
‘Fliegen Sie das Teleskop’
NASA
DLR
Troy Asher
Stephen Cumming

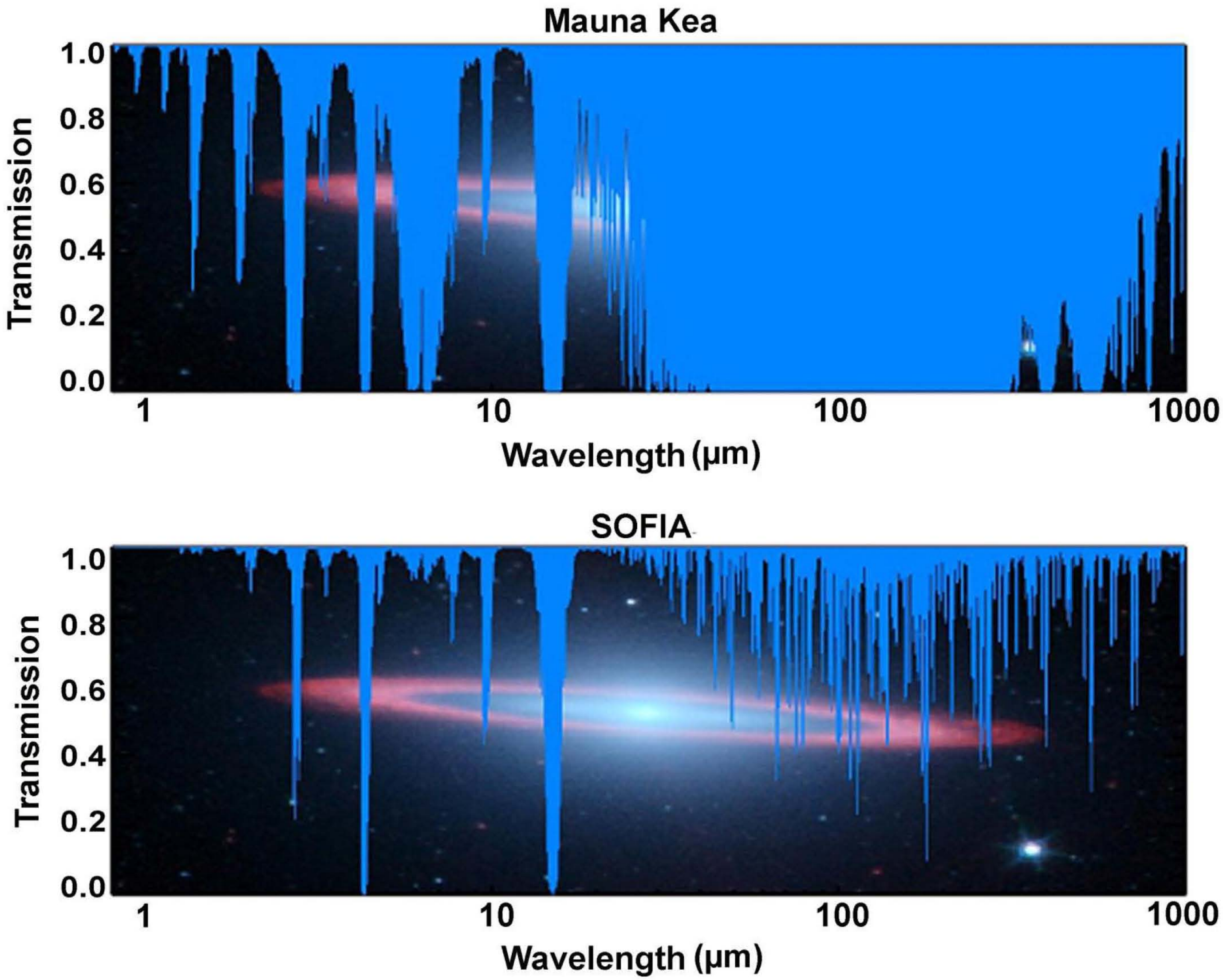
Agenda

- A brief SOFIA overview
- Review of Open Cavities in Flight
- SOFIA Cavity / Door Design
- Flight Test Approach / Managing Test Points
- Flight Test Results
- SOFIA in Action
- Conclusions and Lessons Learned

Stratospheric Observatory For Infrared Astronomy

- International Cooperative Effort between NASA and DLR
  - World's largest flying telescope
  - Operates above > 99% of atmospheric water vapor
  - Operational lifetime planned for 20+ years
  - World-wide deployments: 960 science hours per year
- Aircraft Ops: Dryden Aircraft Ops Facility, Palmdale, CA
- Science/Mission Operations:
  - NASA Ames Research Center, Moffett Field, CA
  - Universities Space Research Association (USRA), Columbia, MD
  - Deutsches SOFIA Institut (DSI), Universität Stuttgart

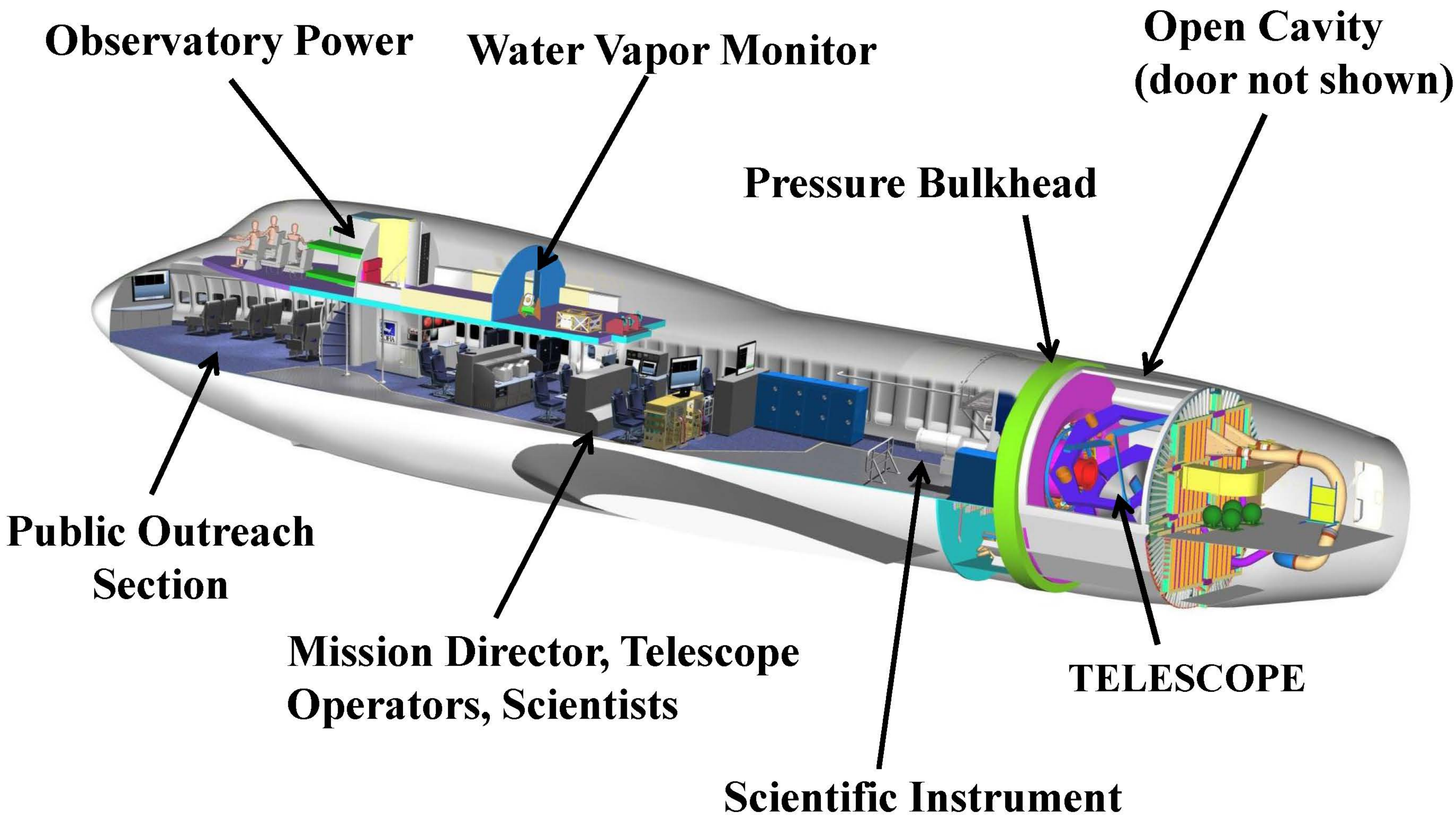
Why Stratospheric?



Observatory - The Aircraft

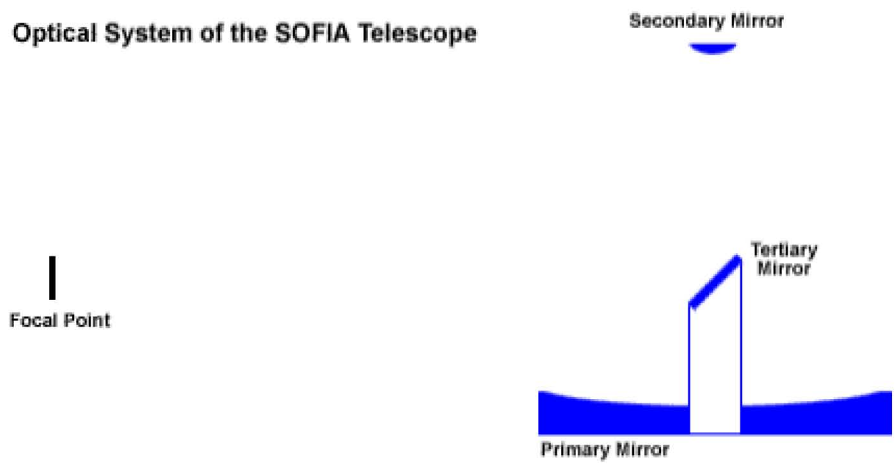
- Boeing 747SP-21 “Clipper Lindbergh”
- Delivered to Pan Am (1977); United Airlines (1986)
- Acquired by NASA in 1997; first flight 2007
- Typical altitude profile 39,000 to 43,000 feet
- MTOW: 696,000 lbs
- Max Alt: 45,100 ft

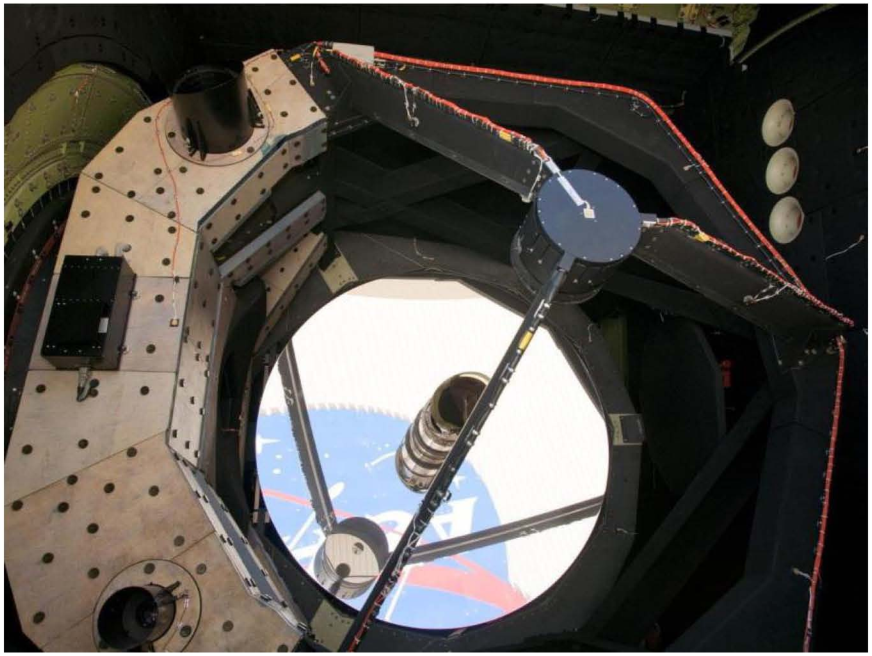
Observatory Layout



Observatory - The Telescope

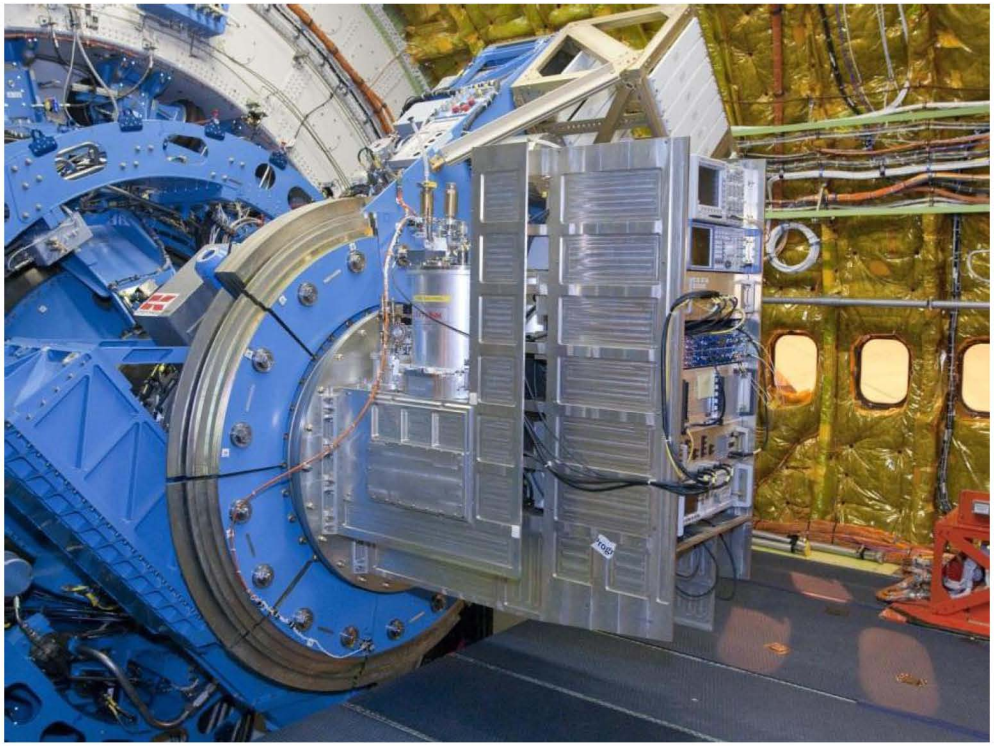
- 2.5m optical/infrared/sub-millimeter
- Built for DLR by MT Aerospace and Kayser-Threde
  - Primary mirror: "Zerodur" glass ceramic from SCHOTT AG
  - Cassegrain Focus in Nasmyth arrangement
  - +15 to +70 degrees above the horizon (full range)
  - Weight: 44,000 lbs/20,000 kg





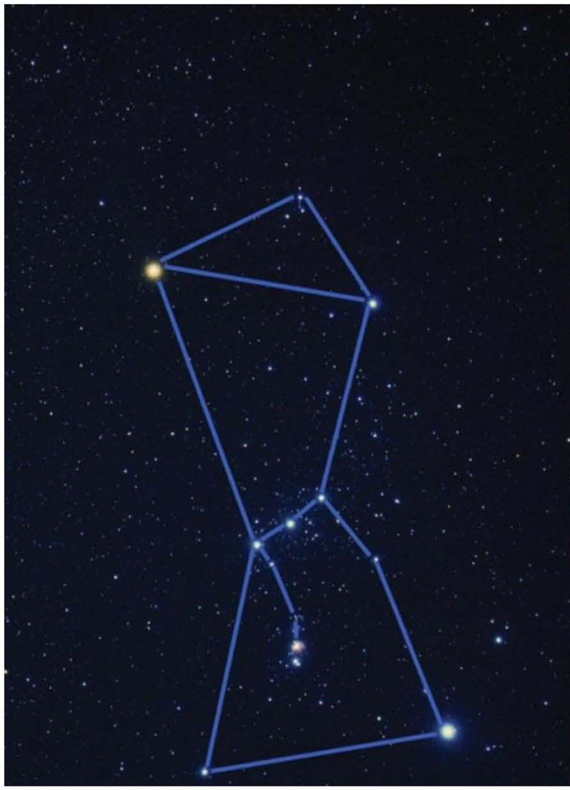
Observatory – Science Instruments

- Initially, 7 Different Scientific Instruments

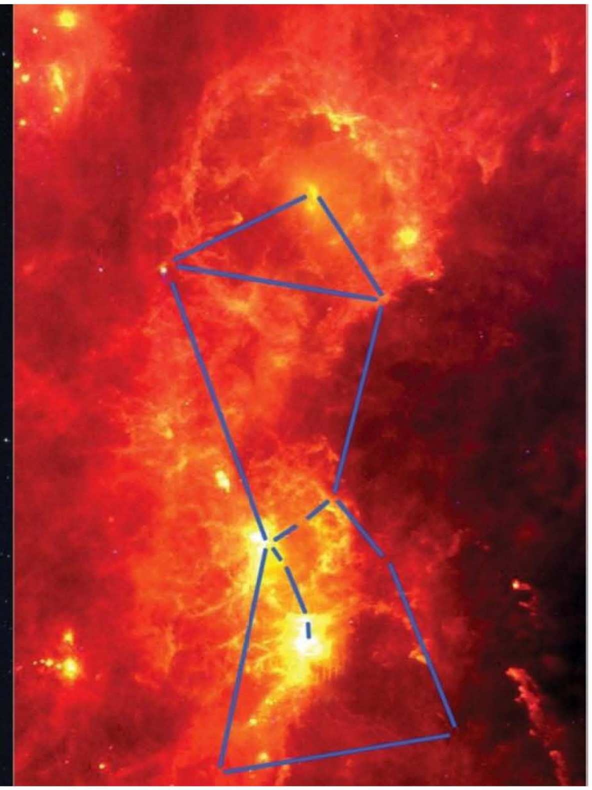


GREAT: German REceiver for Astronomy at Terahertz frequencies spectrometer

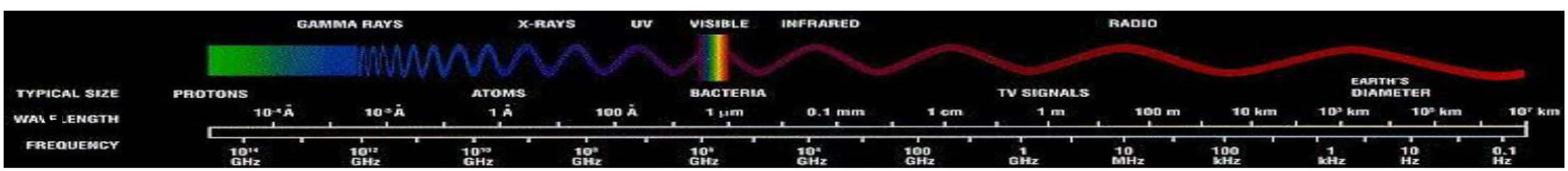
Infrared Astronomy



Orion in Visible Light



Orion in the Infrared



Aerodynamics

Stephen Cumming

Flying with Open Cavities

- Flying a large open cavity can be problematic
  - Cavity resonance is common
  - Severe resonance can cause structural damage or fatigue
- Large aircraft cavities often resonate at higher speeds due to Rossiter modes
- The most common solutions to dealing with resonance are an aerodynamic fence, an over-designed structure or flight envelope limitations

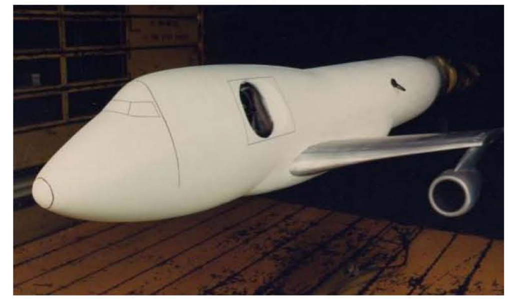
History of Large Cavities in Flight

SOFIA Cavity Design

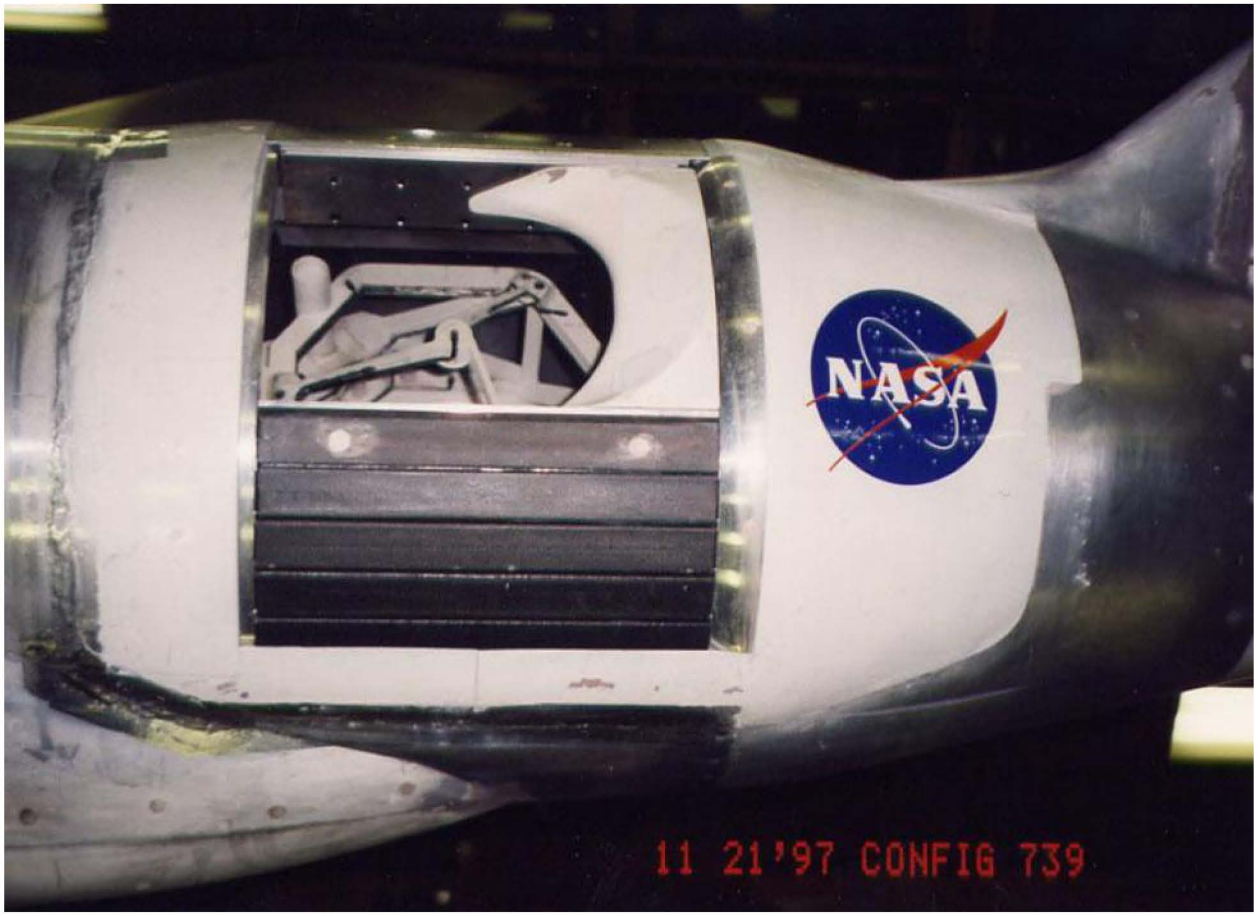
- SOFIA program had several requirements that made commonly used cavity treatments undesirable
  - Provide a platform for observing over a wide range of the electromagnetic spectrum
  - Maximize time at-altitude, on-condition
- Plan was to use a shaped cavity and aft ramp to appropriately control the shear layer and minimize the probability of resonance
- To maximize the probability for success a series of wind tunnel tests were undertaken to design the SOFIA cavity
  - Testing began in 1990 and was completed in 1997
  - 5 series of 7% scale wind tunnel tests were completed

SOFIA Wind Tunnel Tests

- SOFIA I
    - Investigated cavity configurations to prevent resonance
    - Established basic flow control design
    - Several 747 variants tested
    - Forward cavity
- SOFIA II
    - 747-200, 747SP variants tested
    - Aft cavity
- SOFIA III:
    - Investigated effects of different TA model designs
- SOFIA IV:
    - Investigated aero-optical properties of candidate configurations
- SOFIA V:
    - Investigated candidate door designs
    - Tested final cavity design and configuration



SOFIA Cavity Design

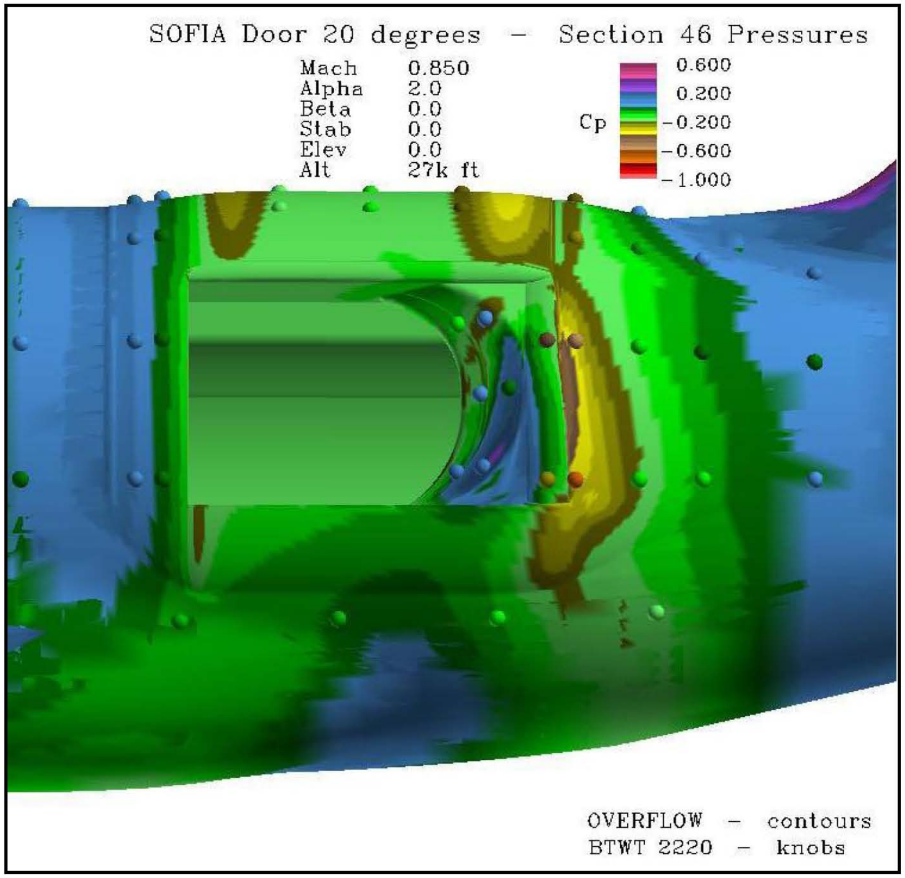


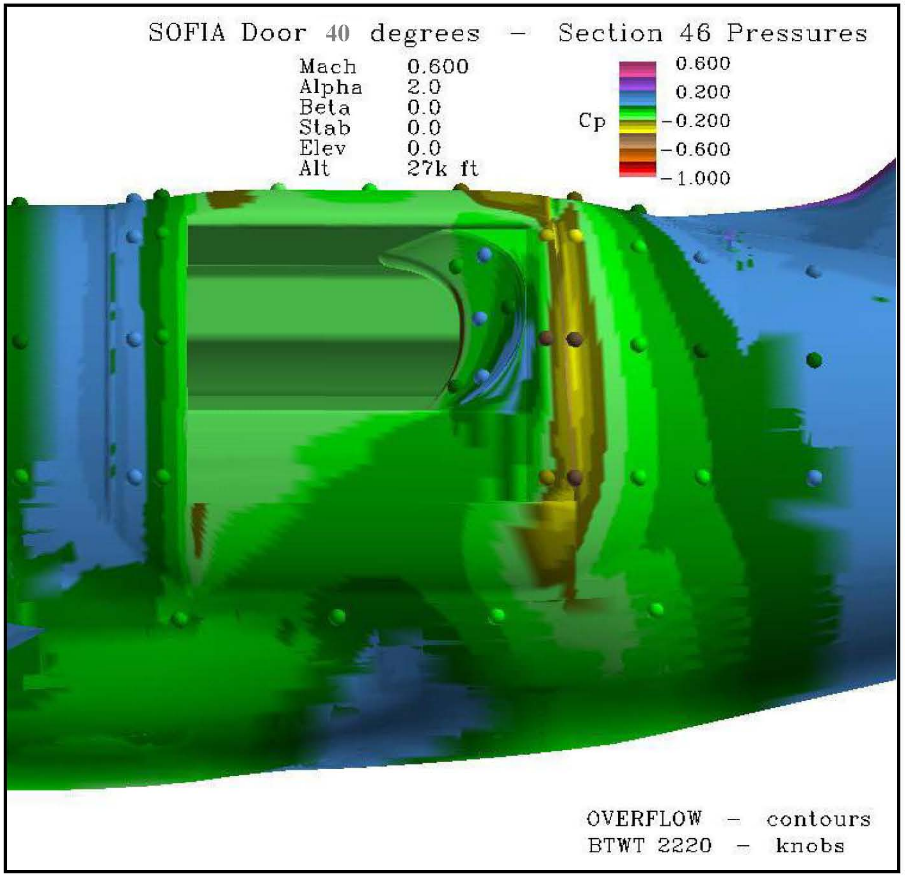
Pre-Flight Analysis and Test

- Substantial testing and analysis was performed prior to SOFIA flight tests
- Aerodynamic and Acoustics tests and analyses:
  - 7% wind tunnel tests
  - 3% wind tunnel tests
  - CFD
  - Baseline flights
  - 6-DOF SOFIA airplane simulation
  - Instrumented Shuttle Carrier 747 for boundary layer data

- Due to the extensive analyses, we had a detailed set of pre-flight predictions for acoustics and possible aerodynamic effects of the cavity

CFD Results

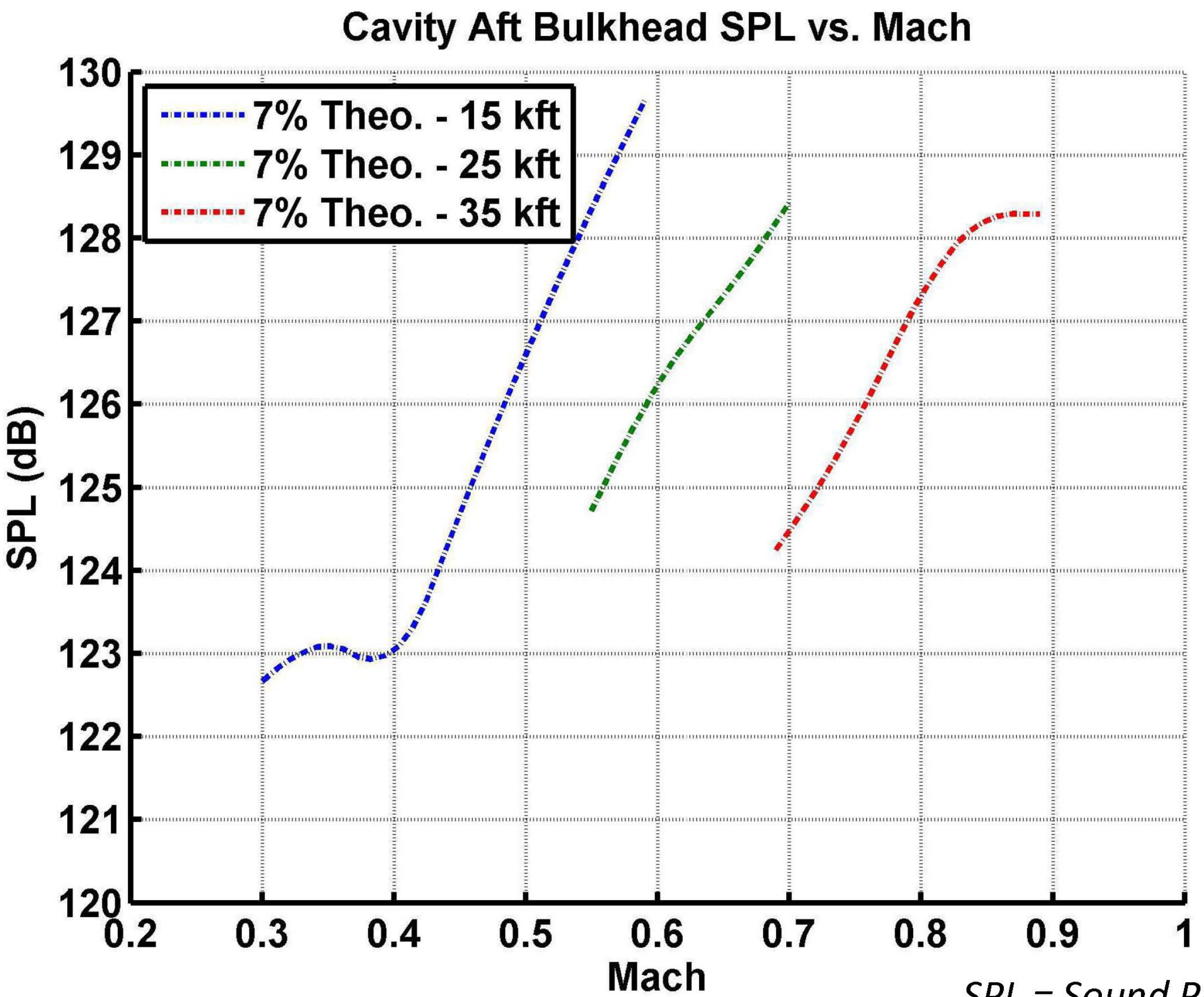

SOFIA Door 20 degrees – Section 46 Pressures
Mach 0.850
Alpha 2.0
Beta 0.0
Stab 0.0
Elev 0.0
Alt 27k ft
Cp
0.600
0.200
-0.200
-0.600
-1.000
OVERFLOW – contours
BTWT 2220 – knobs


SOFIA Door 40 degrees – Section 46 Pressures
Mach 0.600
Alpha 2.0
Beta 0.0
Stab 0.0
Elev 0.0
Alt 27k ft
Cp
0.600
0.200
-0.200
-0.600
-1.000
OVERFLOW – contours
BTWT 2220 – knobs

Pre-Flight Predictions

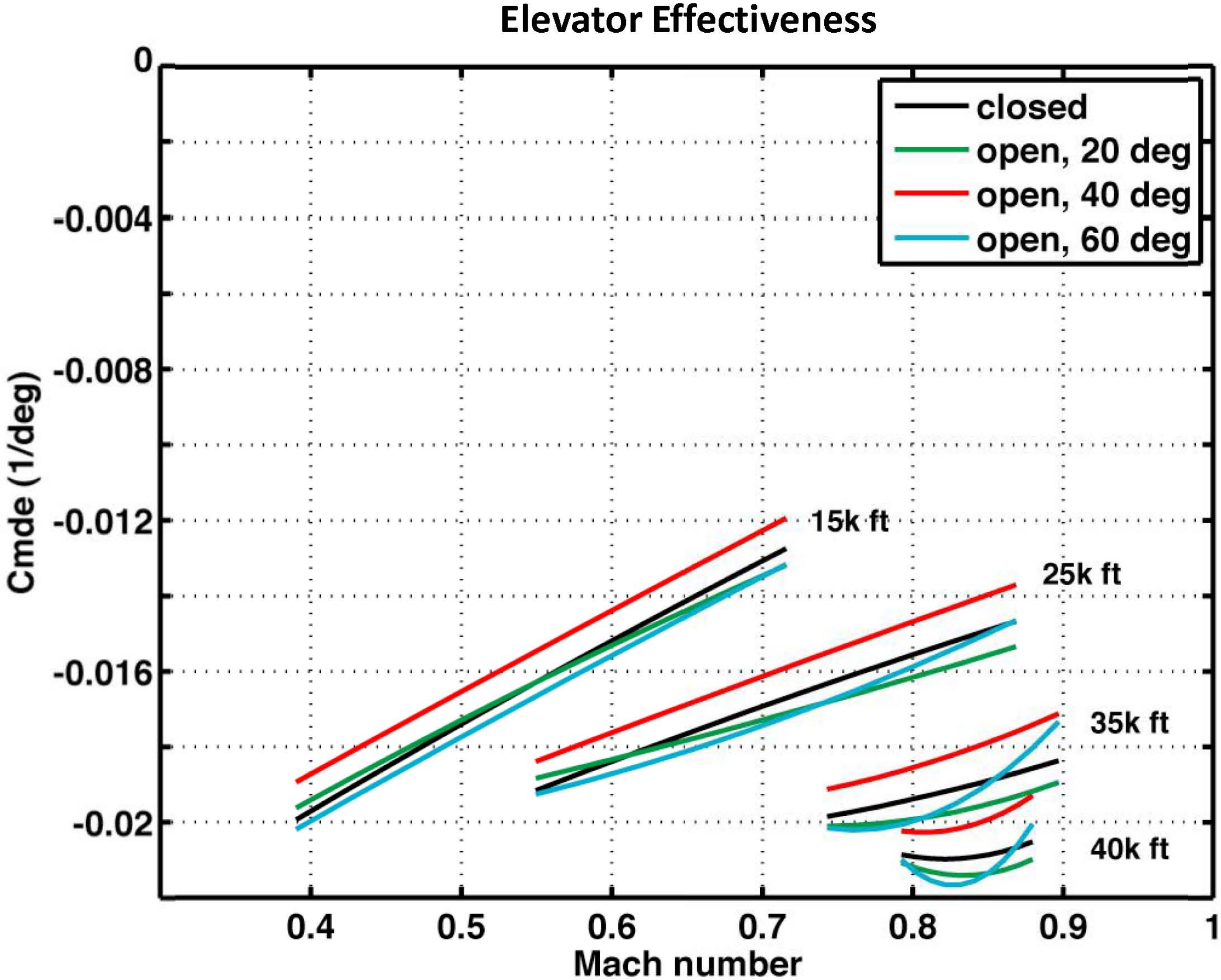
- Predictions for cavity acoustics and stability and control effects were generally positive
- Predicted cavity acoustics were predicted to be well within design range (with some exceptions)
- Predicted stability and control effects due to the cavity were relatively small

Predicted Cavity Acoustics

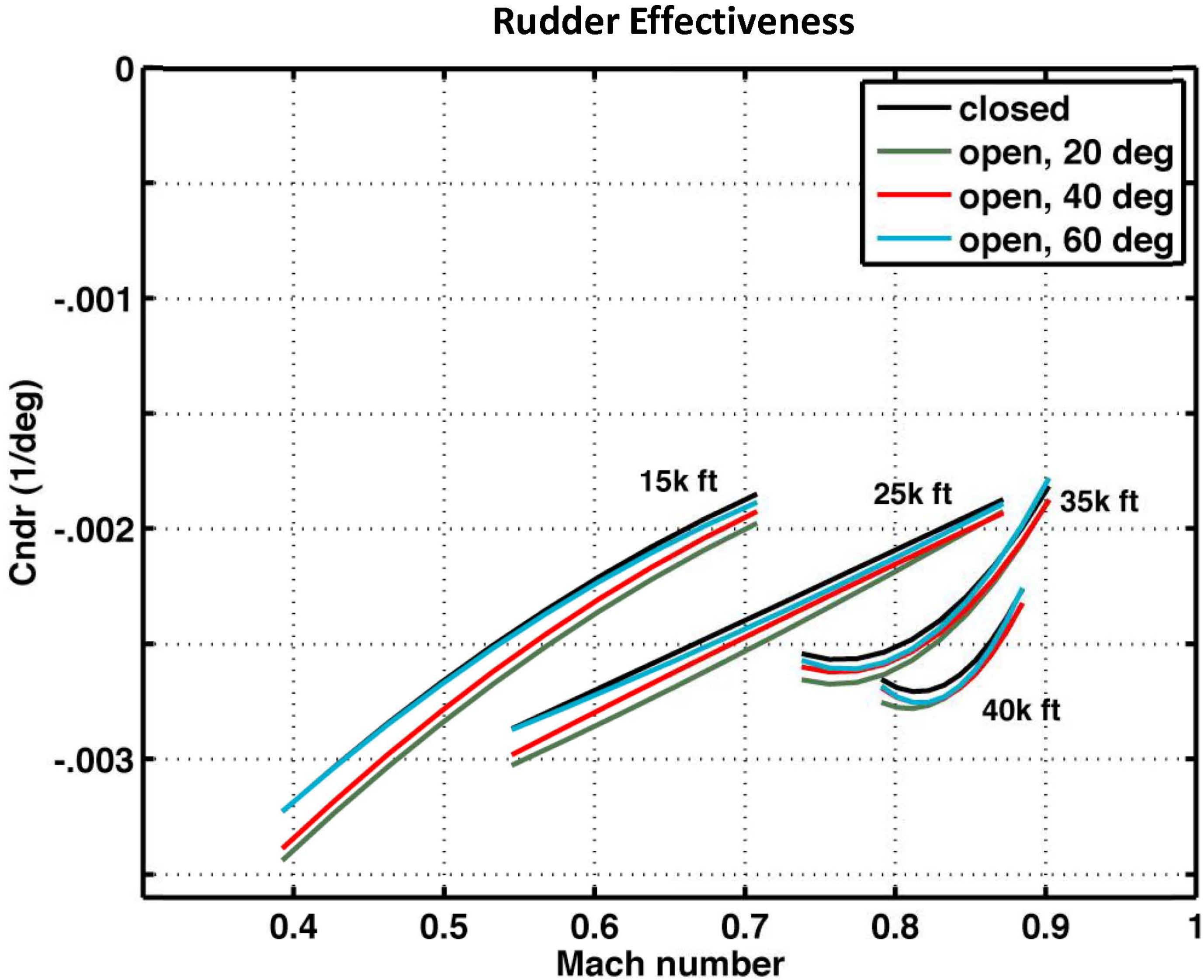


SPL = Sound Pressure Level

Predicted Airplane S&C



Predicted Airplane S&C



Pre-Flight Technical Concerns

- Despite the extensive amount of analysis and test data, there were still serious concerns prior to open door flights:
  - The shear layer control design had not been fully proven outside of wind tunnel tests
  - Scaling issues sometimes make acoustic wind tunnel tests unreliable
  - 3% wind tunnel tests indicated there was a possibility for cavity SPL above limits
  - Predictions for stability and control effects were not considered highly reliable or accurate
  - Some aerodynamic issues, such as possible pitot-static effects were unlikely to be predicted by the available analysis methods

Envelope Expansion Plan

- The set of test points selected for envelope expansion were quite substantial
- Primary drivers for envelope expansion points were acoustics, aerodynamics and S&C
- Large number of test points were driven by a couple key issues:
  - Technical concerns
  - Cavity door system limitations

FLIGHT TEST

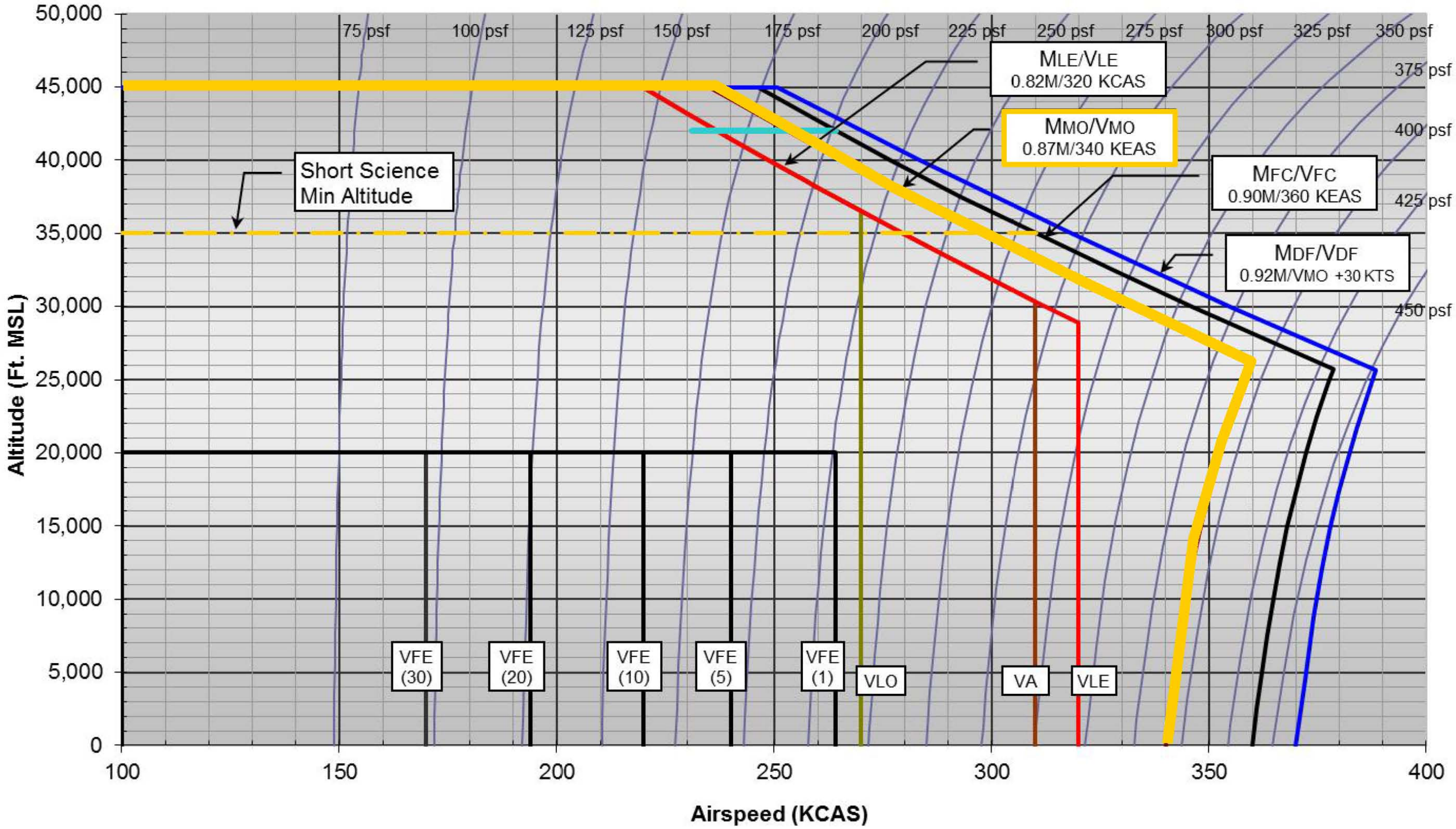
Setting the Stage

- <u>OBJECTIVE</u>: Certify the airplane as a public use aircraft
  - Based on Type Cert. A20WE , Mil-Specs, and NASA best practices
  - Additional engineering & science mission requirements
  - Focus was on envelope expansion and certification of the airframe
    - Some effort to show compliance with mission requirements

- <u>PROGRAM GOAL</u>: Clear SOFIA for "Early Science"
  - Short Science: ≥ 35,000 ft MSL and telescope up to 40° elevation
  - Basic Science: > 41,000 ft MSL and telescope full range (58.3°)

- Program at risk due to imminent funding loss
- Rigid NASA and DLR HQ Milestones in place

Initial SOFIA Flight Envelope

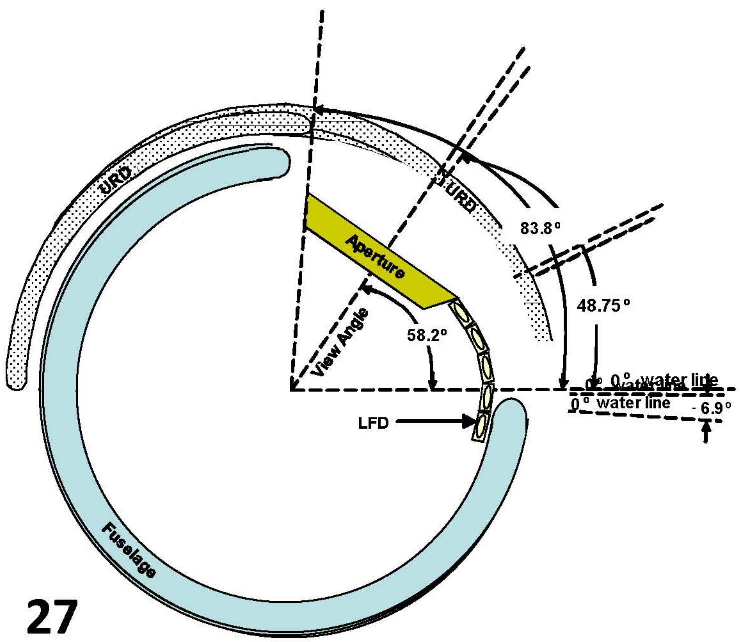


V_{DF}/M_{DF} = **Maximum demonstrated flight dive speed**

V_{FC}/M_{FC} = **Maximum airspeed for stability characteristics**

Test Point Selection

- Concentrate on areas not modeled or wind tunnel tested
- Risk of *acoustic resonance* drove check of multiple door/ aperture positions
  - 10%, 40%, 70%, 100% Open – Door could be moved in flight
  - 23°, 30°, 40°, 50°, 58° Aperture – Set prior to flight



- No data for door open landing configuration
- Included 'Contingency' test points to cover any unknowns

Envelope Expansion
Types of Test Points

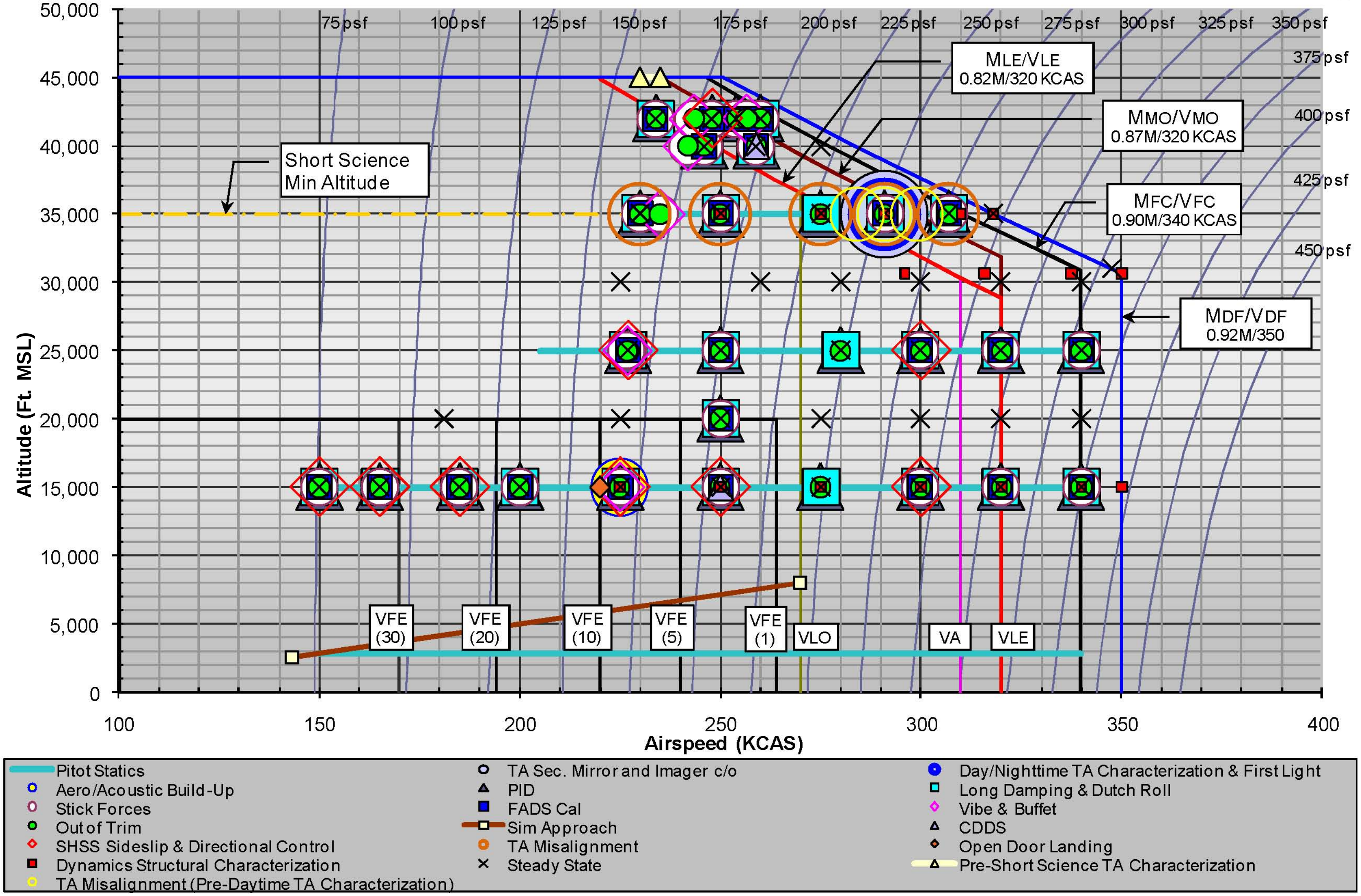
Discipline	Type	Maneuver	URD Position
Aerodynamics	Steady State	Trim shot	Closed, open
	Pitot-statics	Accel/decels	Closed, open
		Tower fly-bys	Closed
	FADS Cal	PUPO, rudder sweeps	Closed, open
	PID	Pitch, roll, yaw, yaw-roll doublets	Closed, open
	Vibration and buffet	Straight & level flight, maneuvering flight	Closed, open
S&C	Static lat-dir stability	Straight, steady sideslips, V_{mca}, 2-Eng go	Open
Dynamics	Flutter	Raps	Closed, open

FADS = Flush Air Data Sensing

Initial Test Point Count

	Planned	% Pts
AERO	1474	48%
AERO/S&C	1314	43%
Total Aero/S&C	2788	91%
S&C	44	1%
CDDS	2	0.1%
Ops	4	0.1%
Science	6	0.2%
Static Structures	5	0.2%
Struct Dynamics	202	7%
TA	15	0.5%
Test Points	**3067**	**100%**

Initial Open Door Test Conditions



V_{DF}/M_{DF} = maximum demonstrated flight dive speed

V_{FC}/M_{FC} = maximum airspeed for stability characteristics

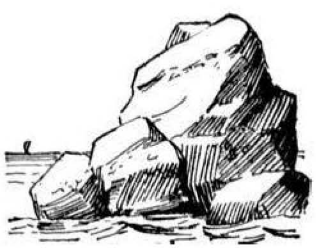
Challenges

- Primary mirror already installed
  - Sun cover
  - Contamination
  - Thermal conditioning
- No test software load
  - Door system designed to always open to 100%
  - Intermediate positions required “Manual Control”
- Separate flight for each aperture setting
- Instrumentation batteries only good for 6 hours
- “Ride-along” testing for Early Science

Reality Strikes

- "You have too many test points!"
- Defining the problem
  - Milestones: "First Light" & "Initial Science" (ISF)
  - 6 hour flights determine max test points/flight
  - Data analysis/inspections drive fly rate

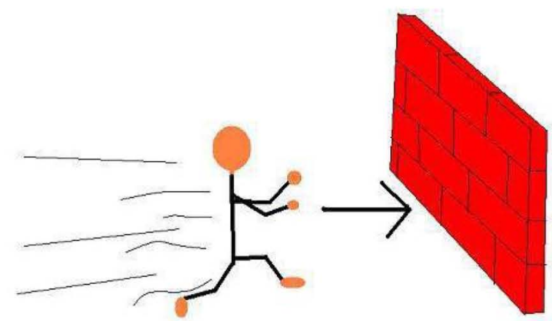
Estimated test capacity: 1000 test points



Fly Rate

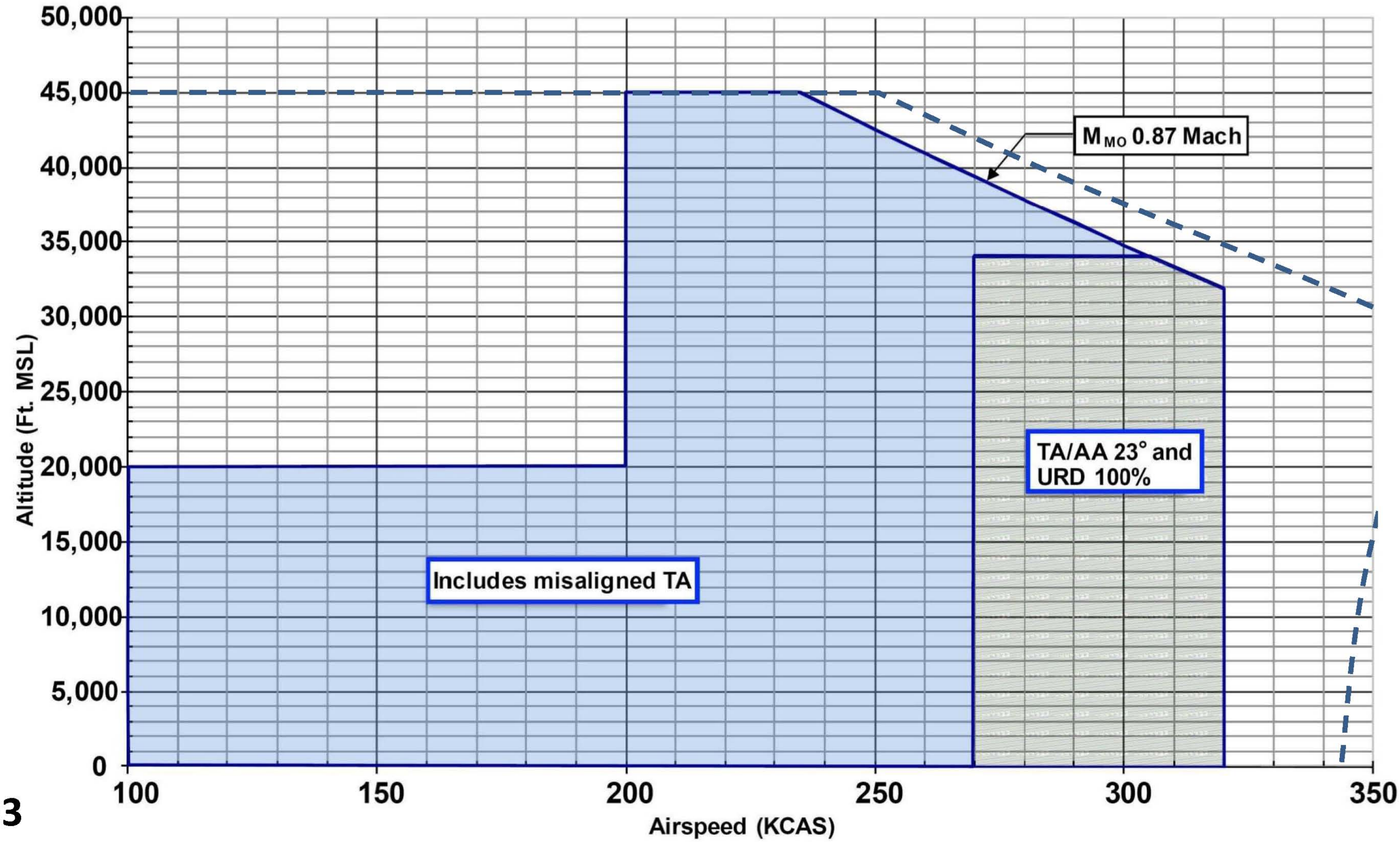
↓ Reduce Test Points

↑ Test Effectiveness



Milestones

Reduced Airspeed Envelope



Other Unneeded Test Points

- Consulted with FAA Designated Engineering Representatives on adequacy of test plan
  - 15 items suggested for deletion from test plan
  - 9 items suggested to add to test plan
  - Majority of suggestions incorporated
- Eliminate “contingency” test points
- Still too many test points

The Approach

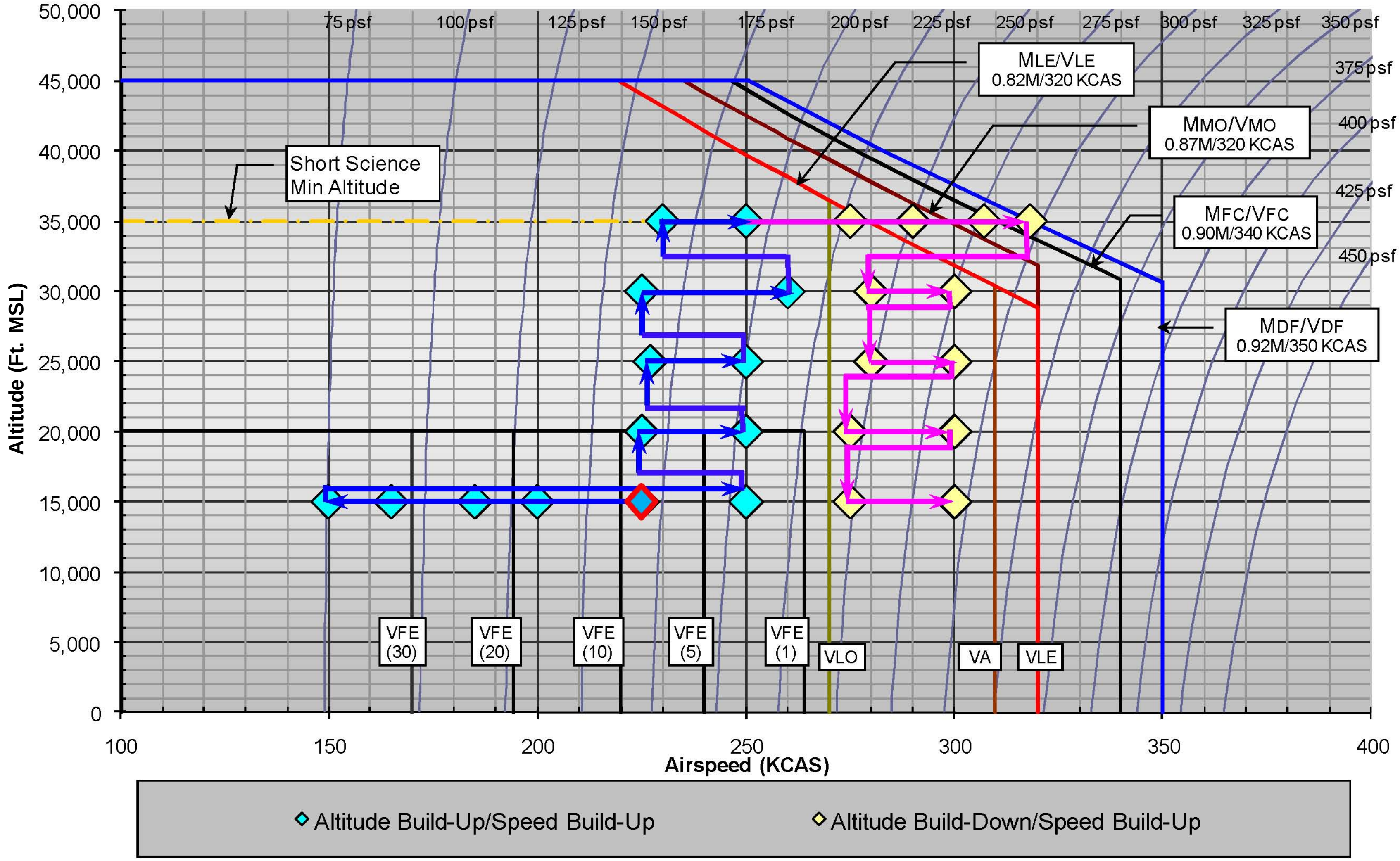
- **"Schedule for Success" Plan for the worst**
  - Assume <u>best-case</u> technical results, and <u>validate with flight test</u>
  - If test results validate models, skip ahead but spot check. Example:
    - Fly 23° aperture at all test conditions
    - Fly 40° aperture at a reduced set of test conditions
    - Go back and spot check 30° aperture

- Publish a "Success Oriented" Schedule
- More investigation (*schedule slips*) if assumptions wrong
- A human-intensive process including extra engineers, "real-time data reduction", multiple tech reviews, etc.

Test Point Sequence

- Clear Aero, Acoustics, S&C and Flutter I.T.B.s
  - Validate test results → review test points → eliminate the unneeded
- Performance, buffet boundary and systems
- Open Door Landing (one) planned in worst-case configuration
  - No wind tunnel or analytical data for ground effect case
  - KAO had an unexpected acoustic event during flight test in the landing flare

Open Door Envelope Expansion Approach

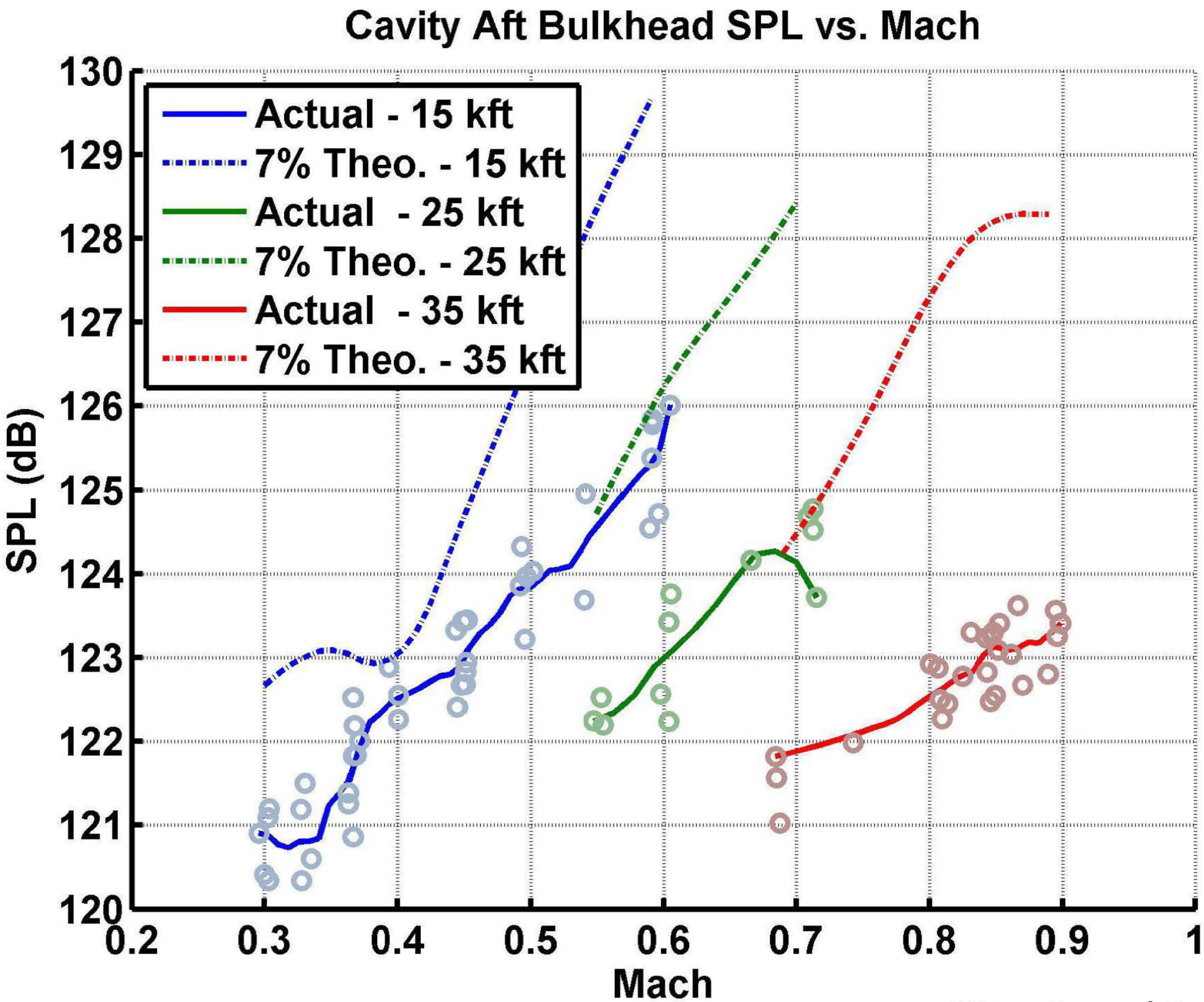


V_{DF}/M_{DF} = maximum demonstrated flight dive speed
V_{FC}/M_{FC} = maximum airspeed for stability characteristics

Flight Test Results

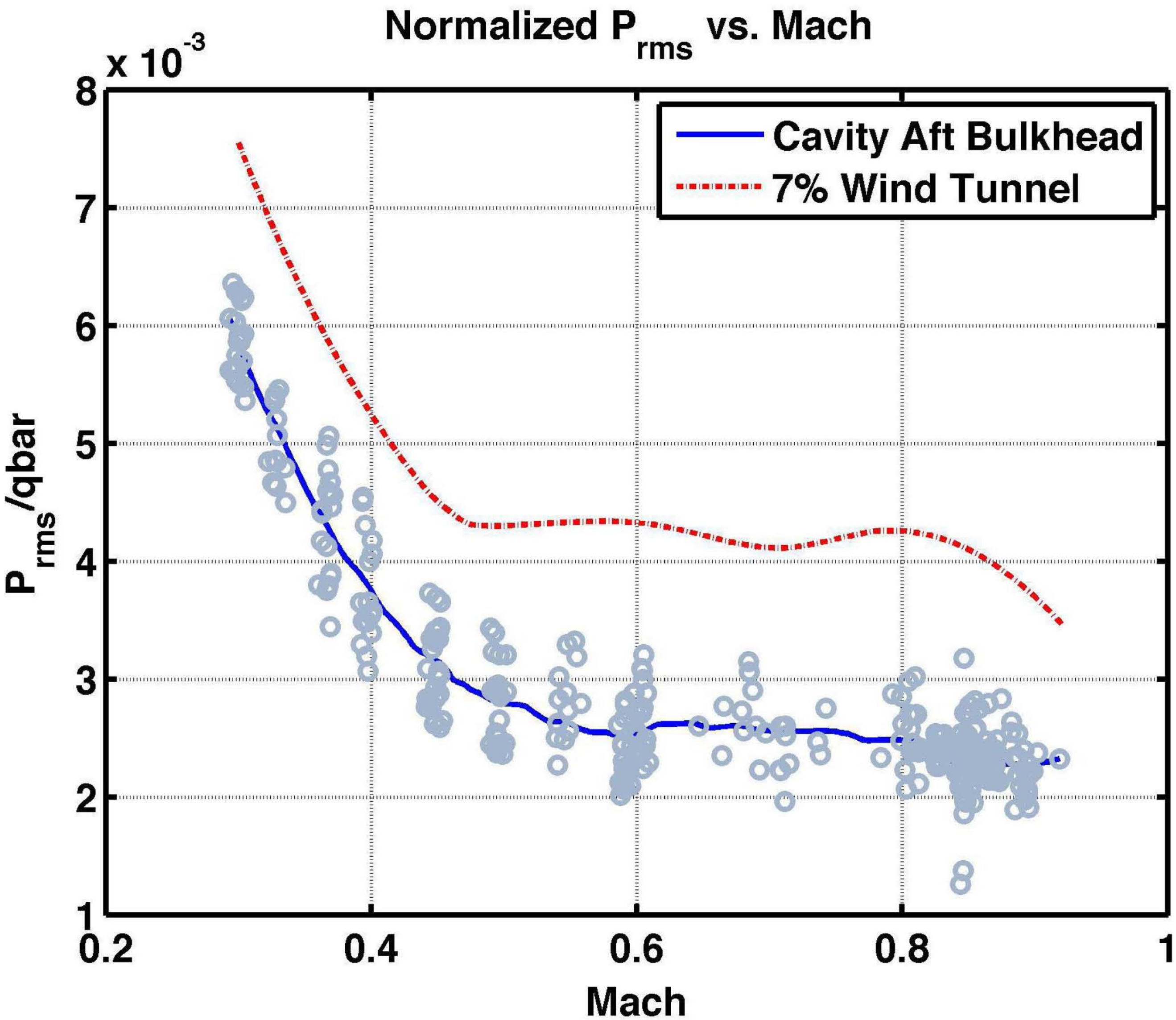
- Final results exceeded expectations
- Found NO substantial or consistent effects on stability and control
- Sound pressure levels in the cavity were below expected values
- Handling qualities not degraded
- Flies like a stock 747

Cavity Acoustics

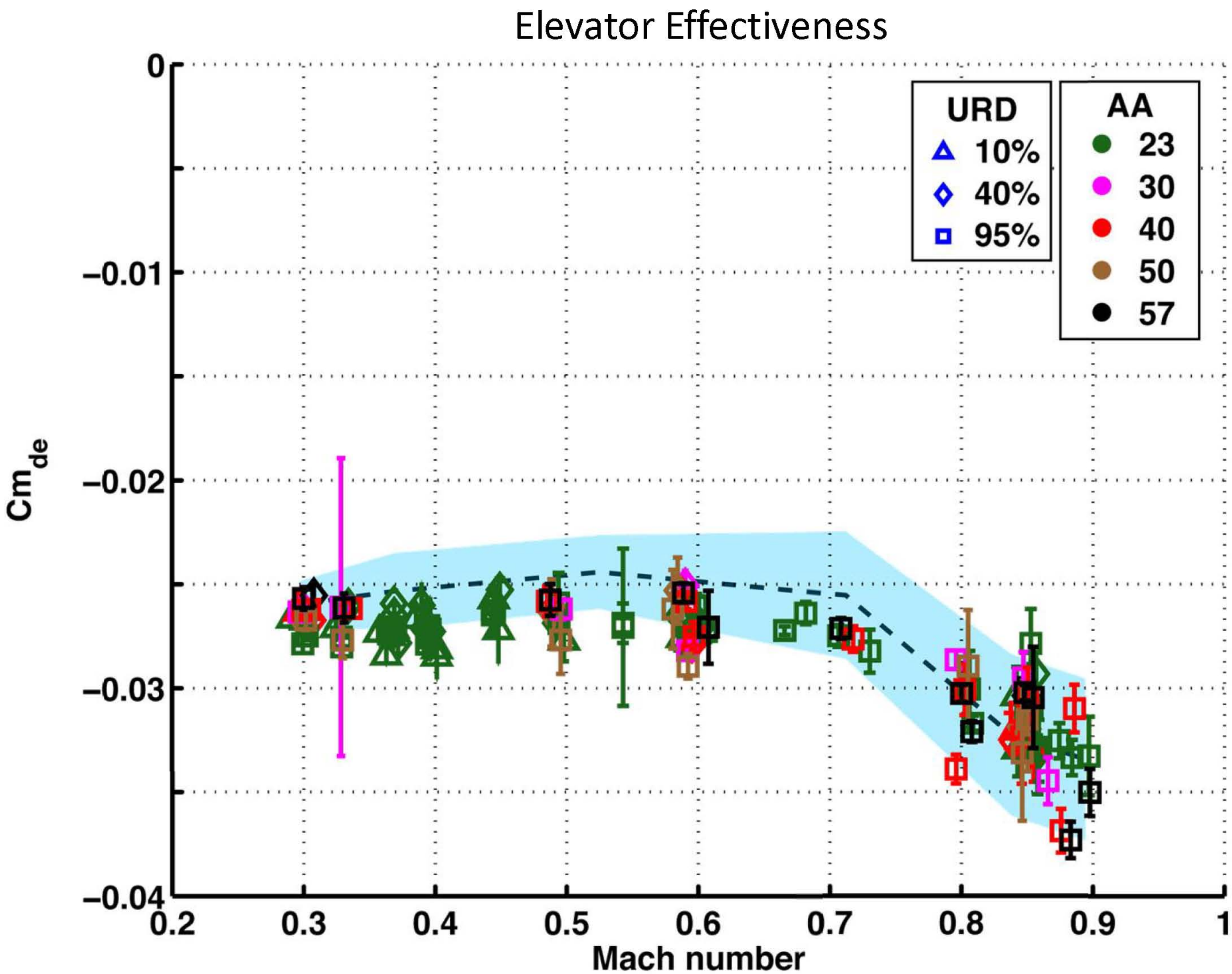


SPL = Sound Pressure Level

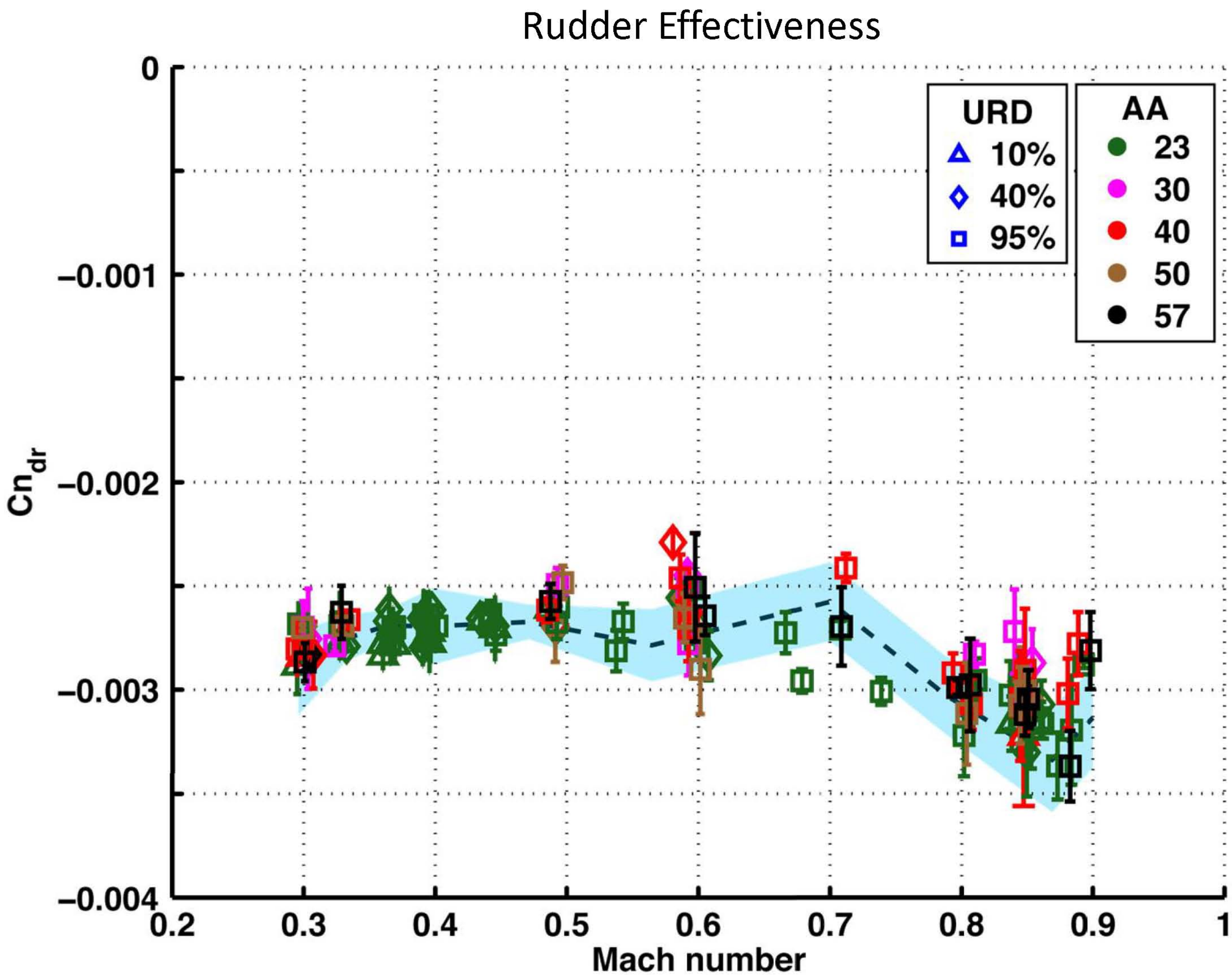
Cavity Acoustics



Longitudinal Control



Directional Control



- G-overshoots during Wind-up turns
- Steady-heading-sideslips at low speed
- Door open landings

First 100% Door Open

Final Score

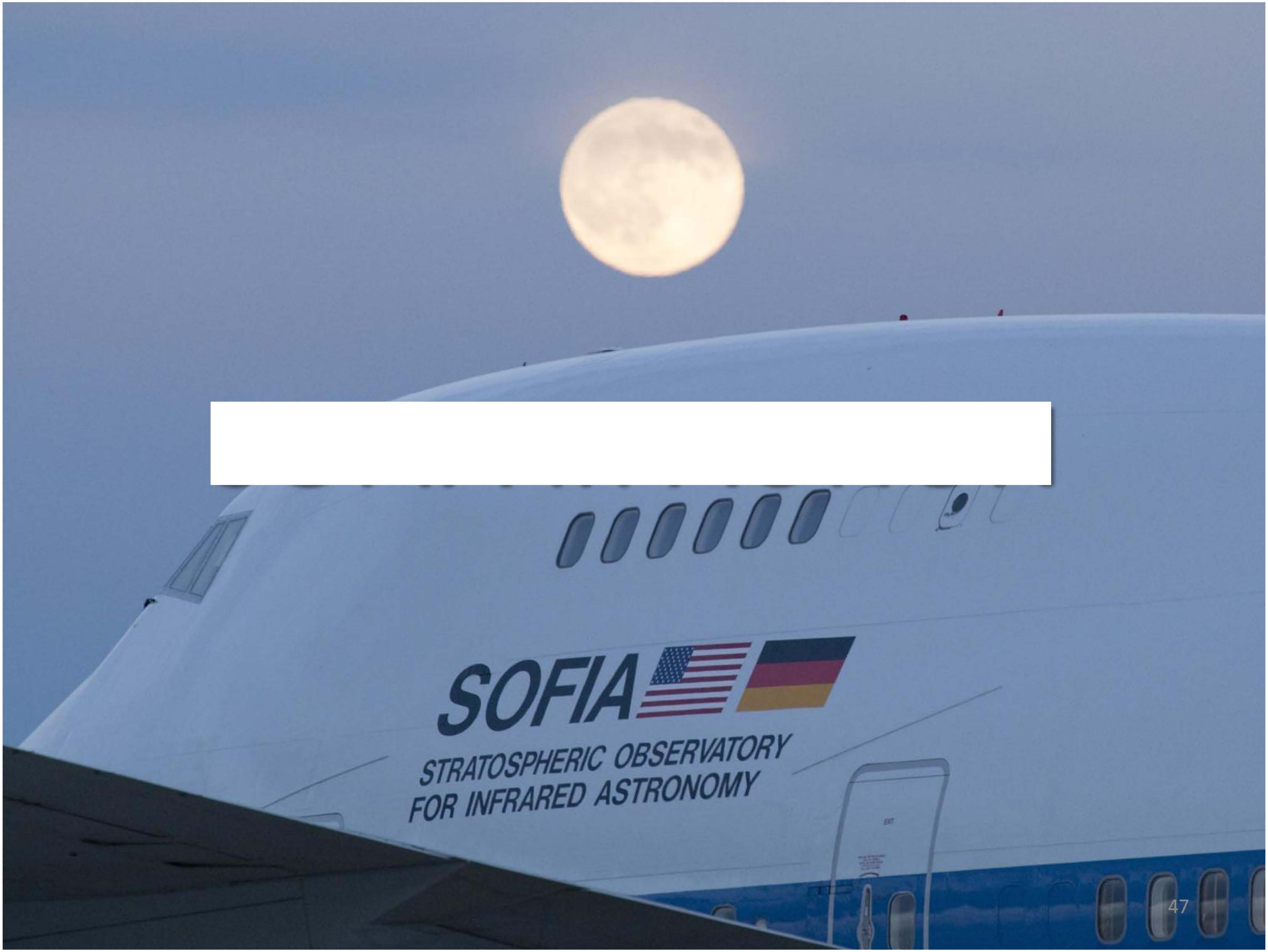
	Planned	% Pts	Flown	Saved	% Redux
AERO	1474	48%	478	996	68%
AERO/S&C	1314	43%	309	1005	76%
Total Aero	2788	91%	787	2001	72%
S&C	44	1%	31	13	30%
CDDS	2	0.1%	2	0	0%
Ops	4	0.1%	4	0	0%
Science	6	0.2%	6	0	0%
Static Structures	5	0.2%	5	0	0%
Struct Dynamics	202	7%	16	186	92%
TA	15	0.5%	14	1	7%
Test Points	3067	100%	865	2202	72%

The Most Common Question

Q: What do you feel when the door opens?

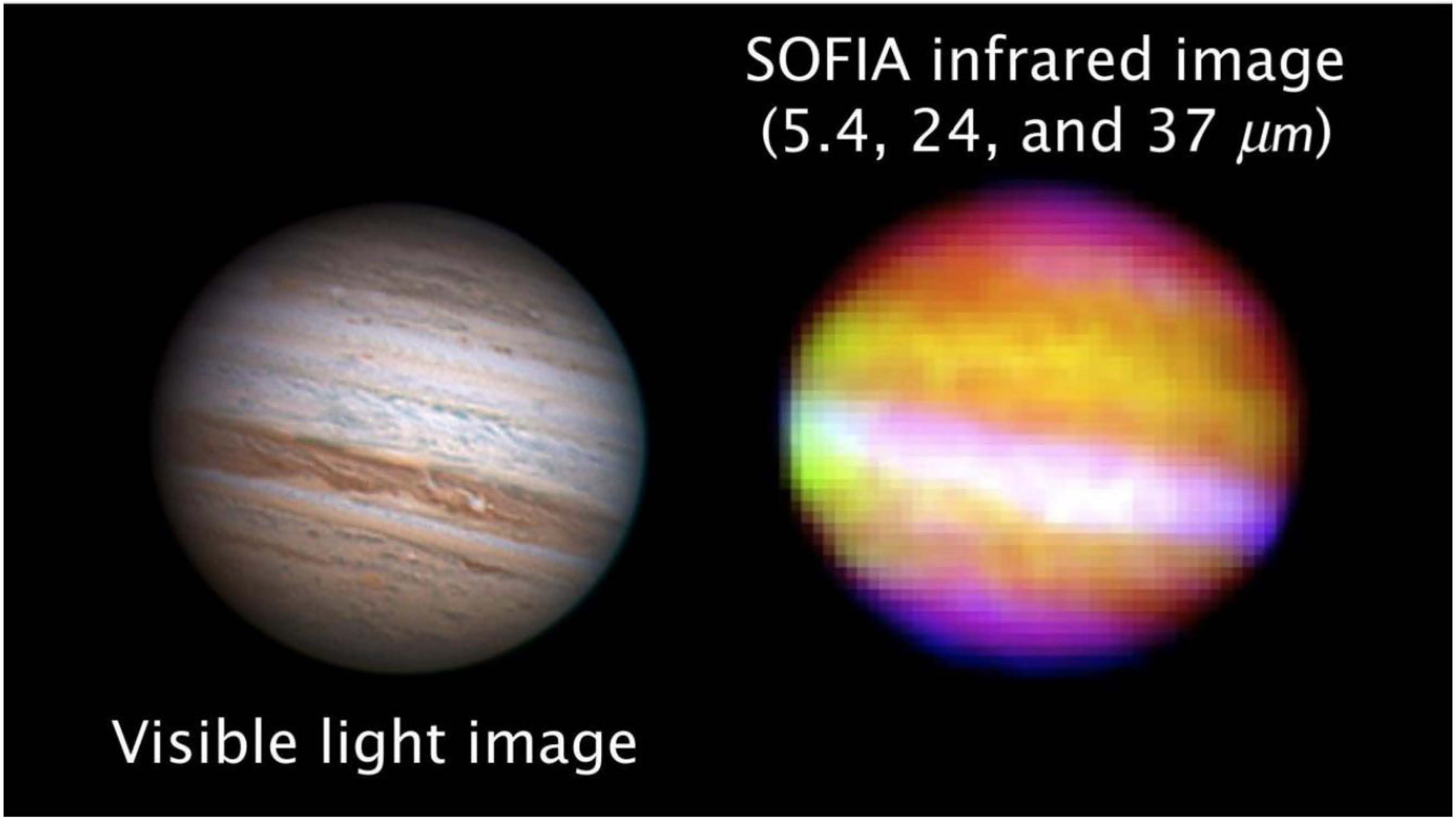
A: NOTHING!

If instrumentation and telescope operation didn’t tell you the door is open, you wouldn’t notice it.

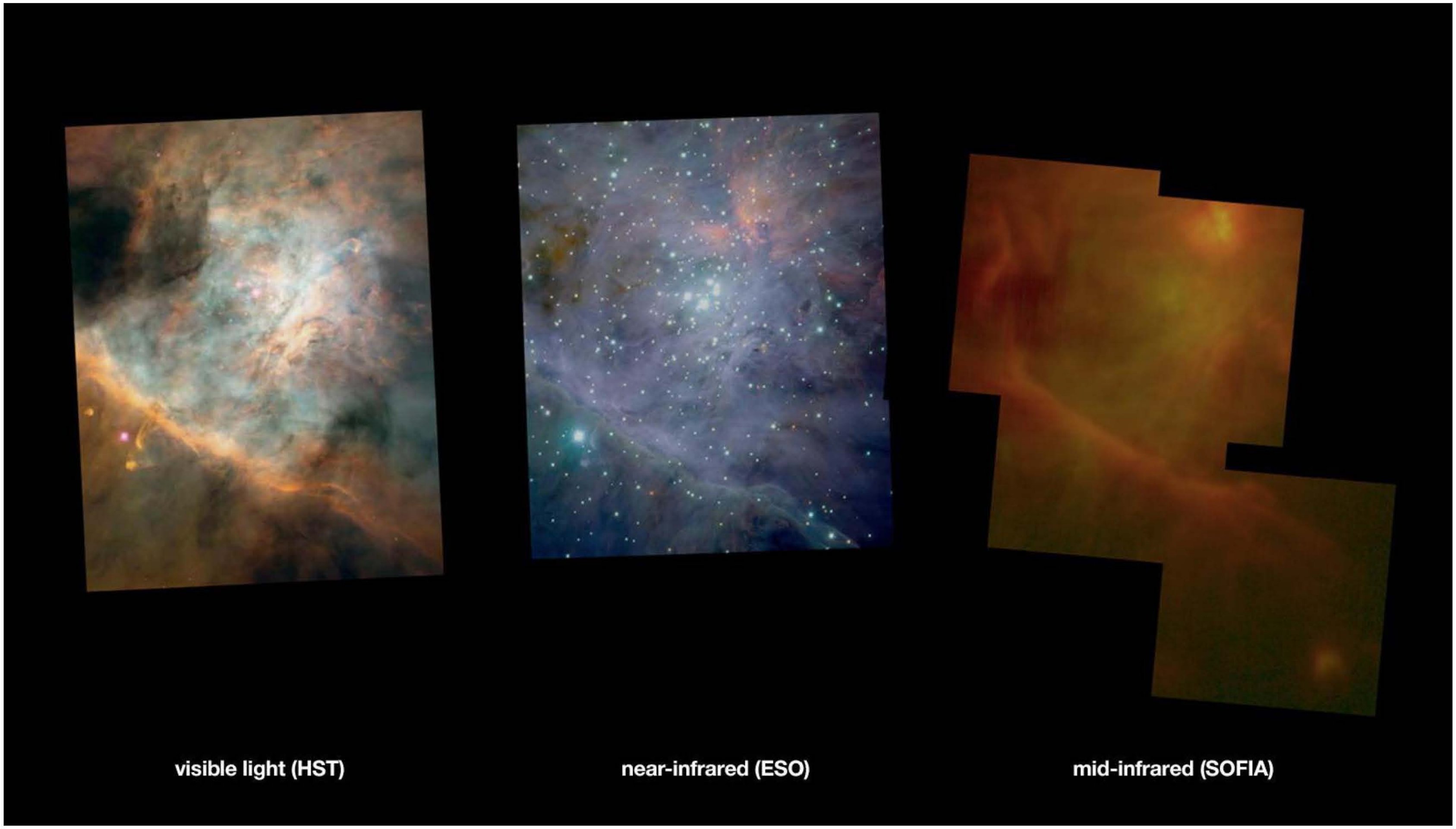

SOFIA
STRATOSPHERIC OBSERVATORY
FOR INFRARED ASTRONOMY

"First Light" Image of Jupiter

May, 2010



Mid-IR image of Orion Messier 42 Star-forming Region

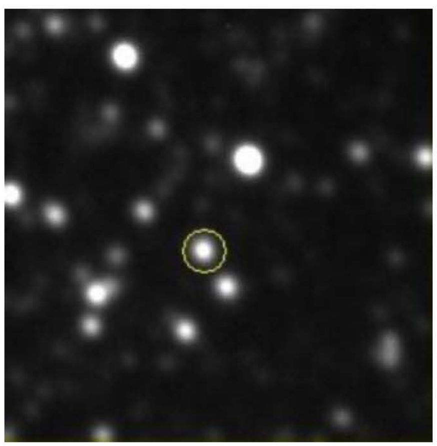


Stellar Occultation by Pluto

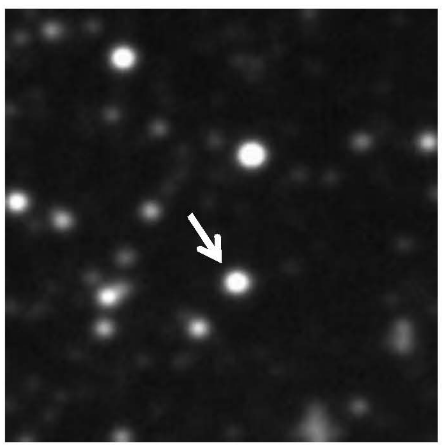
July 23, 2011

- Dwarf planet Pluto (V~14) occulted a star (V~14.4)
- SOFIA met the shadow of Pluto in mid-Pacific
- HIPO (Lowell Obs.) and FDC (DSI) instruments observed the occultation simultaneously

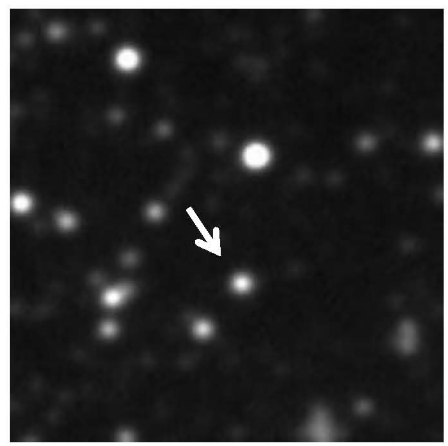
Image sequence from the Fast Diagnostic Camera (FDC)



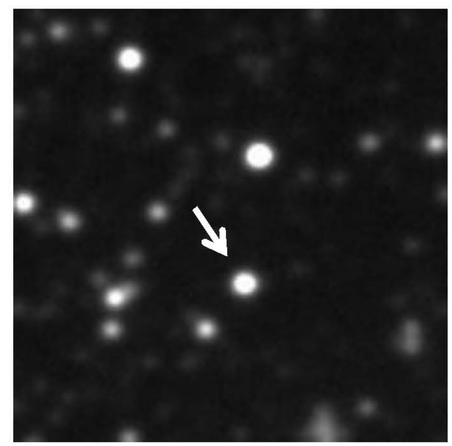
Pluto (circled) is 13 arcsec from the star 200 minutes before the occultation



Just before occultation: Pluto and star merged, combined light!



During occultation: Pluto and star merged, only Pluto light seen

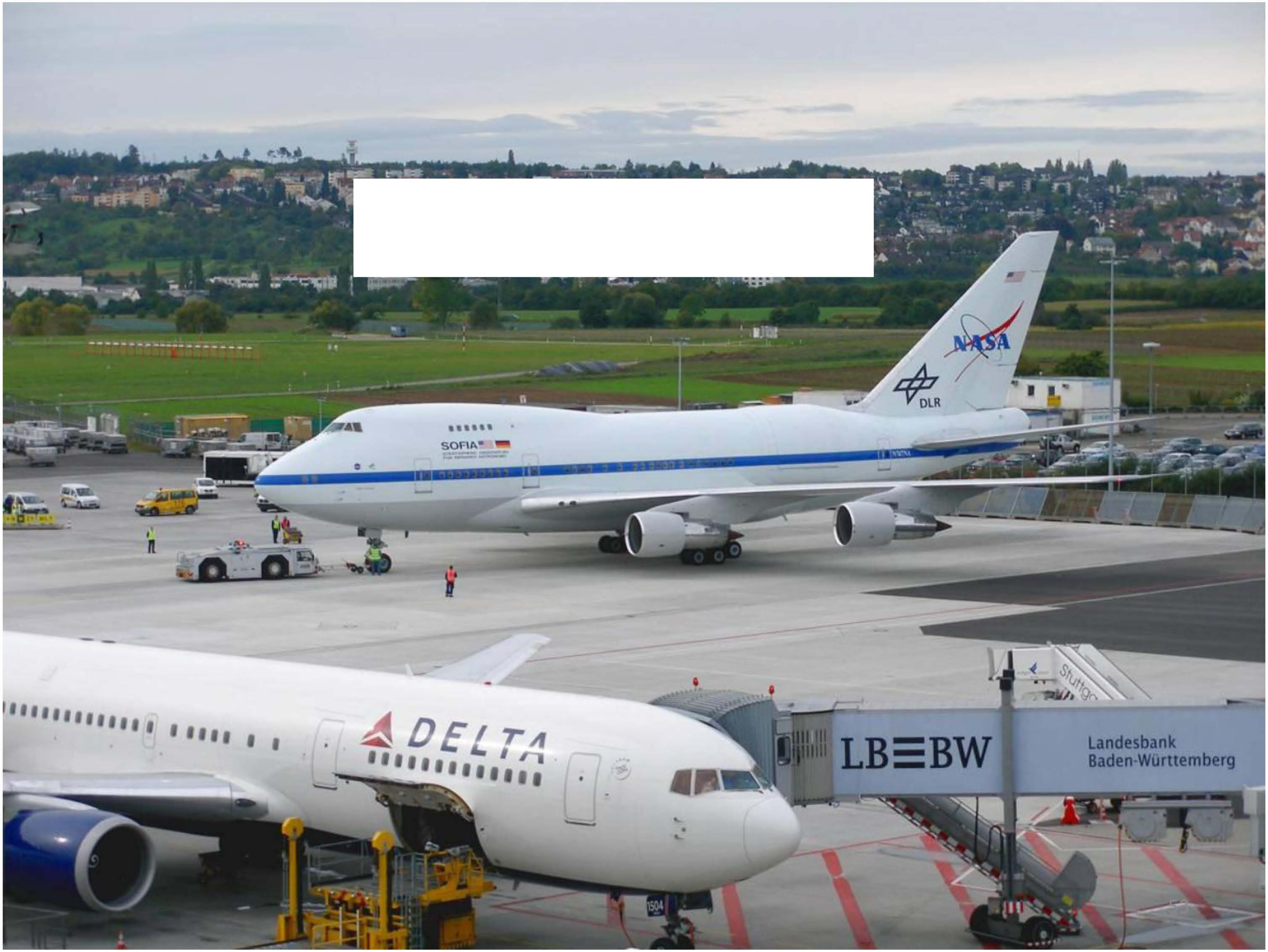


After occultation: Pluto and star merged, combined light!

Conclusions / Lessons Learned

Conclusions/Lessons Learned

1. "Do Your Homework"
   – Investing in baseline, wind tunnel, and ground testing as well as engineering analysis pays huge dividends
2. "Schedule for Success, Plan for the Worst"
   – This is more effective if #1 above was sufficiently done
   – Use all tools available to analyze necessary testing
   – Leave plenty of "off ramps" for unknown events
3. A software version for Flight Test can be very valuable
   – Increases test effectiveness
   – May help avoid unknown effects


SOFIA
NASA
DLR
DELTA
LBBW
Landesbank
Baden-Württemberg

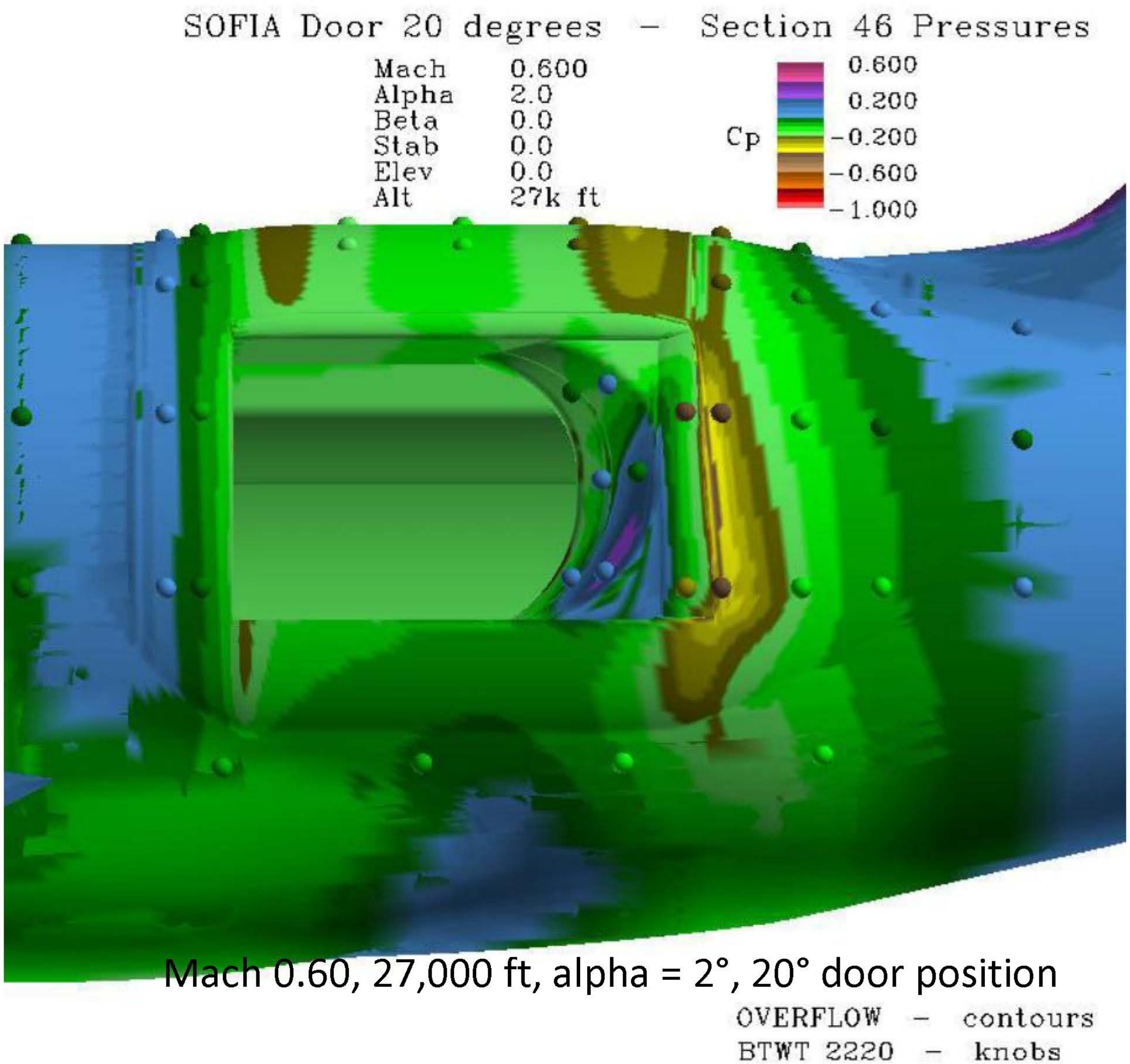
Backup

Program Objectives

Further scientific knowledge in the field of astronomy and astrophysics by complementing and augmenting ground and space-based observation capabilities through development and operation of a next generation airborne observatory.

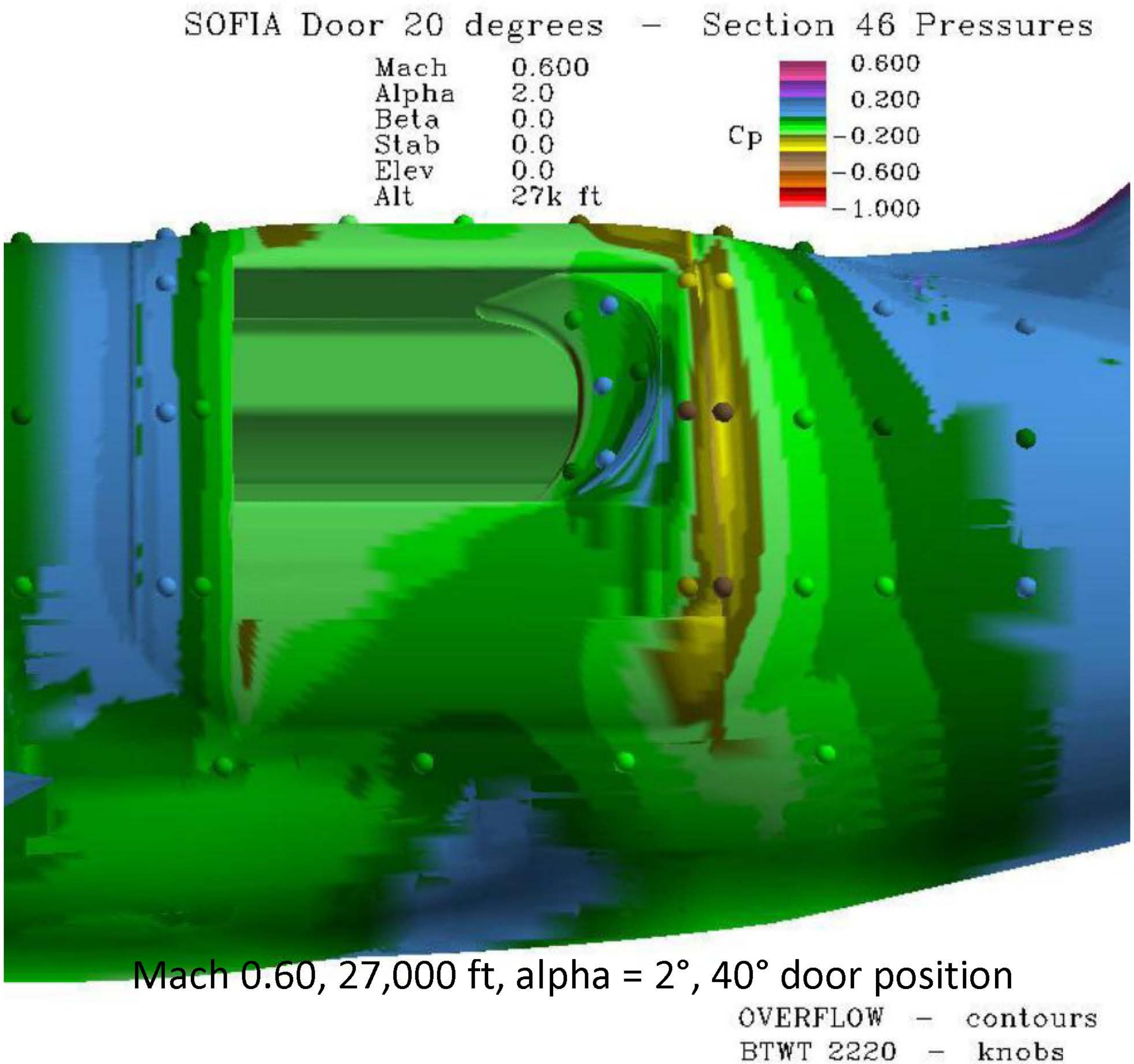
Baseline Flights

CFD Results



Mach 0.60, 27,000 ft, alpha = 2°, 20° door position

CFD Results

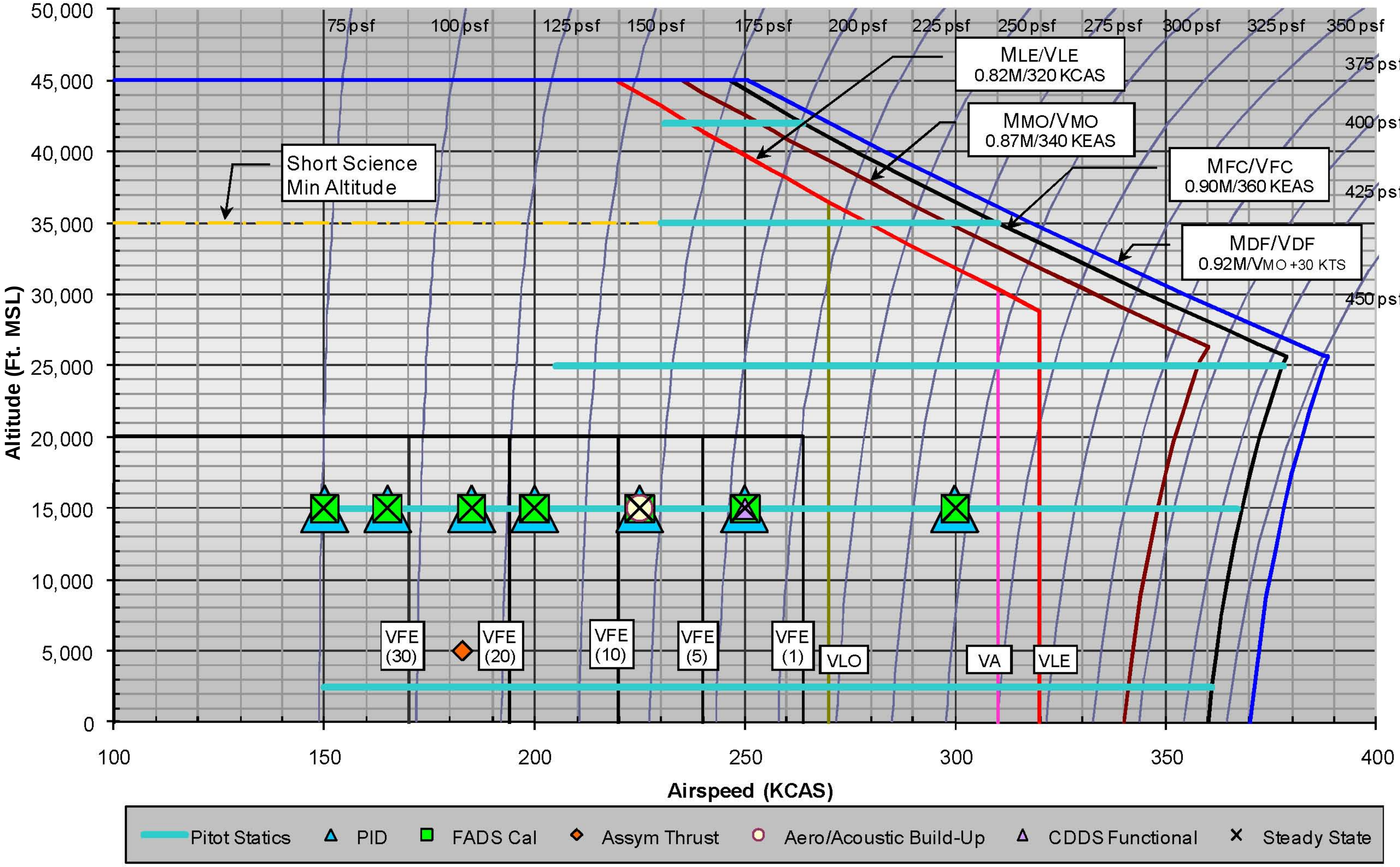


Mach 0.60, 27,000 ft, alpha = 2°, 40° door position

Test Plan Development

- Airworthiness testing
  - Performance
  - Flying/Handling qualities
  - Model validation
  - Demonstration of satisfactory structural characteristics
  - Flutter
  - Ground Vibration Test (GVT) to validate/update FEM
- Major Test Disciplines involved
  - Aerodynamics (incl. acoustics)
  - Stability & Control
  - Structural Dynamics (Flutter)
  - Static Structures (Loads)
  - Door Drive System
  - Science
  - Operations
  - Telescope

Build-Up to Open Door Envelope Expansion



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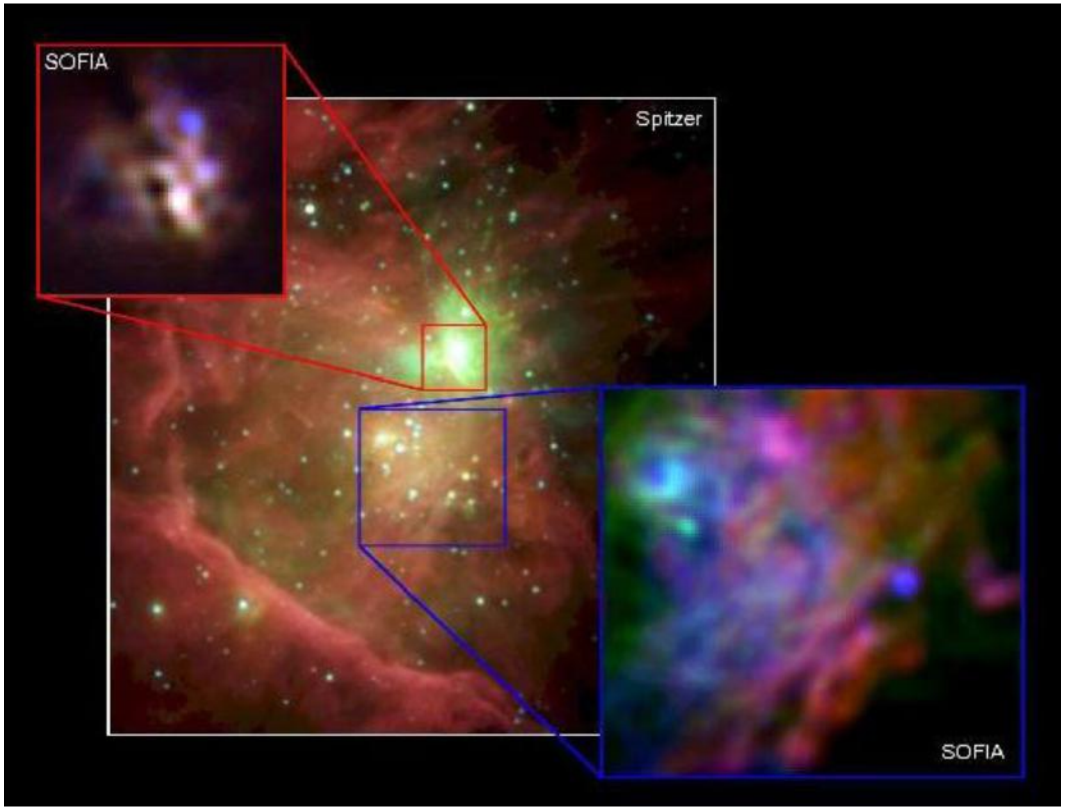
Images from SOFIA

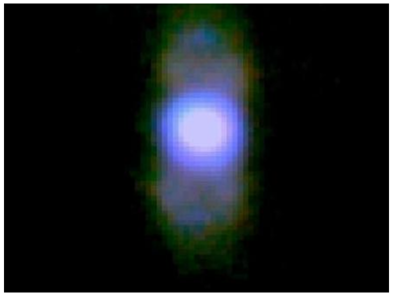
Heart of Orion Nebula



Graphical representation comparing two infrared images of the heart of the Orion nebula captured by the FORCAST camera on SOFIA with a wider image of the same area from the Spitzer space telescope.

SOFIA image -- James De Buizer / NASA / DLR / USRA / DSI / FORCAST; Spitzer image -- NASA/JPL

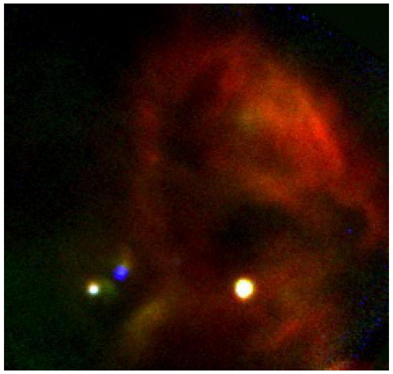
Planetary Nebula M2-9



The last exhalations of a dying star

June 2011, NASA/DLR/USRA/ DSI/FORCAST team/M. Werner, J. Rho

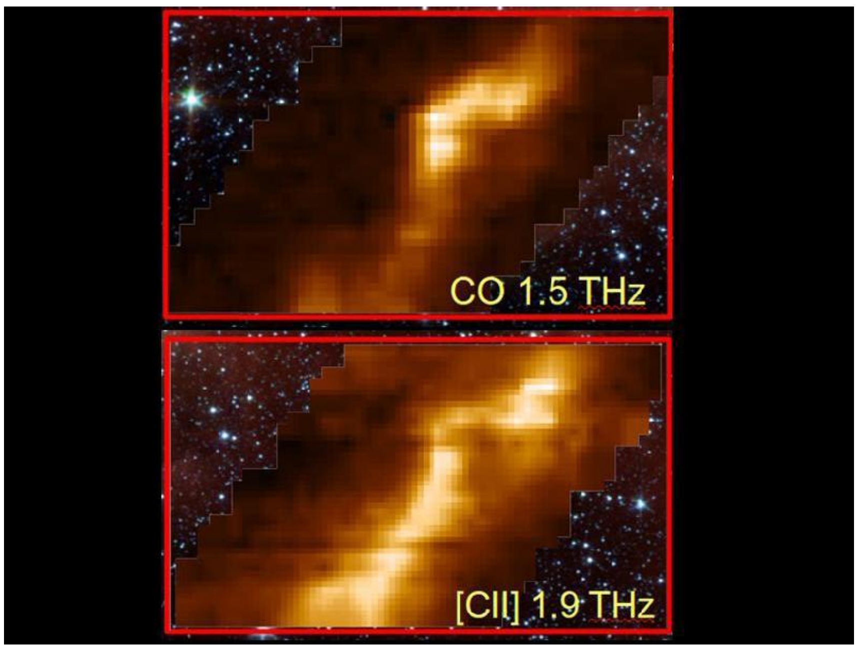
W40



Mid-infrared image of the W40 star-forming region of the Milky Way captured by FORCAST

NASA / FORCAST image, May 18, 2011

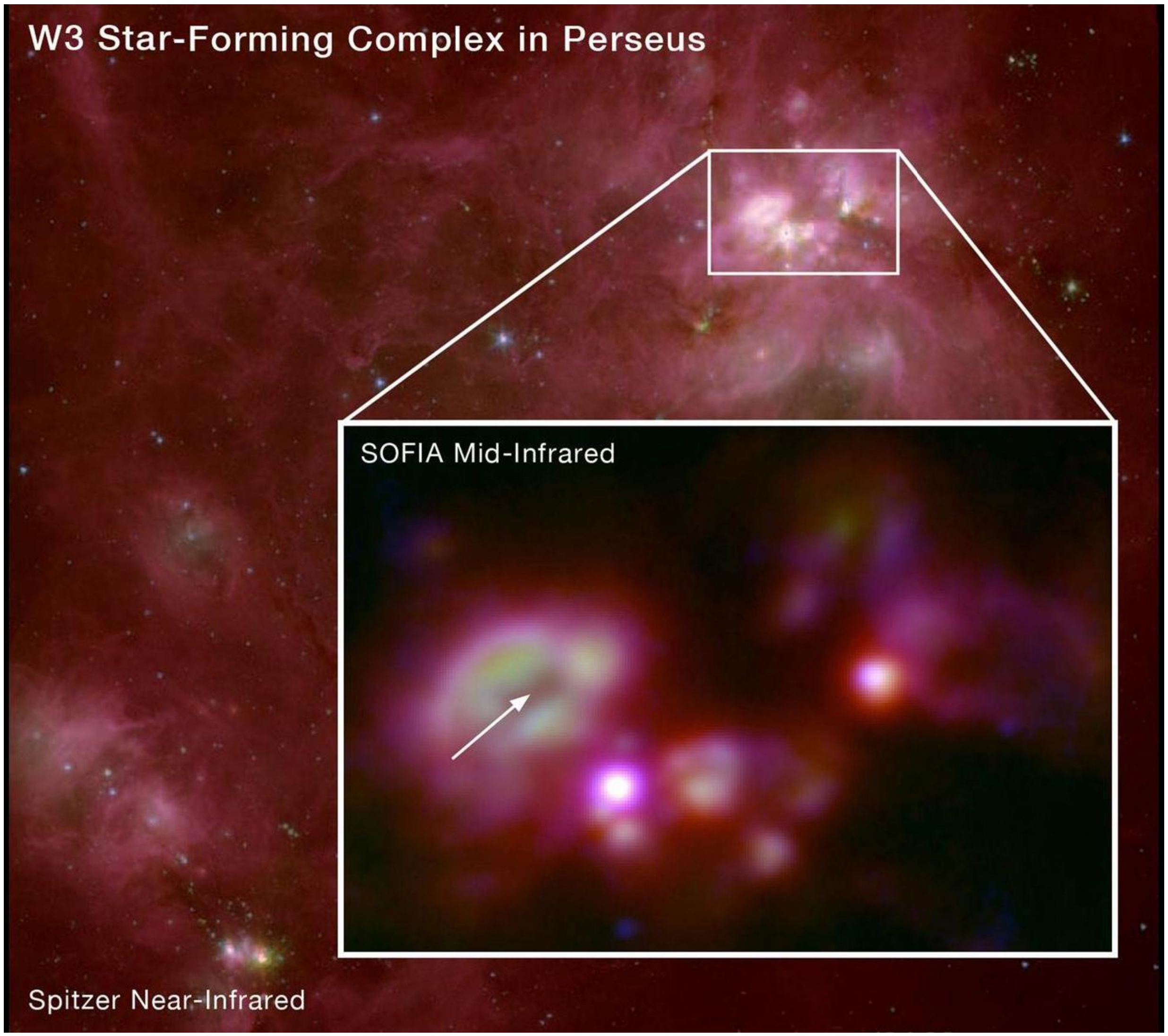
GREAT



- GREAT collected its first THz photons from the M173W star forming cloud April 6, 2011. Superimposed on a near-infrared false-color image measured by the Spitzer Space Telescope are selected spectra of ionized carbon (CII) and warm carbon monoxide (CO). The high spectral resolution of GREAT is used to study the velocity structure across the cloud.

  April 6, 2011
  (GREAT Team/NASA/DLR/USRA/DSI)

W3 Star-forming Region



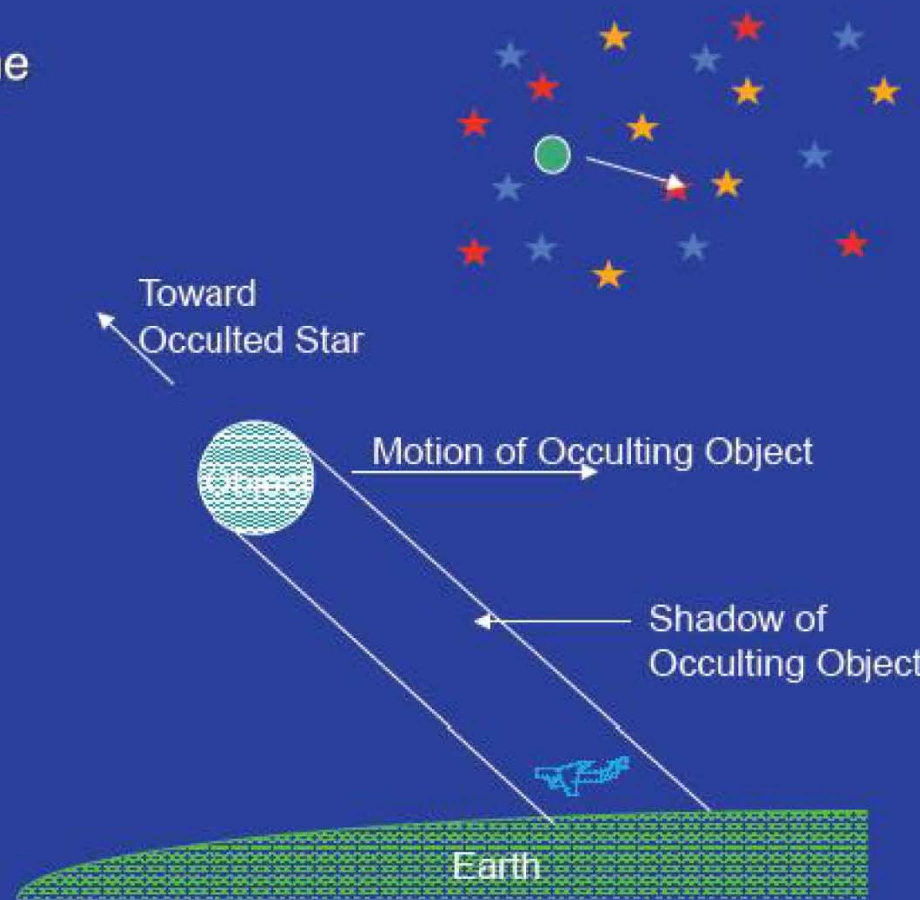
Mid-infrared image of the W3A star cluster (inset) captured by FORCAST in 2011. Image overlaid on a near-infrared image from the Spitzer space telescope. The SOFIA image scale is 150x100 arcseconds and the red, green and blue colors represent 37, 20 and 7 µm. The red, green and blue colors in the background image from Spitzer represent 7.9, 4.5, 3.6 µm.

SOFIA image: NASA / DLR / USRA / DSI / FORCAST team Spitzer image: NASA / Caltech - JPL. 2011

Planetary Science; Occultations

SOFIA is able to:

- Go anywhere on Earth to reach the occultation shadow of an object
- Can probe the sizes, structures (rings & moons), and atmospheres of solar system bodies by measuring how they occult background stars
- This will be the primary objective for HIPO (High-speed Imaging Photometer for Occultations)



Returning to PMD with open door

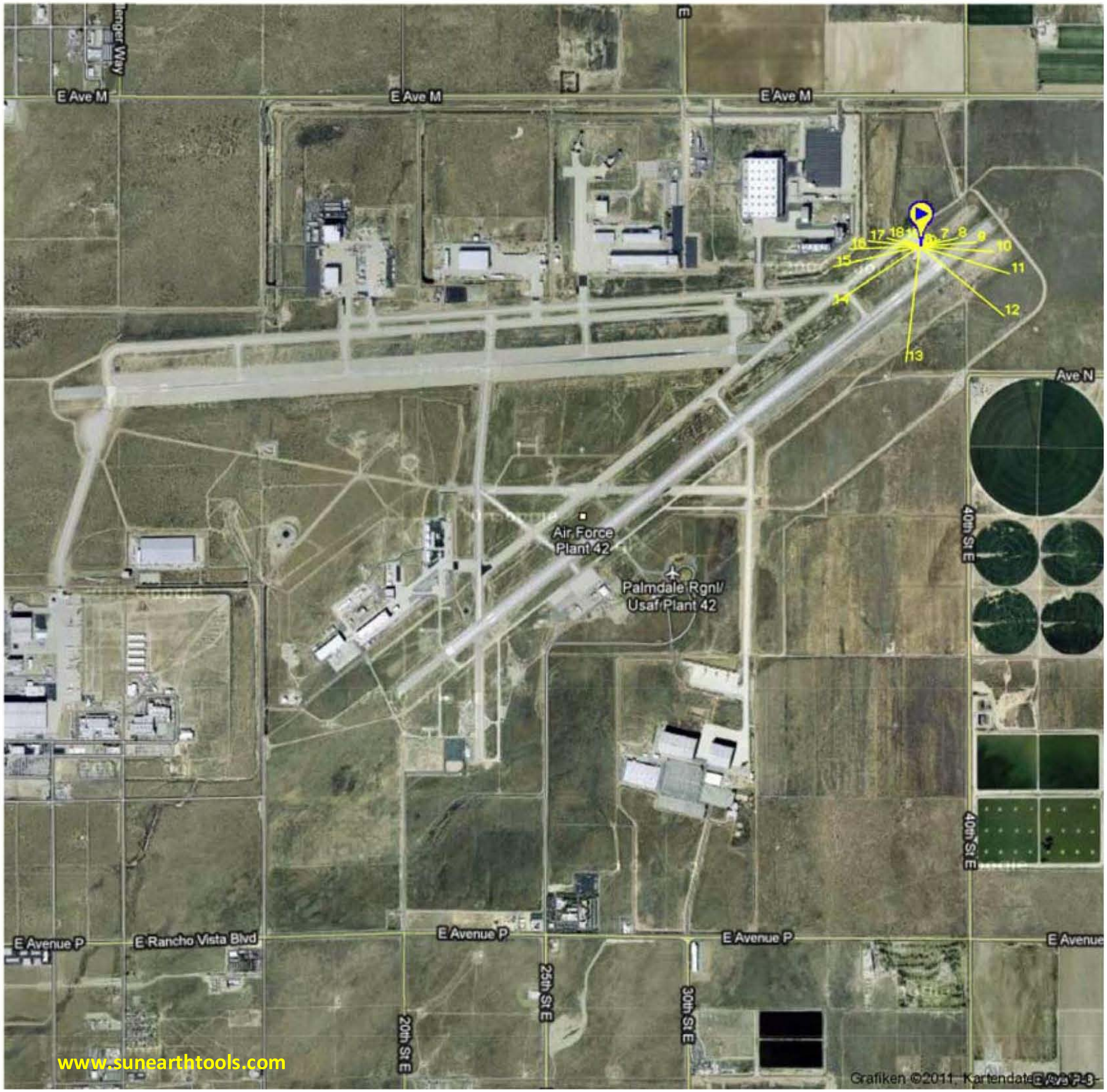
True headings back to Palmdale from the URD decision point are:

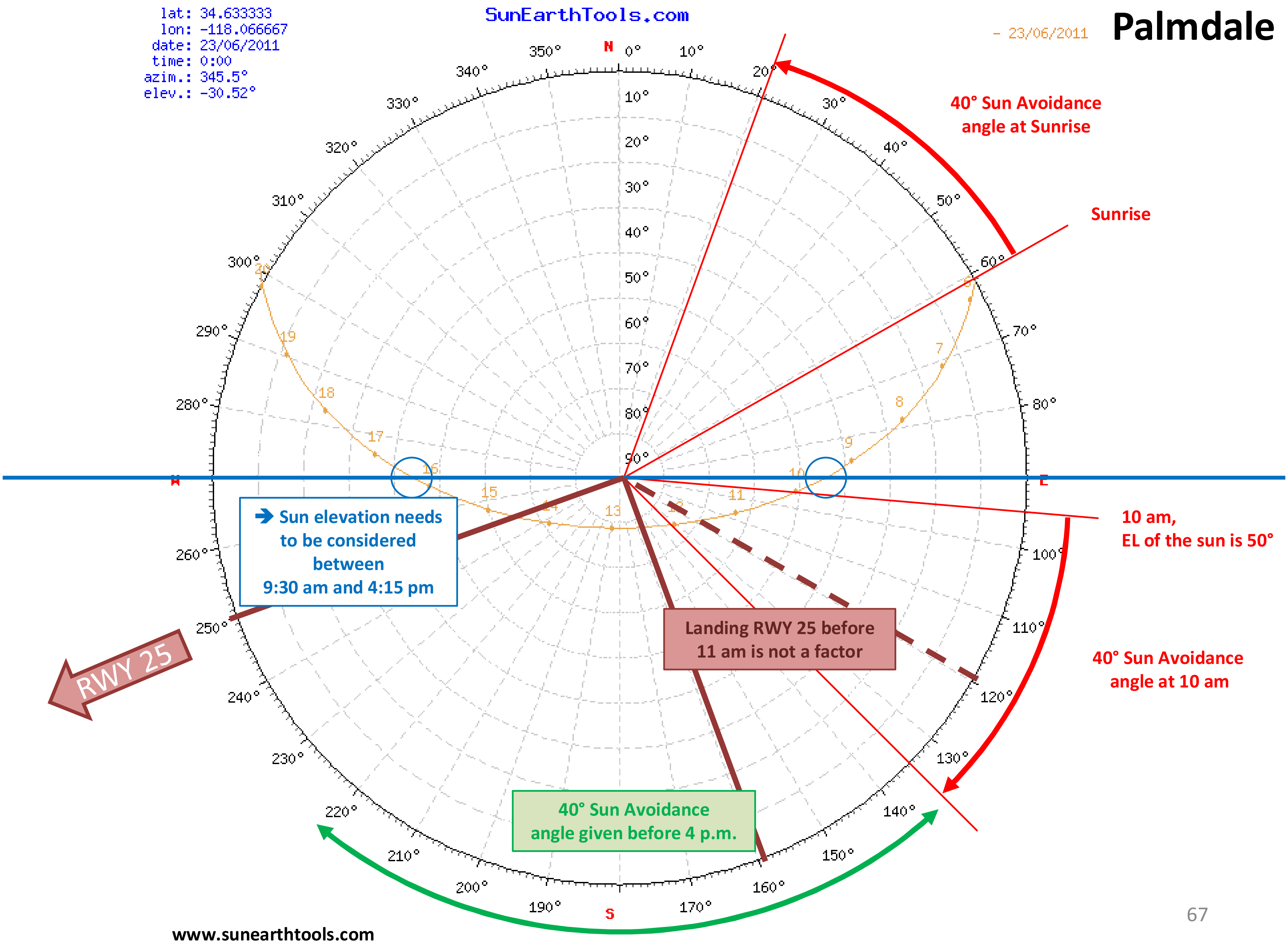
a) default flight plan 23° to 26°

b) alternative flight plan 28° to 32°

➔ No in-flight concern with catching sunlight, because TA is facing north-west

Palmdale

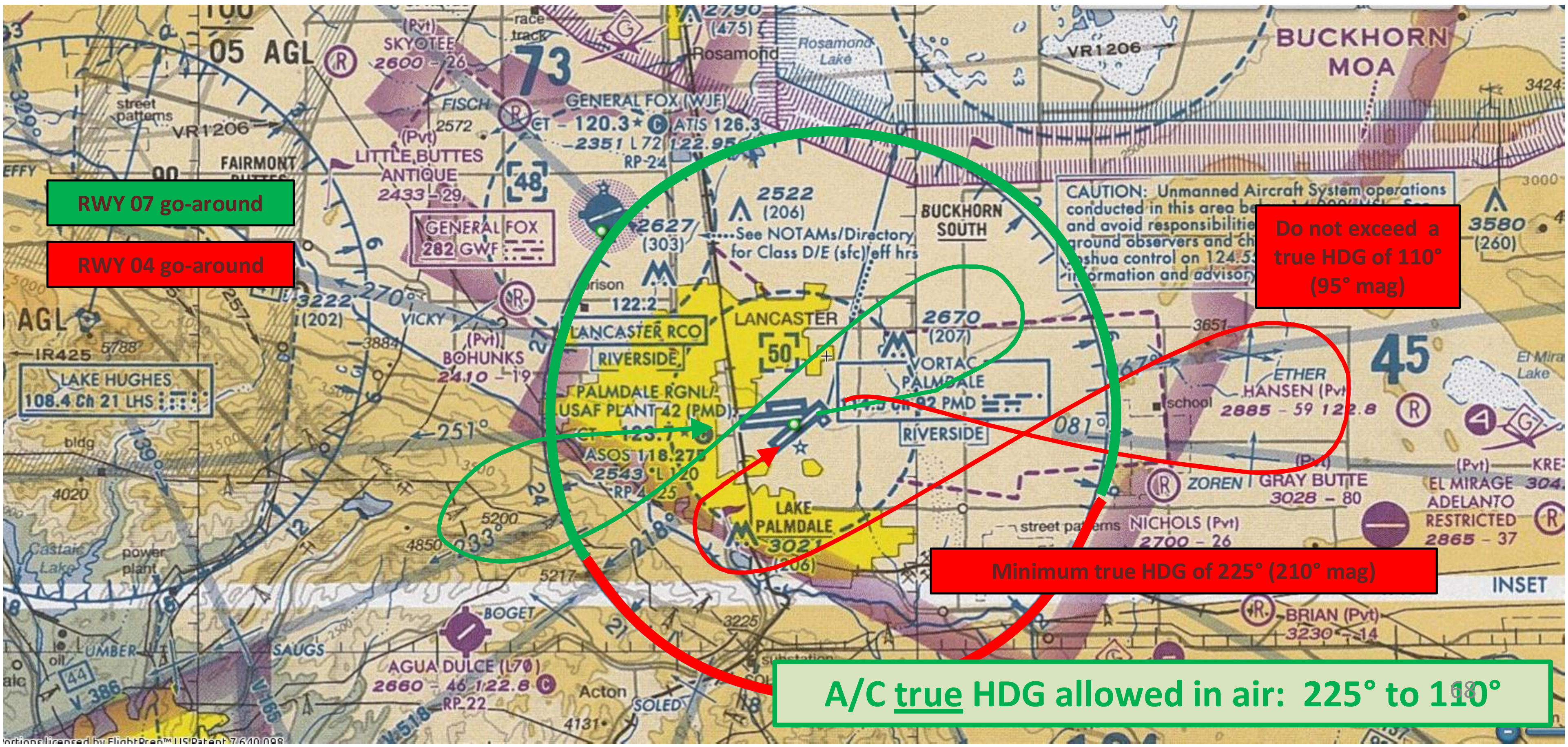

E Ave M
E Ave M
E Ave M
Ave N
40th St E
40th St E
Air Force Plant 42
Palmdale Rgnl/ Usaf Plant 42
E Avenue P
E Rancho Vista Blvd
E Avenue P
E Avenue P
20th St E
25th St E
30th St E
www.sunearthtools.com
Grafiken ©2011

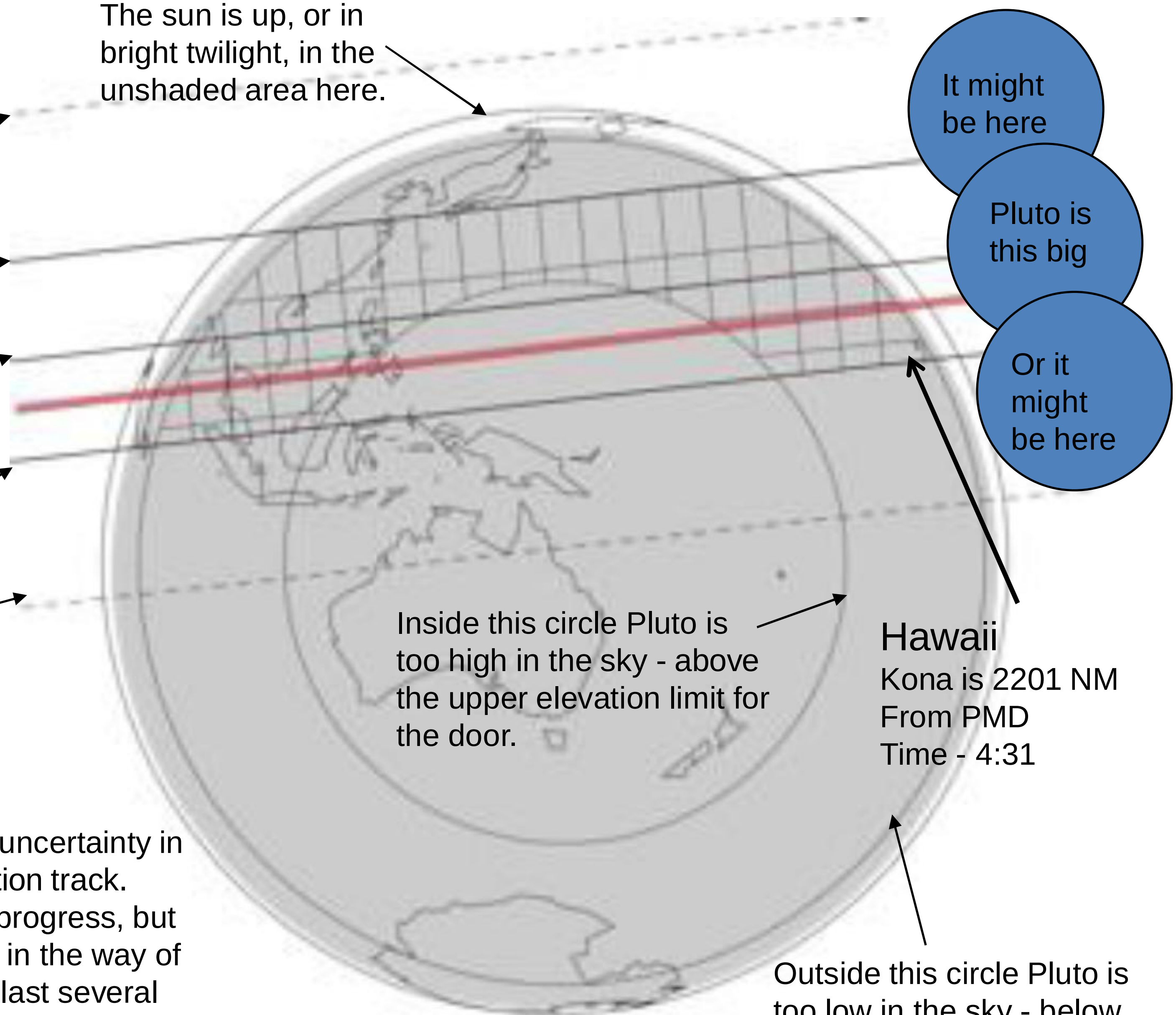


Palmdale
lat: 34.633333
lon: -118.066667
date: 23/06/2011
time: 0:00
azim.: 345.5°
elev.: -30.52°
SunEarthTools.com
- 23/06/2011
40° Sun Avoidance
angle at Sunrise
Sunrise
10 am,
EL of the sun is 50°
40° Sun Avoidance
angle at 10 am
Sun elevation needs
to be considered
between
9:30 am and 4:15 pm
Landing RWY 25 before
11 am is not a factor
40° Sun Avoidance
angle given before 4 p.m.
RWY 25
www.sunearthtools.com

Pilot's in-flight short reference card (6)

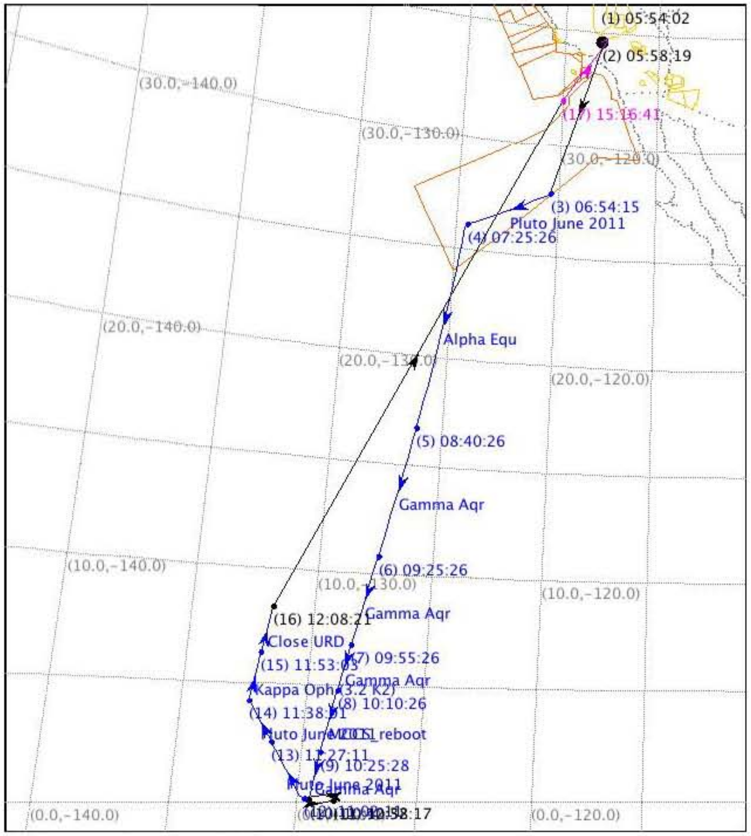
In case of a Go-around in PMD only a 'figure 8' pattern is possible to reposition to a suitable runway



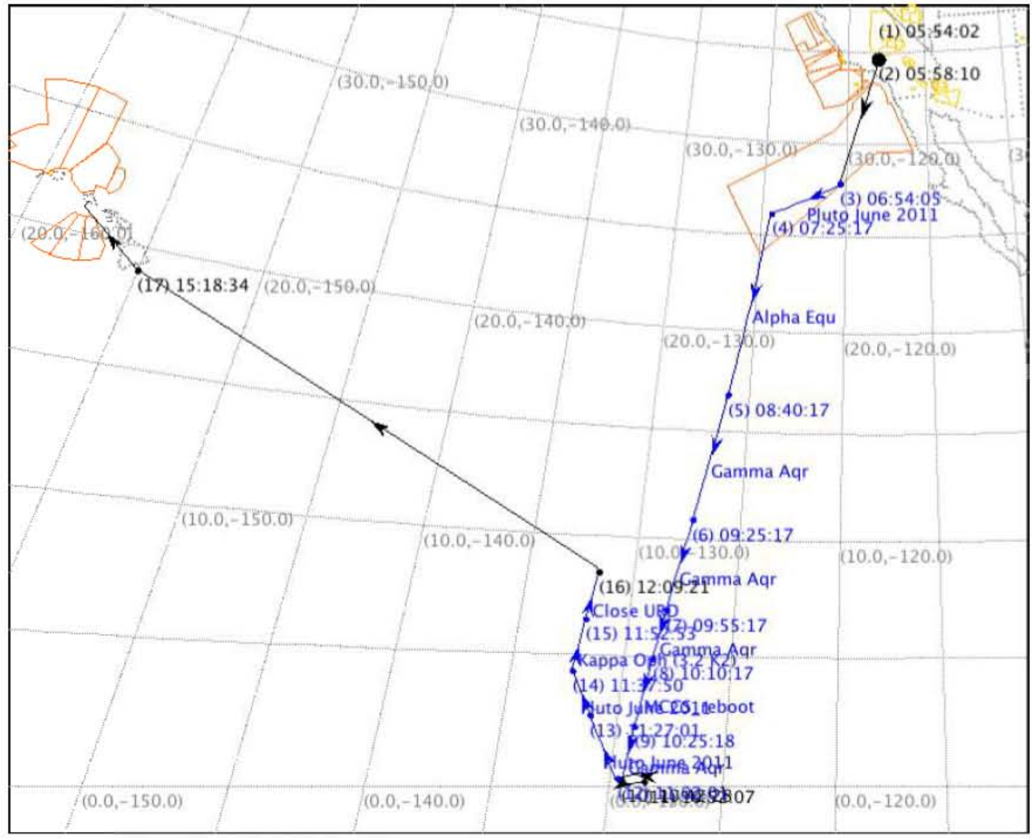


There is still considerable uncertainty in the location of the occultation track. Work to improve this is in progress, but just started. The Sun was in the way of Pluto observations for the last several months and we could only start this work a couple of weeks ago.

Latest default version of the flightplan for 06/23/2011



Flight Plan Name: File: SCAI_2_DAOFrtn.fp
Flight ID: 2011/06/23
Est. Takeoff Time: 2011-Jun-23 05:54 UTC
Est. Landing Time: 2011-Jun-23 15:46 UTC
Flight Duration: 09:52
Weather Forecast : 0000 Sun Jun 19 2011 - 1200 Tue Jun 21 2011 UTC
Saved: 2011-Jun-19 07:17 UTC User: ameyer

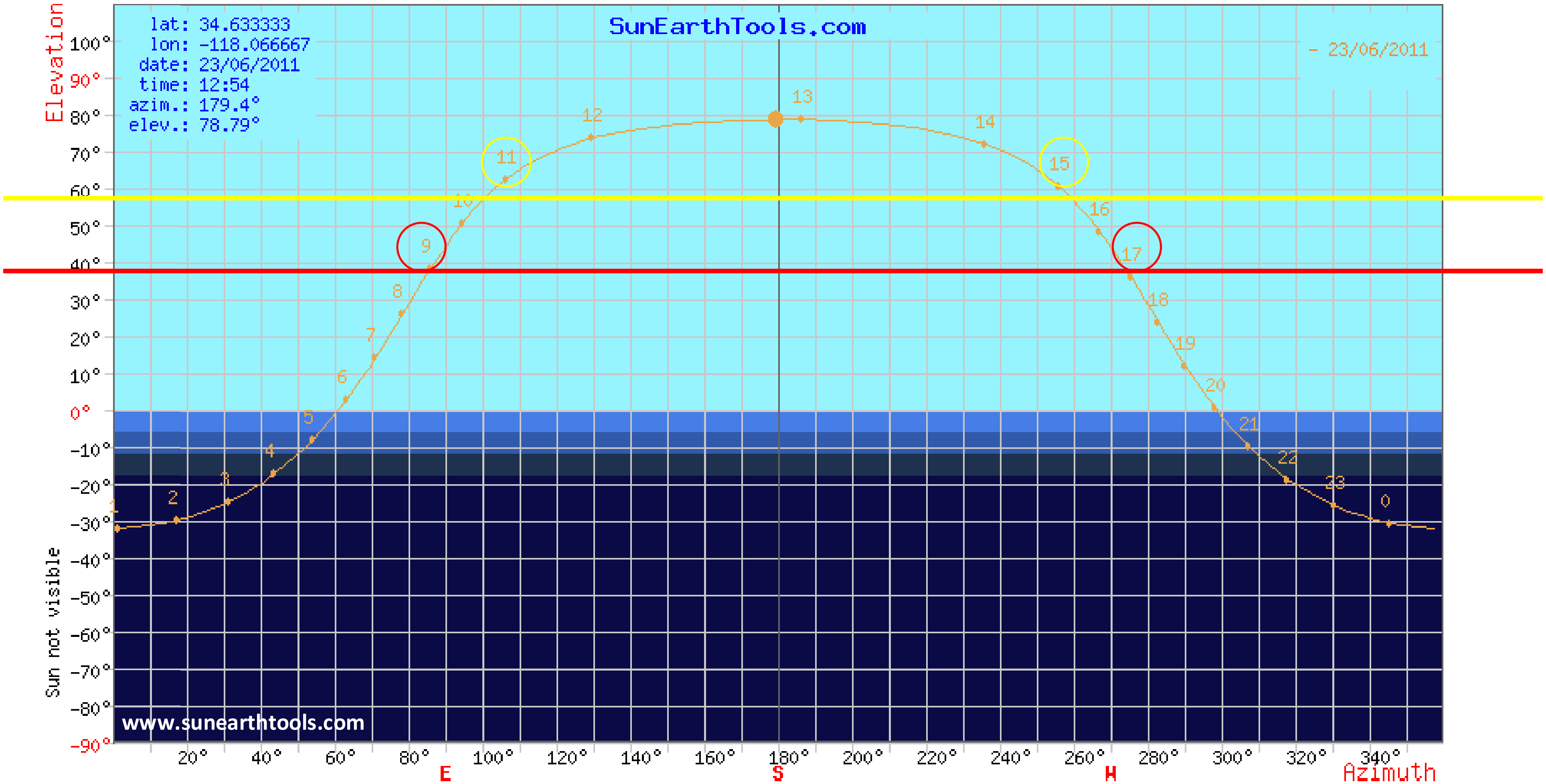


Flight Plan Name: File: SAI2_PHIK_divert.fp
Flight ID: 2011/06/23
Est. Takeoff Time: 2011-Jun-23 05:54 UTC
Est. Landing Time: 2011-Jun-23 15:50 UTC
Flight Duration: 09:56
Weather Forecast : 0000 Sun Jun 19 2011 - 1200 Tue Jun 21 2011 UTC
Saved: 2011-Jun-19 06:10 UTC User: ameyer

➔ In case of an open URD event: landing in HIK is approx. at sunrise

Palmdale

Assuming that CD Dampers will be removed a.s.a.p. after landing and TA will be rotated to 0°:
→ Sun Avoidance Angle in elevation will be 0° + 40° = 40° (red line)



→ No on ground concern with catching sunlight elevationwise between 9 am and 5 pm
→ Even with TA in lowest elevation without removing CD Dampers EL=17° (yellow line) the morning hours 9-11 am are not a concern, because TA is facing west (SOFIA's true heading while parking needs to be 0° +/- 20°

There are different options to reach U as final position for engine shut down in PMD:

- straight in approach RWY 07
- straight in approach RWY 04
- before 11 a.m. only: left pattern to RWY 25, taxiing B, A, E

There are different options to reach DFRC as final position for engine shut down in EDW:

- straight in approach RWY 04, taxiing B or C, F, E
- before 9 a.m. only: left pattern to RWY 22, taxiing B or A, E, F

Pilot's in-flight short reference card (1)

True HDGs back to Palmdale from the URD decision point are between 023° and 032°

→ No enroute concern with catching sunlight, because TA is facing northwest

→ **Whatever TA elevation, aircraft *TRUE* headings verboten in air or on ground are between 110°T and 225°T (general statement valid before 18 UTC = 11 PDT)**

or in other words:

→ **True headings allowed in air or on ground are between 226° and 109° (general statement valid before 18 UTC = 11 PDT)**

SUN AVOIDANCE overrules other Open Door Mission Rules to prevent condensation on TA optics/electronics like gradual descent or mirror warm-up holds.

Pilot's in-flight short reference card (2)

Flight Crew should declare an In-Flight-Emergency
when back in <u>VHF Air Traffic Control range</u>, because of limited HDG range
(inability of flying all HDGs, e.g. holding patterns or 360s impossible)

<u>PMD:</u> (max. SOFIA tailwind component is 10 kts)

There are 3 different options to reach <u>Taxiway U as final position</u> for engine shut down:

- straight in approach RWY 07, taxi to taxiway U, **<u>park aircraft with 080° true heading</u>**
  (preferred – easy taxi and easiest go-around)

- straight in approach RWY 04, taxi via E to U, **<u>park aircraft with 080° true heading</u>**
  (second – easy taxi but longer go-around)

- <u>before **11 a.m.** only:</u> two ~90° left turns allowed,
  1) left turn into left base to final RWY 25 (= 265° true HDG)
  2) left turn into final RWY 25,
  taxiing via B, A, E to U,
  <u>park aircraft with 080° true heading</u>

Pilot's in-flight short reference card (3)

In case of a Go-around in PMD, consider a diversion to EDW
(depending on local time, RWY 22 in EDW is only an option before 10 am PDT)

EDW: (max. SOFIA tailwind component is 10 kts)

There are two options to reach DFRC as final position for engine shut down:

- straight in approach RWY 04, taxiing B or C, F, E to DFRC
  park aircraft with 80° true heading

- before **10 a.m.** only: two ~90° left turns allowed,
  1) left turn into left base to final RWY 22 (= 237° true HDG)
  2) left turn into final RWY 22,
  taxiing via B or A, F, E to DFRC
  park aircraft with 80° true heading

Pilot's in-flight short reference card (4)

In case of a Go-around in PMD, <u>consider</u> a diversion to EDW
(depending on local time, RWY 22 in EDW is only an option before 10 am PDT)

If go-around in PMD was RWY 04 or RWY 07:
RWY 22 in EDW is recommended due to timing issues (see map next slide)

- before **10 a.m.** only: two ~90° left turns allowed,
  1) left turn into left base to final RWY 22 (= 237° true HDG)
  2) left turn into final RWY 22,
  taxiing via B or A, F, E to DFRC
  park aircraft with 80° true heading