‘Fliegen Sie das Teleskop’

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?

Mauna Kea

SOFIA
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 - 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
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
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
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

Cavity Aft Bulkhead SPL vs. Mach

- 7% Theo. - 15 kft
- 7% Theo. - 25 kft
- 7% Theo. - 35 kft

SPL (dB)

Mach

SPL = Sound Pressure Level
Predicted Airplane S&C

Elevator Effectiveness

-0.02
-0.016
-0.012
-0.008
-0.004
0

Mach number

0.4
0.5
0.6
0.7
0.8
0.9
1

15k ft
25k ft
35k ft
40k ft

Closed
Open, 20 deg
Open, 40 deg
Open, 60 deg
Predicted Airplane S&C

Rudder Effectiveness

- closed
- open, 20 deg
- open, 40 deg
- open, 60 deg

Mach number

Cn[dr (1/deg)

15k ft
25k ft
35k ft
40k ft
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
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
Setting the Stage

- **OBJECTIVE:** 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

- **PROGRAM GOAL:** 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

\[ V_{DF}/M_{DF} = \text{Maximum demonstrated flight dive speed} \]
\[ V_{FC}/M_{FC} = \text{Maximum airspeed for stability characteristics} \]
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

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

FADS = Flush Air Data Sensing
# Initial Test Point Count

<table>
<thead>
<tr>
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<th>Planned</th>
<th>% Pts</th>
</tr>
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<tr>
<td>AERO</td>
<td>1474</td>
<td>48%</td>
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<tr>
<td>AERO/S&amp;C</td>
<td>1314</td>
<td>43%</td>
</tr>
<tr>
<td>Total Aero/S&amp;C</td>
<td>2788</td>
<td>91%</td>
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<tr>
<td>S&amp;C</td>
<td>44</td>
<td>1%</td>
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<tr>
<td>CDDS</td>
<td>2</td>
<td>0.1%</td>
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<tr>
<td>Ops</td>
<td>4</td>
<td>0.1%</td>
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<tr>
<td>Science</td>
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<tr>
<td>Static Structures</td>
<td>5</td>
<td>0.2%</td>
</tr>
<tr>
<td>Struct Dynamics</td>
<td>202</td>
<td>7%</td>
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<tr>
<td>TA</td>
<td>15</td>
<td>0.5%</td>
</tr>
<tr>
<td><strong>Test Points</strong></td>
<td><strong>3067</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>
Initial Open Door Test Conditions

**Altitude (Ft. MSL)**

- 50,000
- 45,000
- 40,000
- 35,000
- 30,000
- 25,000
- 20,000
- 15,000

**Airspeed (KCAS)**

- 75 psf
- 100 psf
- 125 psf
- 150 psf
- 175 psf
- 200 psf
- 225 psf
- 250 psf
- 275 psf
- 300 psf
- 325 psf
- 350 psf
- 375 psf
- 400 psf
- 425 psf
- 450 psf

**Initial Open Door Test Conditions**

- Min Altitude
- Short Science Min Altitude

**V\textsubscript{DF}/M\textsubscript{DF} = maximum demonstrated flight dive speed**

**V\textsubscript{IC}/M\textsubscript{IC} = 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
Reduced Airspeed Envelope

- Includes misaligned TA
- \( M_{\text{Mo}} 0.87 \text{ Mach} \)
- \( \text{TA/AA 23° and URD 100\%} \)
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 best-case technical results, and validate with flight test
  – 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

Altitude (Ft. MSL)

45,000
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0

Airspeed (KCAS)

100 150 200 250 300 350 400

MLE/VLE 0.82M/320 KCAS
MMO/VMO 0.87M/320 KCAS
MFC/VFC 0.90M/340 KCAS
MDF/VDF 0.92M/350 KCAS

Short Science Min Altitude

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

Cavity Aft Bulkhead SPL vs. Mach

- Actual - 15 kft
- 7% Theo. - 15 kft
- Actual - 25 kft
- 7% Theo. - 25 kft
- Actual - 35 kft
- 7% Theo. - 35 kft

SPL = Sound Pressure Level
Cavity Acoustics

Normalized $P_{\text{rms}}$ vs. Mach

- Cavity Aft Bulkhead
- 7% Wind Tunnel

Normalized $P_{\text{rms}}/\text{qbar}$ vs. Mach
Longitudinal Control

Elevator Effectiveness

Mach number

Cm_{de}
Directional Control

Rudder Effectiveness

![Graph showing Rudder Effectiveness vs Mach number with different symbols for URD and AA at various percentages.](chart.png)
• G-overshoots during Wind-up turns
• Steady-heading-sideslips at low speed
• Door open landings
First 100% Door Open

Dryden Flight Research Center

SOFIA 747SP
SOFIA 747SP open door flight fully exposes infrared telescope for the first time
December 18, 2009
## Final Score

<table>
<thead>
<tr>
<th></th>
<th>Planned</th>
<th>% Pts</th>
<th>Flown</th>
<th>Saved</th>
<th>% Redux</th>
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<tbody>
<tr>
<td>AERO</td>
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<td>48%</td>
<td>478</td>
<td>996</td>
<td>68%</td>
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<tr>
<td>AERO/S&amp;CO</td>
<td>1314</td>
<td>43%</td>
<td>309</td>
<td>1005</td>
<td>76%</td>
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<tr>
<td><strong>Total Aero</strong></td>
<td>2788</td>
<td>91%</td>
<td>787</td>
<td>2001</td>
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<tr>
<td>S&amp;CO</td>
<td>44</td>
<td>1%</td>
<td>31</td>
<td>13</td>
<td>30%</td>
</tr>
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<td>CDDS</td>
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<td>202</td>
<td>7%</td>
<td>16</td>
<td>186</td>
<td>92%</td>
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<td>TA</td>
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<td>0.5%</td>
<td>14</td>
<td>1</td>
<td>7%</td>
</tr>
<tr>
<td><strong>Test Points</strong></td>
<td>3067</td>
<td>100%</td>
<td>865</td>
<td>2202</td>
<td>72%</td>
</tr>
</tbody>
</table>
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.
“First Light” Image of Jupiter

May, 2010

Visible light image

SOFIA infrared image (5.4, 24, and 37 μm)
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
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
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
Mach 0.60, 27,000 ft, alpha = 2°, 20° door position
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

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

Heart of Orion Nebula

Planetary Nebula M2-9

The last exhalations of a dying star

W40

Mid-infrared image of the W40 star-forming region of the Milky Way captured by FORCAST
NASA / FORCAST image, May 18, 2011

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
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

Sunrise

10 am, EL of the sun is 50°

40° Sun Avoidance angle at Sunrise

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.
In case of a **Go-around** in PMD only a ‘figure 8’ pattern is possible to reposition to a suitable runway

**RWY 07 go-around**

**RWY 04 go-around**

Do not exceed a true HDG of 110° (95° mag)

Minimum true HDG of 225° (210° mag)

A/C true HDG allowed in air: 225° to 110°
Current best estimate of shadow centerline

1-sigma uncertainty position of north edge of Pluto’s shadow

Current best estimate of north edge of Pluto’s shadow

Current best estimate of north edge of Pluto’s shadow

1-sigma uncertainty position of south edge of Pluto’s shadow

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.

The sun is up, or in bright twilight, in the unshaded area here.

It might be here

Pluto is this big

Or it might be here

Inside this circle Pluto is too high in the sky - above the upper elevation limit for the door.

Hawaii
Kona is 2201 NM From PMD
Time - 4:31

Outside this circle Pluto is too low in the sky - below the lower elevation limit for the door.
Latest **default** version of the flightplan for 06/23/2011

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

**PMD:** (max. SOFIA tailwind component is 10 kts)

There are 3 different options to reach **Taxiway U as final position** for engine shut down:

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

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

- **before 11 a.m. only:** 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,
  **park aircraft with 080° true heading**
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, consider 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