Early Operations Flight Correlation of the Lunar Laser Communications Demonstration (LLCD) on the Lunar Atmosphere and Dust Environment Explorer (LADEE)

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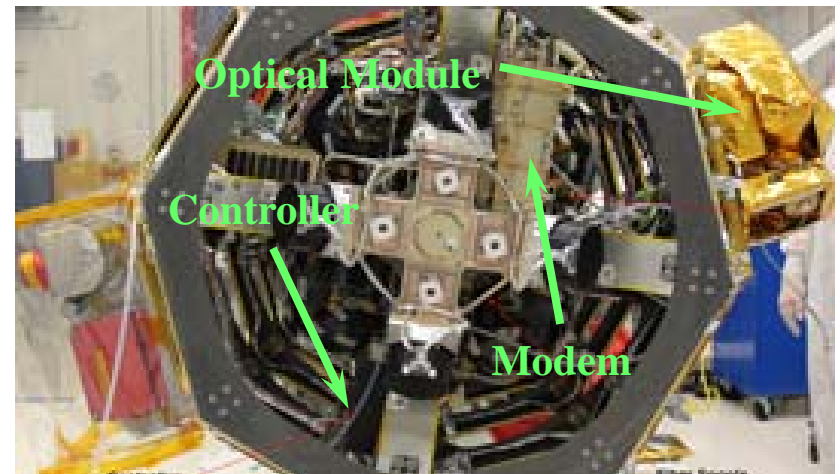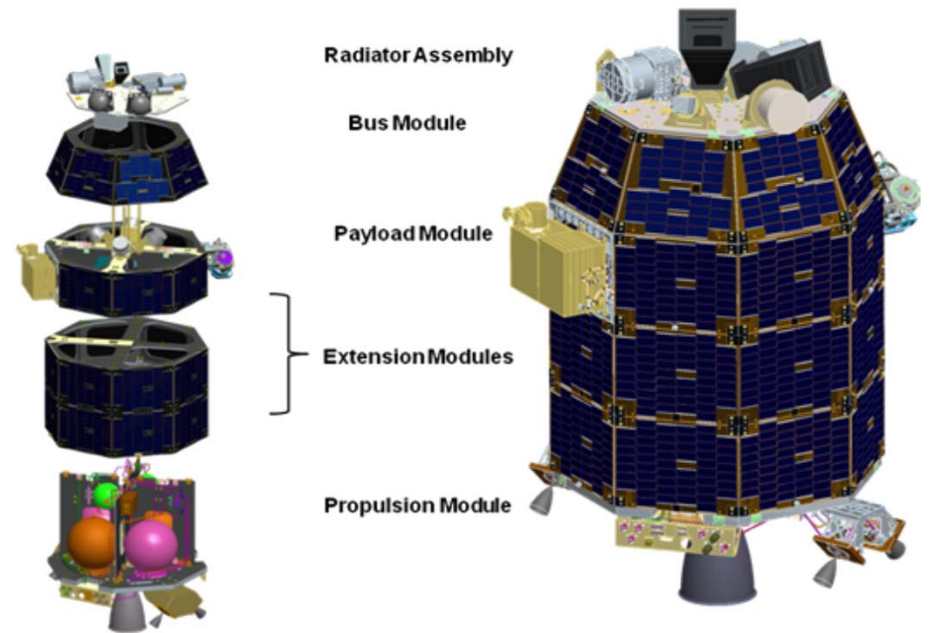*LLCD Mission Manager, NASA GSFC*

GSFC· 2015

Agenda

- Introduction to LADEE and LLCD

- LLCD Motivation

- Early Mission Correlation: LLCD

  – Lessons Learned

- Early Mission Correlation: LADEE

  – Lessons Learned

- Lunar Operation Predictions

- Conclusions

Introduction to LADEE and LLCD

- Low cost mission to study the atmosphere of the moon and to determine the cause of dust suspension in the lunar atmosphere

- Composite, Octagonal Core, Modular Structure
  - Mission rolls about long axis
  - Solar panels on all sides – may act as radiators
  - Top Panel is Radiator

- Three instruments: UVS, NMS, and LDEX

- One Technology Demonstration: LLCD
  - Built by MIT Lincoln Labs, Managed by GSFC
  - Demonstrate high speed, two-way, space based laser communication building on LRO technology
  - Optical Module (External), Modem and Controller (Internal)
  - When Earth is in View, Optical Module "locks" with laser from ground and can send back laser to ground to allow upload and download
  - Operates in power cycled mode only when Earth is in view and to minimize power

Radiator Assembly
Bus Module
Payload Module
Extension Modules
Propulsion Module


Optical Module
Controller
Modem

LLCD Motivation

- Launched on September 6, 2013 from Wallops Flight Facility aboard Minotaur V
- Early check on telemetry showed Modem and Controller were considerably warmer than predictions, even though unpowered
- Concerns were raised about ability to operate in lunar orbit if already warmer than expected
  - Was the model accurate?
- GSFC Thermal contacted to assess model, flight data, and predictions
- 30 day Lunar cruise consisted of predominantly a communication roll maneuver to prevent overheating and provided a relatively stable environment for flight correlation
- Parallel approach
  - Flight correlation to telemetry
 - Predictions for Lunar Orbit to optimize operations
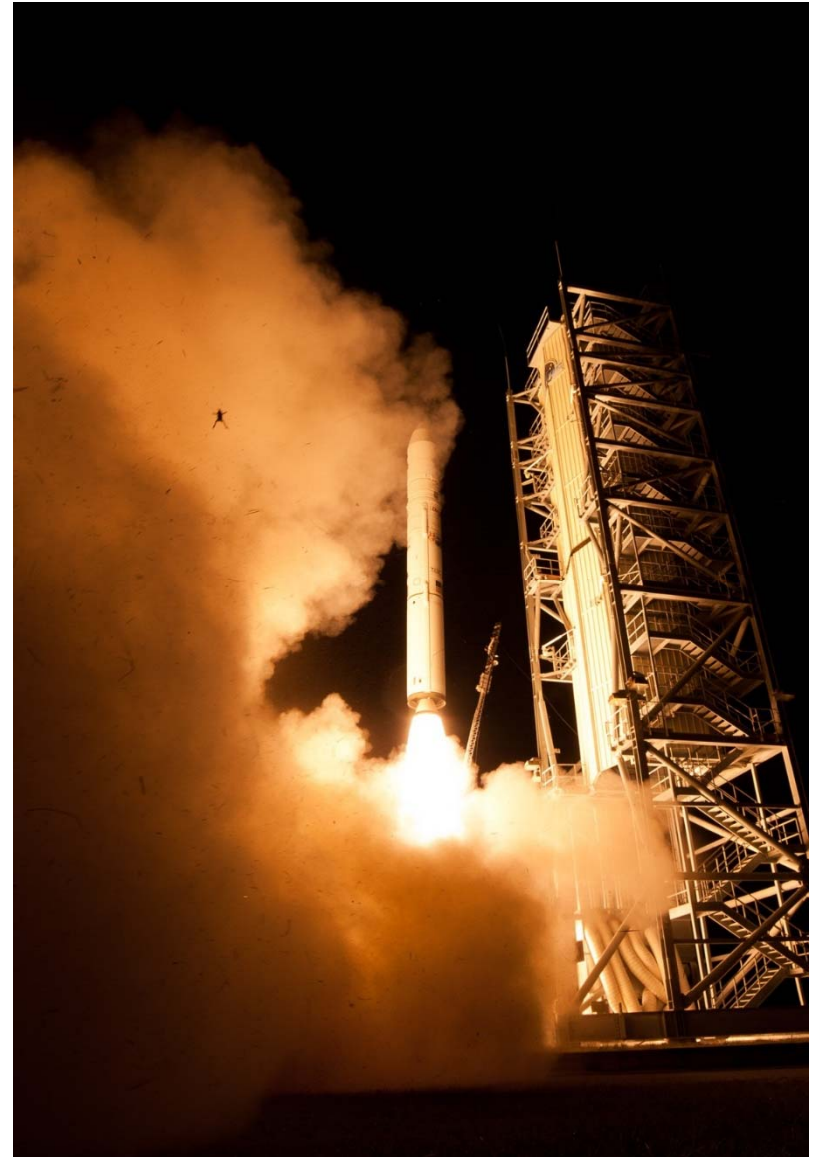
Early Mission Correlation: LLCD

- Communications maneuver consisted of:
  - Roll to place NMS side towards sun for 1 hour
  - Roll to place LLCD side towards sun for 1 hour
- Predictions with TV correlated model showed Modem and Controller under predicted by about 5-6°C while off
  - Design for Controller and Modem was to sink the boxes to internal cruciform panels and radiate internally to inside of solar panels
  - Suggested Panel temperatures were also warmer than expected (radiative sink for LLCD internals)

LLCD OM

NMS
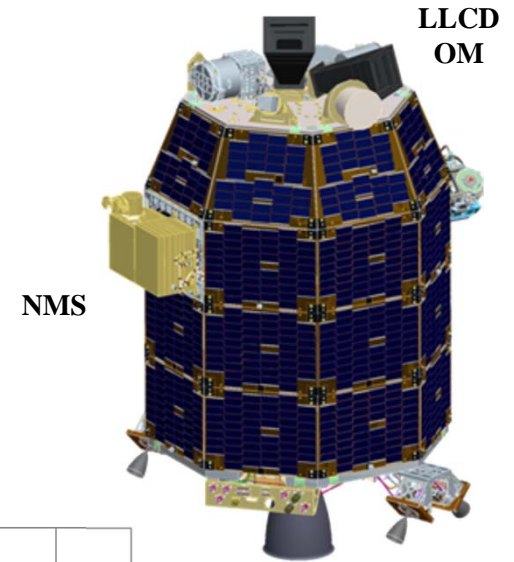
Legend:
- FLIGHT_Modem_Temp1
- FLIGHT_Modem_Temp2
- FLIGHT_Controller
- FLIGHT_Controller_Elec
- MODEL_Modem
- MODEL_Controller

Y-axis: Temperature (C)
X-axis: TIme (minutes)
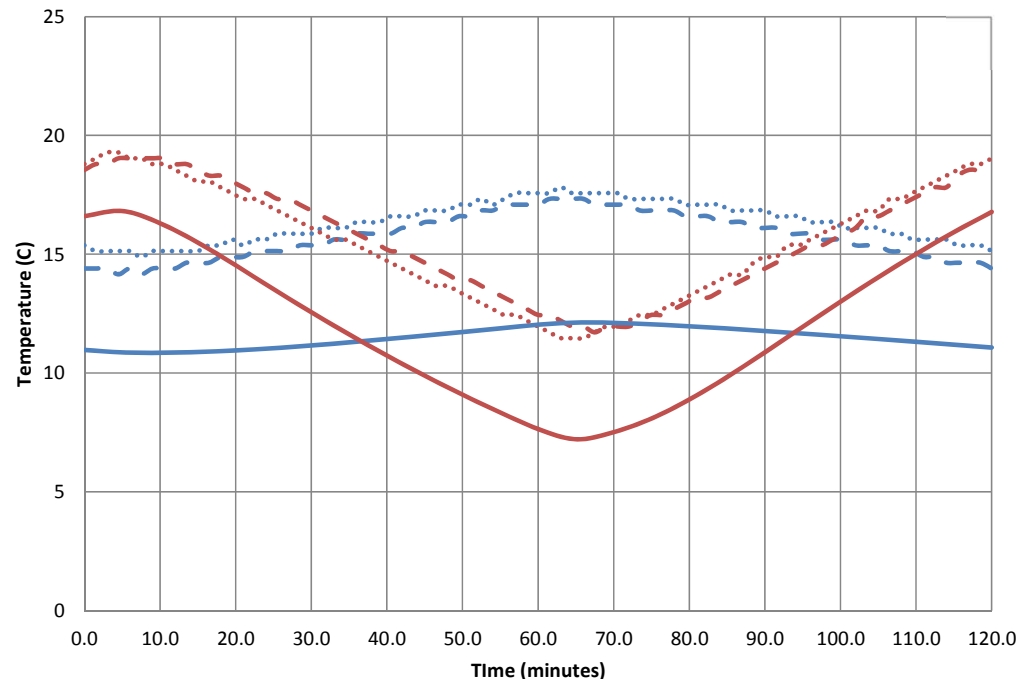
- Investigated Model further
  - Numerous unreasonable duplicate nodes
  - Composite Solar Panels modeled as 2x2 Edge Node surfaces mounted to structure at corners
  - Insufficient to capture hot spot in middle; Lower panel predictions than reality

Lesson Learned: Duplication of node numbers should always be checked to ensure that physically impossible shorts are not present in a thermal model

Lesson Learned: Composite panels should have sufficient nodalization to capture important in-plane thermal resistances that may contribute to higher temperatures.

As Delivered

Updated
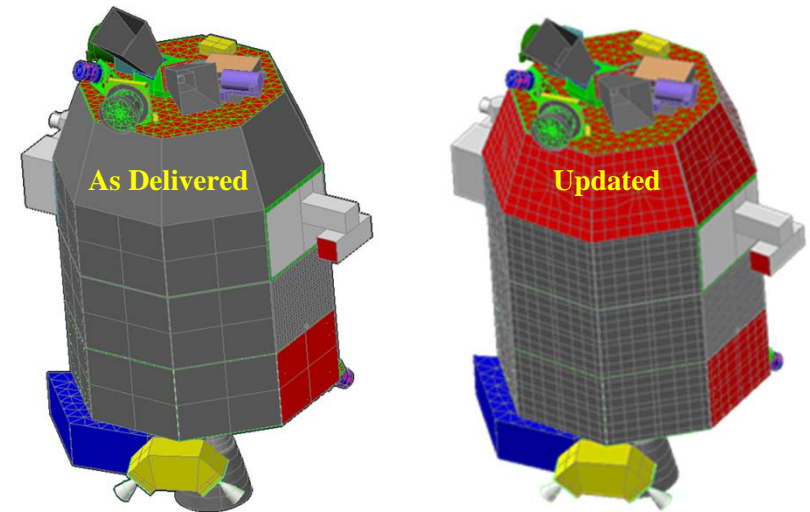
- Power Dissipation
  - To correlate to flight data, a thorough understanding of power dissipations is crucial
  - **Investigating the power dissipation profile for the LADEE spacecraft shows a highly varying power load**
  - This makes correlation more challenging, since the model must also be able to predict this power profile
  - **It also highlighted the need to understand what components are dissipating and how much**
  - **Model was "missing" about 45 W on average**
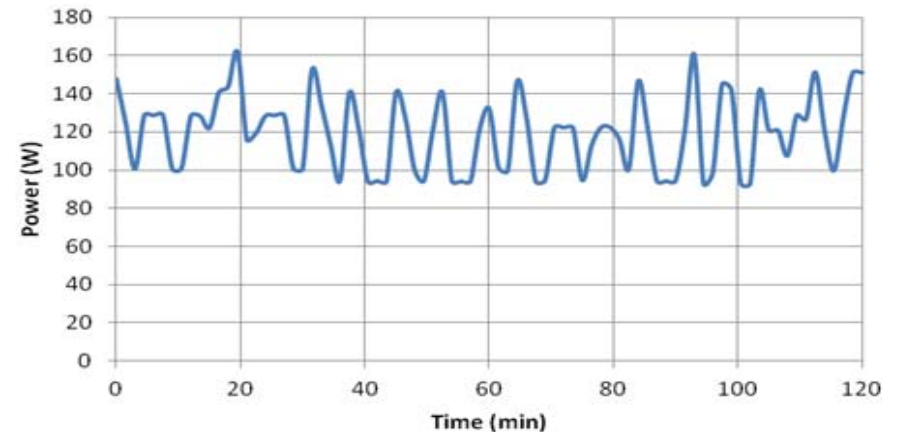
Early Mission Correlation: LADEE

- With early look into model raising questions, and given the strong dependence of the Modem and Controller on LADEE spacecraft temperatures, the investigation expanded to encompass more of LADEE than just LLCD.

- Overall temperatures for many components on LADEE warmer than predicted (not just LLCD)
  - Overall spacecraft was warmer than expected; No telemetry point for "Bulk Spacecraft Temperature"
  - Created "virtual" bulk temperature by averaging 8 solar panel telemetry points from each side
  - Plotted data as is and with 1 hour moving average
  - Overall cooling trends much more evident than over 2 hour window
  - Helped identify best time(s) for stable correlation
 - Helped understand discrepancies with telemetry on different days that was thought to be stable
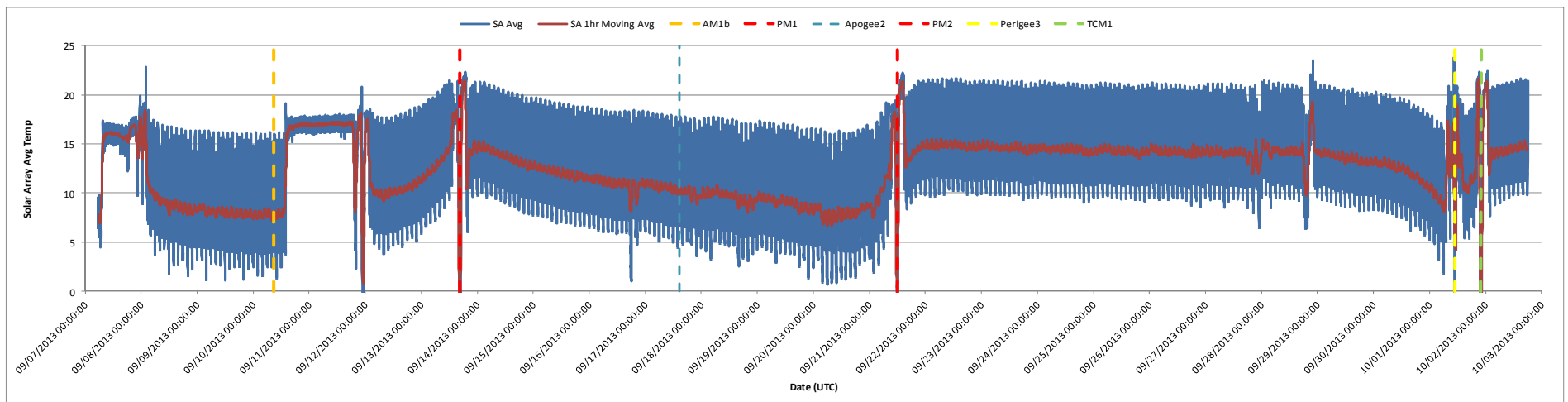
Lesson Learned: Long term views of trending data may reveal trends not seen in short term views

Early Mission Correlation: LADEE

- Further investigations into the overall warmer spacecraft turned to the radiator
  - Model had greatly simplified region, where in actuality significant harness blockage existed as well as a major harness pass through and numerous inserts
  - Less effective radiator results in higher temperatures; knockdown factor applied to ε
  - Underside was an even greater mismatch between effective and actual radiating area
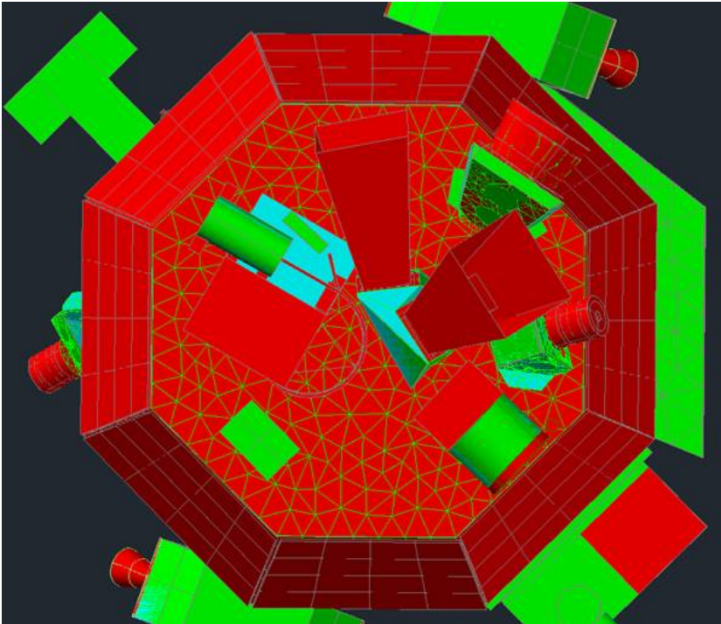
Model Representation
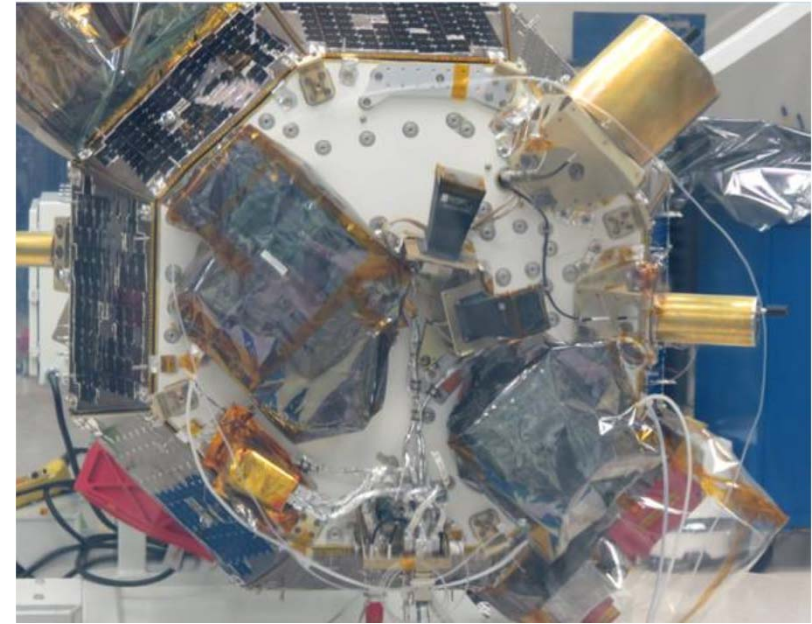
Flight Hardware (ST Baffles removed)

Lesson Learned: It is important to capture the impact of harness, holes, brackets and inserts in as-built radiator panels to correctly model the effectiveness of a flight radiator when the field of view is not 100%. In addition, it is crucial that the thermal model reflects the configuration of the as-built hardware as fully as possible.

Early Mission Correlation: LADEE

- During TV testing, a discrepancy was noted between the flight Solar Array PRTs and test only thermocouples located nearby
  - At some locations this may have been as much as 10°C over a few inches
  - The cause was fairly well understood and linked to the mounting method of the PRTs
- A section of honeycomb about 1" (25 mm) in diameter was removed from the inner facesheet and core. The PRTs were then installed on the inside of the outer facesheet and bonded to the facesheet without any further taping to spread heat
- With M55J composite facesheets, this led to a very localized hot spot on the panels and a misrepresentation of the overall bulk panel temperature
- Although identified in the test, no updates were made to the TV correlated model to simulate this; it was simply noted in the correlation report

Solar Array PRT Mounting

Lesson Learned: It may be important to consider the sensor mounting scheme for flight, particularly on composite structures to accurately represent the component temperature.

Early Mission Correlation: LADEE

- Extracting the power dissipations in flight for all components proved challenging
  - Not all components had direct measurements of power; heaters had only state flags
- The total power draw for each service and the components on the service was known
  - Power Dissipation Values can be assigned to each component where only the state is known
  - Measured + Known State Power Dissipations Values can be compared to known circuit power loads
  - The Power Dissipation Values can be varied until the RSS of the Calculated and Measured Power differences over all times is minimized using an iterative approach (e.g. Microsoft

Lesson Learned: When extracting power dissipations from telemetry data, it may be necessary to infer actual power dissipations from state flags, which could be done by iterating on dissipation for each component and minimizing the Root Sum Square of the error between estimated and measured total power over all timesteps.

Early Mission Correlation: LADEE

- As the full power profile of the flight conditions became clear, the correlation between model predictions and flight data improved greatly
- With a greater confidence in overall model predicts, attention turned back to evaluation of LLCD specifically
  - Flight telemetry from LLCD Turn On cycles was compared to model predicts

- **Matching the slope of the predicted and measured responses of the Modem and Controller allowed for a check of the Thermal Mass**
  - Modem Mass increased
  - Controller Mass decreased
- **Rate of rise as a result of turn on important since LLCD operates in power cycled mode**
  - Direct impact on Operating Time in Lunar Orbit

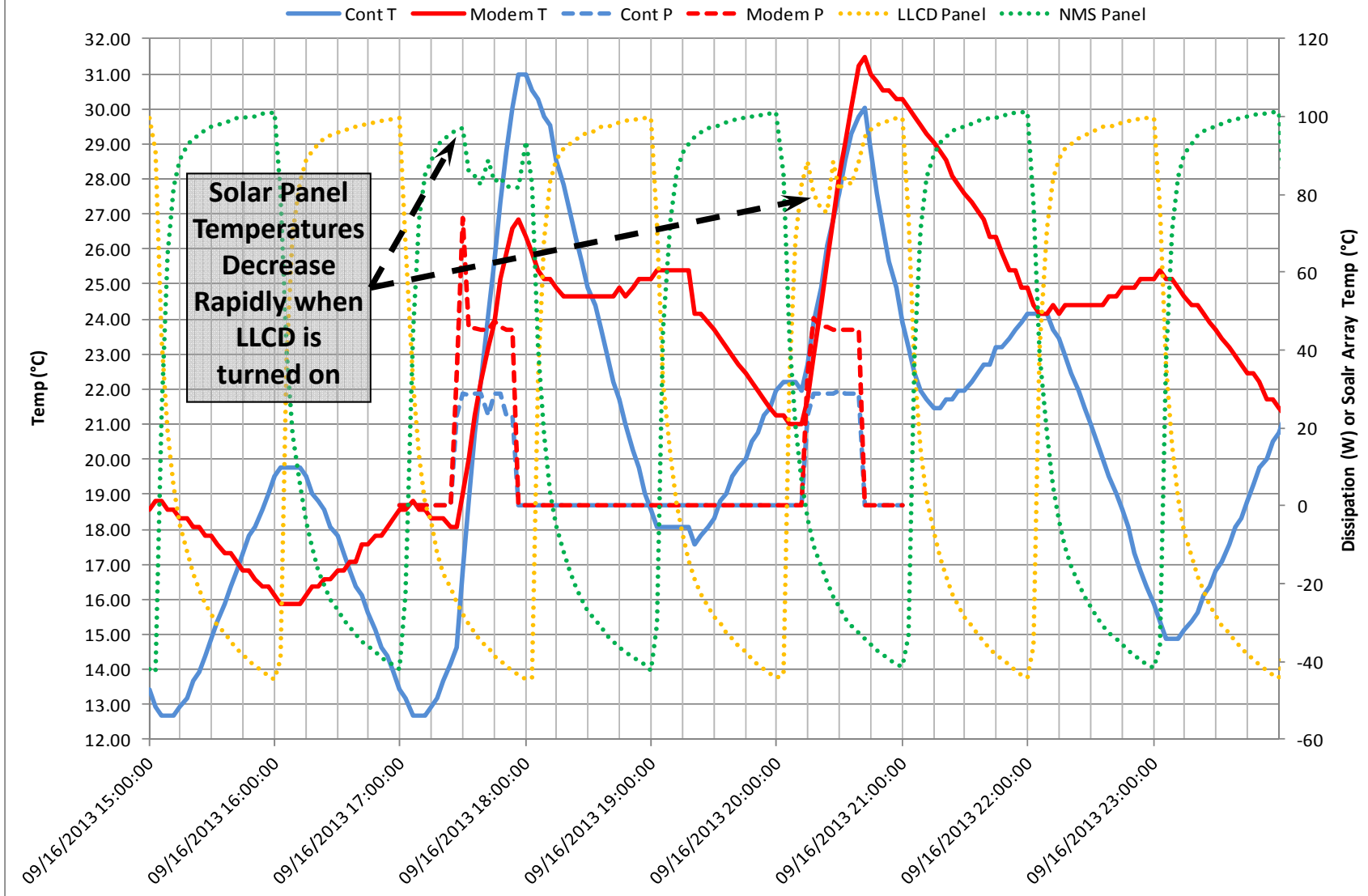LLCD Modem And Controller Behavior for Turn On during Cruise
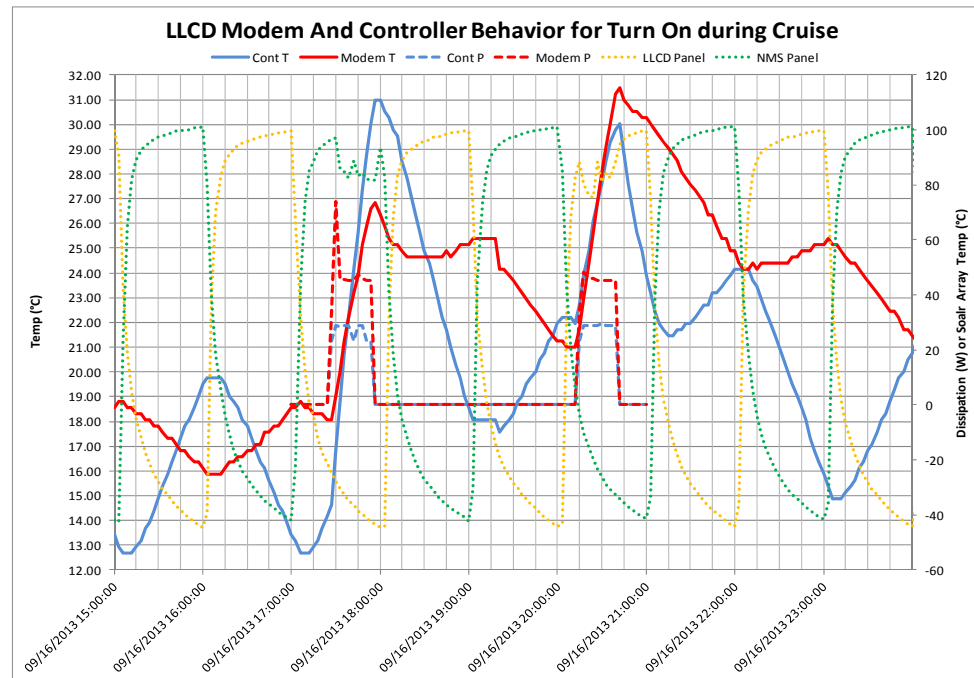
Lesson Learned: It is important to verify the thermal mass of components using test data. This is best done during turn on or transitions, since balance points tend to be steady and minimize any errors associated with energy storage.

Early Mission Correlation: LADEE

Early Mission Correlation: LADEE

- Sudden drop and rise in temperature on the solar arrays when LLCD is turned on and off
- Impact only seen on lower panel temperatures and not top canted panels
- Further investigation revealed that power subsystem did not shunt unused power to dedicated location
  - **Impact was that cells did not convert solar heat into power**
  - Not accounted for in the model (α=0.74 for converting cells for all panels)
  - **Lower panels updated to use α=0.94 for non-converting cells**
  - **More applicable to operations, but not cruise, which was low power mode…**
  - …Until LLCD turned on. Then lower panel power was needed
- **Attempts made to upgrade model to account for dynamic power load**
  - **Updated model to dynamically change absorbed solar load from top panels down based on total spacecraft power load and necessary power conversion**
  - **Complexity of battery charging/discharging state once in lunar orbit proved too difficult to model in the short term. Arrival at the moon also cut this effort short**
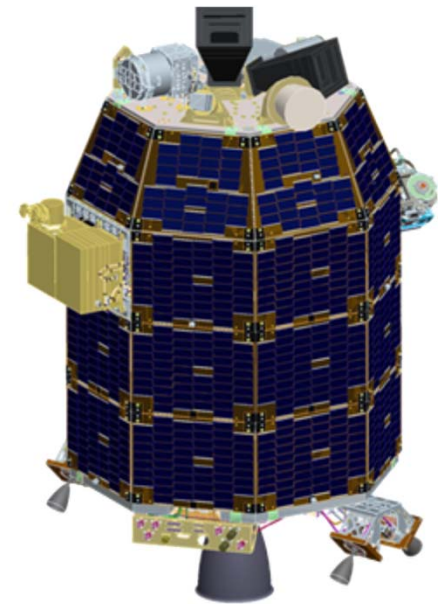
Lesson Learned: For body mounted solar arrays, the power subsystem may have a direct impact on the thermal subsystem by virtue of converting or not converting cells. Incorrect solar absorptivity in the model depending on converting status of the power subsystem may result in incorrect predictions.

Lesson Learned: If the thermal model is attempting to account for the current state of electrical conversion of various solar panels on a spacecraft, the charging state of the battery cannot be neglected.

Lunar Operation Predictions

- While Early Mission Correlation was ongoing, there was a parallel effort to predict LLCD temperatures in lunar orbit

- Predicts focused on achieving ideal thermal environment for LLCD operation by varying the following parameters:
    - Optimum time in orbit to turn LLCD on/off
    - Longest allowable duration for operating time per orbit
    - Number of continuous orbital cycles allowed for operation before over-heating
    - Permissible spacecraft orientations and altitudes in lunar orbit

- Since previous thermal model under-predicted LLCD temperatures, improvements from Early Mission Correlation effort were incorporated into model for use in generating LLCD predicts
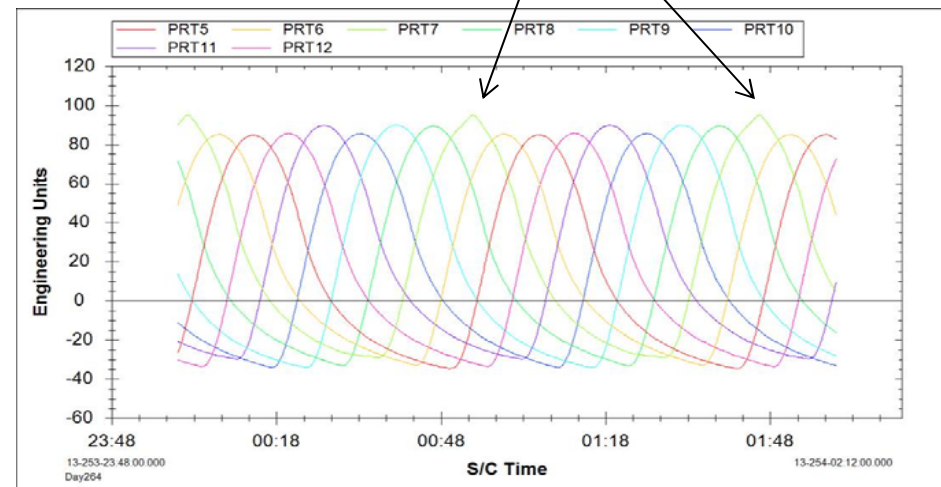
Lunar Transfer Predictions

- During lunar transfer, LADEE performed "Barbecue Roll" maneuver

Solar vector

MG Antenna

LDEX
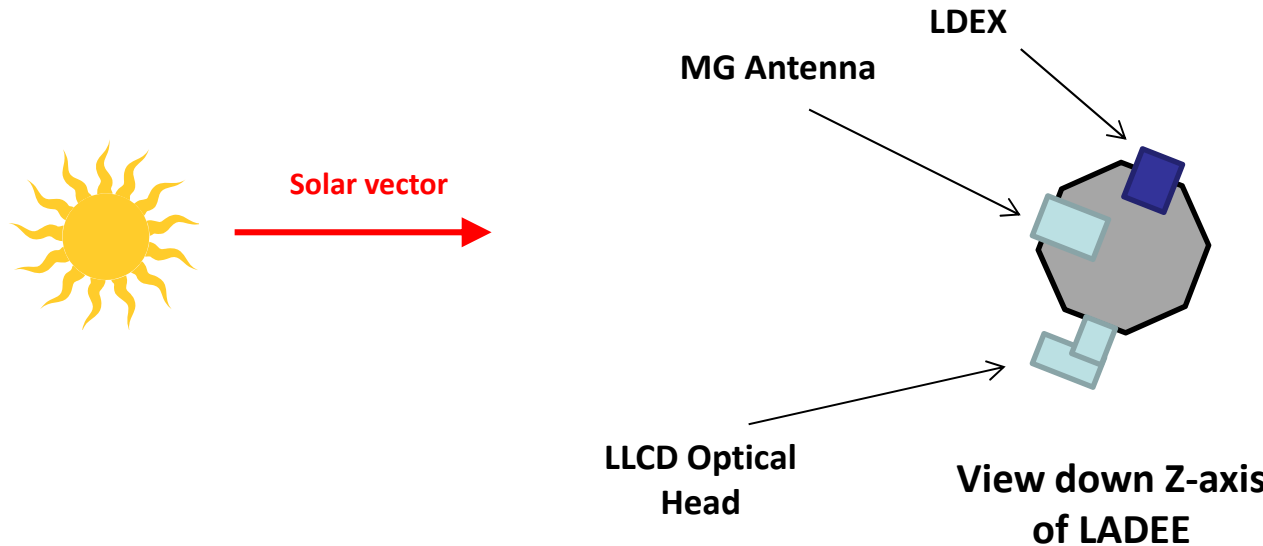
LLCD Optical Head

View down Z-axis of LADEE

PRT 7

- **Solar panel temperatures vary sinusoidally and peak when panel is orthogonal to solar vector**
- **It was noticed from flight telemetry that temperature sensor PRT 7 (located on Solar Panel 7 right below LLCD Optical Module) peaked at higher temperature than other panels**

Lunar Transfer Predictions

- No previous workmanship issue detected for this panel

- Model did not predict higher temperatures on this solar panel

- **Hypothesis formed that higher temperatures were actually due to reflections off of LLCD Optical Module (OM) blanket**
    - **It was found that LLCD OM blanket was not included in thermal model**
    - ➔ **Simplified OM blanket was modeled based on pictures taken during I&T phase**
- **Inclusion of as-built OM blanket model significantly improved predictions of hot spot on Solar Panel 7**
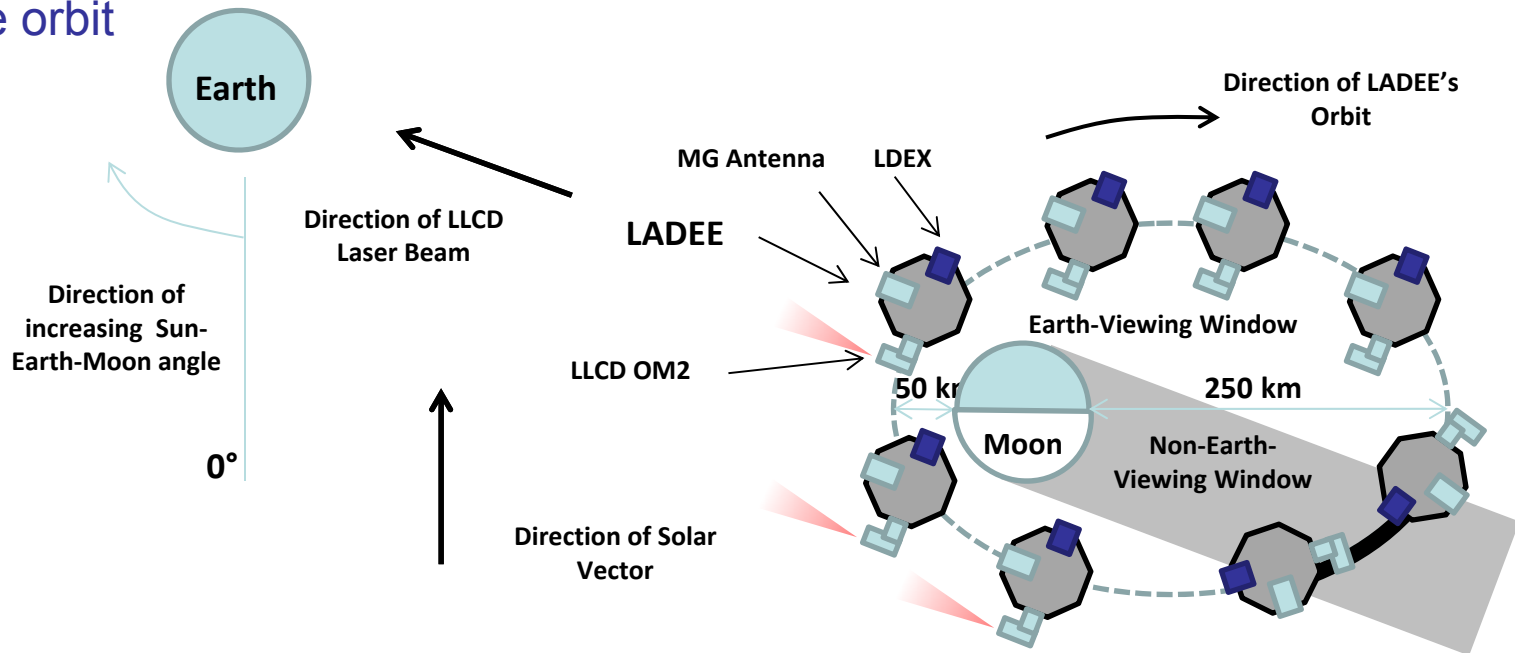
Lesson Learned: For composite, body-mounted solar panel spacecraft, it is crucial to model all externally-mounted MLI blankets to their as-built geometry, especially when the blankets protrude beyond the plane of the solar arrays. Reflections from these blankets may impact the radiative interchanges and resultant heat flows and temperatures of the spacecraft components.

LLCD OM Blanket

Solar Panel 7
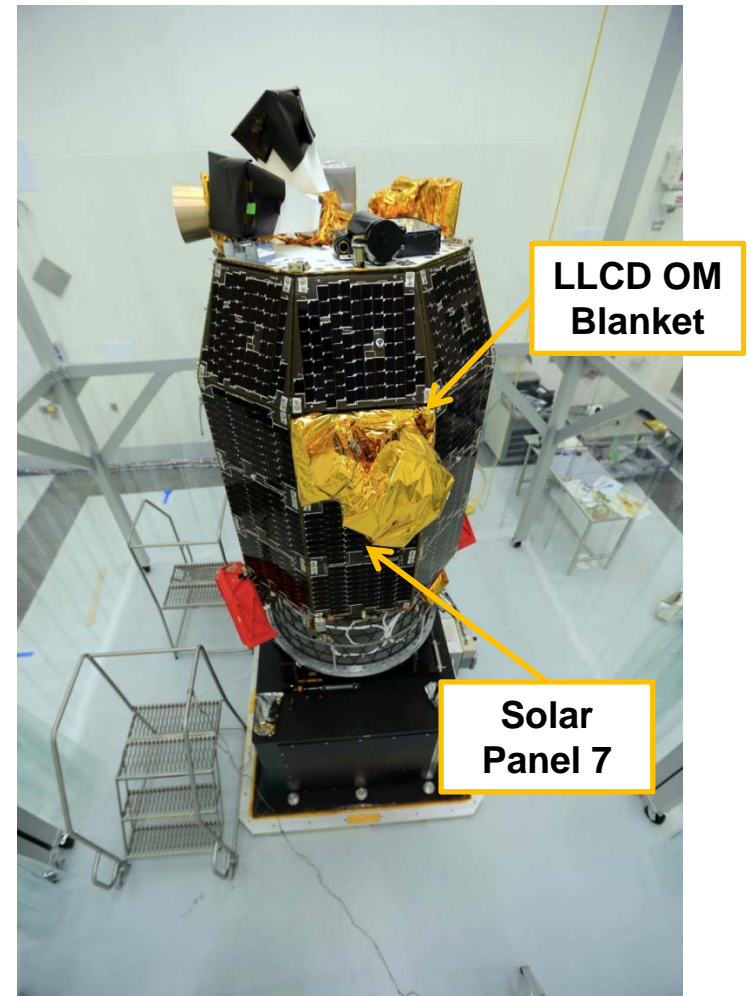
Lunar Operation Predictions

- First set of predictive lunar orbit results were requested for a Sun-Earth-Moon angle of 281° (corresponding to 1st Quarter Moon) in a 50 km periselene x 250 km aposelene orbit

Earth

Direction of LLCD Laser Beam

Direction of increasing Sun-Earth-Moon angle

0°

Direction of Solar Vector

Direction of LADEE's Orbit

MG Antenna   LDEX

LADEE

LLCD OM2

50 km   250 km

Moon

Earth-Viewing Window

Non-Earth-Viewing Window

Goal: Over the course of 12 orbits, operate LLCD for 9 successive orbits at 20-minute operations each orbit, then use the remaining three orbits to cool LLCD components before the next set of operations

1. LLCD optical head inertially fixed on Earth in Earth-viewing window for LLCD Operations. LLCD Operations start at beginning of Earth-viewing window.
2. LADEE transitions to "LDEX Ram" attitude in non-Earth-viewing window
3. LADEE transitions to inertially fixed orbit upon return to Earth-viewing window for restart of LLCD operations

- This orbit produces temperatures that are too hot on the modem
  - Successive orbits cause Modem to heat up to past its red limit (45°C) and asymptote around 51-52°C
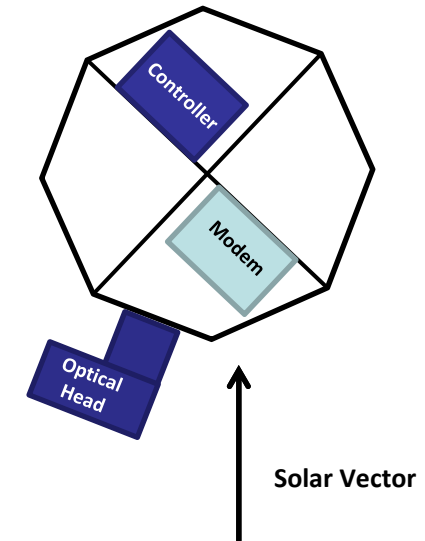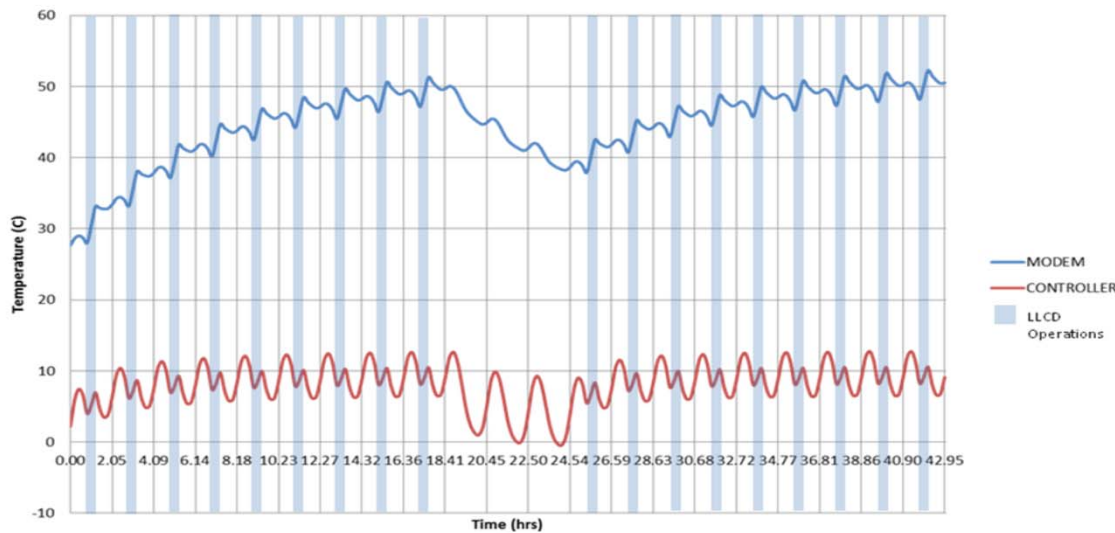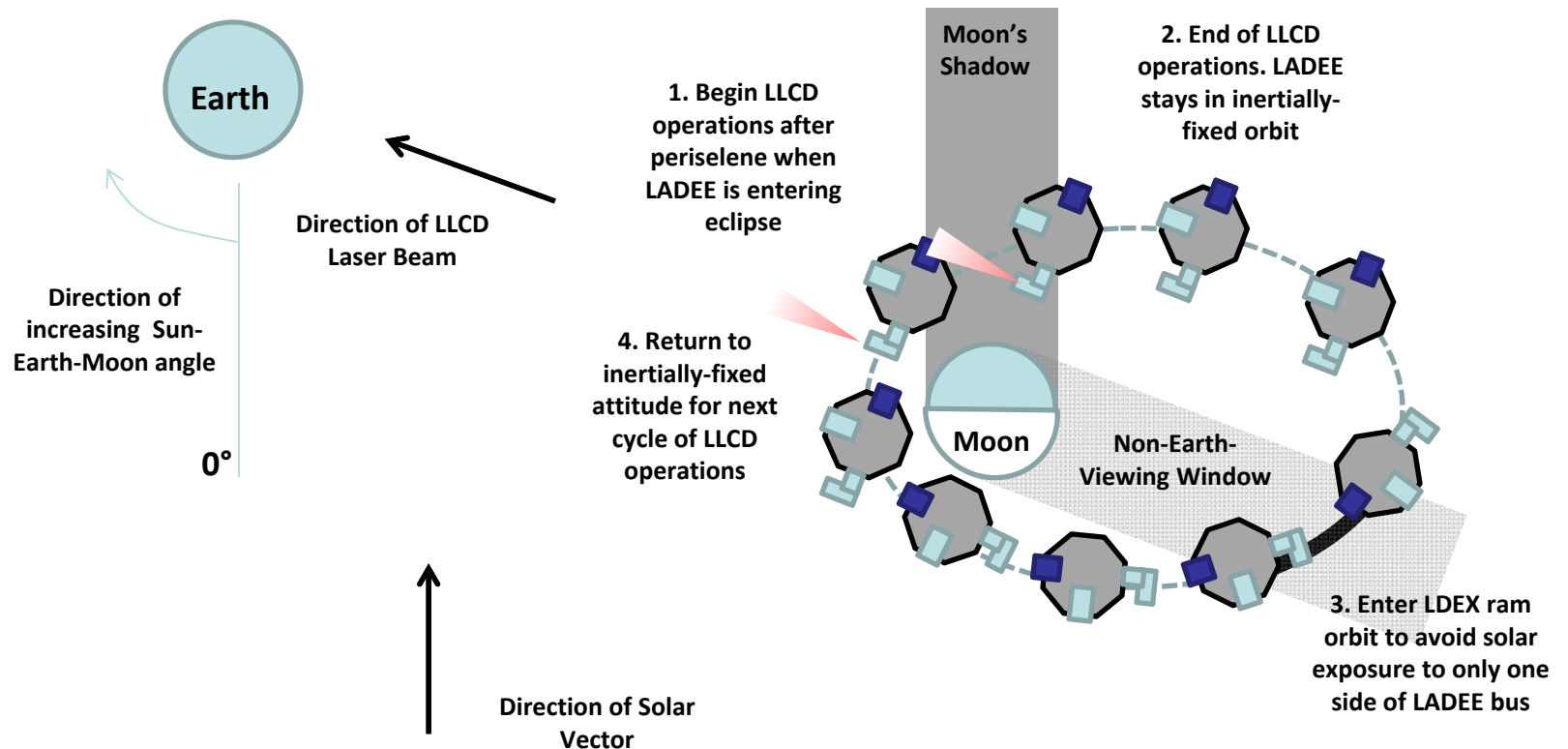

- This was found to be highly dependent on the **orientation** of the internal LLCD components during lunar orbit
- For this orbit in inertially-fixed orientation during LLCD operations, the solar vector is perpendicular to the modem
  ➔ this causes the modem to overheat since the non-Earth-viewing portion of the orbit is too brief for the modem to completely dissipate the heat gained from the Earth-viewing portion

Lunar Operation Predictions

- How do we produce more desirable thermal environments for successive orbits of LLCD operation?

  1. Change the orientation of the spacecraft when not operating LLCD
  ➔ go to "LDEX Ram" orbit
  2. Begin operations when LADEE is in eclipse

Earth

Direction of LLCD Laser Beam

Direction of increasing Sun-Earth-Moon angle

0°

Direction of Solar Vector

Moon's Shadow

1. Begin LLCD operations after periselene when LADEE is entering eclipse

2. End of LLCD operations. LADEE stays in inertially-fixed orbit

4. Return to inertially-fixed attitude for next cycle of LLCD operations

Moon

Non-Earth-Viewing Window

3. Enter LDEX ram orbit to avoid solar exposure to only one side of LADEE bus

Lunar Operation Predictions

3. Go to a higher altitude:

- Higher altitude reduces the incident lunar flux and albedo on the spacecraft
- Since LADEE's design has the solar panels functioning as radiators when facing away from the Sun, reduction of backloading on solar panels allows for lower sink temperature on solar panels ➜ panels act as better radiators
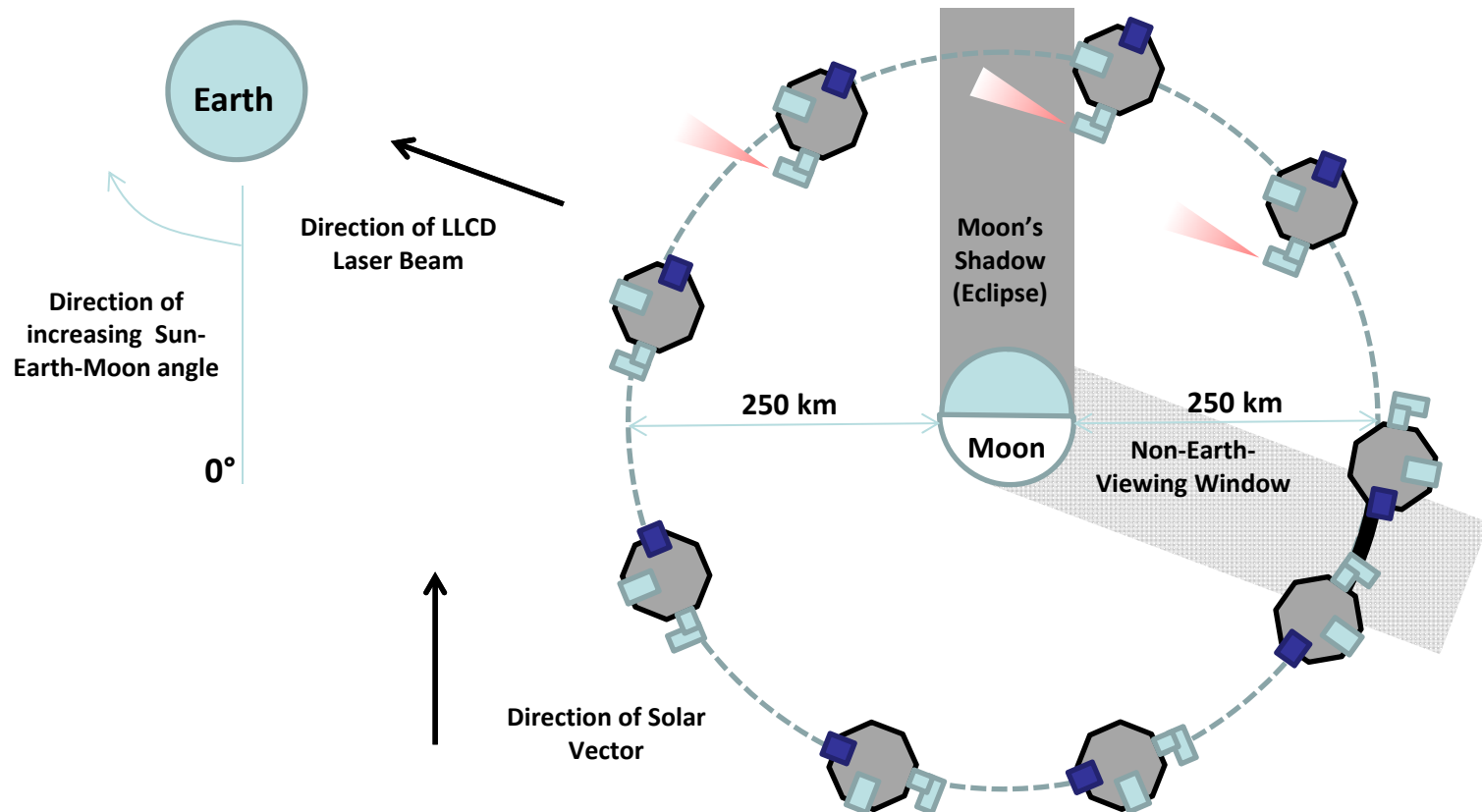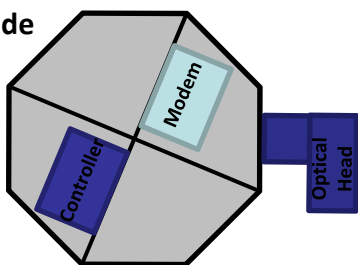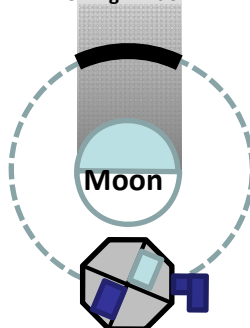
Lunar Operation Predictions

3. Operate at different lunar phases

**Configuration inside LADEE of LLCD components:**

Modem

Controller

Optical Head

**Eclipse and non-Earth-viewing window**

Moon

FULL MOON: best thermal environment
- LLCD operations on sun-side
- However, cooling in eclipse provides excellent sink to dissipate heat before next operation

LAST QUARTER direct solar loading on Controller: LLCD needs to operate in eclipse to reduce temperature
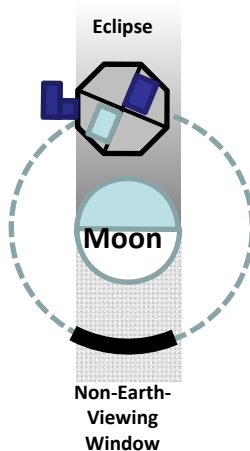
Eclipse

Moon

Non-Earth-Viewing Window

Earth

Eclipse

Moon

Non-Earth-Viewing Window
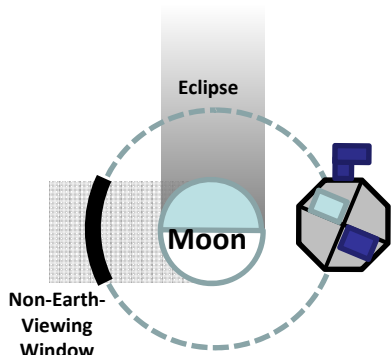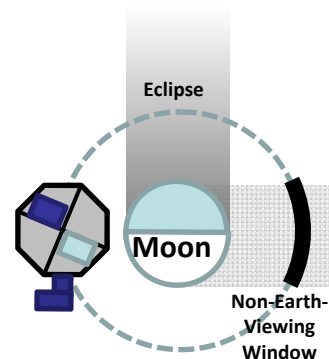
FIRST QUARTER direct solar loading on Modem: LLCD needs to operate in eclipse to reduce temperature

Eclipse

Moon

Non-Earth-Viewing Window

NEW MOON: worst thermal environment
- LLCD operations in eclipse
- After operations, spacecraft must cool with direct solar flux on one side and high lunar flux on the other
- Not sufficient time to cool before next operation

Direction of Solar Vector

Lunar Operation Predictions Summary

- For LADEE's body-mounted solar panel design, the environment seen by the solar panels determines most of the internal temperatures/heat flows since the solar panels also function as radiators
  - Higher altitudes greatly reduced loading from lunar flux and albedo
  - Operations at different lunar phases present vastly different thermal environments for each LLCD component in its LLCD operations and cooldown phases
  - Orientation of spacecraft and duration in that orientation may impact internal temperatures even more significantly than lunar phase
- A combination of altitudes, attitudes, and durations of LLCD operation can be used to achieve the optimal thermal environment

Lesson Learned: For spacecraft with body-mounted solar arrays, a combination of orientations can be used to alleviate thermal stresses or prevent localized heating during the course of an orbit