A Review of SAGE III on ISS Flight Thermal Data

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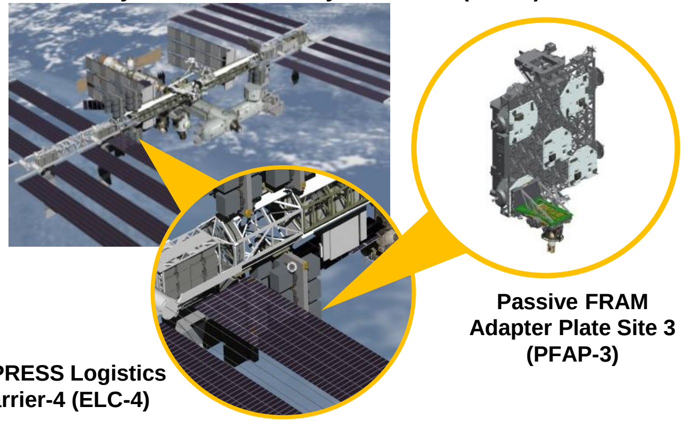
Agenda

- 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

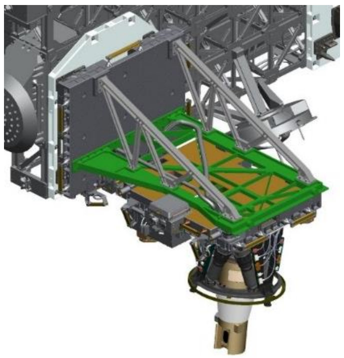
- Stratospheric Aerosol and Gas Experiment, 5th in series of instruments to monitor ozone, aerosols, and other trace gases in stratosphere and troposphere
- Partnership between NASA LaRC, Thales Alenia Space- Italy (TAS-I), and Ball Aerospace and Technologies Company (BATC)
- Instrument Payload (IP) 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

S3 Truss Payload Attachment System-4 Site (PAS-4)



ExPRESS Logistics Carrier-4 (ELC-4)

Passive FRAM Adapter Plate Site 3 (PFAP-3)

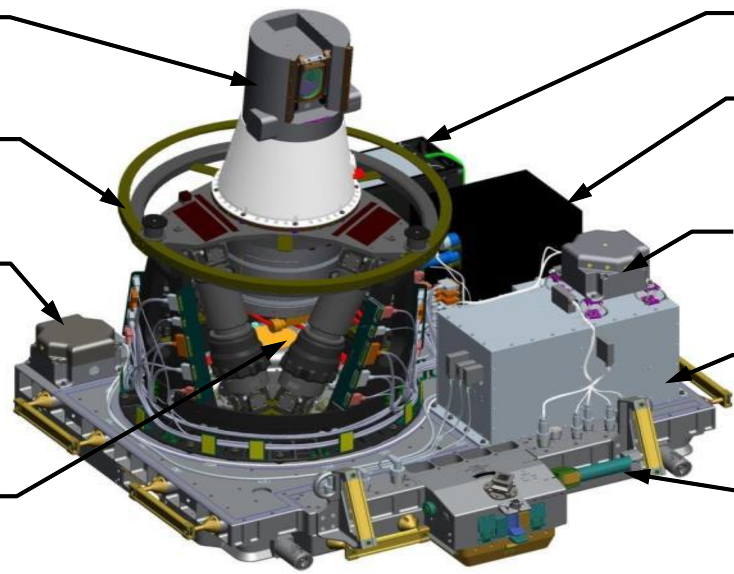


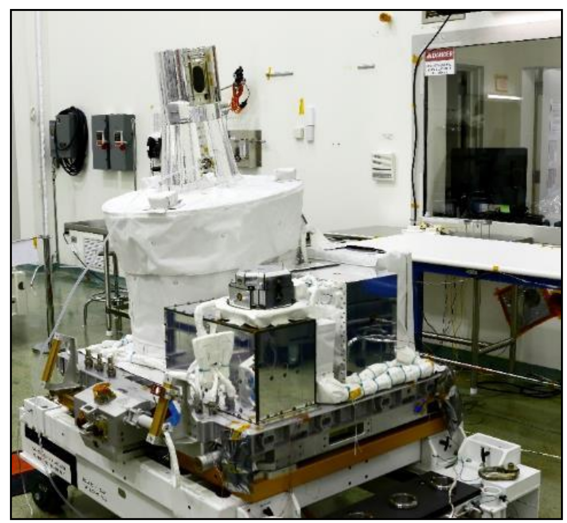
SAGE III On-Orbit Configuration

Payloads in Dragon Trunk (CRS-10)

SAGE III In-Transit to ELC-4

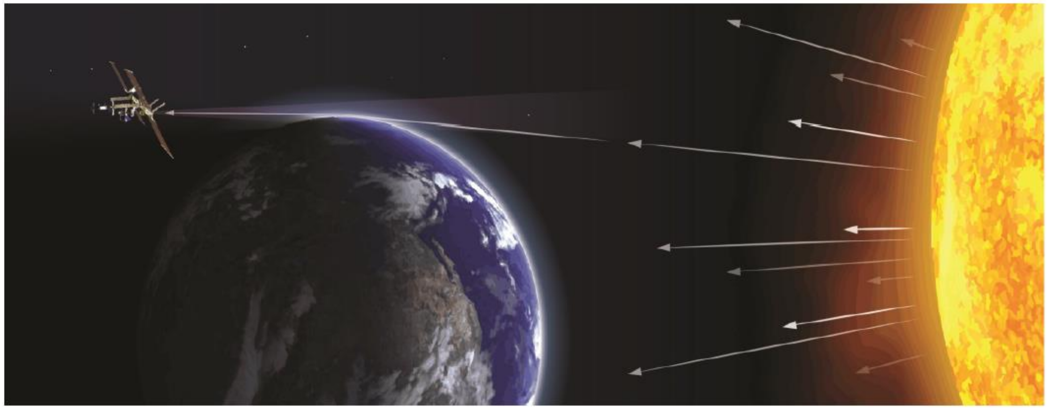
Instrument Payload





On-Orbit Operations: Science Events

Solar Occultation



10,328 occultation (solar & lunar) events acquired (7/1/17 - 8/1/18)

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.

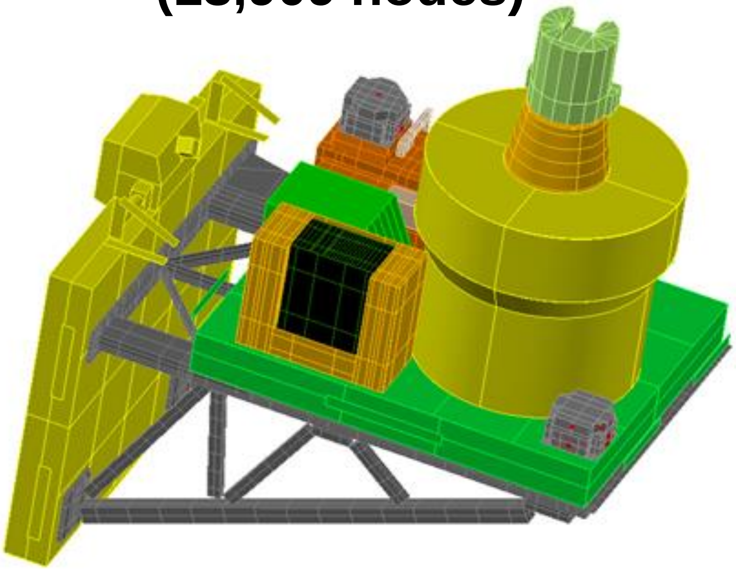
Thermal Analysis Overview

- 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[2]

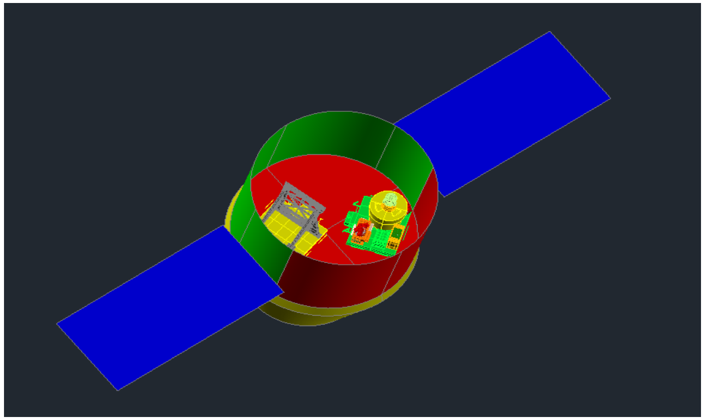
[2]Amundsen, R.M.; Davis, W.T.; Liles, K.A.K; McLeod, S.M; Correlation of the SAGE III on ISS Thermal Models to Test and Flight Data, TFAWS-2017-PT-02, Presented at Thermal and Fluids Analysis Workshop, August 21-25, 2017, Huntsville, AL.

Thermal Models

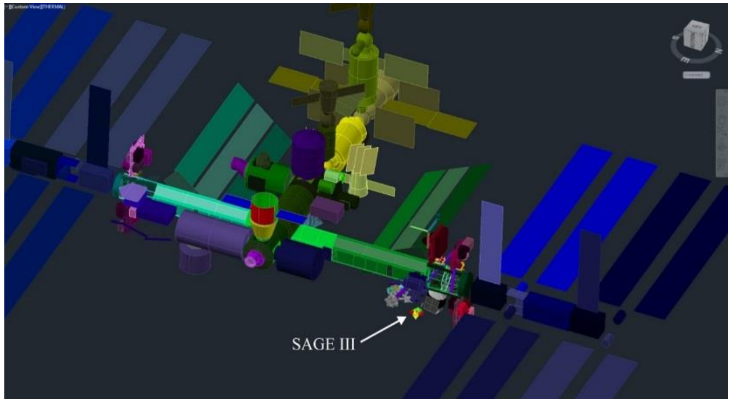
Detailed integrated IP and NVP model (13,909 nodes)



SAGE III integrated with Dragon



SAGE III integrated with ISS

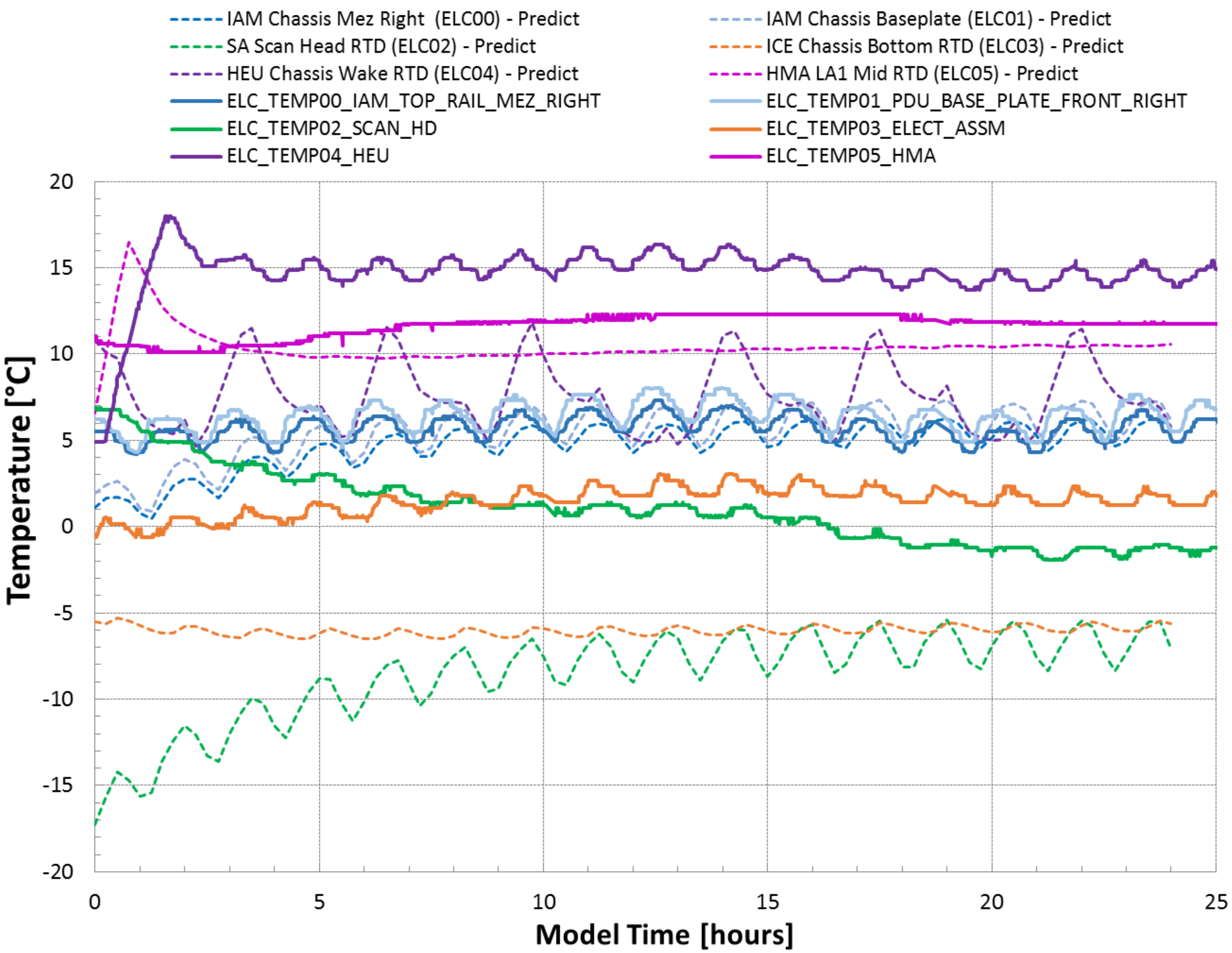


Overview of Flight Correlation Efforts

- 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

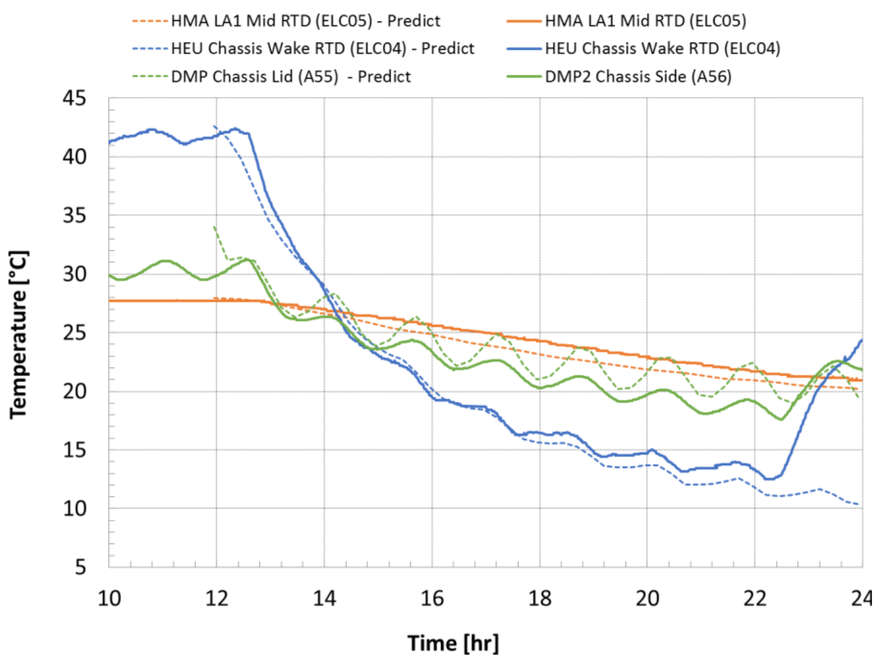
- Comparison between prediction and data following installation at ELC-4 prior to payload activation (β = -14)
  - Model accurate or under-predicts, conservative in survival case

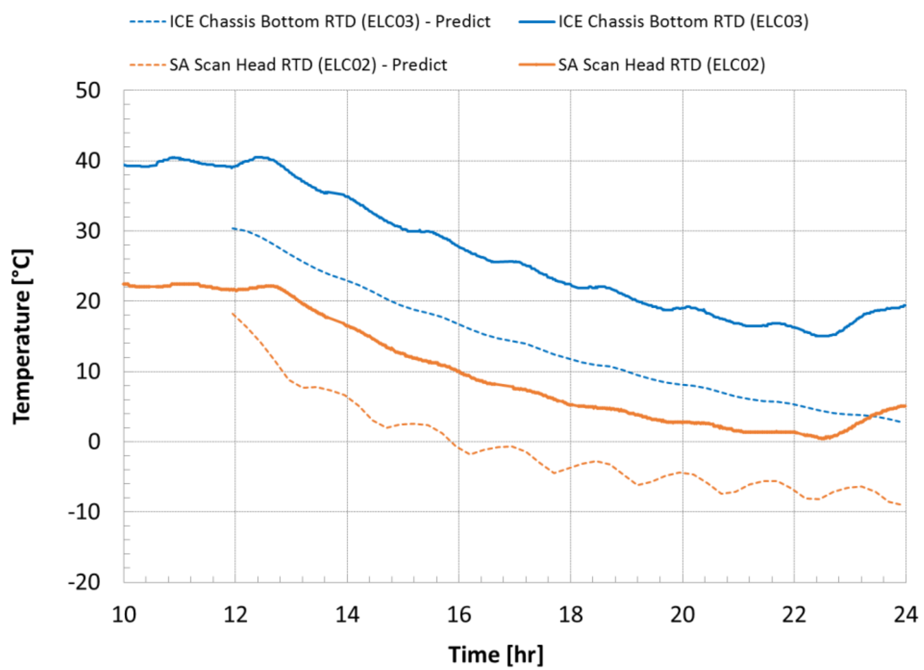


Solid lines are flight data
Dashed are predicts

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



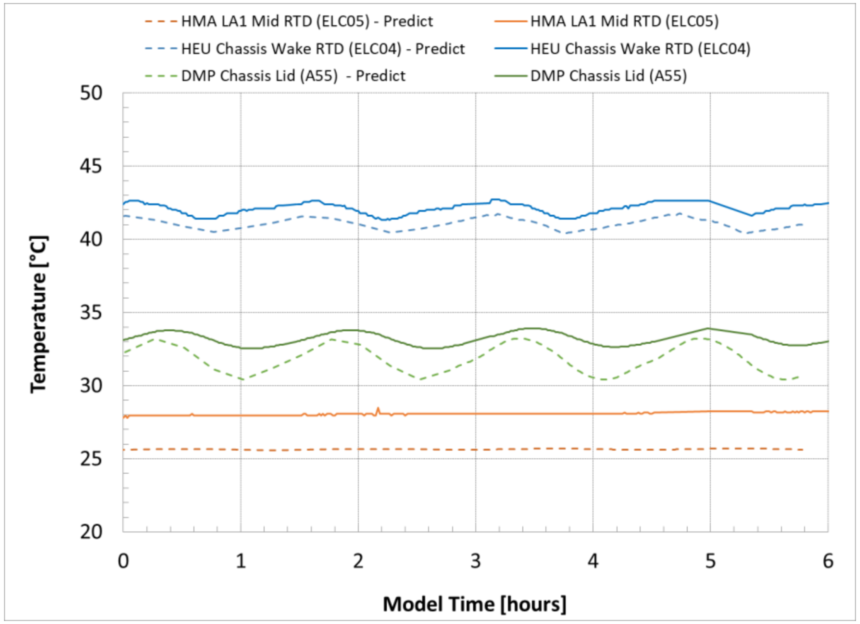


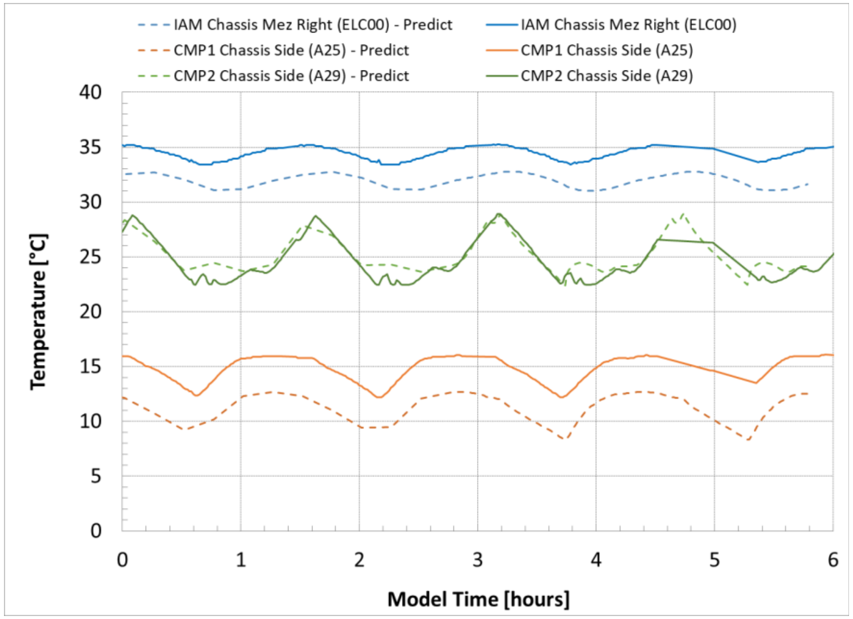
Comparison to Flight Data – Operational

- 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

Comparison to Flight: Worst-Case Hot

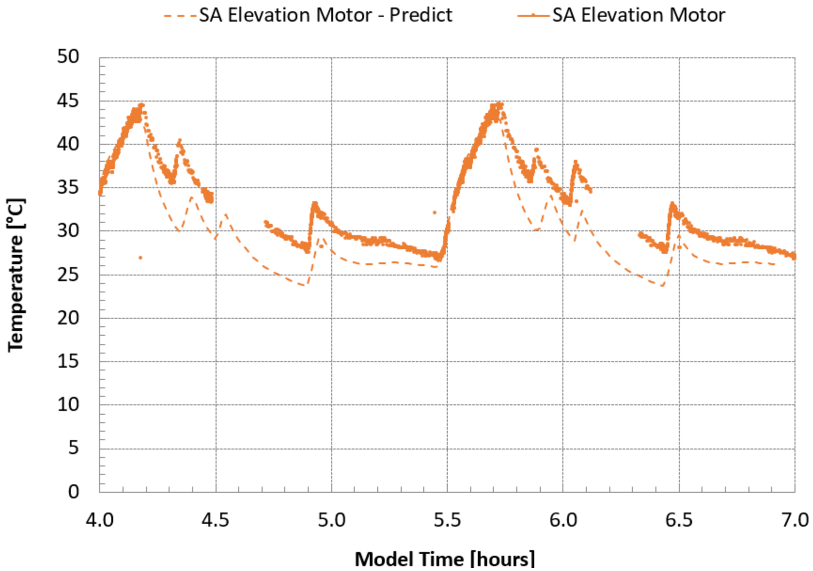
- Design of Experiments (DoE) analysis was effective in determining the worst-case beta angle for SAGE III
  - Model predicted 47° as worst-case hot; flight data shows that most components reach maximum temperatures at a beta angle of 41° (ISS beta angle range is -75° to +75°)
  - Sensor Assembly reaches 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



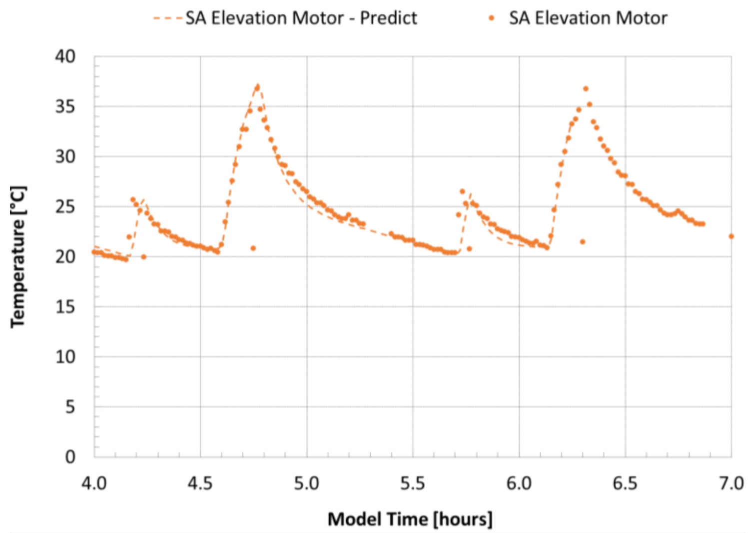


Comparison to Flight: Science Events

- 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

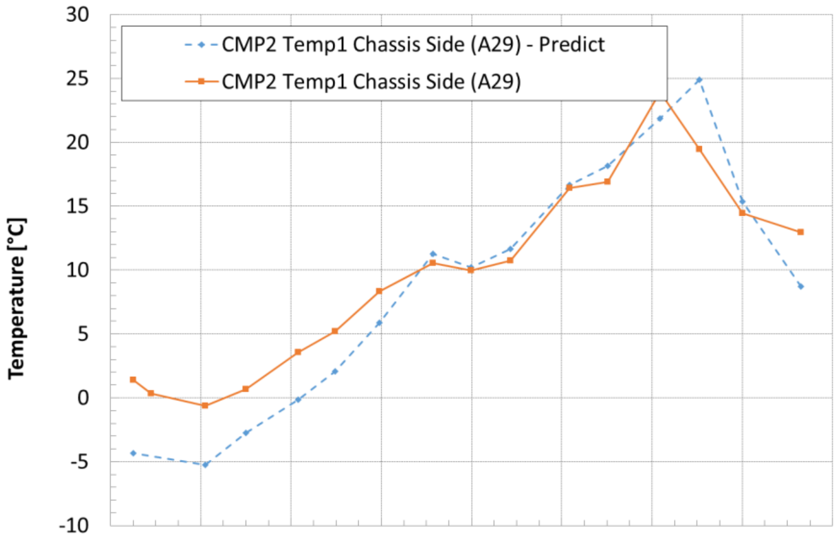


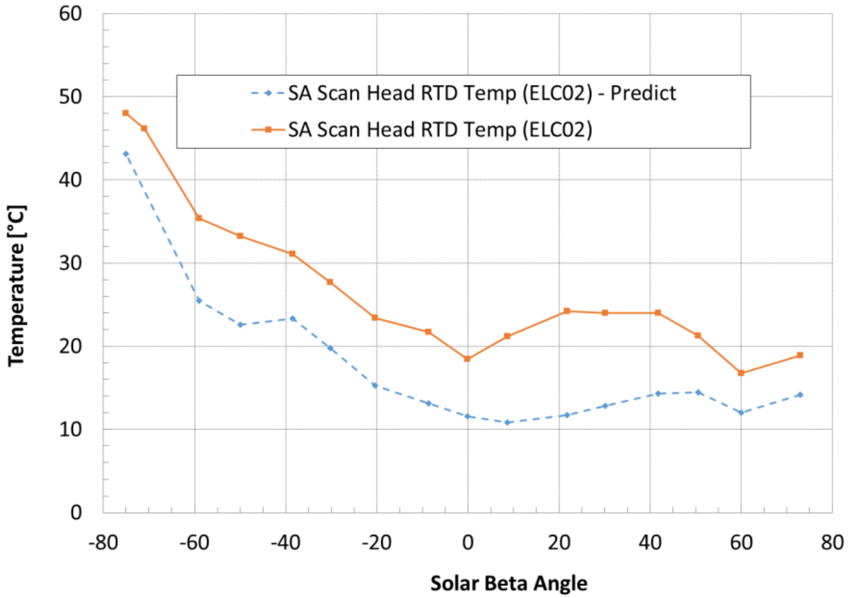
(β = -24º)



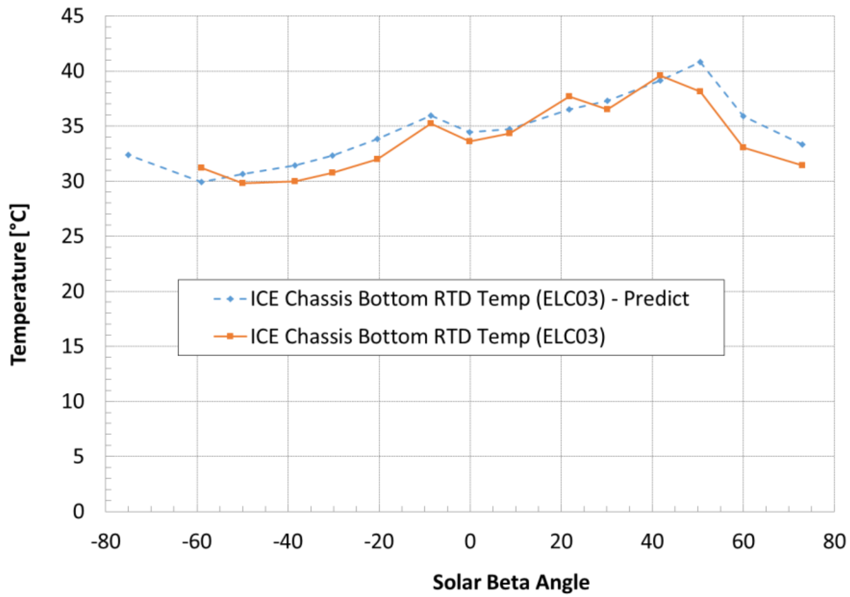
(β = 50º)

Comparison to Flight: Variation with Beta

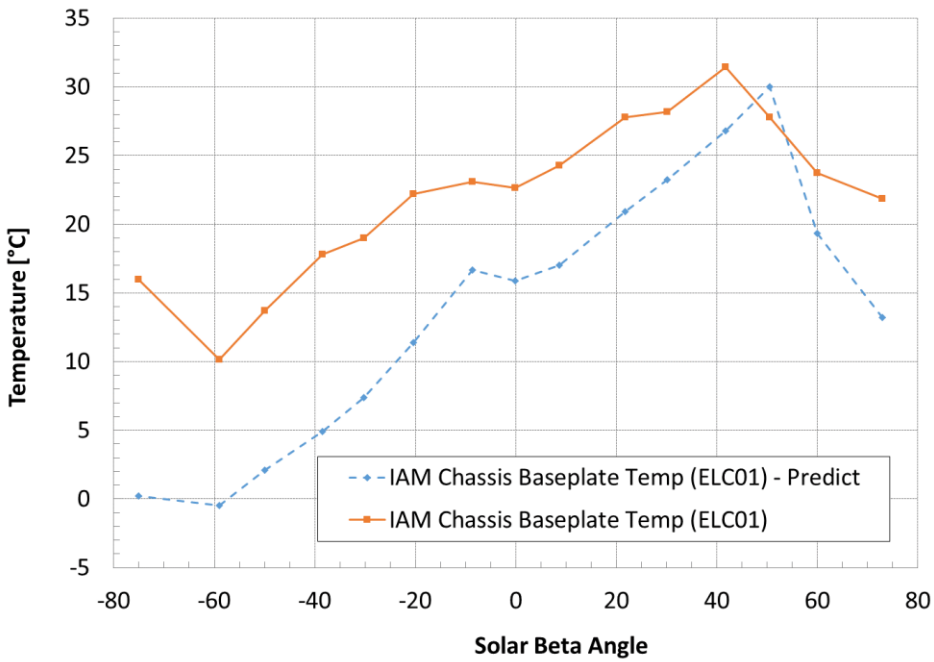




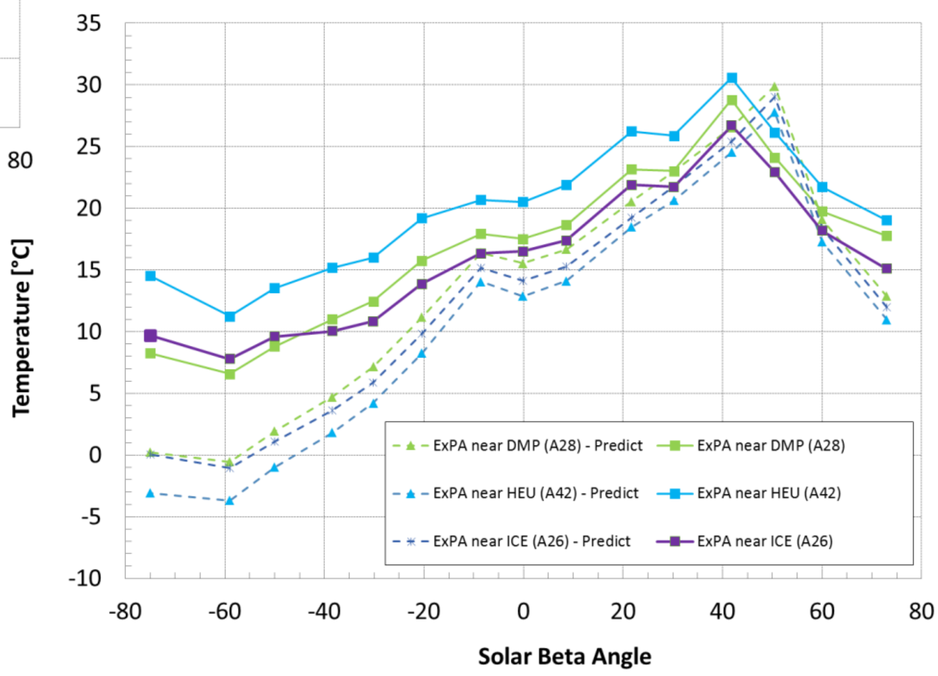
- Variation over beta angle matched well by model for most components



IAM & ExPA Variation with Beta Angle

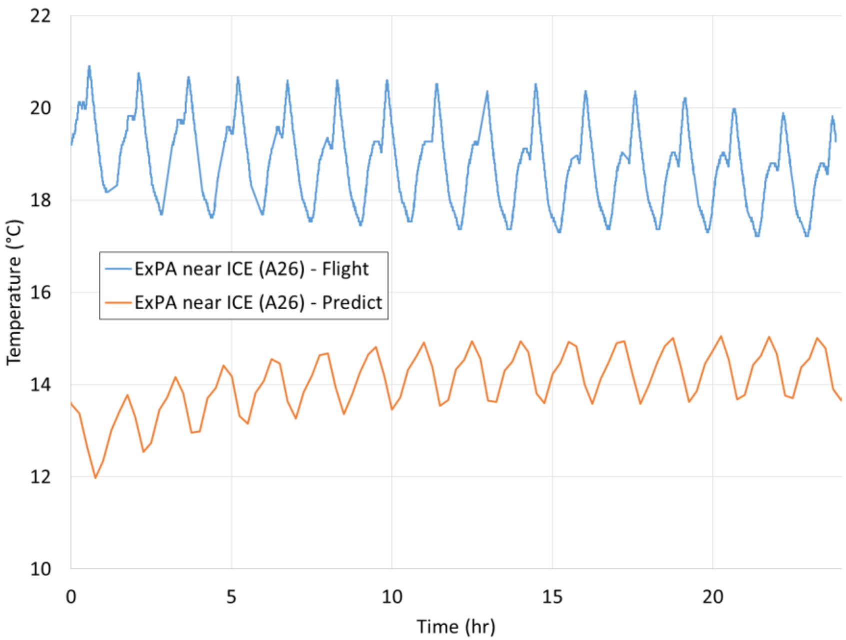


- ExPA and ExPA-mounted components: Under-prediction at high beta angles

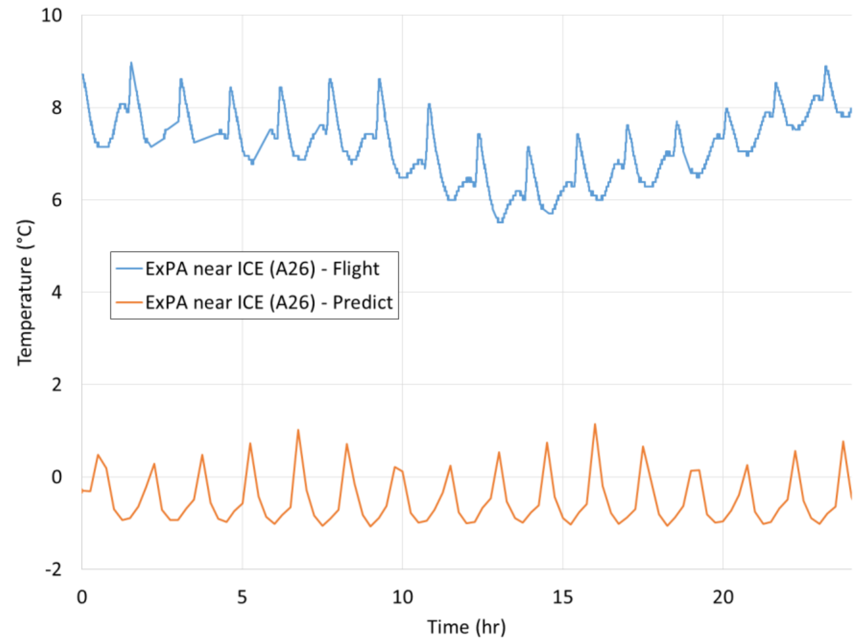


Beta Variation Potential Issue

- 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



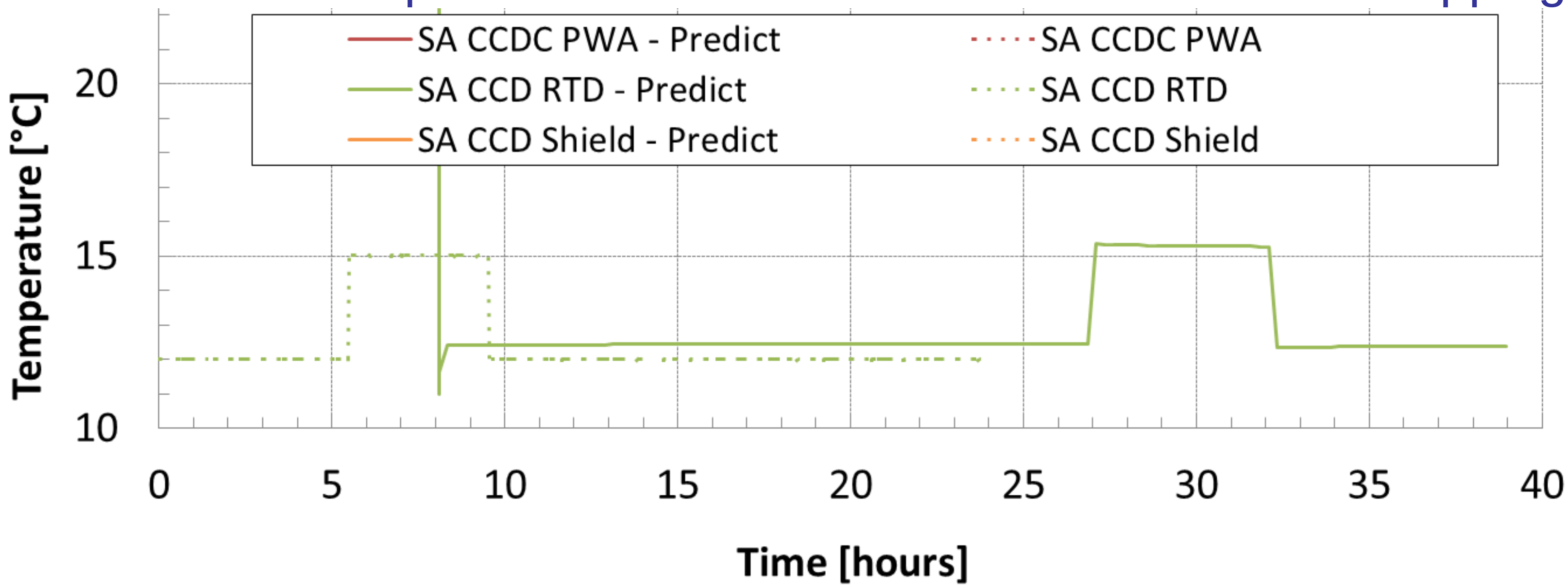
Beta 60



Beta -59

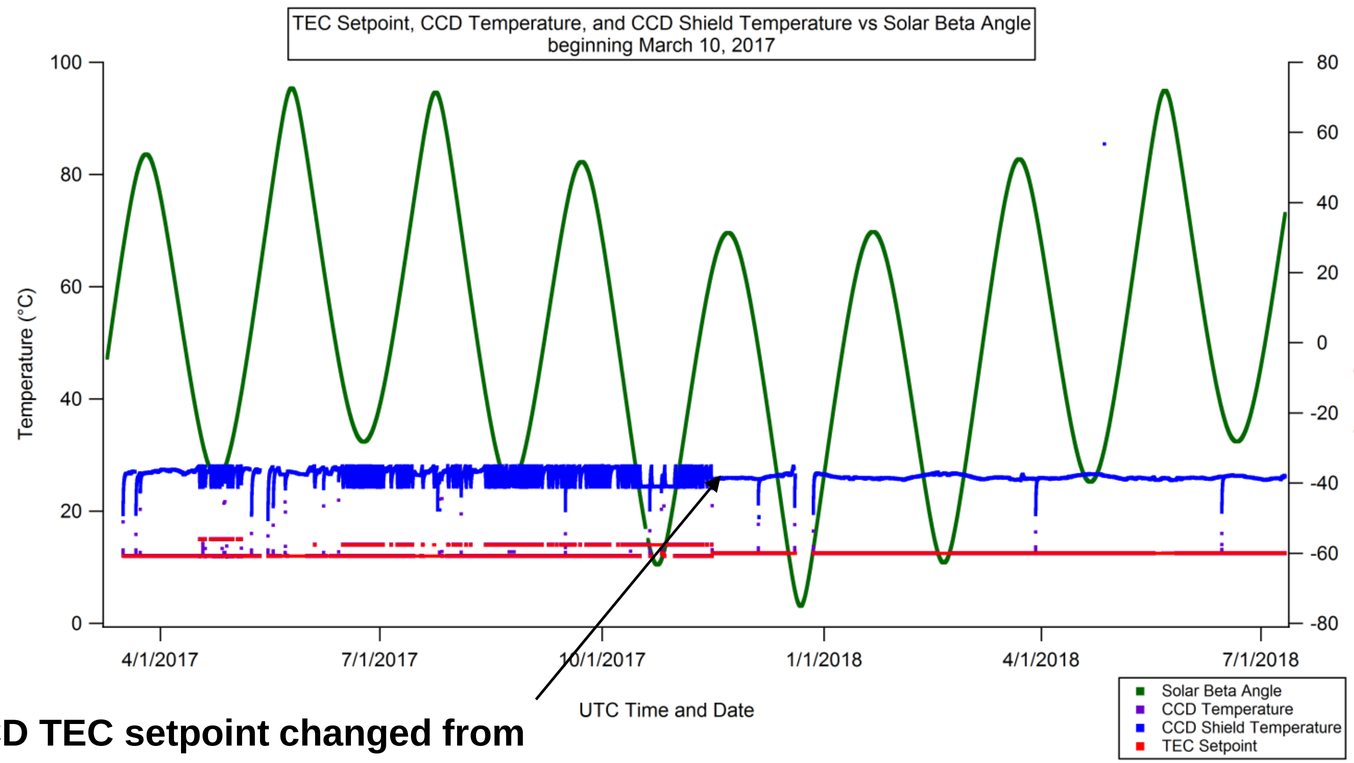
TEC Performance

- 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

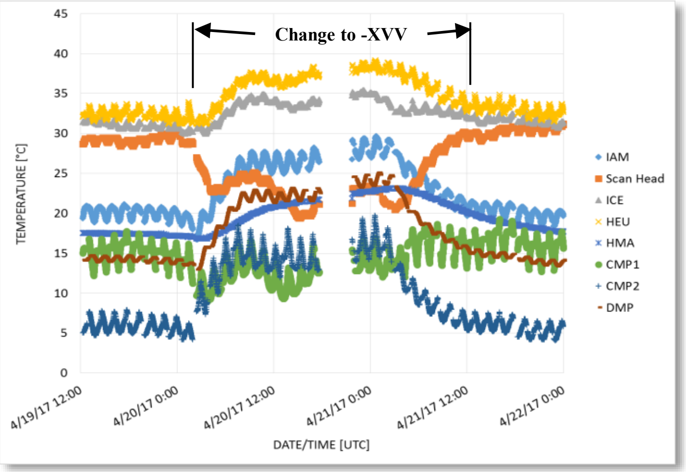
- Initial set point resulted in CCD TEC temperature instability
  - Increased complexity of science data processing
- CCD thermal stability achieved following TEC setpoint change
  - TEC behavior extremely stable after set point change

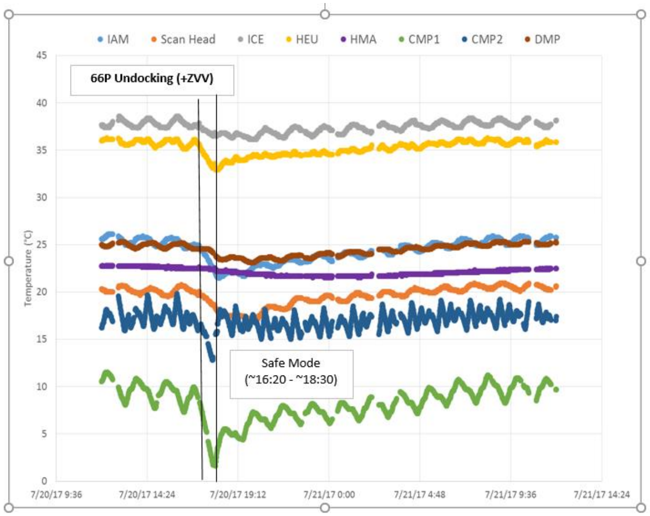


CCD TEC setpoint changed from Low +12C/High14C to Low +12.5C/High 13.5C

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 $\beta = -70°$
- 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