Correlation of the SAGE III on ISS Thermal Models to Test and Flight Data

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Agenda

• SAGE III on ISS background
• Approach to Thermal Vacuum (TVAC) Testing and Correlation
• TVAC Correlation Achievements and Lessons Learned
  – Interface Adapter Module TVAC
  – Instrument Assembly TVAC
  – Chamber Characterization
  – Instrument Payload TVAC
  – Summary of lessons learned
• Correlation to Flight Data
• Summary
SAGE III on ISS Background

- Stratospheric Aerosol and Gas Experiment
- Fifth in a series of instruments developed to monitor ozone, aerosols, and other trace gases in Earth’s stratosphere and troposphere
- Partnership between NASA Langley Research Center (LaRC), Thales Alenia Space- Italy (TAS-I), and Ball Aerospace and Technologies Company (BATC)
- Launched to the International Space Station (ISS) via Space X Falcon 9 in February 2017
- Consists of two payloads – Instrument Payload (IP) and Nadir Viewing Platform (NVP)
Instrument Payload (IP)

- Sensor Assembly (SA)
- Hexapod Mechanical Assembly (HMA)
- Contamination Monitoring Package (CMP) 2
- Disturbance Monitoring Package (DMP)
- Hexapod Electronics Unit (HEU)
- Interface Adapter Module (IAM)
- Contamination Monitoring Package (CMP) 1
- Instrument Control Electronics (ICE)
- ExPRESS Payload Adapter (ExPA)
General TVAC Test Approach

• All TVAC test scenarios modeled in Thermal Desktop® (TD) within system flight model
• Primary goals:
  – Evaluate behavior in vacuum at hot and cold conditions
  – Obtain data for model correlation
• Test profiles included these 5 thermal balances:
  – Unpowered hot & cold
  – Heater-only cold
  – Operational hot & cold
• Transient unpowered cool-down with constant environment included in test profile
General Correlation Approach

• Pre-test model predictions used as starting point
• Thermal model correlated to balances and transient power-on and power-off
  – Unpowered cases completed first; fewest variables
• Measurements included flight sensors, test TCs, and subsystem current draw
• Main adjustments made during correlation:
  – Contacts between parts
  – Optical properties
  – Component dissipated power
• Transient analysis performed for better accuracy
• Root-mean-square (RMS) errors calculated over entire timeline, all sensors
• Goal for model correlation: RMS error < 5°C
Interface Adapter Module (IAM) TVAC

- New build, flight computer and power distribution unit
- MLI on back, silver Teflon all other sides
- Operational and survival heaters controlled via mechanical thermostats
- Tightly-coupled to chamber interface plate in flight-like configuration using thermal epoxy
- Primary adjustments made in correlation:
  - Power dissipation
  - Conductors from boards to chassis, chassis to adapter plate
IAM Correlation Quality

- Overall RMS error is less than 2°C - indicates excellent correlation

<table>
<thead>
<tr>
<th>Steady-State Results</th>
<th>Hot Unpowered</th>
<th>Hot Powered</th>
<th>Cold Unpowered</th>
<th>Cold Powered</th>
<th>Overall RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall RMS error (°C)</td>
<td>1.7</td>
<td>1.1</td>
<td>1.0</td>
<td>3.1</td>
<td>1.9</td>
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<tr>
<td>Flight sensor RMS error (°C)</td>
<td>0.9</td>
<td>1.1</td>
<td>0.7</td>
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<td>2.0</td>
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<td>Avg error (°C)</td>
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<td>0.4</td>
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<tr>
<th>Transient Results</th>
<th>Hot Cooldown</th>
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<tr>
<td>Overall RMS error (°C)</td>
<td>1.1</td>
</tr>
<tr>
<td>Flight sensor RMS error (°C)</td>
<td>1.2</td>
</tr>
<tr>
<td>Avg error (°C)</td>
<td>0.1</td>
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</tbody>
</table>
IAM Correlation Plots

Hot Powered Steady-State

4-hr Cool-Down Transient
IAM TVAC Correlation Lessons Learned

• Test TCs should be attached with high-conductivity tape to minimize error if TC bead lifts off surface
• Mock payload interfaces should be as flight-like as possible for subsystem-level TVAC
  – Surface characteristics (roughness, finish, etc.)
  – Fastener torque specifications
  – More temperature sensors typically available to characterize interface
Instrument Assembly (IA) TVAC

• Consists of the Sensor Assembly (SA) and Instrument Control Electronics (ICE)
  – Hardware built in late 1990’s

• IA contains heaters, rotating azimuth motor, rotating scan mirror, thermo-electric cooler (TEC)

• Exterior surfaces mainly silver-Teflon

• Conductive interfaces designed to be flight-like

• Quartz lamps used for heating (6 zones)

• Primary adjustment made in correlation
  – Contact between parts
IA Correlation Quality

• Overall RMS error for flight sensors less than 1.5°C - indicates excellent correlation
• Main adjustments were to contacts

<table>
<thead>
<tr>
<th>Balance Results</th>
<th>Hot Unpowered</th>
<th>Hot Powered</th>
<th>Cold Unpowered</th>
<th>Cold Heater-only</th>
<th>Cold Powered</th>
<th>Overall Average</th>
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<tbody>
<tr>
<td>Overall RMS error (°C)</td>
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<td>2.8</td>
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<td>1</td>
<td>1.8</td>
<td>1.4</td>
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<td>Avg error (°C)</td>
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<td>0.3</td>
<td>1.1</td>
<td>0.6</td>
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<th>Cold Powerup</th>
<th>Cold Heater Powerup</th>
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<td>Overall RMS error (°C)</td>
<td>1.4</td>
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<td>2.8</td>
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<td>1.4</td>
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<td>0.9</td>
<td>1.3</td>
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<td>Avg error (°C)</td>
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<td>0.1</td>
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<td>0.8</td>
<td>-0.7</td>
<td>0.3</td>
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</table>
IA Correlation Plots

Cold power-on transient

Azimuth heater operation
IA TVAC Correlation Lessons Learned

- Correlation of heater operation to heater-only balance worked well
- Unpowered cool-downs helpful in thermal mass correlation
- Transient cases provide more accurate prediction of behavior, even for quasi-steady-state
- Correlation of TEC behavior
  - Required modification of TEC parameters due to degradation
  - Test data when TEC data went out of the control range valuable
- Chamber shroud had larger gradients than expected, should be well-instrumented
- Issues with quartz lamps led to facility characterization test to perform IA model correlation
  - Fraction of infrared (IR) vs. solar
  - No power measurement
• Heater plate system designed for payload-level test
  – Avoids quartz lamps
  – Allows for independent control of subsystems
• Test to characterize heater plate system
  – Verify capability to achieve target temperatures
  – Determine heater plate gradients
  – Correlate thermal model of chamber
• Test paused to remove MLI from two plates to achieve goal temperatures; repeated test conditions
• Primary correlation adjustments:
  – MLI
  – Plate emissivity
  – Contact between plates and frame
  – Mesh on plates
Characterization Correlation Quality

- Overall RMS error for final configuration below 5°C - indicates good correlation
  - Errors higher in original configuration due to using standard TD modeling method for MLI covering surfaces at different temperatures
  - Slight tendency toward over-prediction
- Model accurately tracked response of neighboring plates to heater power changes - gives a high level of confidence in the model

<table>
<thead>
<tr>
<th>Errors on mock payload and ExPA (°C)</th>
<th>RMS error</th>
<th>Hot Survival</th>
<th>Hot Op</th>
<th>Cold Survival</th>
<th>Hot Op 2</th>
<th>Cold Survival 2</th>
<th>Overall Average</th>
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<td></td>
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<td>Average error</td>
<td>4.5</td>
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<td>-1</td>
<td>-1.5</td>
<td>3.1</td>
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<th>Errors on heater plates and frame (°C)</th>
<th>RMS error</th>
<th>Hot Survival</th>
<th>Hot Op</th>
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<th>Hot Op 2</th>
<th>Cold Survival 2</th>
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<td></td>
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<td>3.4</td>
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<td>1.4</td>
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<td>0.9</td>
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</tbody>
</table>
Characterization Correlation Plots

Heater plate cooldown correlation

Neighboring plate reaction to cooldowns
Characterization Lessons Learned

- For MLI covering multiple plates at different temperatures, cannot use Insulation tab on TD surface
  - Insulation must be modeled explicitly to get correct radiative transfer under MLI
- Place temperature sensors to verify basic assumptions, such as thermal contact between parts
- Chamber emissivity lower than assumed at cold conditions
- Plate gradients ~10°C despite even distribution of heaters across aluminum plates
  - Well-predicted following correlation
Instrument Payload (IP) TVAC

- Flight IP and custom heater plate system
- IP contains operational and survival heaters, multi-layer insulation (MLI), silver Teflon, and TECs
- Included orbit simulations for correlation to a flight-like transient motor power profile
- Primary adjustments made in correlation:
  - Contact between trolley and chamber
  - Emissivity
  - MLI effective emissivity
  - Conductance to the ExPA and between parts
Overall IP Correlation Quality

- Facility thermocouple data not included in RMS error calculations due to excessive noise
- Overall RMS error is less than 2.5°C - indicates remarkable correlation for a complex model
  - Slight tendency toward under-prediction

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<th>Cold Unpowered</th>
<th>Hot Powered</th>
<th>Cold Powered</th>
<th>Hot Cooldown</th>
<th>Cold Cooldown</th>
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<tr>
<td><strong>RMS error for flight sensors (°C)</strong></td>
<td>1.1</td>
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<tr>
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<td>-2.3</td>
<td>-1.2</td>
<td><strong>-0.6</strong></td>
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Correlation to operation of elevation motor during science events

Correlation to operation of heater and TEC
Hot unpowered transient correlation

Hot powerup transient correlation
IP Correlation Lessons Learned

• High noise observed in test TCs due to wire routing – check prior to test start

• Balance sequence effective for correlation
  – Unpowered correlation first, quasi-steady-state and then transient
  – Transient for heater power-up
  – Transient to powered operation
  – Powered balance
  – Power-off for cooldown transient

• Accurate power calculations required measured current and resistance

• Run time reduced via modification of TEC power dissipation equation
Flight Correlation

• SAGE III launched on SpaceX CRS-10 mission in February
• Operational on ELC-4 since March 10\textsuperscript{th}
• Beta angle range experienced to-date between $-38^\circ$ and $+73^\circ$
• Primary areas of focus:
  – Worst-case beta angles for hot operations
  – Elevation motor temperature during science events
  – ExPA temperature at high-negative beta
• Major model adjustments:
  – Power
  – Optical properties
  – Conductors between internal instrument parts
Flight Correlation Quality

- Beta 41° worst-case hot case for most components
  - Good matching; overall RMS error is < 3°C
- Beta -38° worst-case hot case for SA (to-date)
  - Good matching for SA
  - ExPA-coupled components under-predicting by up to 12°C

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<thead>
<tr>
<th></th>
<th>β = 73°</th>
<th>β = 50°</th>
<th>β = 41°</th>
<th>β = -24°</th>
<th>β = -38°</th>
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<td>Avg error for</td>
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Flight Correlation Plots

Limb-Scatter Event Correlation
\( (\beta = 41^\circ) \)

Unpowered Correlation
\( (\beta = 45^\circ) \)
ExPA Temp as a Function of Beta Angle

- ExPA under-prediction increases as beta becomes more negative
Conclusions

• Model quality very good: overall TVAC RMS error < 3°C

• Lessons learned: test definition and setup
  – Create test conditions focused on thermal behavior for correlation
  – Quartz lamps solar output can make correlation problematic
  – Characterizing new chamber equipment prior to payload testing is highly beneficial
  – Ensure TCs placed so basic assumptions can be verified
  – Make interfaces as flight like as possible

• Lessons learned: correlation
  – Best practice - proceed from simple to complex; correlate to hot and cold
  – Correlation to transients more reliable than to steady-state
  – Use of single model for flight and ground test scenarios greatly improves efficiency
  – RMS error very effective single measure of model quality

• Correlation, though complex, is worthwhile for flight predicts and finding systemic errors in the model
Acknowledgements

• Thank you to the SAGE III project personnel, and the Systems Integration and Test branch personnel, for support in accomplishing this TVAC testing.