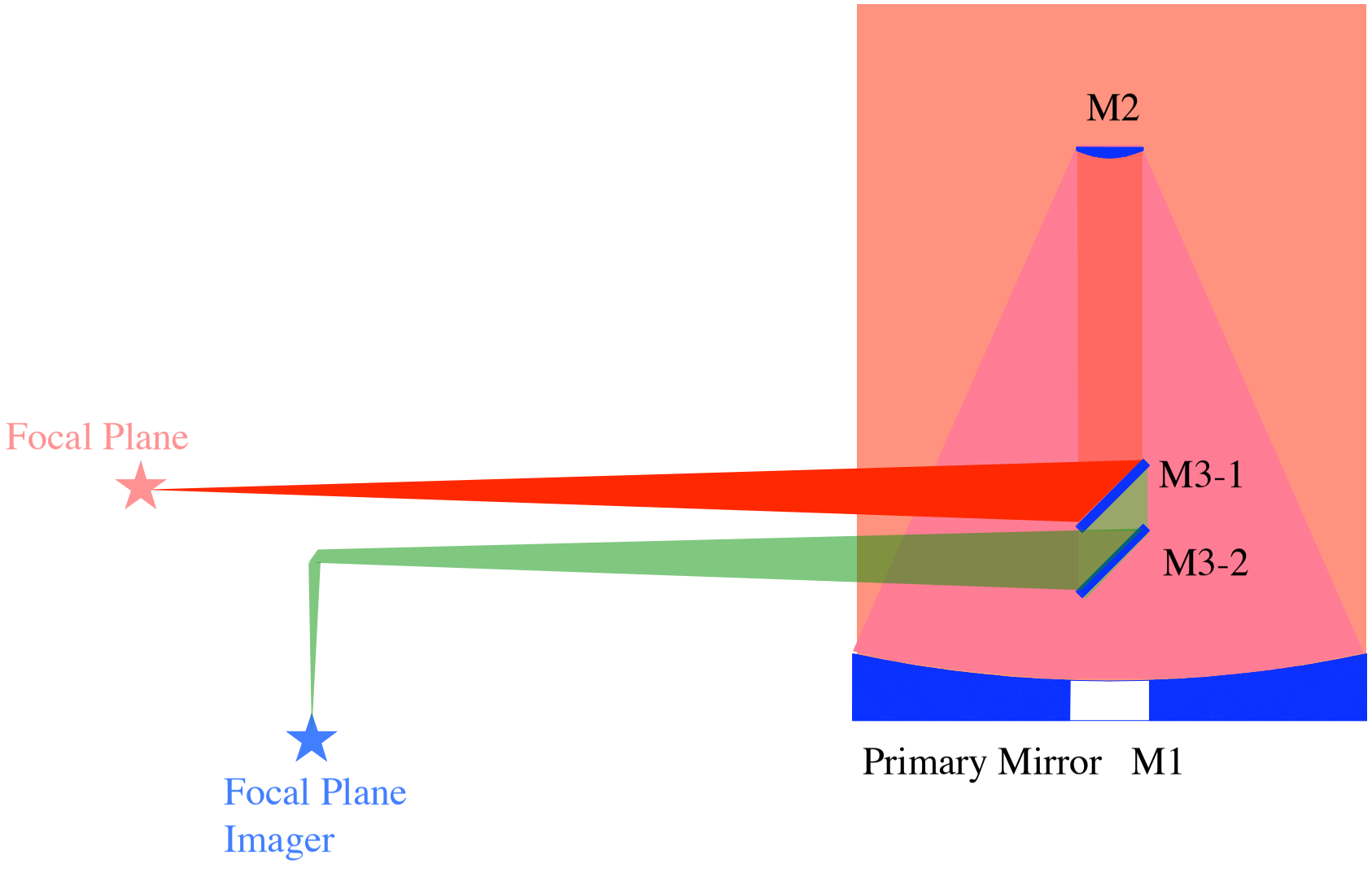

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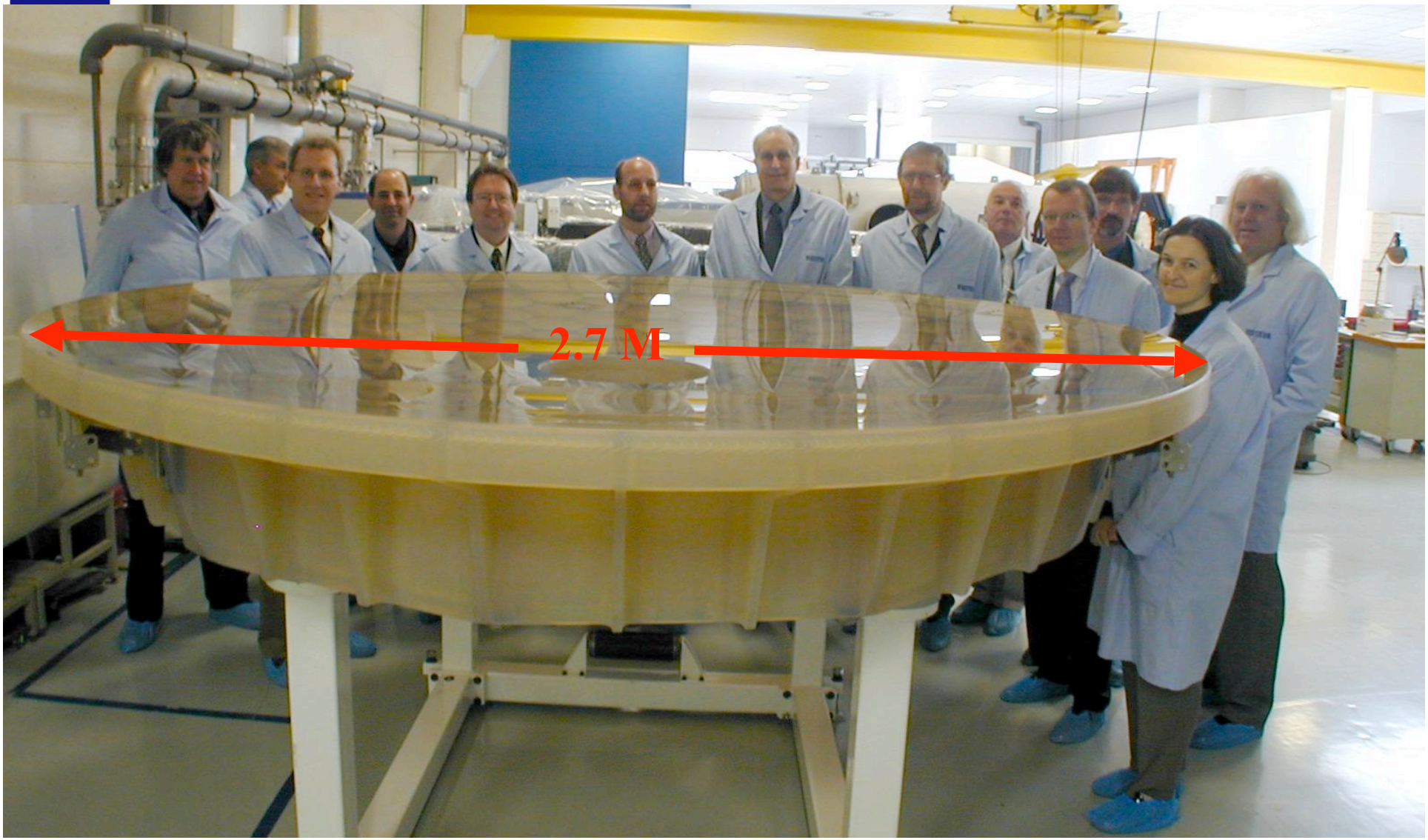
2.5 Meter effective aperture



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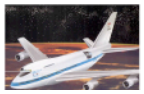
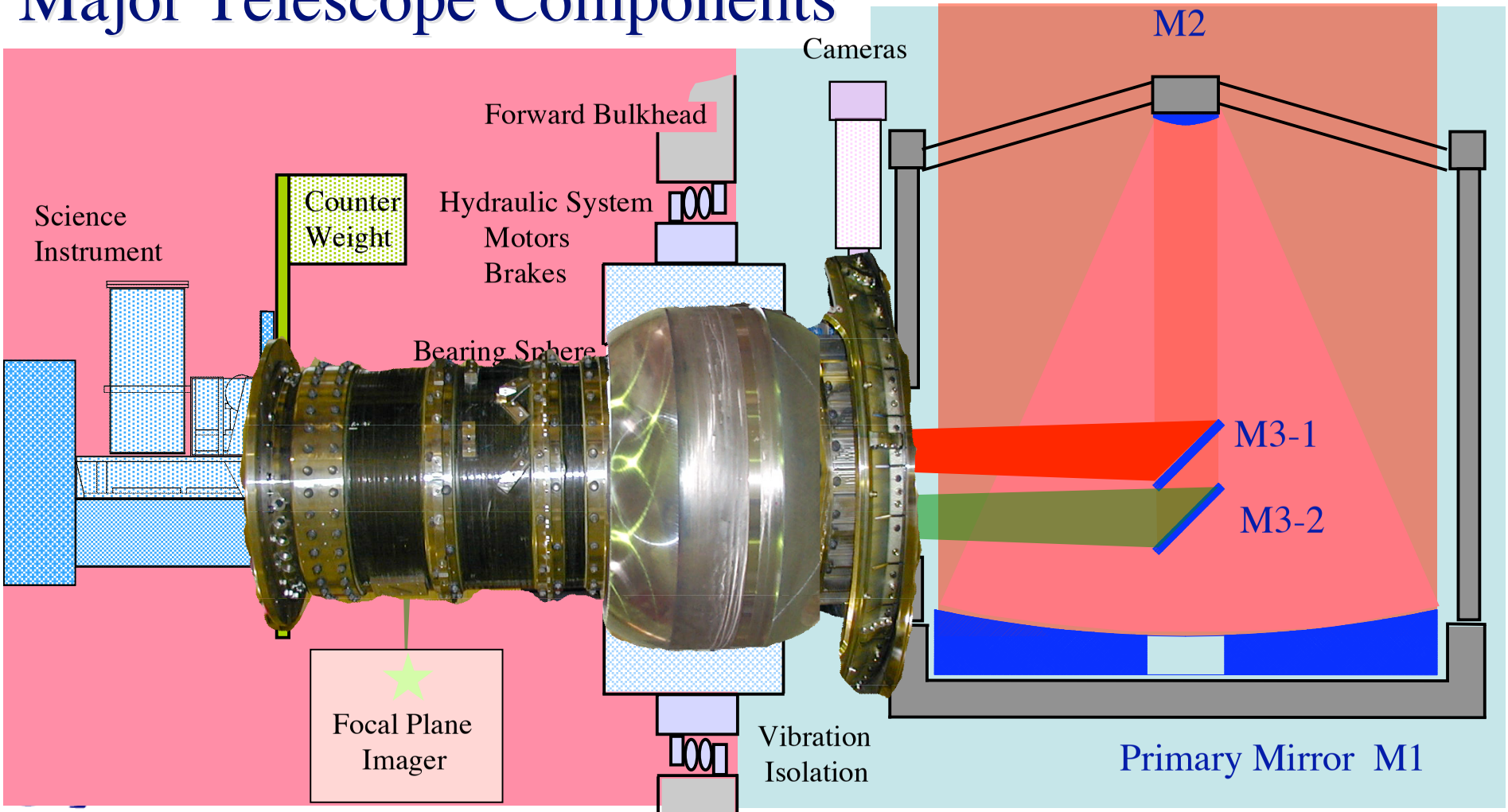
Major Telescope Components



Major Telescope Components



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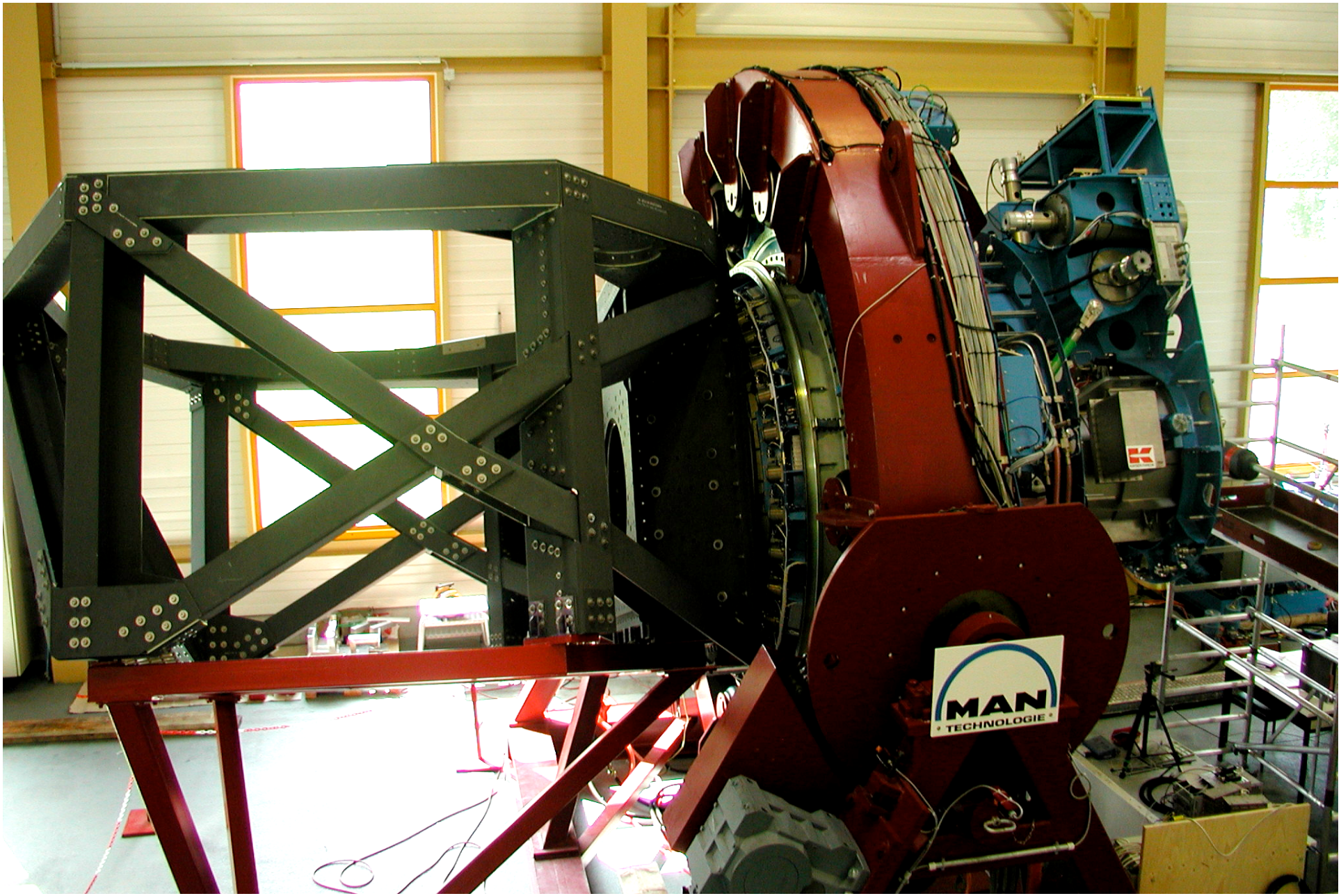
Telescope pre-ship integration



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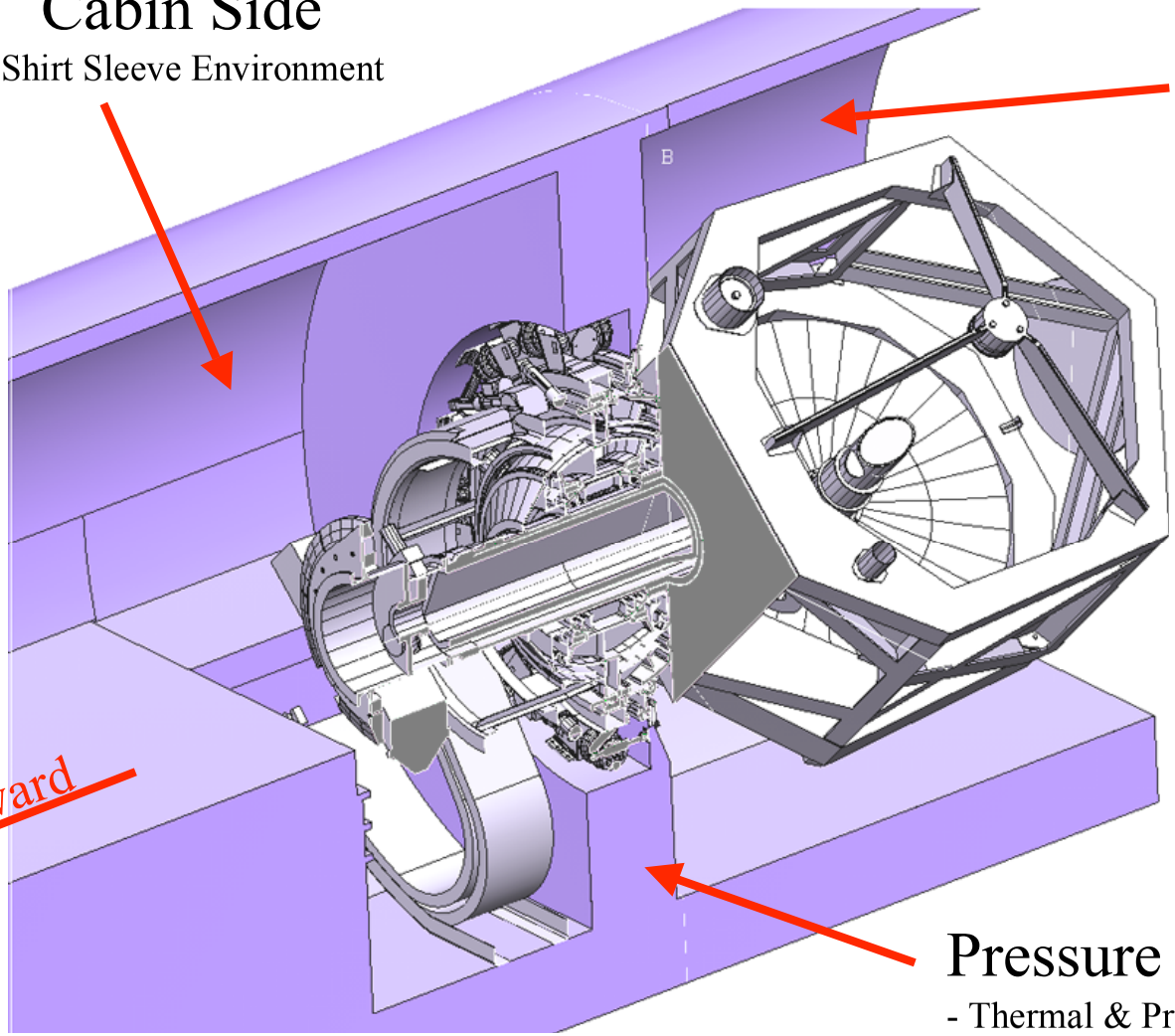
Configuration: Instrument Access in Cabin

SOFIA Stratospheric Observatory for Infrared Astronomy

Cabin Side
- Shirt Sleeve Environment

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



Forward

Pressure Bulkhead
- Thermal & Pressure Boundary

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Bulkhead - Flight Hardware

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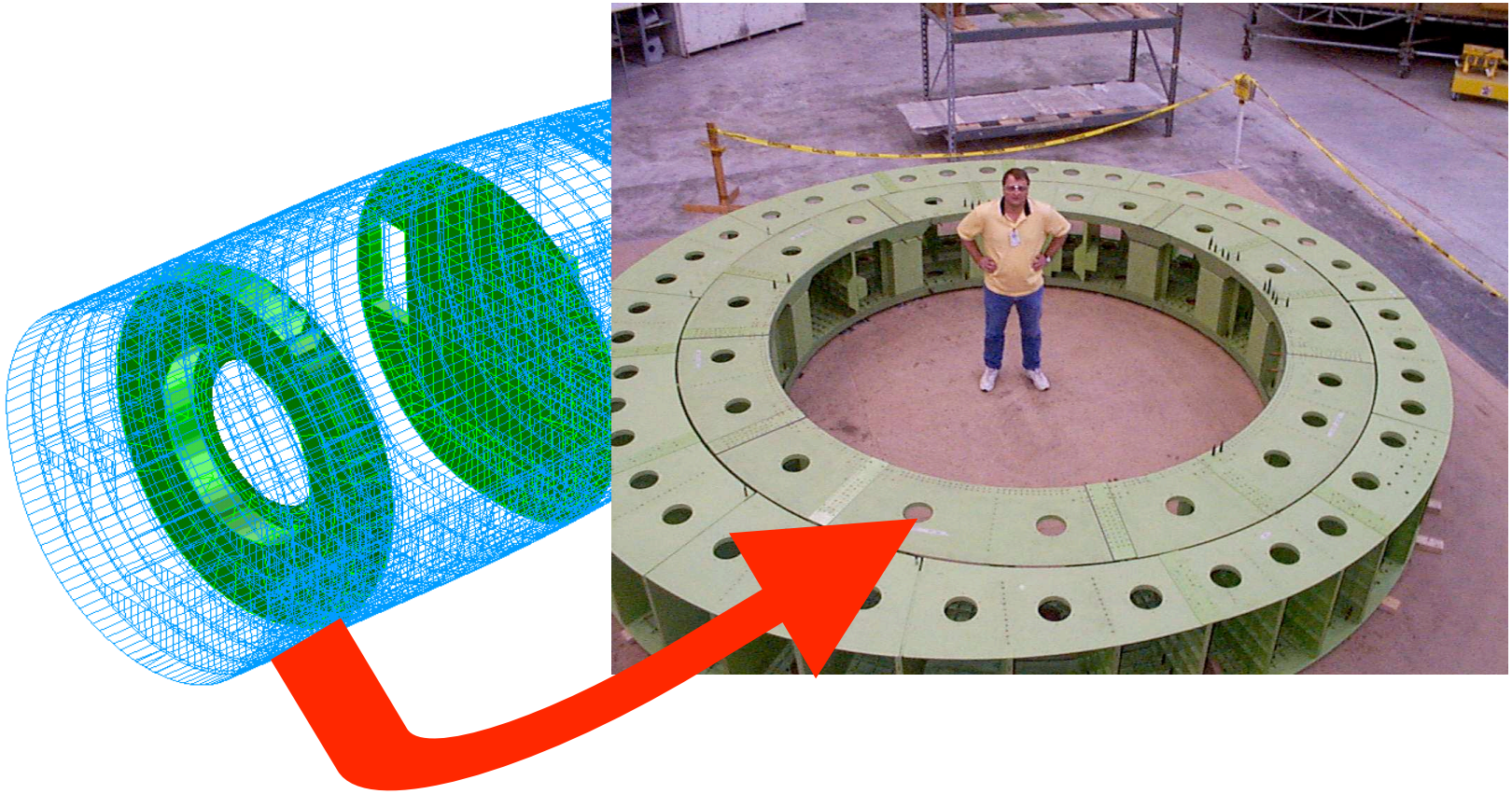
New Pressure Bulkhead



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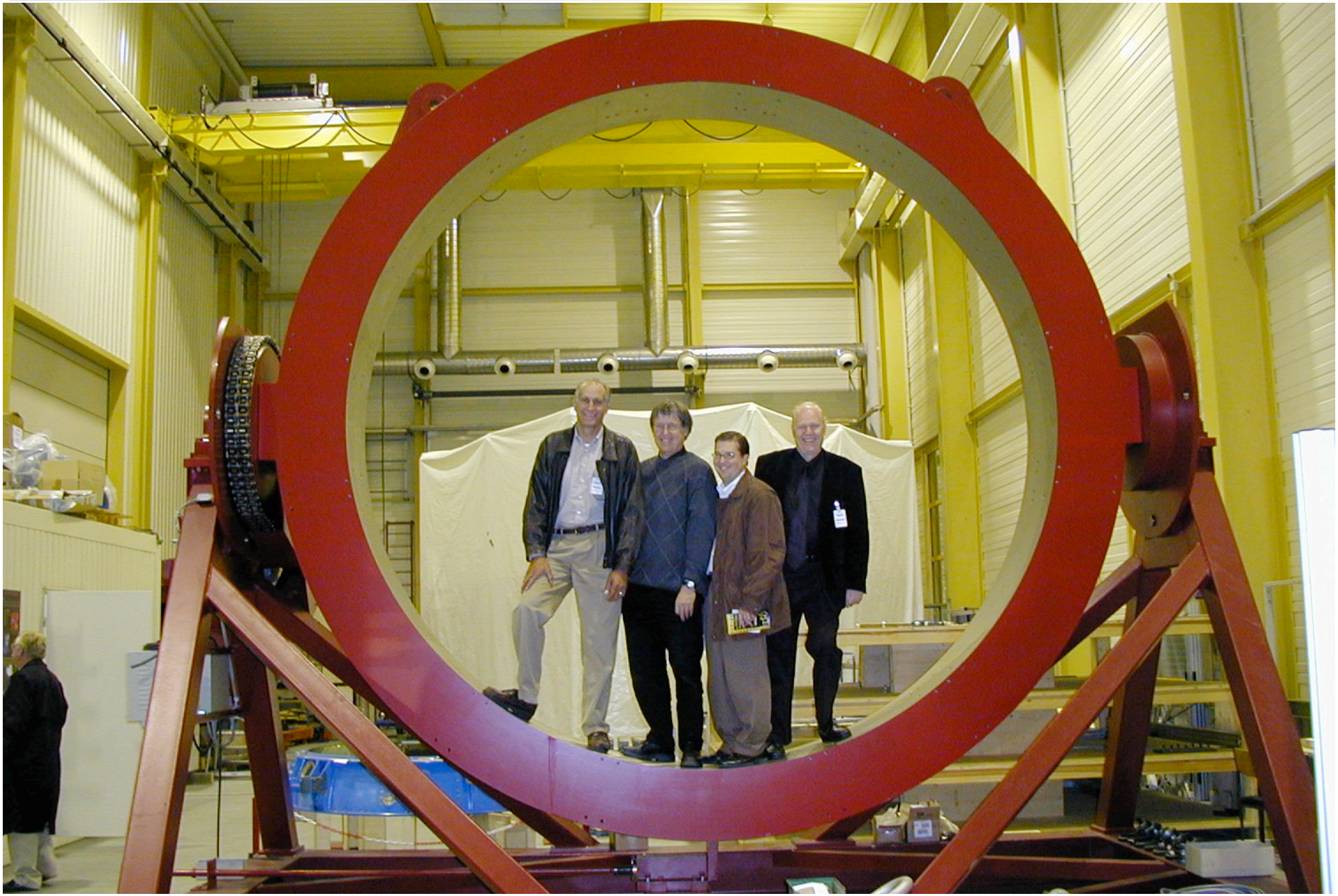
Bulkhead Simulator for TA Integration



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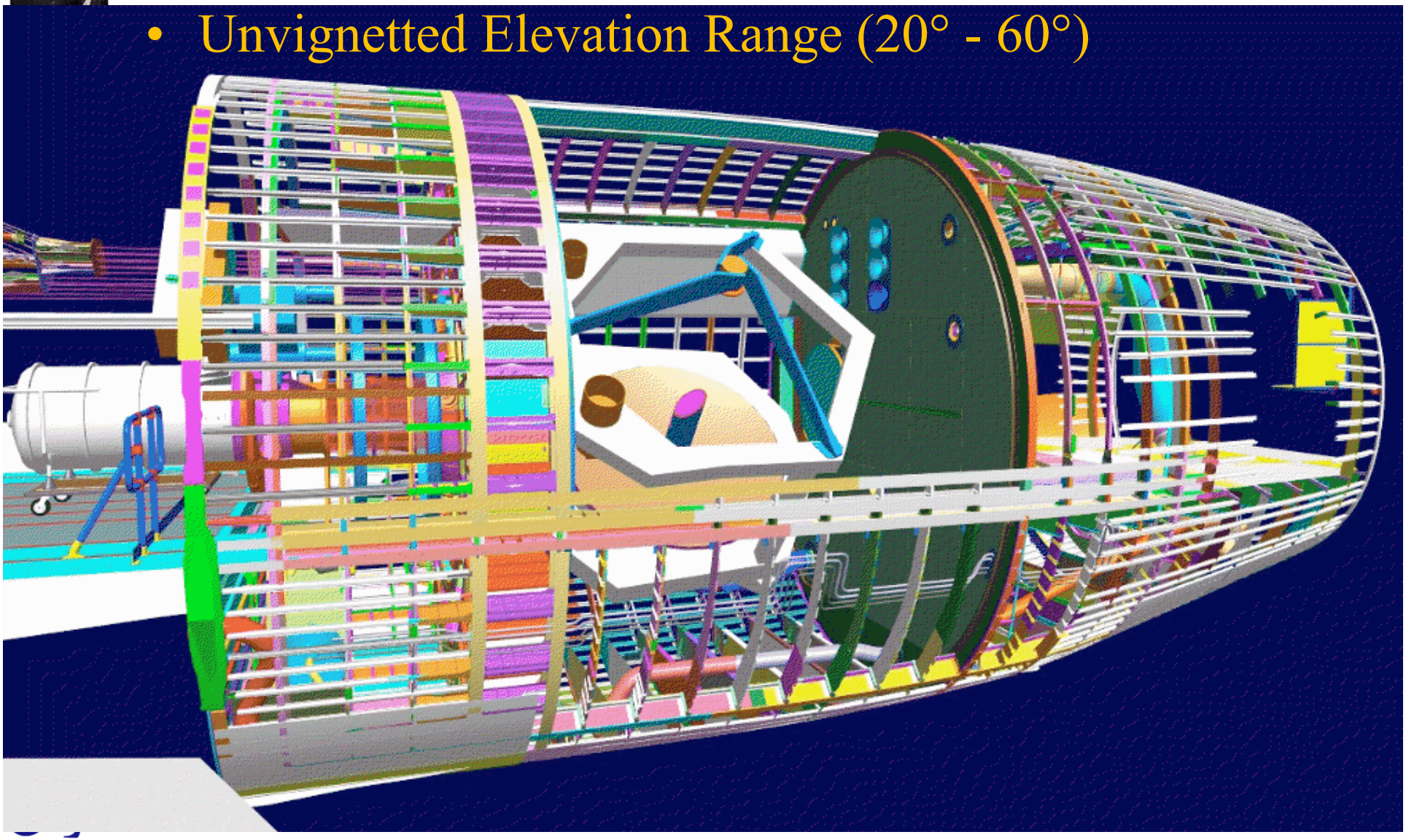
Large Structural Opening

- Unvignetted Elevation Range (20° - 60°)



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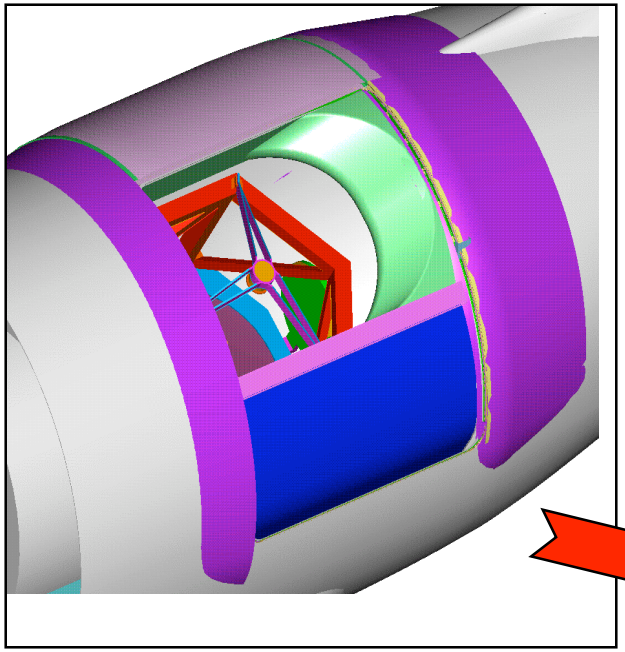
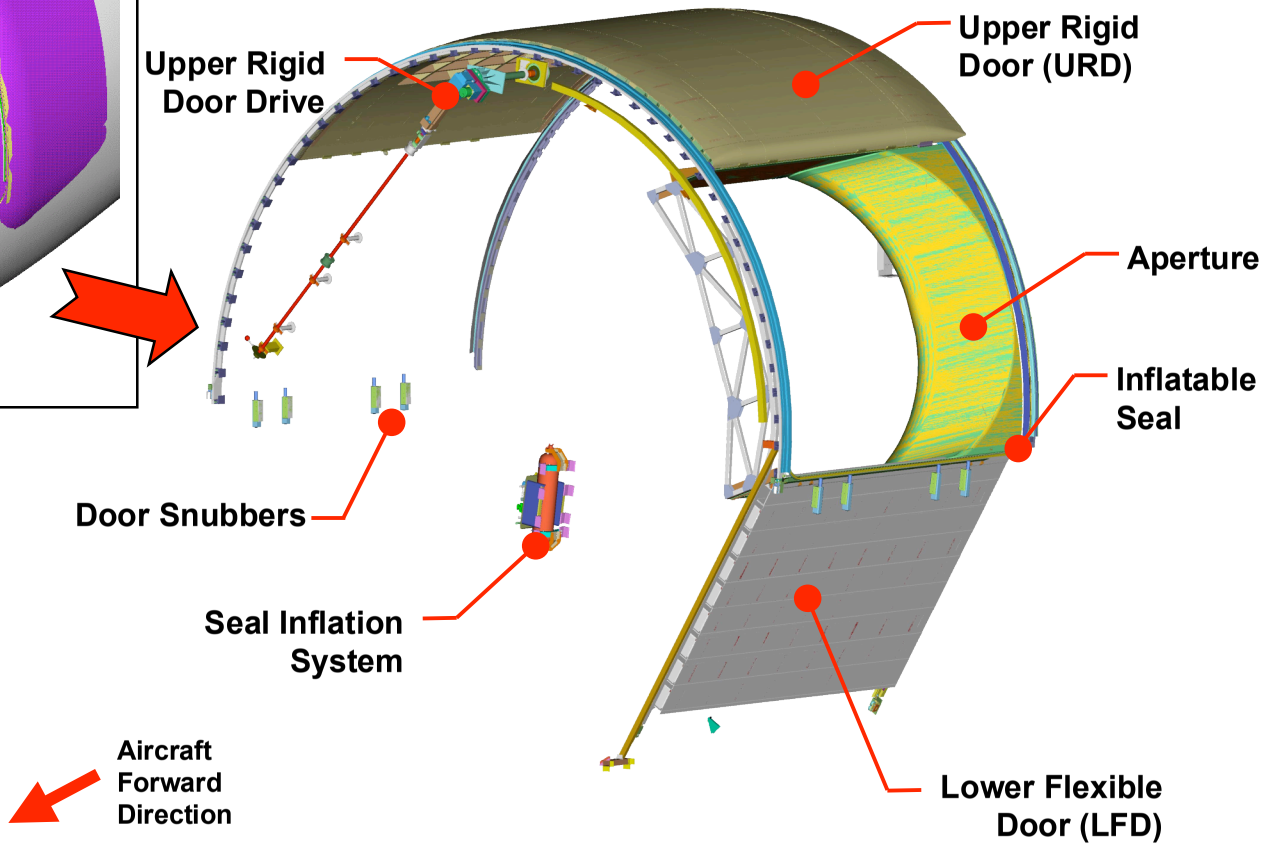
Cavity Door System

SOFIA Stratospheric Observatory for Infrared Astronomy





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Technical Challenges

SOFIA Stratospheric Observatory for Infrared Astronomy

- 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

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Technical Challenges

SOFIA Stratospheric Observatory for Infrared Astronomy

- 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…

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SOFIA Wind Tunnel Testing Overview

SOFIA Stratospheric Observatory for Infrared Astronomy

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 Dec1995 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
  - Part 1 Sept 1998 to Oct 1998 & Part 2 Jan 1999 to Feb 1999
- High Speed Tests - Boeing Transonic Wind Tunnel
  - November 1998

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SOFIA 7% model in Ames 14ft Transonic Wind Tunnel

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

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SOFIA CFD Predictions

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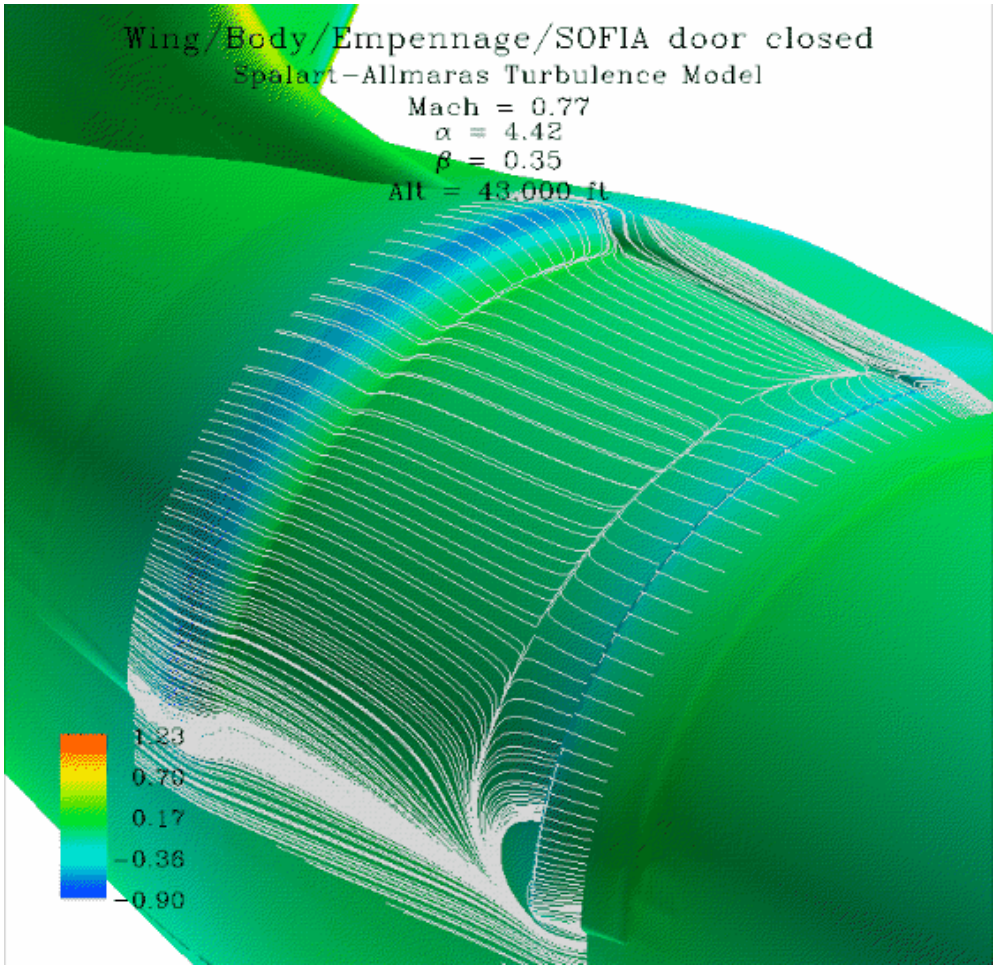
- Example of CFD flow over the mod



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SOFIA Wind Tunnel Data

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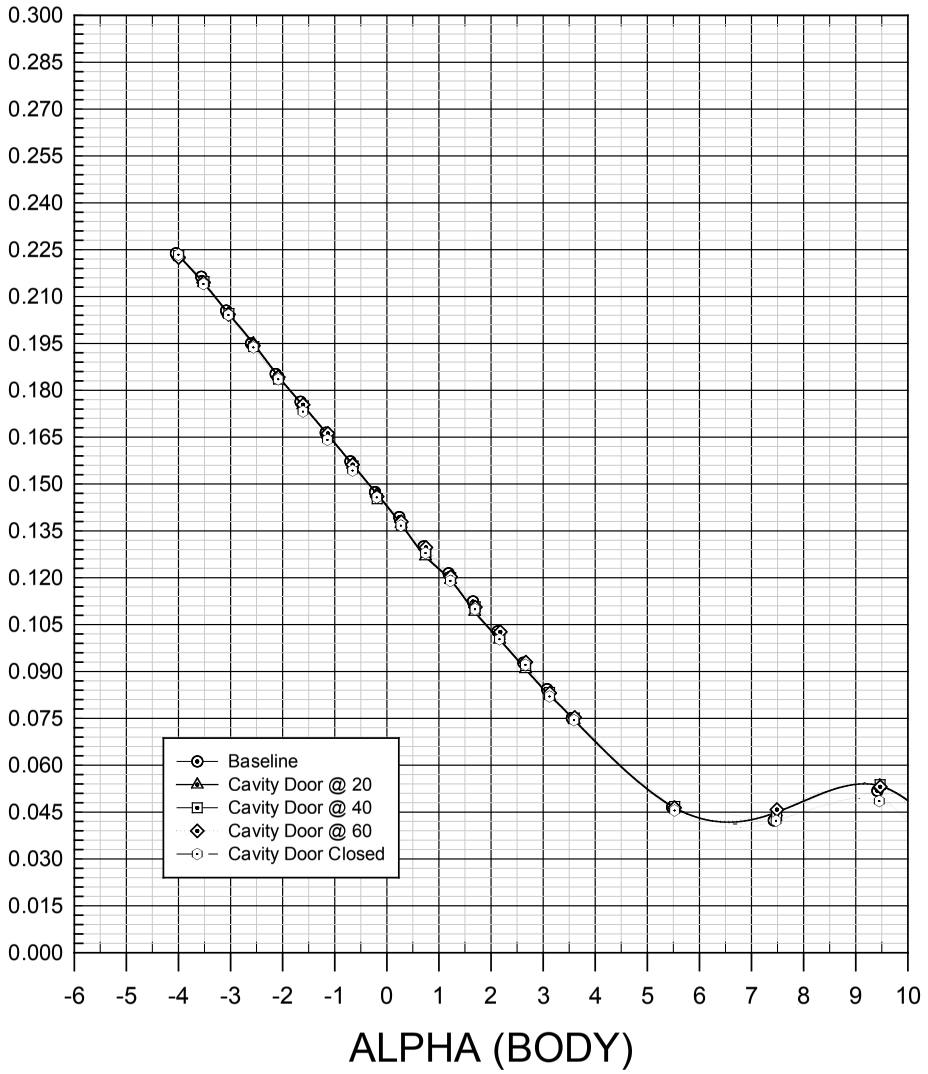
- Stab & Control
- Negligible change in drag and pitching moment
- No other F&Ms affected



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Objectives

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- 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

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Summary

SOFIA Stratospheric Observatory for Infrared Astronomy

- 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**

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Telescope arrival in Waco- Sept 2002

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Unloading Telescope Pieces

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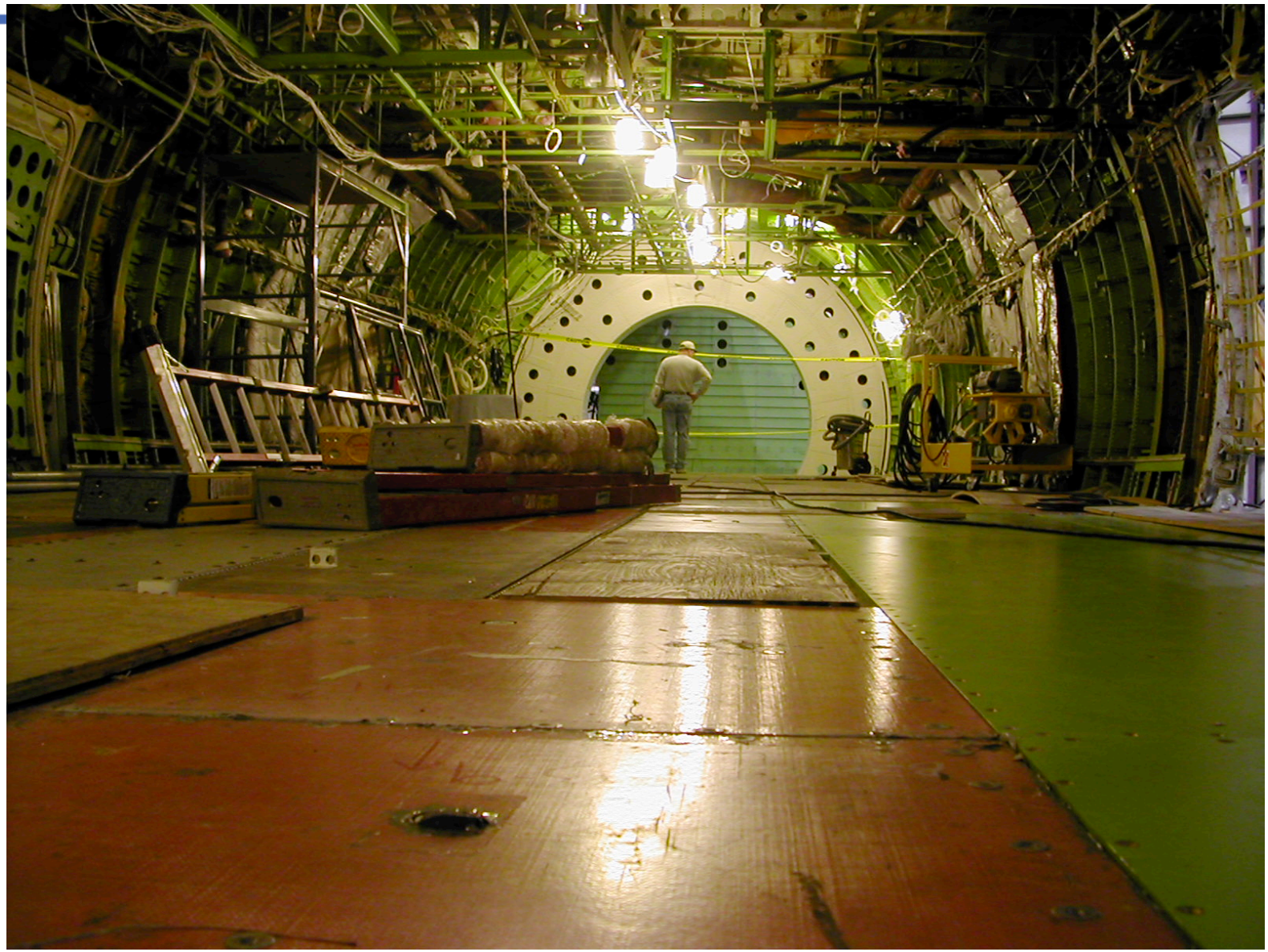

Inside aircraft just before SUA installation

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Lowering SUA into cavity 2/2003

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SUA in place

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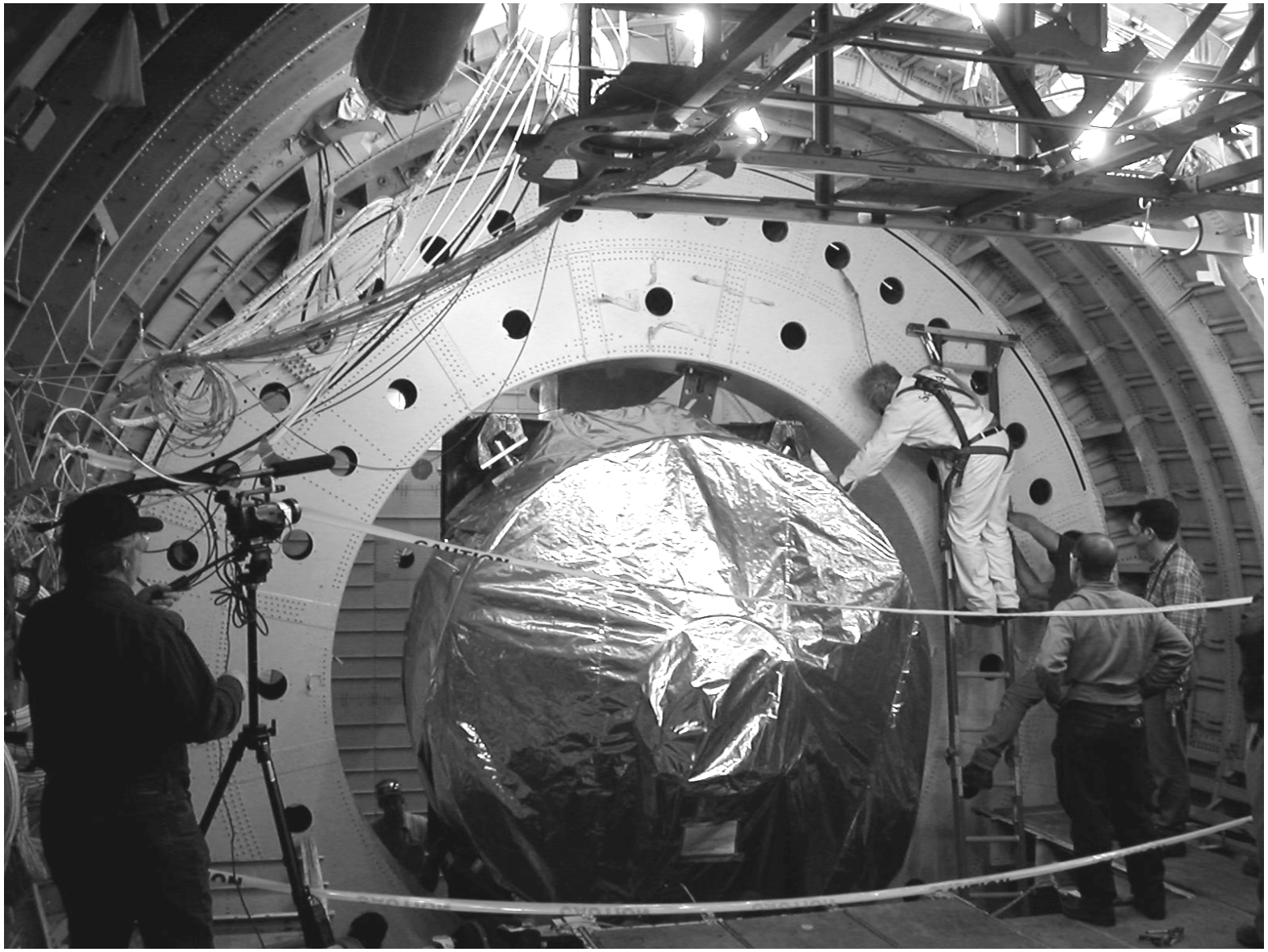

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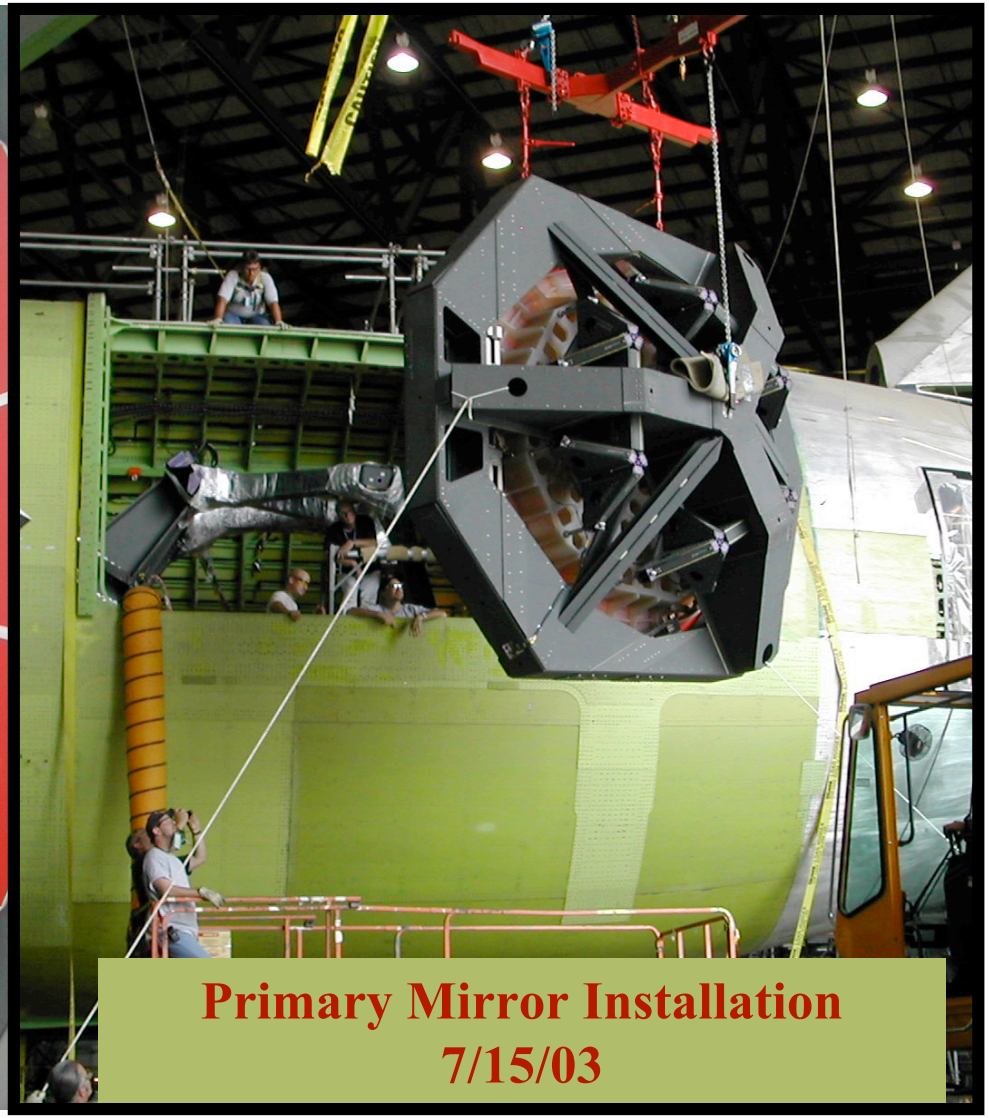

Primary Mirror Installation
7/15/03

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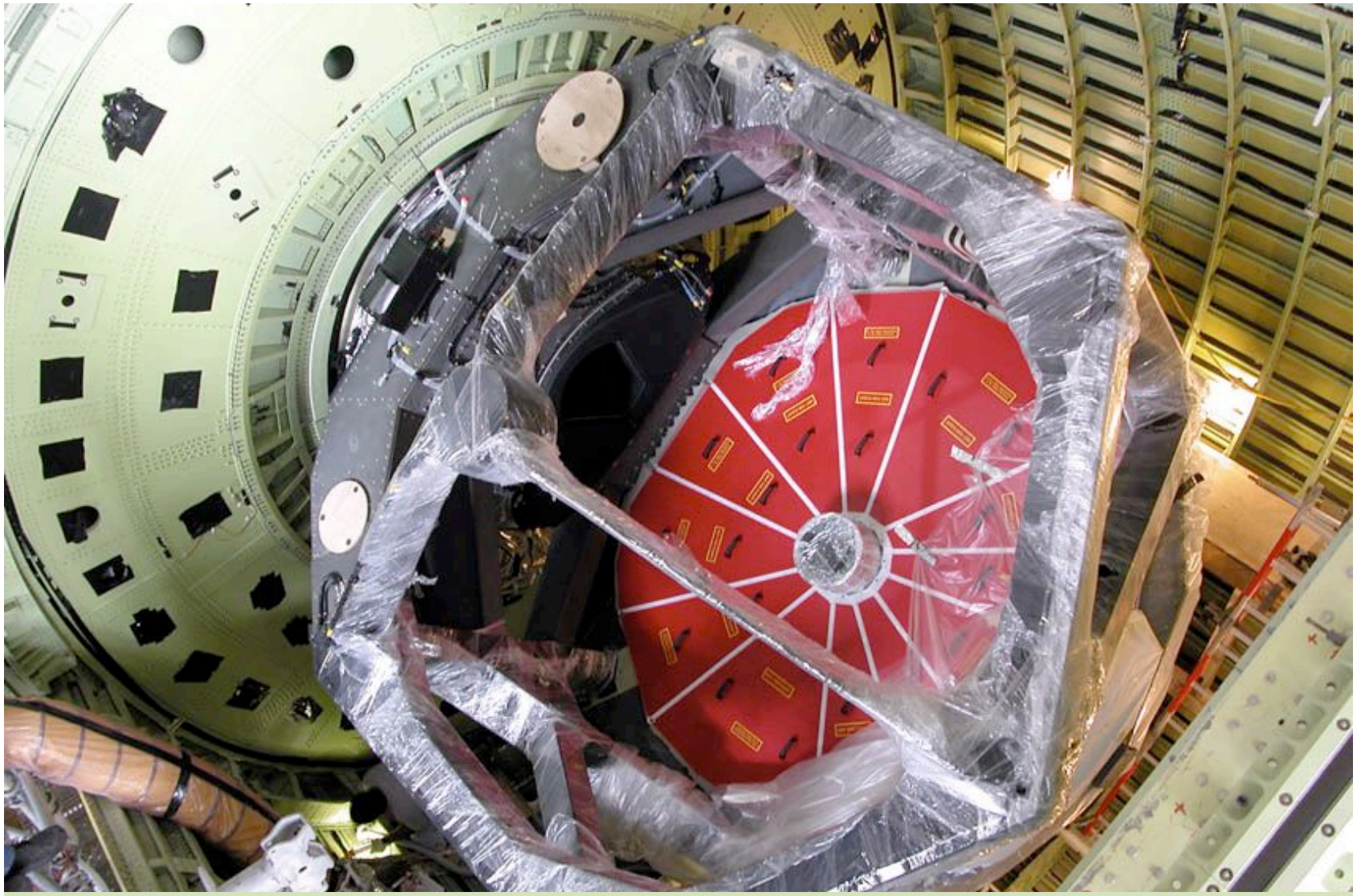

Telescope inside Aircraft Cavity

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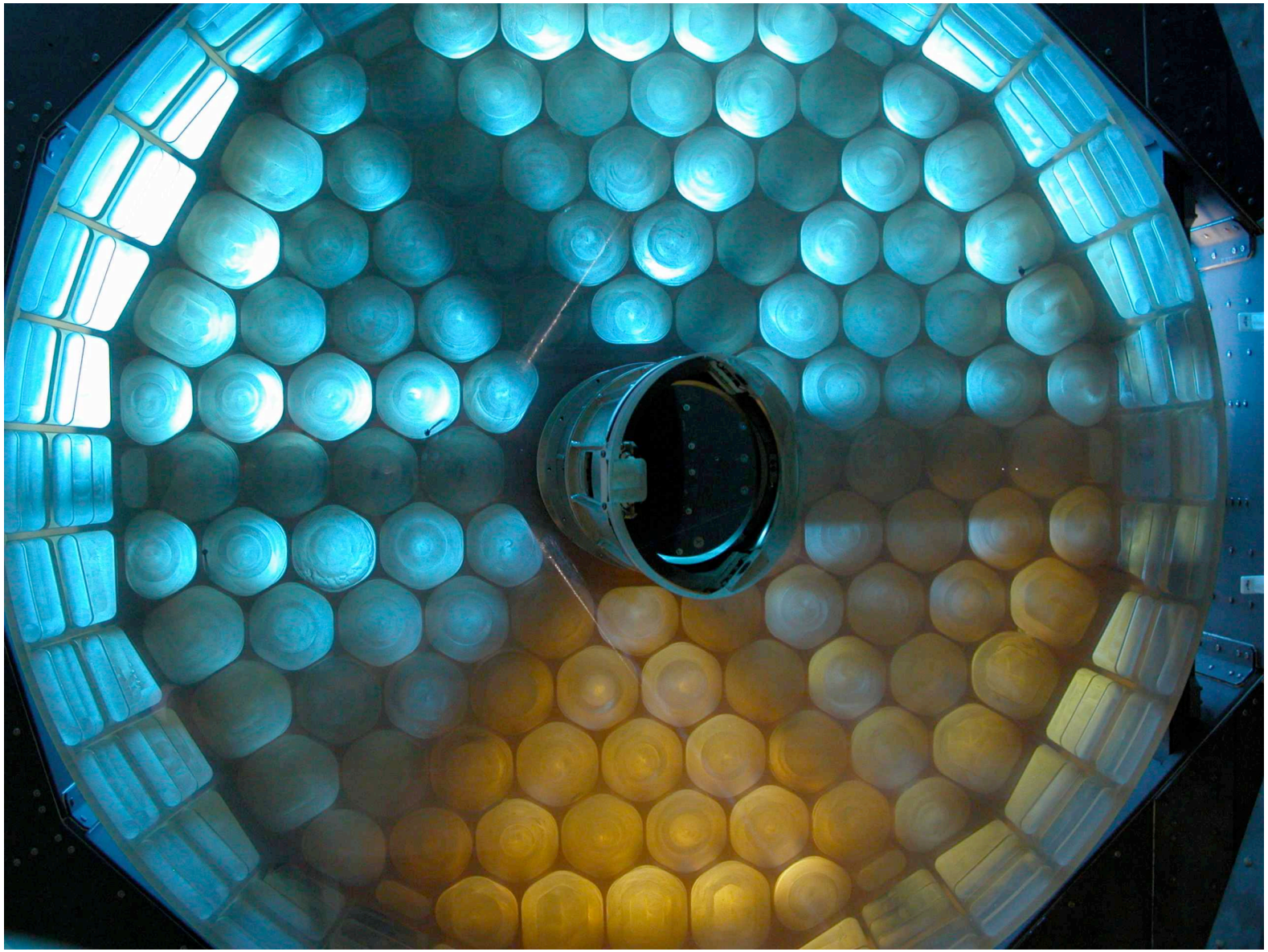

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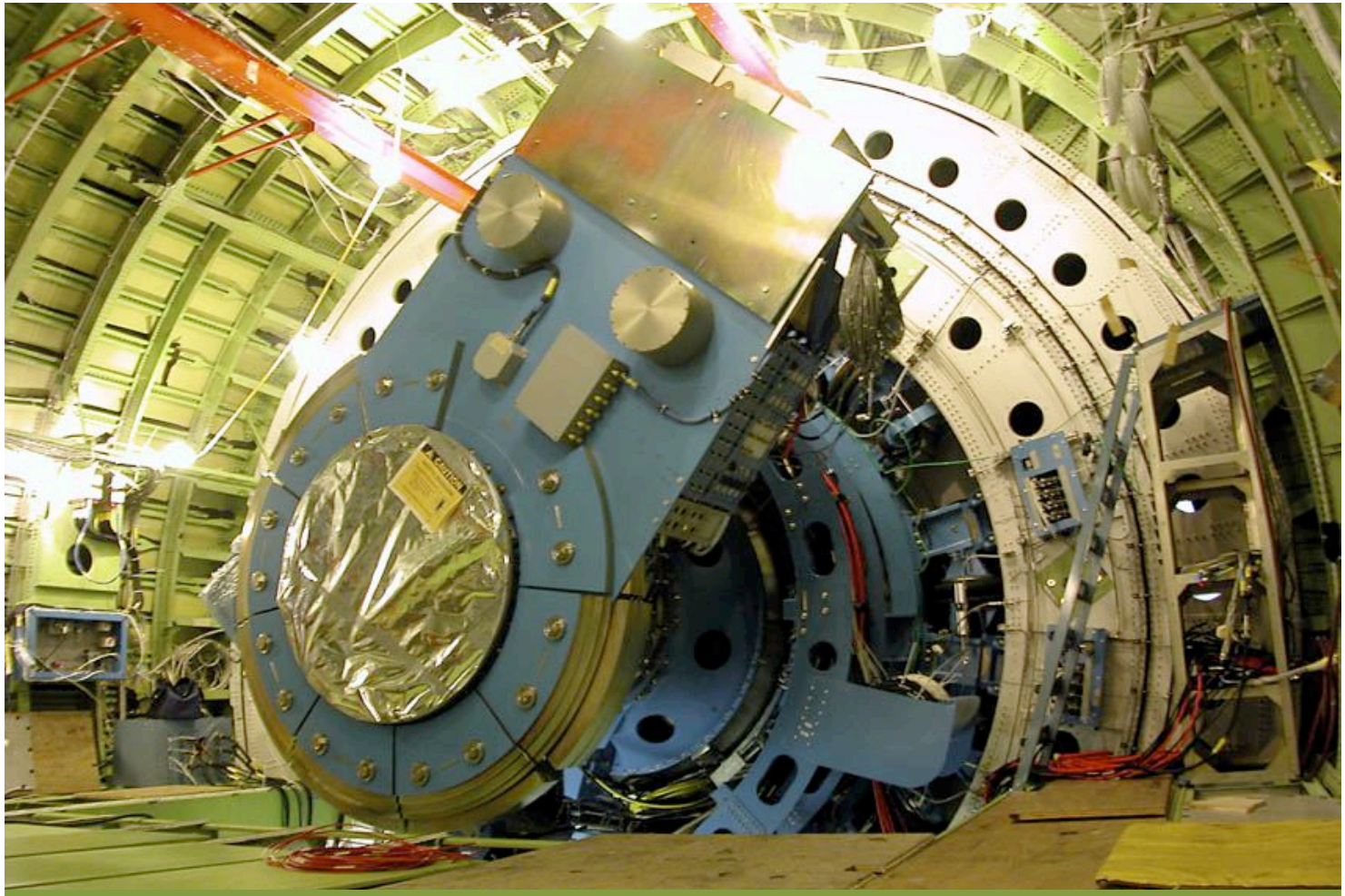

Inside the aircraft - Fall 2003

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First Light
August 2004

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Roll out from paint hangar September 2006

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Questions?

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