A Review of SAGE III on ISS Flight Thermal Data

Kaitlin Liles, Ruth Amundsen & Warren Davis
NASA Langley Research Center

Presented By
Kaitlin Liles
Agenda

• SAGE III on ISS Overview
• Thermal Design and Analysis Overview
• Comparison of Flight Data to Predictions
• TEC Performance
• Impact of ISS Maneuvers
• Flight Rules and Limits
• Summary
SAGE III on ISS Background

- Stratospheric Aerosol and Gas Experiment, 5th in series of instruments to monitor ozone, aerosols, and other trace gases in stratosphere and troposphere
- Partnership between NASA LaRC, Thales Alenia Space- Italy (TAS-I), and Ball Aerospace and Technologies Company (BATC)
- Instrument Payload (IP) and Nadir Viewing Platform (NVP) payloads
- Launched to the International Space Station (ISS) via Space X Falcon 9 on 2/19/17 and began powered operations on 3/10/17
- Commissioning completed in June 2017; currently performing nominal science operations
Instrument Payload

- Sensor Assembly (SA)
- Hexapod Mechanical Assembly (HMA)
- Disturbance Monitoring Package (DMP)
- Contamination Monitoring Package (CMP) 1
- Contamination Monitoring Package (CMP) 2
- Interface Adapter Module (IAM)
- Instrument Control Electronics (ICE)
- Hexapod Electronics Unit (HEU)
- ExPRESS Payload Adapter (ExPA)
On-Orbit Operations: Science Events

Solar Occultation
- 10,328 occultation (solar & lunar) events acquired
  
Limb Scattering
- 4,948 limb events acquired

(7/1/17 - 8/1/18)
Thermal Design Overview

- The IP is thermally controlled via a combination of active and passive design elements
  - Kapton thin-film heaters
  - Thermo-electric coolers (TECs)
  - Multi-layer insulation (MLI) blankets
    - Including small blankets to prevent astronaut finger entrapment
  - Thermal tapes
    - Early concurrence required from ISS due to glint and heat flux constraints
  - Conductive interfaces designed for thermal isolation or to facilitate good thermal contact
    - Challenging at times due to limited space and fixed bolt patterns on the ExPA

- IP temperatures monitored via a total of 98 sensors
  - No payload temperature telemetry available in the Dragon trunk or during transfer to ELC-4
  - Six channels of temperature measurements available via ISS ELC data stream when IP is mounted to ELC-4 and powered off
Thermal Design Lessons Learned Summary

• Full-scale mockups are extremely beneficial when developing flight hardware
  – Especially for MLI blanket development
• Consider thermal constraints early in interface design\(^1\)
  – Fastener pattern, material selection, etc.
• Consider telemetry availability when determining temperature monitoring locations
  – Which subsystems power on first
  – Which items expected to approach limits
• Substantial variation in best practices; apply guidance carefully
  – Heater watt density guidelines
  – Use of aluminum over-tape

\(^1\)Davis, W. T.; Liles, K. A.; and Martin, K. J.: SAGE III Lessons Learned on Thermal Interface Design. Presented at Thermal and Fluids Analysis Workshop, August 3-7, 2015, Silver Spring, Maryland.
Thermal Analysis Overview

- Thermal models created using Thermal Desktop® (TD)
- Development took place over 6 years by team of 9 analysts
- Detailed model integrated with reduced versions of Dragon & ISS
- Integrated model contains all configurations
  - Ground testing (2 TVAC chambers)
  - Transit to ISS
  - Transport from Dragon to ELC-4
  - On-orbit operations at ELC-4
- Reduced model delivered to ISS and SpaceX for inclusion in high-fidelity ISS and Dragon models
- Analysis effort included a total of ~600 cases, with ~90 run routinely to predict temperatures for all mission phases
- IP correlated to test data very well with overall RMS error of 2.4°C

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2Amundsen, R.M.; Davis, W.T.; Liles, K.A.K; McLeod, S.M; Correlation of the SAGE III on ISS Thermal Models to Test and Flight Data, TFAWS-2017-PT-02, Presented at Thermal and Fluids Analysis Workshop, August 21-25, 2017, Huntsville, AL.
Thermal Models

Detailed integrated IP and NVP model
(13,909 nodes)

SAGE III integrated with Dragon

SAGE III integrated with ISS
Overview of Flight Correlation Efforts

• Primarily focused on operational cases:
  – Worst-case beta angles for hot operations
  – Elevation motor temperature during science events

• Major model adjustments:
  – Power
  – Optical properties
  – Conductors between internal instrument parts

• Beta angle range covered by correlation: -38 to +73°
  – ISS experienced this beta angle range during the SAGE III commissioning period
Comparison to Flight Data - Survival

- Comparison between prediction and data following installation at ELC-4 prior to payload activation ($\beta = -14$)
  - Model accurate or under-predicts, conservative in survival case

Solid lines are flight data
Dashed are predicts
Comparison to Flight - Unpowered Cool Down

- Comparison when the payload powered off ~10 hours ($\beta = +45$)
- Model accurate or conservative
- Gives accurate time-to-limit analysis
  - Critical for understanding response to ISS activities
Comparison to Flight Data – Operational

• Most components worst case hot at a beta angle 41°
  – DoE analysis effective in determining worst-case beta
  – Model accurate at worst-case hot beta angle (within ~3°C)

• Transient thermal response during science events (elevation motor) accurate or slight over-predict
  – Elevation motor is the limiting item for duration of science events

• Model overall trend versus beta angle matches flight data well
  – Model under-predicts ExPA temperature with increasing magnitude as beta angle decreases
• Design of Experiments (DoE) analysis was effective in determining the worst-case beta angle for SAGE III
  – Model predicted 47° as worst-case hot; flight data shows that most components reach maximum temperatures at a beta angle of 41° (ISS beta angle range is -75° to +75°)
  – Sensor Assembly reaches maximum temperatures at high negative beta angles due to increased solar flux; model predicted this trend

• Model shows excellent matching at worst-case hot beta angle
  – Overall root-mean-square error for all flight temperature sensors is <3°C
• Accurate modeling of the Sensor Assembly (SA) elevation motor transient thermal response is critical
  – Temperature increases quickly when operating and is the limiting item for ability to perform long-duration science events
• Correlated prediction is accurate and the model can be reliably used to assess flight scenarios

\[(\beta = -24^\circ)\]  
\[(\beta = 50^\circ)\]
Comparison to Flight: Variation with Beta

- Variation over beta angle matched well by model for most components
IAM & ExPA Variation with Beta Angle

- ExPA and ExPA-mounted components: Under-prediction at high beta angles
Beta Variation Potential Issue

- At extreme beta angles, a spike is present on flight data for ExPA that does not occur in predicts.
- Theory is that some real solar intrusion is being shadowed in the model and not captured, thus predicts are low at extreme betas.

Beta 60

Beta -59
TEC Performance

- TEC uses low/high setpoint logic
  - If cannot hold at low temp, it flips to high
- In flight, original TEC setting worked at beta 50, but as beta went negative, TEC started to flip to high setpoint
- Model was correlated for warmer TEC hot side, but did not flip at negative beta, partly due to ExPA underpredict
- Artificial 100 W added to ExPA at high betas, yielding flight flip behavior
- Allowed new set point to be selected which would not cause flipping
TEC Performance

• Initial set point resulted in CCD TEC temperature instability
  – Increased complexity of science data processing
• CCD thermal stability achieved following TEC setpoint change
  – TEC behavior extremely stable after set point change

CCD TEC setpoint changed from Low +12C/High14C to Low +12.5C/High 13.5C
Impact of ISS Maneuvers

- Thermal analysis is requested when ISS is planning off-nominal scenarios
- Many ISS activities have a minor (<5°C) impact on SAGE III temperatures
  - Parking of solar arrays & radiators, reboosts, yaw bias maneuvers
- Several major shifts in ISS attitude have occurred since SAGE III was installed; temperature response consistent with predictions
  - -XVV (180° ISS rotation in yaw)
    - Flight rule defined to modify science event duration time in this attitude
  - +ZVV (90° ISS rotation in pitch)
Flight Rules and Limits

- Flight rules were defined during the commissioning phase based on review of thermal data.
- Guidance was provided on science event duration capability vs. beta angle; goal is to avoid reaching yellow limit.
  - Maximum duration limited by elevation motor or Instrument Control Electronics (ICE) temperature, defined in beta angle increments of ~10°.
- Increase in Sensor Assembly (SA) temperature at high negative beta angles led to creation of a rule to power off below $\beta = -70^\circ$.
- Final assessment of thermal limits was performed during commissioning.
  - Minor adjustments made to power-on limits and board-level yellow limits.
  - Hot power-on limits only checked if powered off for >24 hours.
Conclusions

• SAGE III on ISS thermal model very effective in predicting flight behavior
• Variation of payload temperatures over the range of ISS beta angles well-predicted
  – Model may have slight excess ExPA shadowing at high negative betas
• Most ISS activities have negligible impact to SAGE III thermal performance
• Flight rules and thermal limits are appropriate for on-orbit operations
• Slight tweak in TEC set points can eliminate excessive chatter