Thermal Design of the Instrument for the Transiting Exoplanet Survey Satellite

A Thesis Presented

By

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ABSTRACT

TESS observatory is a two year NASA Explorer mission which will use a set of four cameras to discover exoplanets. It will be placed in a high-earth orbit with a period of 13.7 days and will be unaffected by temperature disturbances caused by environmental heating from the Earth. The cameras use their stray-light baffles to passively cool the cameras and in turn the CCD’s in order to maintain operational temperatures. The design has been well thought out and analyzed to maximize temperature stability. The analysis shows that the design keeps the cameras and their components within their temperature ranges which will help make it a successful mission. It will also meet its survival requirement of sustaining exposure to a five hour eclipse. Official validation and verification planning is underway and will be performed as the system is built up. It is slated for launch in 2017.

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1. Background

The Transiting Exoplanet Survey Satellite (TESS) is a 2 year principal investigator-led NASA Explorer Mission. Its purpose is to perform an all-sky transit survey of the nearby bright stars in order to detect exoplanets. The mission is led by George Ricker of the Massachusetts Institute of Technology Kavli Insitute for Astrophysics and Space Research (MKI) with support from many organizations including the Orbital ATK, MIT Lincoln Laboratory, NASA GSFC, SpaceX to name a few. MKI is the science center and are responsible for the overall Instrument which consists of four cameras on an optical bench as well as the Data Handling Unit (DHU). They are directly responsible for the camera electronics and the associated software as well as procuring the DHU. MIT Lincoln Laboratory (LL) is responsible for the lens assemblies as well as the surrounding mechanical and thermal design for the instrument other than the DHU. GSFC provides the program management as well as the mission level systems engineering. Orbital ATK is in charge of the spacecraft and observatory integration while SpaceX is the launch vehicle provider and thus is responsible for delivering the observatory into orbit.

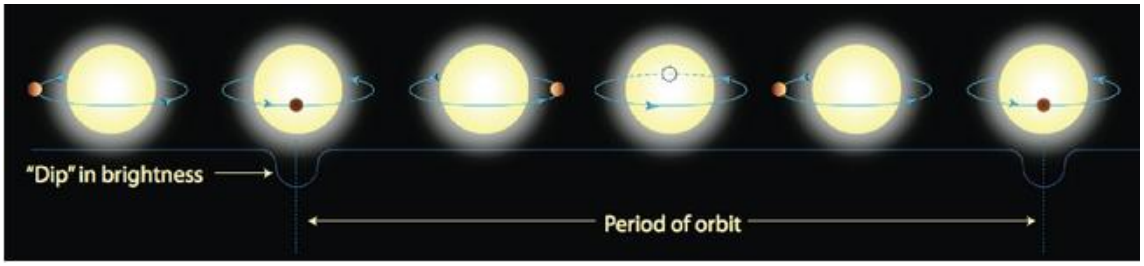


Figure 1: Transit Signature of an Exoplanet

2. Science Overview

TESS will monitor over 200,000 nearby stars and attempt to detect planets orbiting them. It does this by measuring the amount of light coming from the stars. If a stat dims in brightness that means that there is planet passing in front of it. These signals tend to be extremely small and have led to certain characteristics of the system including the thermal and mission design which will be explored further later in this paper.

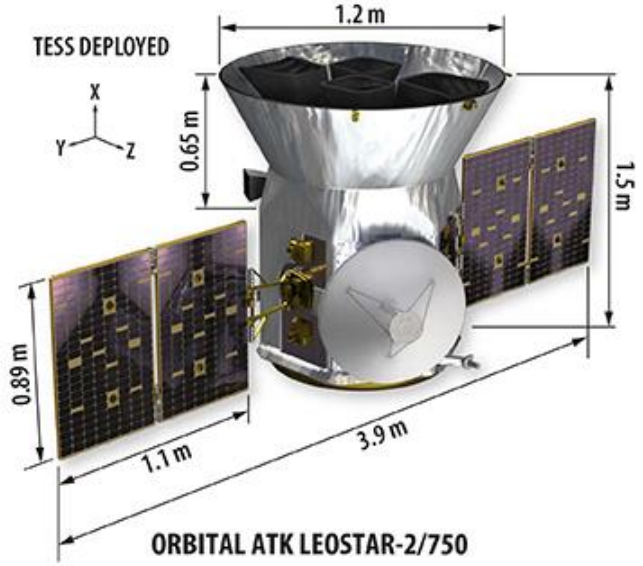


Figure 2: TESS Observatory

3. Spacecraft Overview

The basis for TESS is the Orbital ATK LEOStar-2 spacecraft. It is a flexible, high performance spacecraft which has a 433W single-axis solar array as well as a Mono-propellant propulsion system which will lift TESS into its final orbit. Other key features include a high speed 100 Mbps Ka-band downlink antenna, as well as a pointing system with better than 3 arc-second performance. The TESS instrument sits atop the spacecraft inside the Camera Accommodation Structure (CAS). The CAS serves to thermally insulate the instrument from both solar loading and also from the spacecraft. It consists of three pairs of two composite struts with ball joints on both ends which attach to titanium brackets. These brackets then bolt to the Camera Structure Assembly (CSA) and the sunshade. The sunshade is covered in Multi-Layer Insulation and shields the CSA from the sun which allows it to reach the cold temperatures necessary for operation.

Figure 3: Camera Accommodation Structure

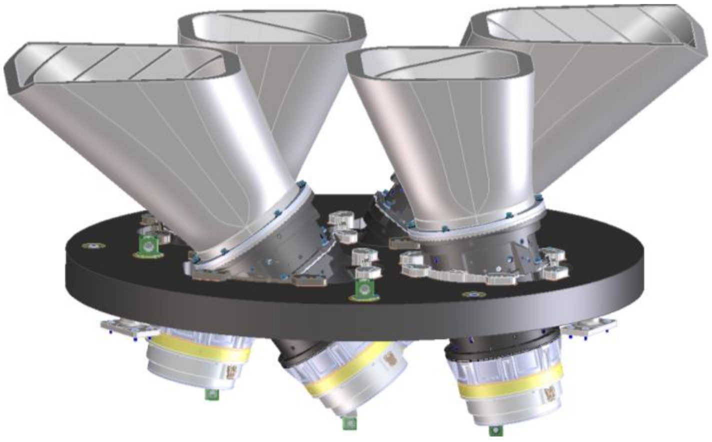


Figure 4: Camera Structure Assembly

4. Instrument Overview

The TESS Instrument consists of four 24° x 24° field of view cameras optimized to work between 600 nm and 1000 nm as well as the DHU. The cameras have aluminum lens barrels and are mounted on a composite plate designed to reduce thermal-mechanical distortions on orbit using the low coefficient of thermal expansion (CTE) of the composite plate. The barrels are made of aluminum due to its light weight but this also presents the issue of a large CTE mismatch between the camera barrels and the composite plate. For this reason the cameras are held on the camera plate with blade flexures made of invar. The flexures are designed with strategic stiffness. They are stiff in the vertical axis in order to survive launch but compliant in the radial direction which allows them to take up the relative change in size of the camera barrels over the large temperature drop from the room temperature fabrication of the barrels and camera plate down to the operational temperature of -75°C.

The cameras can be broken down into three main pieces. The first piece is the detector assembly. It houses the camera electronics as well as the CCD's. The CCD's are provided by the Microelectronics Laboratory at LL and are of the highest quality providing extremely low dark current which is needed for the detection of exoplanets. For this mission in order to get the dark current low enough the CCD's need to be operated at or below -60 C. The main heat sources in the cameras are the camera electronics circuit boards which sit behind the CCD's. The main heat path for the camera electronics is up through the lens barrels and out the stray light lens baffles. This presents several unique thermal challenges which will explored in greater depth later in this paper.

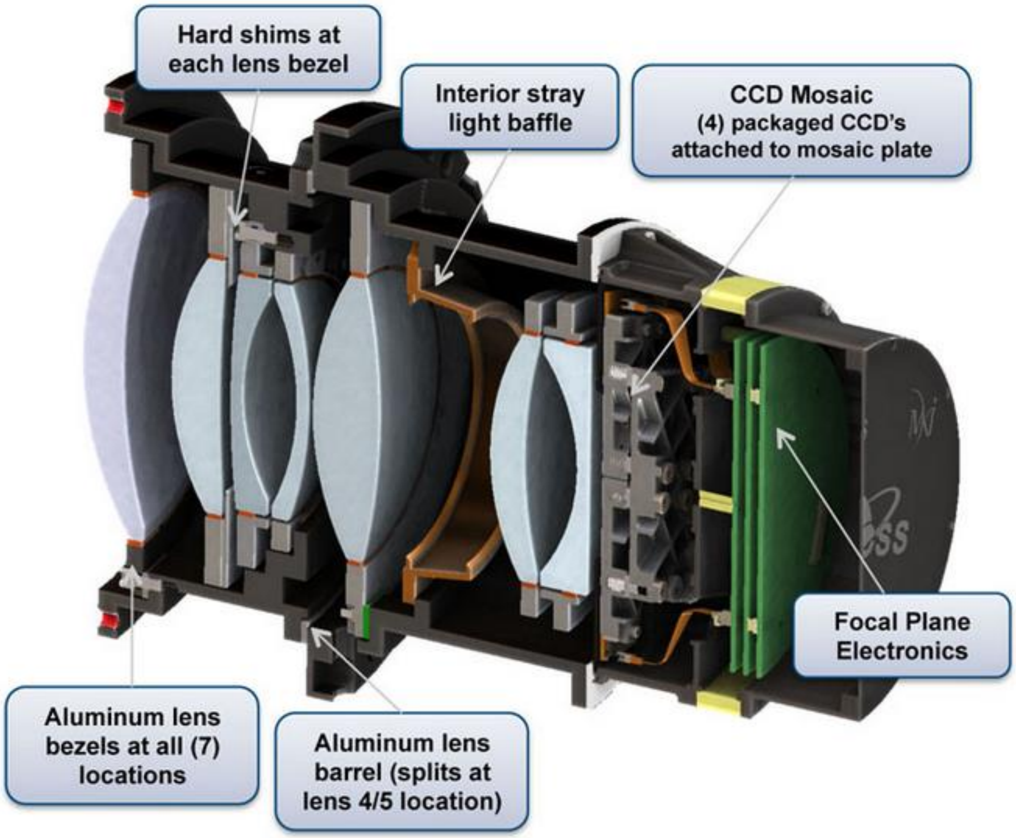


Figure 5: TESS Camera Detailed View

The next major part of the camera is the lens assembly. It is a seven element F/1.4 lens design which is made out of aluminum and utilizes silicone bonded lenses in aluminum bezels to achieve an effective collection area of 50 cm^2 after accounting for transmission losses. Its barrel serves a second duty as the heat path from the detector assembly to the lens hood.

The final piece of the camera is the lens hood which contains the stray light baffles and also serves as the main radiator. The stray light baffles are important because they eliminate extra light coming in from unwanted sources like the moon and the earth. The inside of the stray light baffle is also painted black which helps it serve as the radiator for the cameras.

5. Environments

The operational environments for TESS can be classified into three general groups. The first group will be the primary operational environments which is where all of the science data collection will happen. This is the most crucial orbit since it's where the operational requirements need to be met. The second group of environments can be called the launch and commissioning environments. In these environments the TESS instrument just needs to survive and provide limited functionality with the most important thing being that it arrives at its final operational station intact. The last group is the on-ground testing environments. These environments vary in purpose and condition from atmospheric testing of the cameras during integration to performance verification as well as thermal model validation while thermal vacuum testing. This section will primarily focus on the operational thermal environments with the others covered as needed in the rest of the paper.

The orbit which is designed for TESS is a unique High Earth Orbit (HEO). Its main criteria were to provide a stable thermal environment while also allowing for an all-sky survey using the instrument. The stable thermal environment is necessary because planetary detection signals using the transit photometry method are very small and any disturbance in the temperature of the instrument could result in a false detection of a planet. The TESS mission is a two year all-sky survey and its altitude needs to be stable over that time period in order to eliminate the need for extra propellant to perform station keeping. In order to keep the orbit altitude stable the orbit was designed to harness the moons gravity and this manifests itself with the orbit being 2:1 resonant with the moons orbit which means for every single moon orbit TESS orbits the Earth twice.

For the first year TESS will observe the northern hemisphere in thirteen two week segments while for the second year TESS will observe the southern hemisphere while experiencing an identical thermal environment. For those two weeks the observatory will face anti-solar +/-15° which helps to provide the stable thermal environment. The TESS orbit is highly elliptical and with a nominal perigee of 17 Re and an apogee of 59 Re. At its apogee TESS is farther from the Earth than the moon is which limits the thermal disturbances caused by the Earth infrared radiation as well as albedo.

The bulk of the orbit consists of High Altitude Science Operations (HASO) which is all but five hours of the 13.7 day orbit. During this five hour segment the spacecraft reorients and points the HGA toward the communications ground stations on the earth and downlinks the science data which was collected over the duration of the orbit. This reorientation produces the largest temperature disturbance while on orbit.

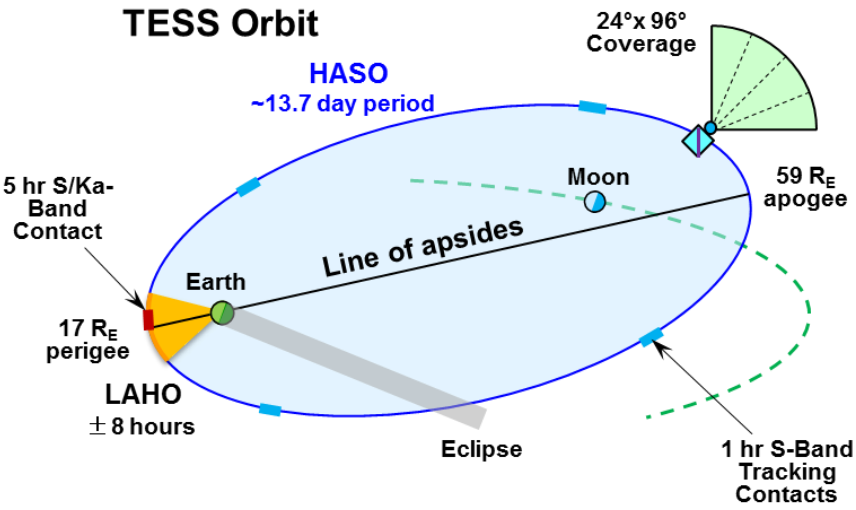


Figure 6: TESS Orbit

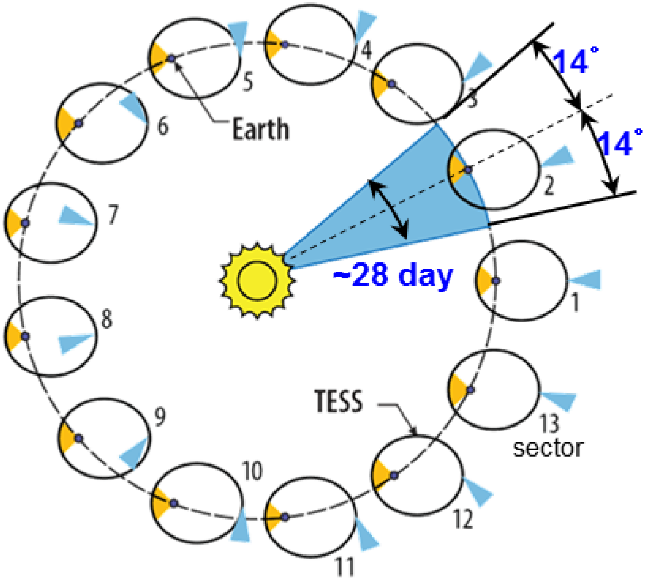


Figure 7: TESS Observation Sectors and with Observatory Orientation shown in blue

As shown above TESS is always facing the away from the sun while performing science in order to limit thermal disturbances on the cameras. However, there is still a natural environmental variation in the flux coming from the sun which causes variations in both the temperature of the spacecraft and the amount of heat coming through the sunshade which results in a change in temperature of the cameras. For this particular orbit the solar flux varies between 1354 W/m^2 at Earth's apogee and 1414 W/ m^2 at Earth's apogee. There are similar variations in Earth IR as well as albedo but they do have a noticeable influence the temperature of the observatory.

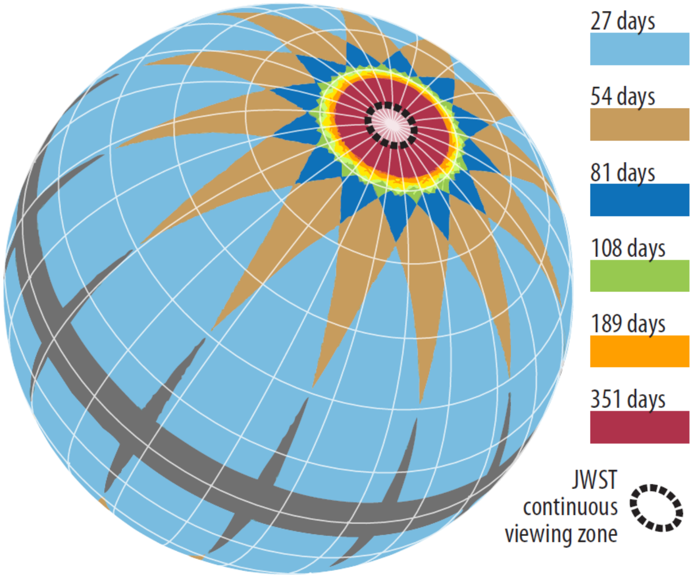


Figure 8: TESS Observation Sectors with Coverage Time Periods

6. Temperature Requirements

The TESS cameras have a strict set of temperature requirements which must be met in order for them to operate properly. They are shown below. The primary driving thermal requirement is the CCD temperature. In order to achieve the extremely low dark current levels required for detection of planets the CCD's need to be below -60 C. The primary feature of the TESS thermal design is that the system is passively cooled through the lens hoods, which means that if the CCD's are cold then everything downstream of them needs to be colder. This sets the lens operational temperature.

Table 1: Temperature Requirements

Components	Temperatures (°C)			
	Operational		Survival	
	Min	Max	Min	Max
Lens Assembly Average	-85	-65	-95	50
Optical Elements	-90	-60	-105	50
CCD	-95	-60	-100	50
FPE Boards	-40	55	-50	85
Camera Plate	-130	-20	-130	85
Lens Hood	-130	-60	-130	85

The secondary driving requirement is temperature of the focal plane electronics boards. Electrical components have set ranges which have to do with their internal structure and are set by the manufacturer. If you operate outside of these ranges then it is very likely that the component or board will not function properly and could even fail catastrophically. This heavily influenced the design of the detector assembly.

7. Thermal Design

The instrument thermal design philosophy centers around minimizing temperature disturbances on orbit as well as minimizing complexity and power draw. One way the instrument is minimizing power draw and complexity is to passively cool the CCD's. This reduces the complexity, cost, size, weight and power of the system. Usually when CCD's need to be kept as cold as the TESS CCD's they are cooled using thermoelectric coolers which would require extra power and control electronics. This additional power would require more radiator space which would lead to extra complexity, cost, size, weight and power to the system which we wanted to avoid. Other options like vapor cycle coolers would do the same thing.

Since the lens assemblies have no focus mechanism (also to simplify the system) they will operate properly in a relatively narrow temperature range of -85°C to -65°C and an optimal temperature of -75°C. Given that narrow temperature range and the uncertainties in thermal modeling a way need to be found to eliminate the estimated 15°C of design uncertainty. The way that is dealt with in the cameras is to cold bias the system below -85 C. This was chosen because there is a 10°C difference between the lens assembly average temperature and the CCD temperature. This means that even if the model is off by the worst case 15°C on the warm side the CCD and the lens would still meet their operational temperature requirements. However, in the most likely scenario the cameras will use offset heaters to raise the temperature of the lens to -75°C.

The main radiator responsible for cold biasing the system is the lens hood. With its black paint and high conductivity aluminum material it makes and ideal radiator. The outside of the lens hoods are covered in MLI with Silver Teflon tape underneath. In the case that we go through thermal vacuum testing and modeling validation and we find that the system is running warmer than expected we will use remove some or all of the

MLI covering the lens hoods to expose more radiator area covered in high-emissivity Silver Teflon tape.

In order to achieve the cold temperatures required for operation the TESS instrument needs to be shielded from the sun as well as the spacecraft. The CAS is covered in MLI as well as the bottom of the camera plate and the top of the spacecraft. The blankets are 15 layers of aluminized Mylar with Dacron mesh in between. The MLI insulates by providing additional radiation barriers in between whatever it's covering and the environment. Since there's no convection in space the blankets can be relatively slim, adding minimal bulk and weight while doing an excellent job. The CSA is also kept insulated from the spacecraft via titanium mounting posts. The titanium has a very low conductivity and a small cross section which provides a high thermal resistance but is still strong enough to satisfy the structural design requirements.

7.1 Detector Design

The detector assembly is a particularly challenging part of the instrument thermal design. This is because the focal plane electronics need to be operated at a temperature much different than the CCD but they are less than two inches away. The design thus needed to have essentially two different thermal zones. The first zone is the cold zone which contains the CCD's while the second zone is the warm zone containing the focal plane electronics boards. In to create the warm zone the design mounts the focal plane electronics on low conductance titanium standoffs to a low emissivity gold coated thermal shield. The two sections are also connected by a low thermal conductivity G10 spacer which serves to increase the thermal resistance between the two halves. This is not a traditional way of mounting electronics boards. Usually, boards are mounted as conductively as possible to a metal chassis in order to get the heat out as efficiently as possible. However, in this situation if we did that then boards would have gotten to cold and fallen outside their required temperature range. To complete the design the inside of the housing around the boards is black anodized which has a high emissivity in the IR in order to facilitate radiative heat transfer between the boards and the wall. This enables increased radiation heat transfer from the boards to the housing. The design helps achieve a balance of conduction and radiation between the boards and the housing. The cold side of the housing utilizes a copper thermal strap to thermally sink the CCD’s to the detector housing wall and thus keep them as cold as possible. The top of the detector then connects to the bottom of the lens assembly.

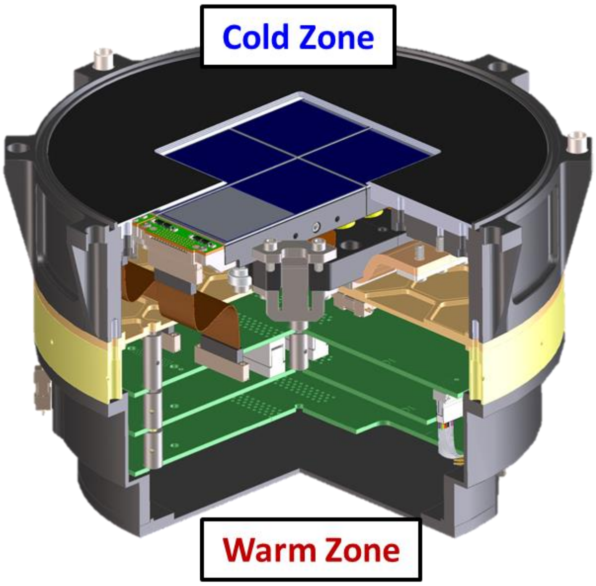


Figure 9: Detector Thermal Zones

7.2 Thermal Margins and Temperature Deratings

When designing a system for high thermal reliability it is important that to remember that predictions are usually not exactly correct. On top of that, during the testing process it is important to stress the parts so any parts that would fail later on in the life of the instrument fail during testing instead. To deal with this problem a system of thermal margins has been established. These margins vary from organization to organization but since TESS is a project funded by NASA Goddard Space Flight Center (GSFC) the margin formulas used will come from GSFC in combination with the NASA Gold Rules.

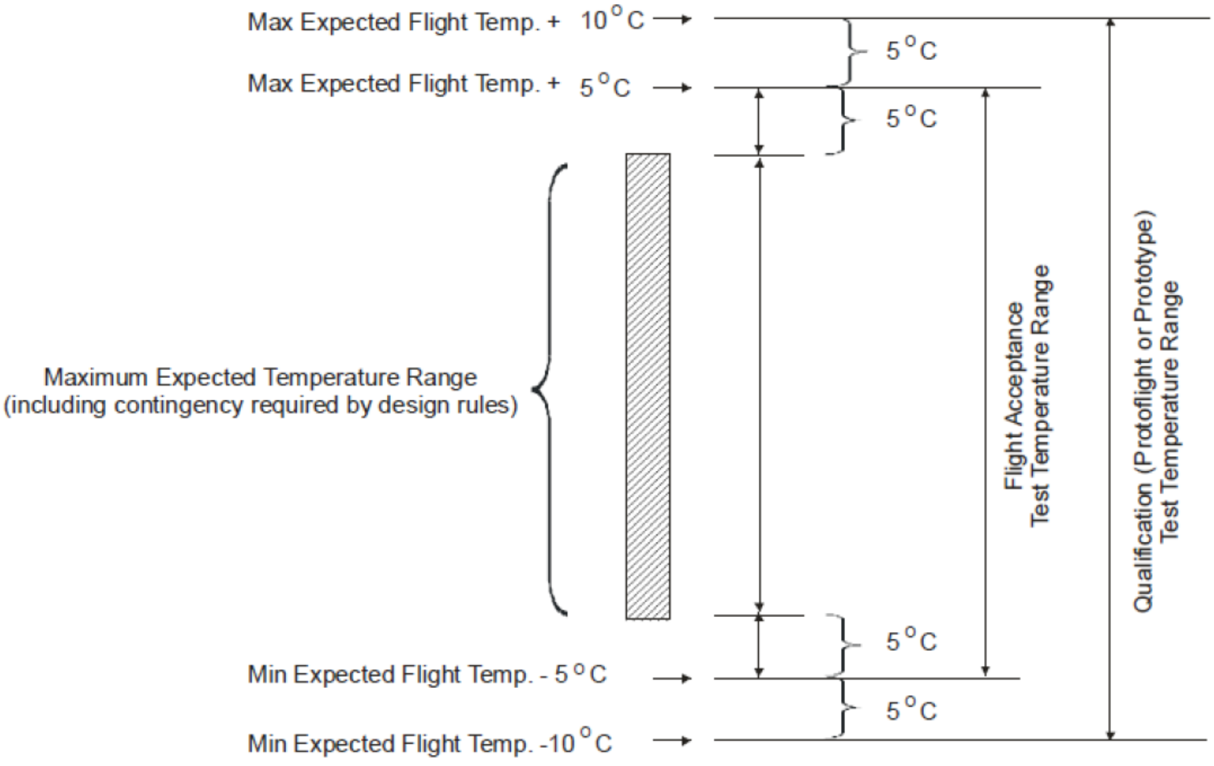
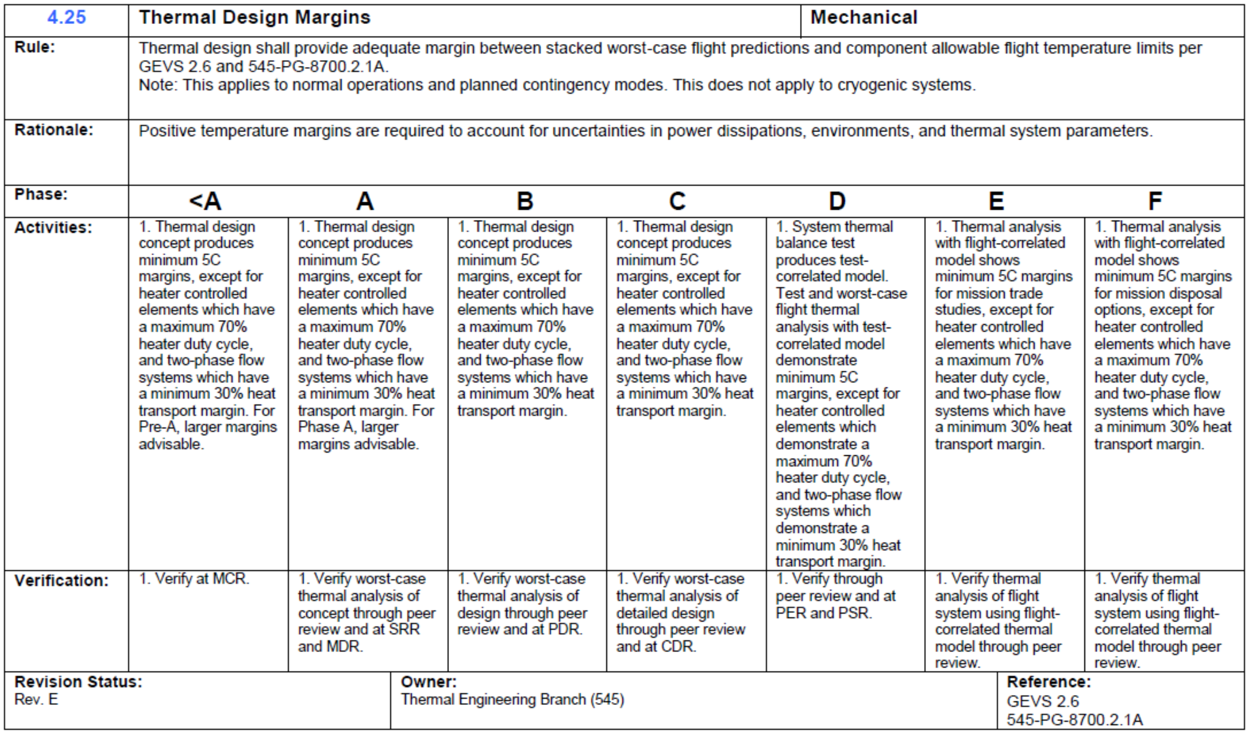


Figure 10: Thermal Design Margins from GSFC-STD-7000A

GSFC-STD-7000A is the General Environmental Verification Standard at NASA GSFC. It covers everything from electromagnetic interference and compatibility to structural design margins as well thermal margins. For thermal environment verification TESS is being run as a Protoflight mission which corresponds to a certain level of testing. This means that the program will not be using a qualification unit which will not fly followed by a flight unit. For programs which perform testing on a non-flight unit before a flight unit it allows the flight unit to undergo less stressful testing which can be advantageous under certain scenarios.

Since the TESS program is a Protoflight program we will be testing 10°C beyond the model predictions plus model uncertainty as shown by the table above. The instrument thermal design will incorporate the minimum 5°C margin as well as an additional 5°C margin. This means that the instrument will be tested 20°C beyond model predictions.

Table 2: NASA Gold Rules on Thermal Model Uncertainty Margins



4.25	Thermal Design Margins				Mechanical		
Rule:	Thermal design shall provide adequate margin between stacked worst-case flight predictions and component allowable flight temperature limits per GEVS 2.6 and 545-PG-8700.2.1A. Note: This applies to normal operations and planned contingency modes. This does not apply to cryogenic systems.						
Rationale:	Positive temperature margins are required to account for uncertainties in power dissipations, environments, and thermal system parameters.						
Phase:	**<A**	**A**	**B**	**C**	**D**	**E**	**F**
Activities:	1. Thermal design concept produces minimum 5C margins, except for heater controlled elements which have a maximum 70% heater duty cycle, and two-phase flow systems which have a minimum 30% heat transport margin. For Pre-A, larger margins advisable.	1. Thermal design concept produces minimum 5C margins, except for heater controlled elements which have a maximum 70% heater duty cycle, and two-phase flow systems which have a minimum 30% heat transport margin. For Phase A, larger margins advisable.	1. Thermal design concept produces minimum 5C margins, except for heater controlled elements which have a maximum 70% heater duty cycle, and two-phase flow systems which have a minimum 30% heat transport margin.	1. Thermal design concept produces minimum 5C margins, except for heater controlled elements which have a maximum 70% heater duty cycle, and two-phase flow systems which have a minimum 30% heat transport margin.	1. System thermal balance test produces test-correlated model. Test and worst-case flight thermal analysis with test-correlated model demonstrate minimum 5C margins, except for heater controlled elements which demonstrate a maximum 70% heater duty cycle, and two-phase flow systems which demonstrate a minimum 30% heat transport margin.	1. Thermal analysis with flight-correlated model shows minimum 5C margins for mission trade studies, except for heater controlled elements which have a maximum 70% heater duty cycle, and two-phase flow systems which have a minimum 30% heat transport margin.	1. Thermal analysis with flight-correlated model shows minimum 5C margins for mission disposal options, except for heater controlled elements which have a maximum 70% heater duty cycle, and two-phase flow systems which have a minimum 30% heat transport margin.
Verification:	1. Verify at MCR.	1. Verify worst-case thermal analysis of concept through peer review and at SRR and MDR.	1. Verify worst-case thermal analysis of design through peer review and at PDR.	1. Verify worst-case thermal analysis of detailed design through peer review and at CDR.	1. Verify through peer review and at PER and PSR.	1. Verify thermal analysis of flight system using flight-correlated thermal model through peer review.	1. Verify thermal analysis of flight system using flight-correlated thermal model through peer review.
Revision Status: Rev. E		**Owner:** Thermal Engineering Branch (545)				**Reference:** GEVS 2.6 545-PG-8700.2.1A	

7.3 Offset Heater Design

When designing a lens for a camera without an active focus mechanism such as the TESS lens one needs to have a temperature range in mind. This is because the position of the CCD will change relative to the lens over temperature depending on the material used for the lens housing. The TESS program chose aluminum for lens housing material because of its relatively low density to stiffness ratio and its ease of procurement and machinability. However, aluminum also has a coefficient of thermal expansion of around 22 µm/m, which is large for a metal. Due to the shift in position of the CCD relative to the lens assembly performance over temperature, the temperature range for the lens assembly was set at between -65 and -85°C. Even though there's a range over which the lens would meet requirements, the optical team has stated that the performance would be best at -75°C. For this reason along with the fact that the CCD's need to be kept below 60°C the camera lens barrels are cold biased below their operational range and outside the thermal uncertainty margin of 10°C. The object of this is to allow the temperature of the cameras to be controlled by a heater on orbit instead of depending purely on temperature predictions.

The TESS camera heaters are known as offset heaters since the cameras start at a temperature offset from their optimal operational temperature. It was important that the heaters emit very low electrical noise so linear regulators were chosen to take 15 V power from the DHU and regulator the current flow. It's also important that the heaters have some redundancy for reliability reasons so there are three of them. The optical team also did not want gradients induced in the lens barrel so the heaters are spaced 120° around the lens barrel. The heaters are run open-loop with a human on the ground setting the current flow rather than having a closed loop control system in place to automatically adjust the temperature by adjusting the current. The diagram of the heaters is shown below.

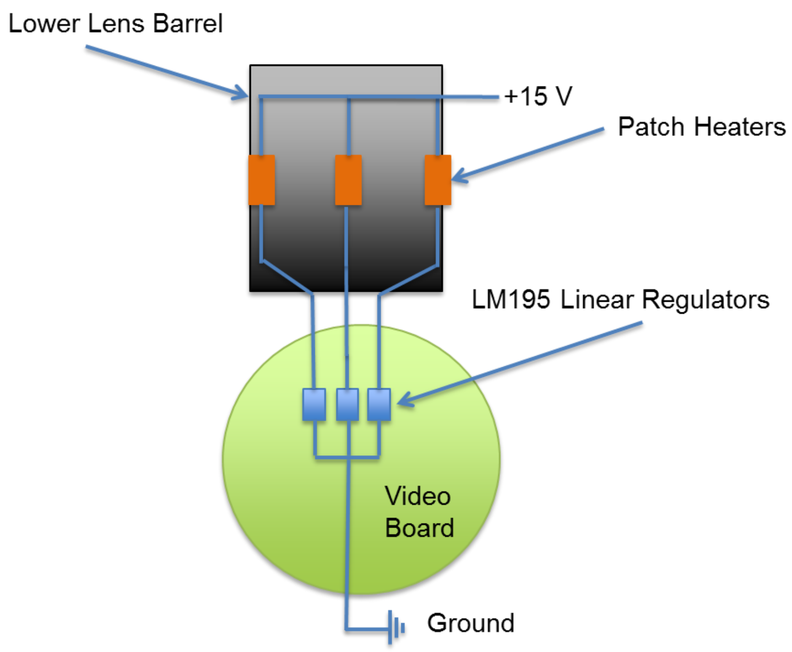


Figure 11: Offset Heater Diagram

7.4 Survival Heater Design

There are two possible states for the instrument to be in while on orbit: operation and survival. During operation the power that will keep the instrument within its operational range will be the power dissipated by the camera electronics along with the offset heaters. The thermal design of the system will be configured with these power numbers in mind. During the survival state both the DHU and the camera electronics will be off. Therefore the instrument needs a second source of heat in order to maintain its survival temperatures. That's where the survival heaters come in. For most missions the survival heaters are controlled by a set of mechanical thermostats which are actuated by an internal bimetallic switch. The thermostats have a "dead-band" range whereby at the lower temperature they turn on and once they reach the higher end of the temperature range, they then shutoff.

The primary reason for having these thermostats is because the power coming to the survival heaters is usually unregulated spacecraft battery voltage. For TESS the spacecraft battery voltage can vary from between 20 V all the way to 35 V. Given the nature of the survival heaters as the backup power source keeping the instrument from failing due to exceeding the low temperature limits of electronics and camera lenses it is important to size the survival heaters for the lowest battery voltage. The TESS survival heaters require 11.1 W of survival heater power per camera for 8.1 W camera electronics operational dissipation. This means that they would need to be 36 ohm resistance heaters. At the max spacecraft voltage they would surely overheat the cameras, not to mention waste excess power by dissipating 34 W! By having a thermostat most instruments get around this risk and control the flow of power to their survival heaters. The thermostats result in a higher degree of safety for spacecraft and instrument by allowing the heaters to dissipate on average over time the same amount of power regardless of spacecraft voltage.

For the TESS instrument, a method of controlling the power to the survival heaters was necessary but there was significant concern that the switching of the thermostats on and off would cause temperature fluctuations in the other cameras. This would happen in a scenario where one camera is turned off in the event of a software or hardware malfunction for that particular camera but the other cameras would still be on and taking science data. As stated previously there is a desire to keep temperature fluctuations to a minimum. Another reason to avoid thermostats was because they would need to be placed on the detector housing which would be colder during operation than in survival mode. This would cause the survival heaters to cycle during operation which would cause temperature fluctuations on the camera. Ideally, the thermostats and heaters would have been placed on the camera electronics boards but there wasn't any room there. This would have simplified the design to a large extent but the electrical engineers were strongly opposed to it.

Therefore, an alternative design was formulated which will use power regulators onboard the DHU. These regulators will supply 15 V power regardless of whatever the voltage is coming from the spacecraft. The way the survival heaters are enabled or disabled is through a comparator switch. This switch senses the current going into a camera. If that current falls below a certain threshold it powers the survival heaters on. A diagram of the circuit is shown below.

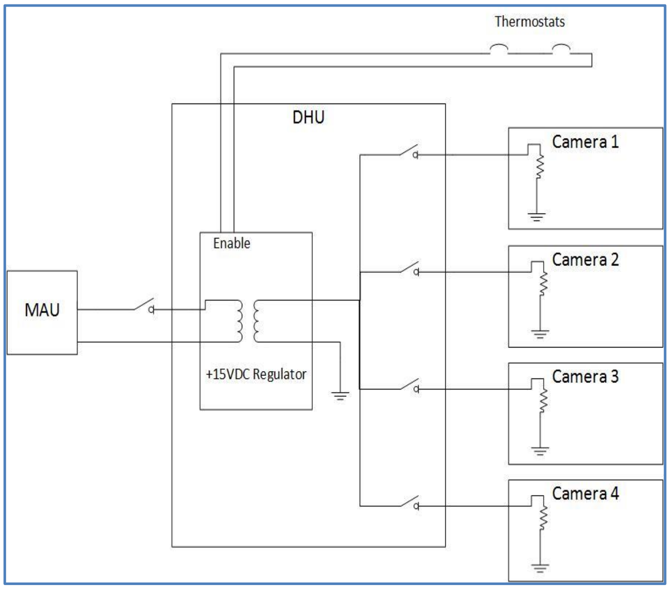


Figure 12: Survival Heater Circuit Diagram

The survival heaters are thin film kapton supplied by Tayco® and are placed on the inside of the detector housing. In order to prevent overheating while on the ground the voltage regulators have enable lines which are controlled by a set of two thermostats in series on one of the cameras.

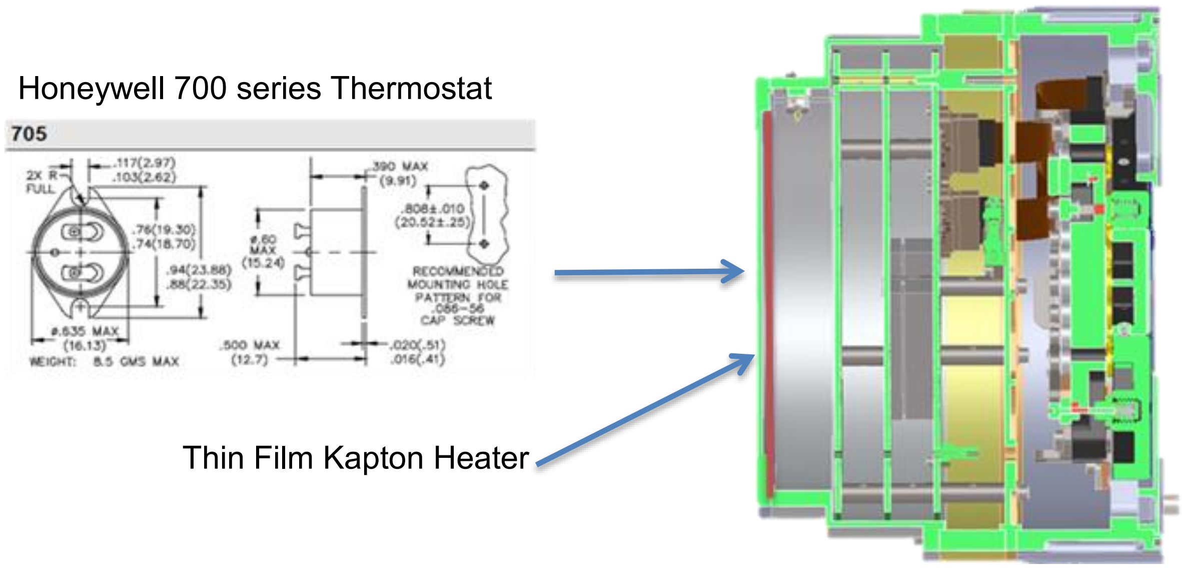


Figure 13: Survival Heater and Thermostat Placement

7.5 Temperature Monitoring

When the instrument is on orbit it will be very important to have knowledge of the camera temperature. The main reason for this is to monitor the health of the system and make sure components are within their temperature ranges. During operation of the cameras the TESS instrument will be able monitor ten different RTD's on each camera. The most important ones are on the camera lens barrel. Although they are not used in a closed-loop control system with the offset heaters, they are still used to inform the scientists on the ground what the temperature of the lens is. In order to set the temperature of the lens an offset heater power setting will be selected and then manually iterated upon if necessary. The other RTD's are of slightly less importance but will be quite useful for correlating the model on orbit and in the thermal vacuum chamber. Most of the RTD's have backups so if one fails on orbit the temperature can still be found.

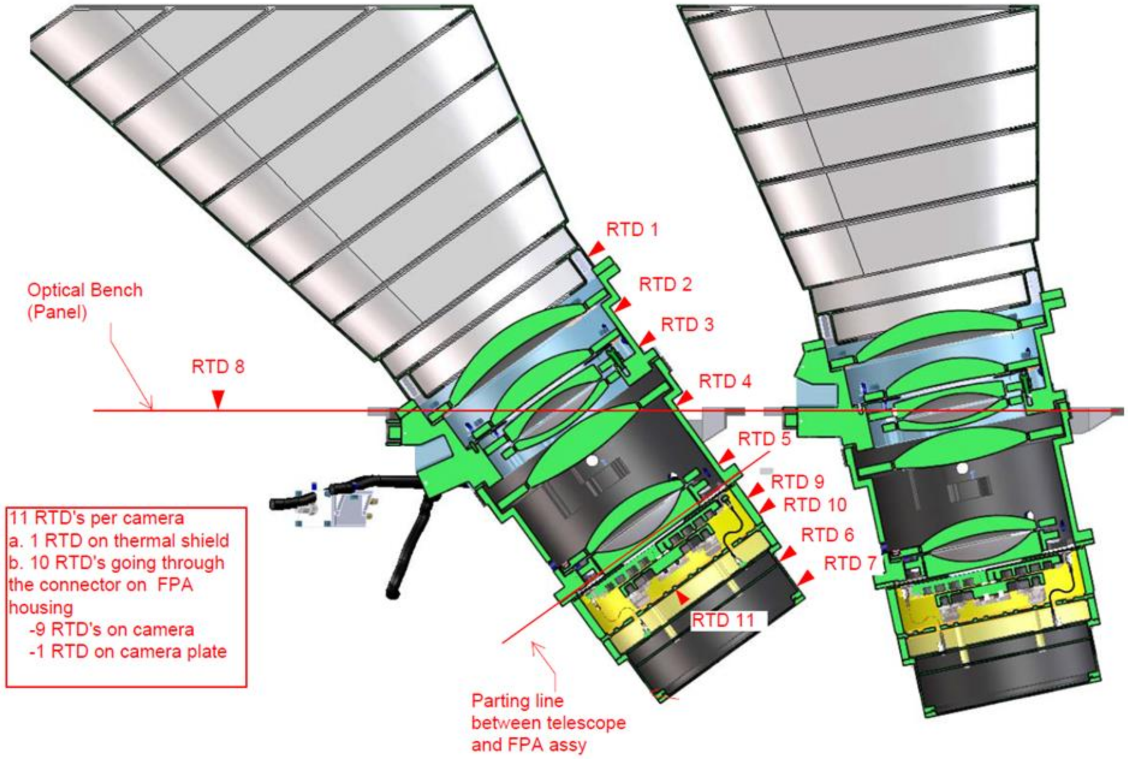


Figure 14: Camera RTD Locations

There is a second set of RTD's which are shown below. They are located on the underside of the camera plate and their purpose is model correlation on orbit while also helping to understand how temperature changes in the camera plate relate to shift of the pointing angles for the cameras. There is a final set of RTD's which read by the spacecraft MAU. RTD's read by the MAU are needed because if the cameras and DHU are off then the other two sets of RTD's cannot be read. This set consists of a single RTD on the back of each camera's detector housing.

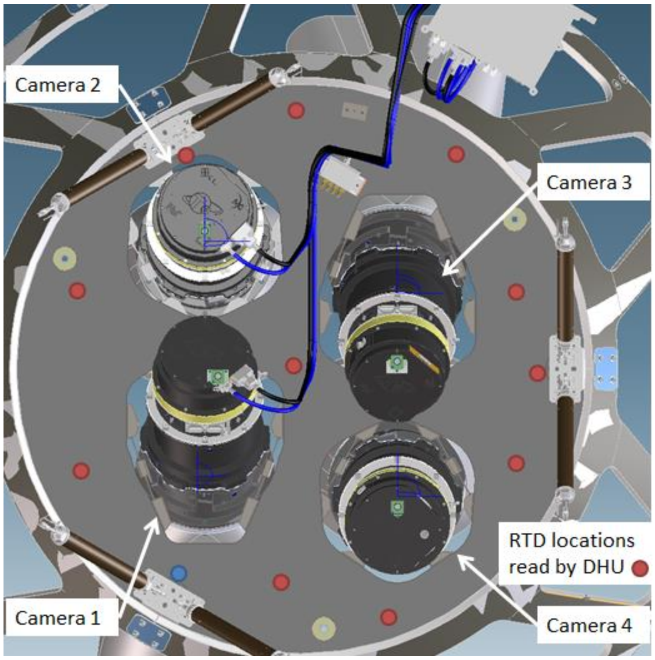


Figure 15: Camera Plate RTD Locations

7.6 Design Flexibility Using Thermal Control Surfaces

The TESS cameras have a range of power dissipations from 4.8 W to 8.1 W. This is caused by uncertainty in the electrical design of the system. Once the electronics boards are built and tested the power dissipations will be better known and will remain relatively constant over the life of the mission. Due to the high uncertainty in possible power dissipation the thermal design needs to be flexible. The main way chosen to deal with the power uncertainty is by allowing for the possibility of removing MLI and exposing more surface area of the CSA directly to deep space. This effectively increases our radiator area and allows us to dissipate more power while achieving similar temperatures. Underneath the MLI is white paint which has a high emissivity and provides a good radiator surface. Our MLI blankets are 15 layer blankets with StaMet or Aluminized Kapton outer layers and aluminized Mylar inner layers. StaMet was chosen due to the unique combination of electrically dissipative properties and its relatively low solar absorptivity to IR emissivity values compared to the other statically dissipate outer MLI layers such as black carbon coated Kapton. It was also chosen over Germanium coated black Kapton because of its reduced susceptibility to damage due to humidity exposure.

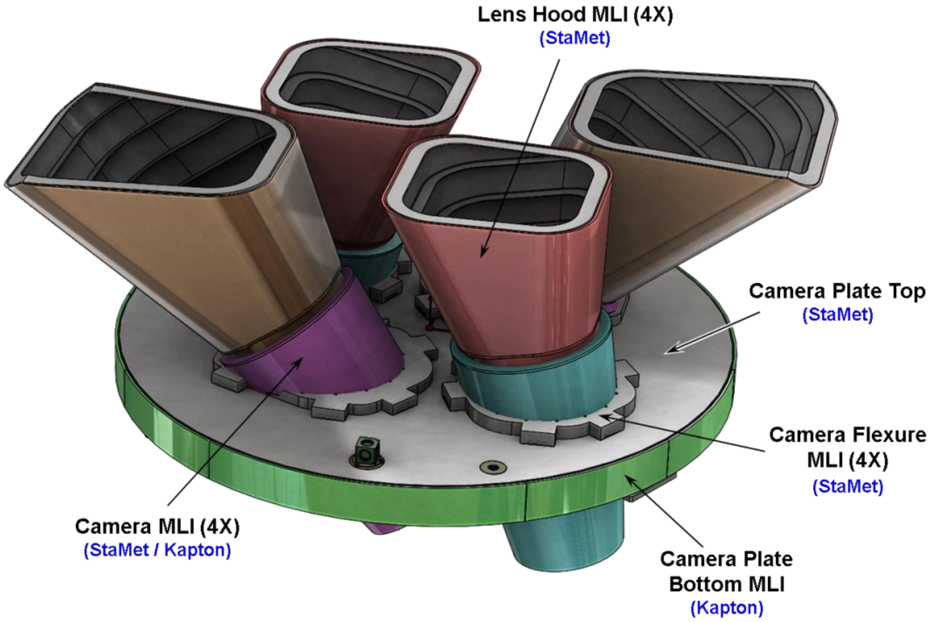


Figure 16: TESS Baseline MLI Configuration

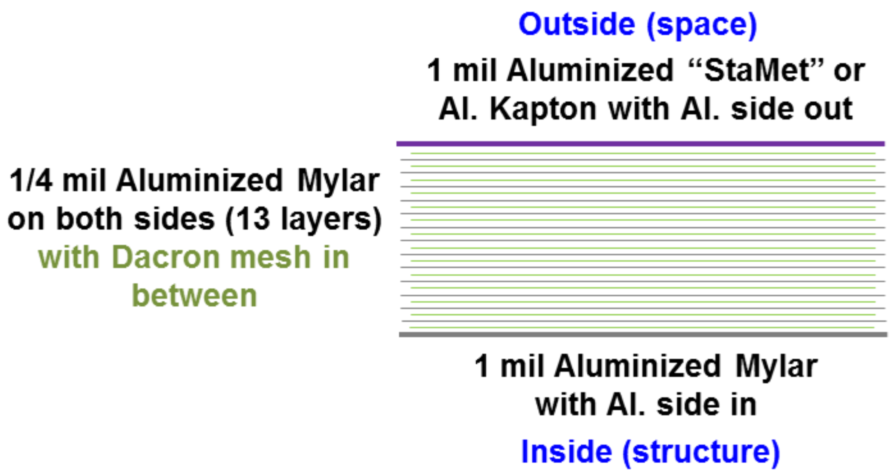


Figure 17: MLI Blanket Layup

8. Thermal Modeling

When designing a system such as the TESS observatory it is important to be able to capture the level of detail necessary to predict temperatures accurately. If the temperatures are not predicted accurately then the system will not work as designed and could even fail to operate at all. If the CCD's are not kept cold enough then the signal to noise ratio will be too low and the system will not be able to detect planets. If the camera electronics boards are too warm then the junctions of the electrical components could overheat and the system could destroy itself. On the other hand, if the system gets too cold then the electronics could cease to function due to either critical failure of electrical components because of CTE mismatches between the components and the board or a soft failure like not meeting performance requirements.

For the thermal modeling of the TESS instrument we have selected a piece of software called Thermal Desktop® which is produced by a company named Cullimore and Ring Technologies located in Boulder, Colorado. It is a graphical interface for run as an add-on to AutoCAD which allows one to create graphical representations of a thermal system. It is one of several industry standard tools which allows us to trade thermal models easily with our mission partners. That way when Orbital ATK or SpaceX needs to build a thermal model a thermal model of the instrument can be sent to them and the respective organization can integrate and use the model easily without having to build their own model. The reverse is also true and can be used as a way to validate the model and to make sure everyone is on the same page. This is one reason why the tool was selected as the one to do the modeling of the system. The tool also incorporates Monte-Carlo ray tracing for radiation view factor calculation as well as heating rate calculations. The tool utilizes their add-on radCAD® to perform that operation, converts the view factors to radiation conductors, combines the radiation conductors with the pure conduction conductors, makes a conductor network and then sends it to their SINDA® solver which uses the finite difference method to solve the heat transfer equations.

In order to actually build the model one starts with the CAD model and builds a combination of simple shapes as well as conductors, nodes and adds physical properties. Below is a picture of the TESS CAD model followed by a picture of the thermal model.

Figure 18: TESS CSA and CAS CAD Model

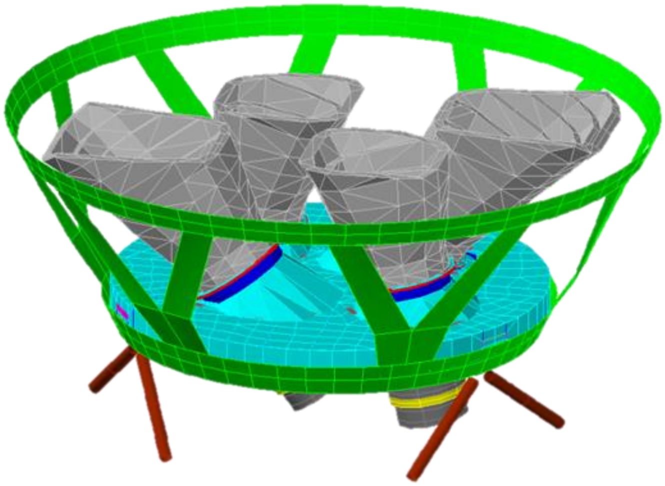


Figure 19: TESS CSA and CAS Thermal Model

The most obvious differences one notices about the CAD model vs. the thermal model is that the CAD model is much, much “smoother” looking than the thermal model. This is because the thermal model must be discretized into a reasonable number of surfaces in order for it to solve in a relatively short amount of time. The process to go from full CAD model to thermal model can be characterized as a process of selective simplification. One needs to make decisions on where detail is needed for overall accuracy of the model and how much detail is needed to determine whether or not a component is exceeding its temperature limits.

One of the most common ways of simplifying an object is taking a 3D object and representing it as a 2D surface. This is very common for objects which are very thin in relation to their overall characteristic dimensions or for objects which have a very high conductivity. For example as shown below the lens hoods are 0.080” thick but have perimeters of over 20”. The combination of small thickness relative to characteristic dimensions with low heat fluxes through the thickness means there is no need to represent the thermal gradients in the thickness of “Z” direction. This halves the number of nodes needed to represent this object.

Figure 20: Lens Hood CAD Model

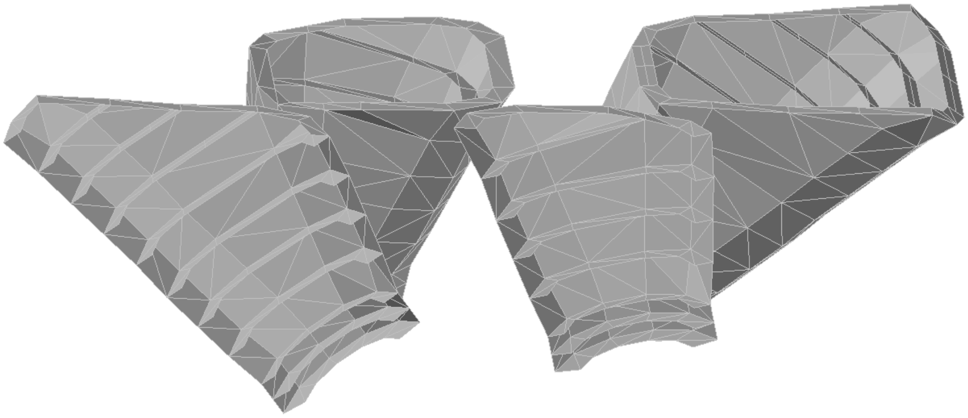


Figure 21: Lens Hood Thermal Model

Another way of reducing the level of detail in a thermal model is to take objects that are primarily conduction and represent them as pure conductors without any radiation properties. A very good example of this is the use of conductors to represent the camera flexures. The camera flexures were modeled in a separate finite element analysis software and found to have a conductance of 61 W/°C. Since the flexures are made out of Invar 36, a material with little sensitivity to temperature we don’t care about the temperature of them in great detail. The surface area of the flexure is low and they are covered with MLI which means their radiation impact will be small. This allows us to eliminate the detail of modeling the entire camera flexure and approximate it with conductors connecting the camera barrels to the camera plate.

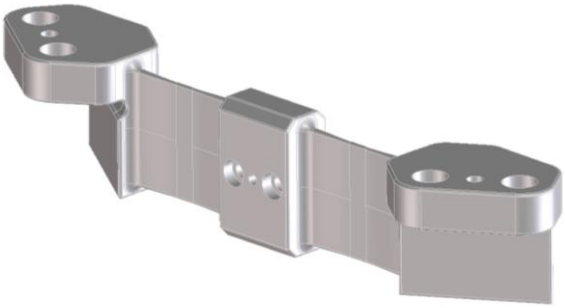


Figure 22: Camera Flexure CAD Model

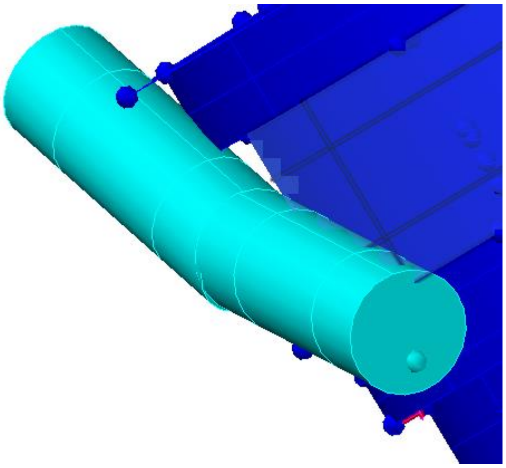


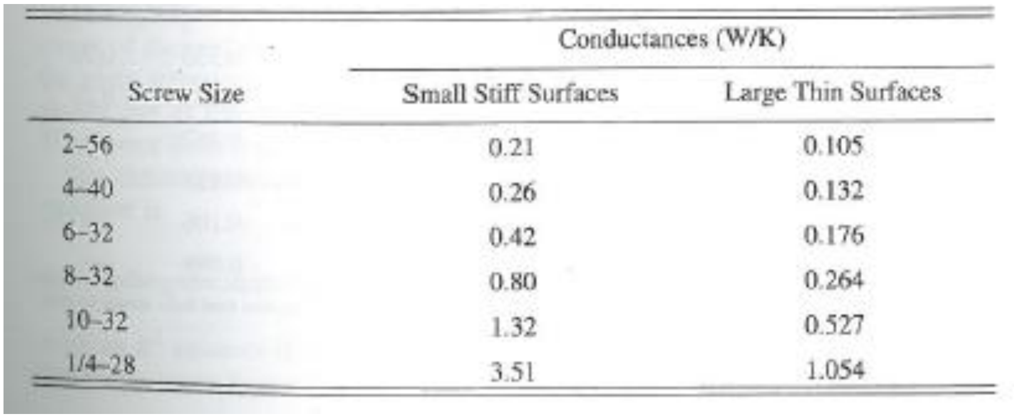
Figure 23: Camera Flexure Thermal Model

A similar technique has been applied all over the model to represent bolted joints. Since one doesn’t really care about the actual temperature of the bolts it’s very easy to use a conductor to represent the thermal connection between the two surfaces that the bolt is joining. For the thermal conductance between two joined surfaces the thermal resistance is determined by a few things. The primary heat path is through the area around the bolt and the factors determining the size and conductance of that area are surface roughness, material stiffness, hardness, and size and torque of the bolts or screws used to join the surfaces together.

When one zooms in on a material down to the microscopic level one can see that surfaces of materials which appear smooth to the naked eye are actually quite rough. If a material is relatively rough than the actual contact areas between two surfaces will be smaller than the contact area between two surfaces which are smoother. A smaller contact area means the conductance will be lower.

Thermal conductance at interfaces really only happens around the bolted joints. This is because a certain amount of pressure is needed to create the high thermal contact zone. This generally extend to an area roughly between roughly the bolt body diameter and double the bolt head diameter. The actual size of this contact area is influenced by the stiffness of the material and the design. For thinner, more compliant materials and designs the clamped area is lower and thus the thermal conductance is also lower. For designs which use stiffer materials and are thicker the clamped area tends to be larger and thus the thermal conductance is higher. An example of a thick, stiff part of this design is the camera barrel flanges which are 0.25” thick and bolt together. For this model the TRW thermal interface resistance guidelines have been used which can be found in the “Spacecraft Thermal Control Handbook” and are shown below.

Table 3: TRW Thermal Interface Conductances



Screw Size	Conductances (W/K)	
	Small Stiff Surfaces	Large Thin Surfaces
2–56	0.21	0.105
4–40	0.26	0.132
6–32	0.42	0.176
8–32	0.80	0.264
10–32	1.32	0.527
1/4–28	3.51	1.054

8.1 Thermal Interface to Spacecraft

Since the spacecraft and instrument are being engineered by separate entities it is important to control the interface between the two pieces of hardware. For this reason a document call the Mechanical and Thermal Interface Control Document (MTICD) was created which controls the mechanical and thermal interfaces between the spacecraft and the instrument. The mechanical part of the document specifies interface dimensions, instrument mass, cable routing, center of mass, interface fasteners and launch vibration loads among many other things. The thermal part of the document specifies assumed temperature ranges of the spacecraft, thermal resistance between instrument and the spacecraft, temperature range of the spacecraft on orbit, surface thermal-optical properties, MLI blanket specifics and as well as software to be used for analysis.

A draft of this document was created soon after the program was funded and has gradually evolved over time just as the design has based on thermal best practices and increased knowledge of the system. For example, originally instead of a thermal resistance between the instrument and the spacecraft coupled with spacecraft temperature ranges forming thermal link between the instrument and spacecraft, a requirement of total heat transfer was levied on the spacecraft. This was one of the first things that changed after the author of this paper read the document. One can easily see that this doesn't make any sense because the spacecraft only controls one part of the heat transfer equation. The spacecraft can only control its thermal resistance to the instrument. For this reason the MTIC now specifies a thermal resistance of "at least 10^{o}C/W at each of the three mounting locations." In addition the document specifies that the top surface of the spacecraft will be covered in MLI, its effective emissivity of 0.05 and the outer surface properties of vapor deposited aluminum on Kapton®.

In early sensitivity studies the spacecraft team showed that the instrument's temperature had little impact on the spacecraft's temperature with the above measures put in place so they were able to put in place a range of temperatures which the spacecraft could stay within. The temperatures specified during operation are between 0°C and 40°C and are specified as at the top deck of the spacecraft. During survival scenarios the temperature range expands to -10°C to +40°C. These temperature ranges along with a thermal model of the CAS supplied by the spacecraft thermal engineer allowed the instrument team to build a thermal model of the instrument and surround it with an accurate thermal model of the CAS while maintaining the simplicity of using boundary nodes and structure for the rest of the spacecraft. This cuts down on node count which reduces model run times while making sure that the cases bound the problem.

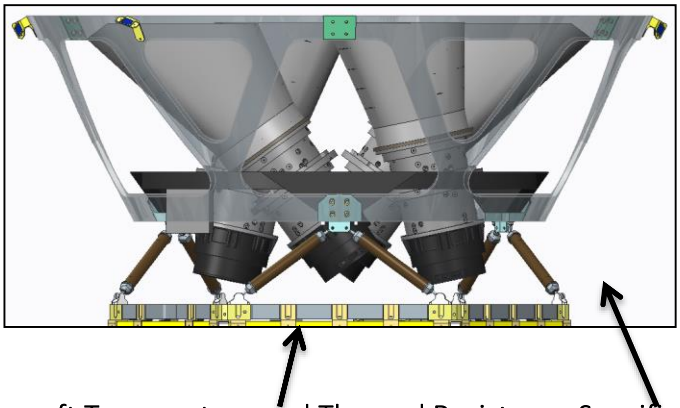


Figure 24: Spacecraft Temperature and Thermal Resistance Specification Locations

In the MTICD special attention was paid to blanket construction and orientation because of the need to keep the CCD’s cold. The blankets on the sunshade are there to limit heat transfer from the sun while the blankets on the top of the spacecraft as well as the bipod struts limit heat transfer from the spacecraft.

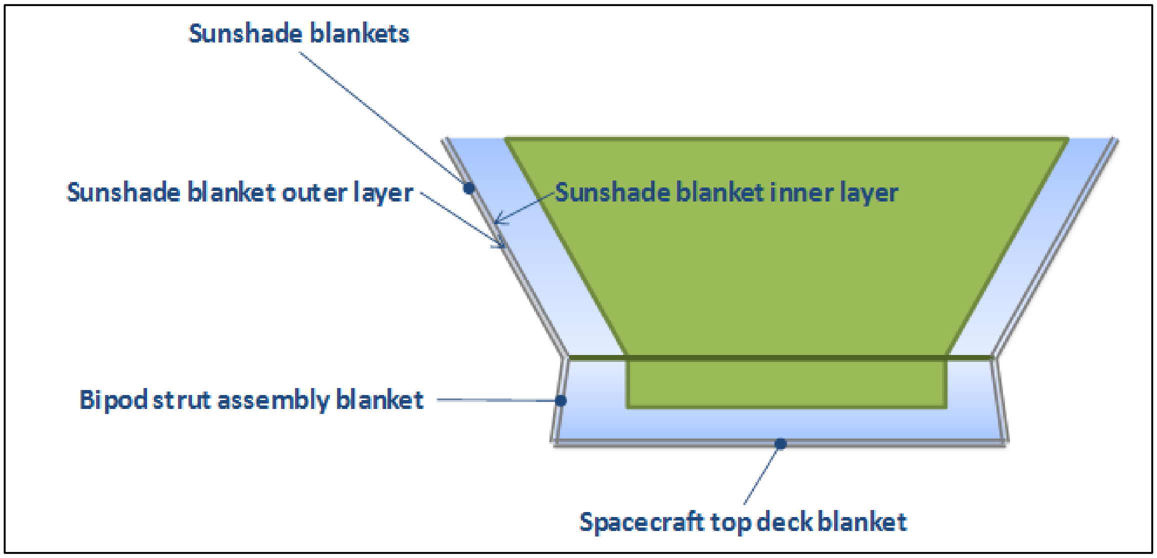


Figure 25: MTICD Blanket Locations

The sunshade is covered in two separate MLI blankets. One blanket is on the outside of the sunshade and one is on inside. The exposed surfaces are covered in StaMet® which is manufactured by the Dunmore Corporation. StaMet® was chosen because it has a low solar absorptivity to infrared emissivity ratio, does not exhibit changes in properties over time, is statically dissipative and is not susceptible to damage due to humidity exposure. A low solar absorptivity to infrared emissivity ratio is important because it lowers the temperature of the blankets when they are exposed to the sun which reduces the heat transfer through them which then reduces the thermal disturbance on whatever is behind the blanket. It's also important that the MLI material's properties do not change over the course of the mission. The most popular MLI outer surface material for many years was aluminized-Kapton but one of the drawbacks of it was the fact that over time in exposure to UV rays it begins to break down and its solar absorptivity increases. This change impacts expected temperature ranges and makes the thermal design more difficult. It is also important that the outer surface of the MLI be statically dissipative so it doesn't build up charge over the life of the observatory. Static charge can sometime build up and cause electro-static discharge which can be a danger to electronic equipment. There is one material, vapor deposited germanium on black Kapton which fulfills all of the previously listed requirements but it is susceptible to damage from humidity. This led us to StaMet which has solar absorptivity to infrared emissivity ratio of 0.56/0.76.

In addition to specifying the outer surfaces of the MLI blankets around the sunshade, the instrument has asked the spacecraft to further limit heat transfer between the two MLI blankets by specifying the innermost layers of each MLI blanket as vapor deposited aluminum on Kapton. The vapor deposited aluminum side of aluminized kapton has a much lower emissivity of around 0.05 than the kapton side at 0.83. This reduces the heat transfer to the inner MLI blanket and thus the instrument.

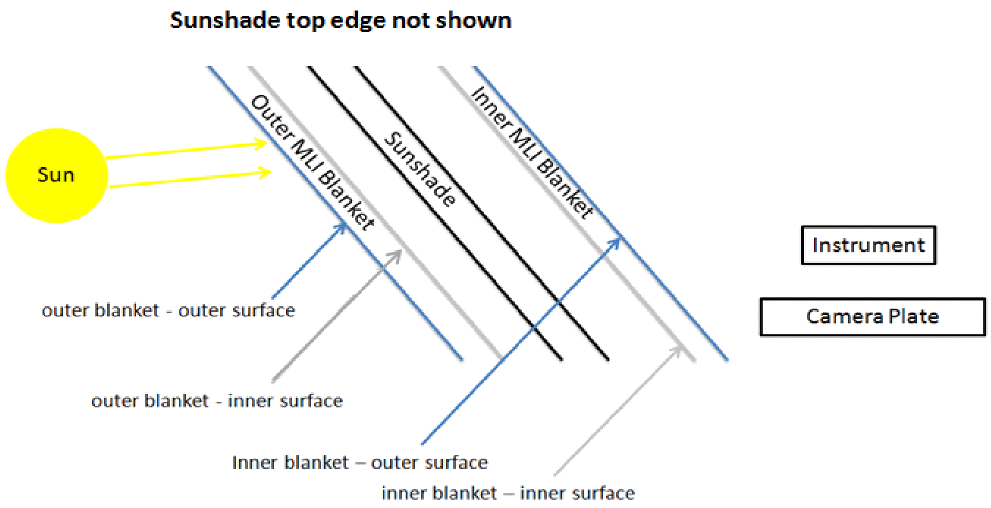


Figure 26: Sunshade Blanket Structure

8.2 Analysis Cases

When performing thermal analysis it is important to be efficient in one's analysis. A program has a finite amount of time and money and it is the engineer's job to execute in as efficient a manner as is possible while ensuring the quality and performance requirements are met. For thermal engineering this means creating a set of bounding cases which envelope the most extreme conditions. This means identifying a hot and cold bounding cases for operational and survival. For the TESS instrument, given our large range of possible FPE baselines power (4.7 W to 8.1) it was necessary to develop four operational cases. Even though the range of expected power is large, it is only unknown at this point. Once the boards have been manufactured and tested their power will remain relatively constant over the life of the boards and on-orbit. The analysis of four cases shows not only that the design can accommodate a large range of powers but also the expected variation for a given power the life of the instrument.

For the TESS instrument during operation there are a number of conditions and variables to change in order to come up with a bounding case. Solar flux, spacecraft temperature and observatory tilt angle have the largest impact on instrument temperature during HASO. Solar flux variations are important because more or less solar flux means more or less heat coming through the sun shade causing temperature variation in the instrument. Luckily this happens on yearly cycles and not faster than that. Spacecraft temperature has an impact on instrument temperature because its sets the boundary condition for conduction and radiation. Sensitivity studies have shown that For the 40°C temperature variation provided by the spacecraft the instrument changes temperature by about 5°C. Spacecraft tilt angle also has an impact on instrument temperature because at higher spacecraft tilt angles more solar radiation hits the sunshade and thus hits the instrument. Two factors that don't have a significant impact on instrument temperatures during HASO are Earth IR and Albedo. They have been included for completeness but at TESS's high altitude their influence is negligible. As one can see in the figure below even in a GEO orbit which is only at 42,164 km their flux is nearly 0, especially when comparing it to the solar flux at greater than 1300 W/m^2. At TESS's minimum altitude of over 108,000 km it is easy to see that the Earth has little influence on TESS's temperature.

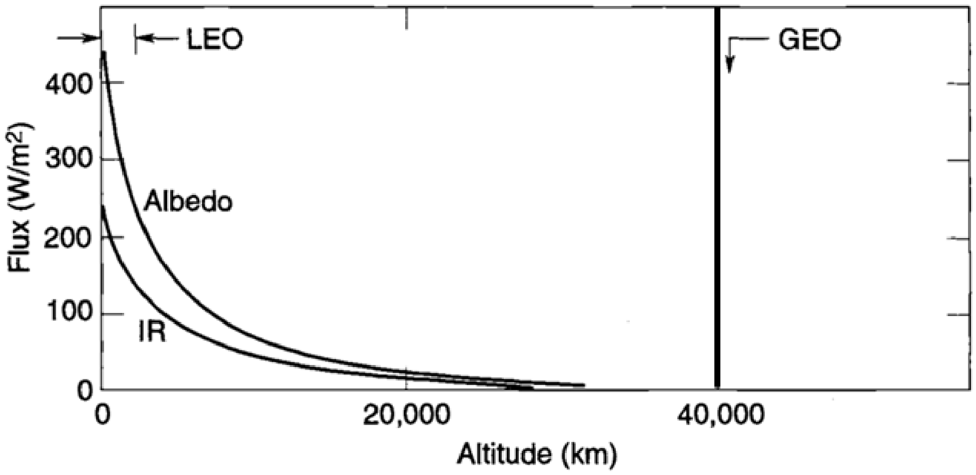


Figure 27: IR and Albedo at Various Orbital Altitudes

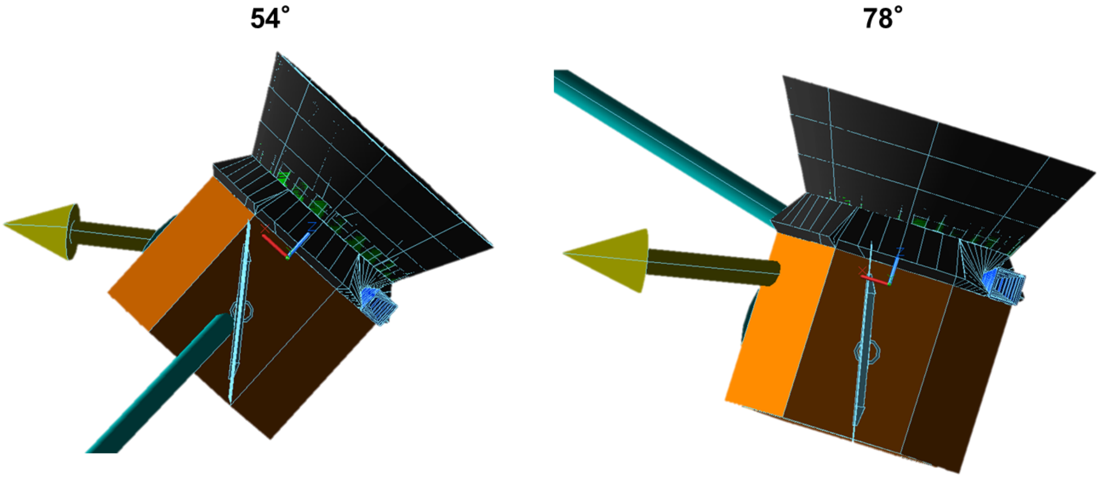


Figure 28: Spacecraft Tilt Angle with Solar and Earth Vectors

When TESS downlinks its data to earth it has to re-orient to point its high gain antenna (HGA). This can cause a variety of sun angles on the spacecraft and sunshade. However, the sun will never go into the sunshade and the change in orientation happens in a matter of minutes (much faster than the instruments ~13 hour time constant) so it was easy to develop bounding cases. The instrument team worked with the spacecraft team to come up with three possible solar angles during LAHO transmits that would envelope the problem.

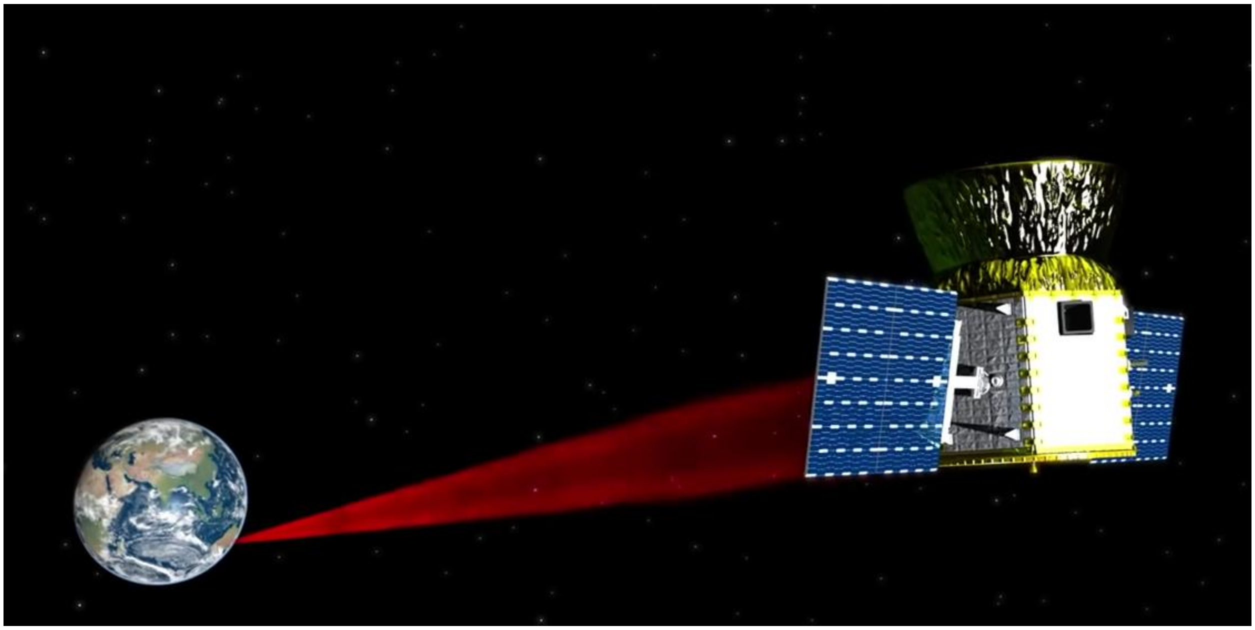


Figure 29: Observatory Transmitting During LAHO

The first angle is the most similar to the sun angle during HASO. This places sun on the HGA. The second angle is sun on the bottom of the spacecraft and the final case has sun on the spacecraft panel on the opposite side of the spacecraft from the HGA. This is the driving case and the results will be presented for this case because it produces the largest temperature pulse.

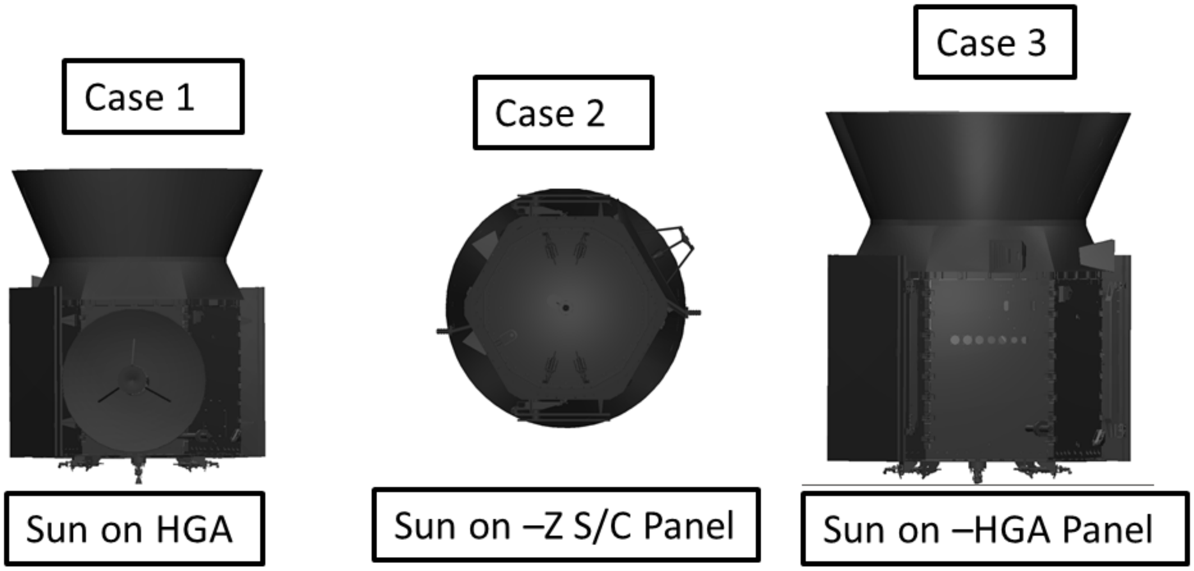


Figure 30: Spacecraft Sun Angles during LAHO Transmit

Table 4: Cold and Hot Case Parameters

FPE Baseline Power	**4.7 W**		**8.1 W**	
	Cold	Hot	Cold	Hot
Spacecraft Temperature(°C)	0	40	0	40
Solar Flux (W/m^2)	1317	1419	1317	1419
Earth IR (W/m^2)	217	261	217	261
Albedo	0.25	0.4	0.25	0.4
Thermo-optical Properties	BOL	EOL	BOL	EOL
Camera Plate Top Face MLI	Yes	Yes	No	No
MLI on Lens Hoods 1 and 3	Yes	Yes	Yes	Yes
MLI on Lens Hoods 2 and 4	Yes	Yes	No	No
Spacecraft Attitude during HASO	54°	78°	54°	78°
Offset Heaters on	Yes	Yes	Yes	Yes
Camera 4 in Survival Power	No	Yes	No	Yes

8.3 Temperature Results

Below are shown the temperature results for the hot and cold cases for both 4.7 W of focal plane electronics power and 8.1 W. Results show positive margins for both hot and cold cases. There is also a plot showing temperature variation of the CCD's over a given orbit. Maximum temperature variation is less than a degree for normal operation. A five hour eclipse was also added to the cases analyzed, which is shown towards the end of the transient results.

Table 5: Temperature Results for 4.7 W Camera Electronics Power

Components	Cold Op Limit	Cold Case		Hot Case		Hot Op Limit
		Min	Max	Min	Max	
CCD	**-95°C**	-71	-67	-72	-66	**-60**
Video Board	**-40**	-16	0	-24	-11	**55**
Interface Board	**-40**	-14	8	-22	-7	**55**
Auxiliary Board	**-40**	-4	-8	-11	-6	**55**
Lens Assembly Average	**-85**	-72	-79	-76	-72	**-65**
Camera Plate Average	**-110**	-58	-60	-51	-49	**80**
Lens Hoods	**-115**	-105	-80	-102	-82	**80**
Total Offset Heater Power		12.7 W		5.5 W		

Table 6: Temperature Results for 8.1 W Camera Electronics Power

Components	Cold Op Limit	Cold Case		Hot Case		Hot Op Limit
		Min	Max	Min	Max	
CCD	**-95°C**	-71	-67	-70	-66	**-60**
Video Board	**-40**	-3	22	-4	17	**55**
Interface Board	**-40**	3	30	3	24	**55**
Auxiliary Board	**-40**	18	30	18	24	**55**
Lens Assembly Average	**-85**	-76	-72	-77	-73	**-65**
Camera Plate Average	**-110**	-86	-83	-80	-78	**80**
Lens Hoods	**-115**	-105	-82	-103	-80	**80**
Total Offset Heater Power		15.0 W		6.3 W		

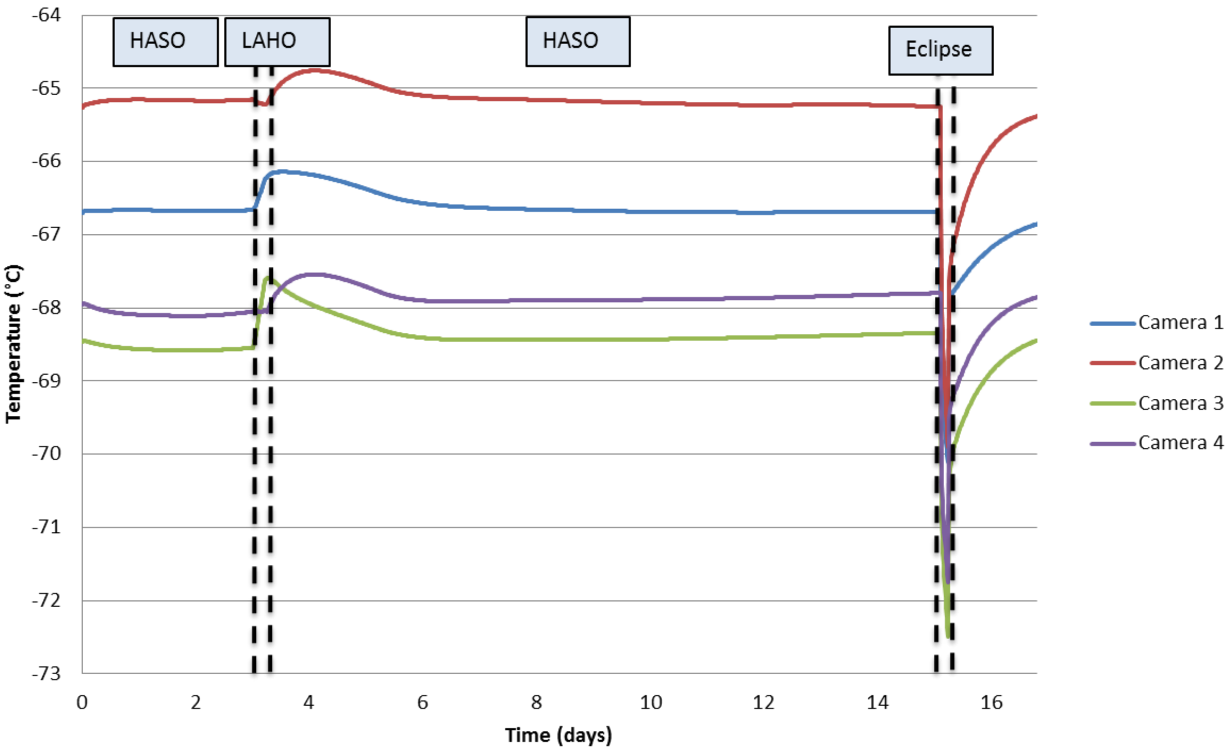


Figure 31: CCD Temperatures over an Orbit

8.4 Survival Analysis

The whole TESS mission was designed around imparting minimal thermal disturbances on the instrument. This includes the spacecraft design as well as the orbit design. For spacecraft and instrument survival the most demanding case will almost always be an extended eclipse. Other, more conventional orbits experience many more eclipses than TESS will but TESS's eclipses can be quite long. Our longest eclipse will be five hours. Luckily, for the instrument it will be barely noticeable in terms of temperature disturbance. Spacecraft temperature is set to the lower end of the range at -10°C with low solar flux and the survival heaters powered on. All components remain within their allowable temperatures ranges with positive margin.

Table 7: Cold Survival Temperature Results

Components	Cold Survival Limit	Low Power		NTE Power	
		Min	Max	Min	Max
CCD	**-95°C**	-69.2	-73.0	-78.7	-75.5
Video	**-55**	-20.8	-6.5	-20.1	-6.6
Interface	**-55**	-14.2	2.3	-4.1	15.8
Auxiliary	**-55**	-7.5	-5.5	4.4	21.5
Lens Elements	**-105**	-81.7	-70.5	-88.0	-77.1
Lens Hood	**-115**	-102.0	-81.8	-110	-88.7
Camera Plate	**-110**	-63.8	-37.1	-102	-53.5
Total Power		34.5 W		44.5 W	

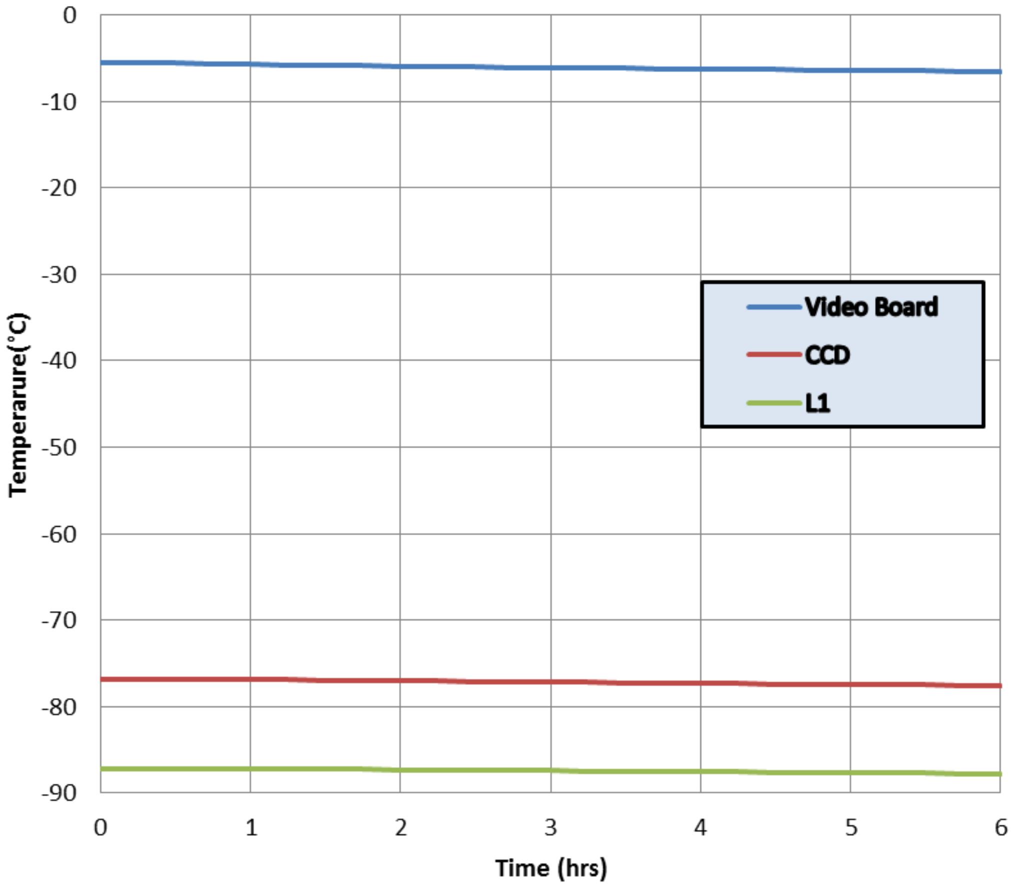


Figure 32: Temperature Results for Eclipse

8.5 Heat Generation and Flow Paths

When designing a system it is important to understand the heat flow paths because it can help one with trade studies and also help one validate the thermal model. Understanding how heat flows within a model can be extremely helpful when performing trade studies because it lets one know where the heat is going and thus can inform which resistances should be tweaked to achieve the desired result. Thermal Desktop has the capability in post processing to produce the heat flows between nodes so if one goes through the whole model, piece by piece computing heat flows, then one can create a heat flow map of the system. For the TESS model the heat flow paths for the high power (8.1 watts base) dissipation case have been computed and described below at both the detector assembly level as well as at the system level.

8.6 Detector Heat Flow

With the TESS thermal model Heat is generated in the camera electronics and CCD's which then needs to get conducted out of the cameras and radiated to space. The heat generated by the camera electronics is conducted and radiated out in roughly equal portions. The 2.3 watts of heat is conducted through the standoffs to the thermal shield and up the detector assembly walls to the lens. 0.2 Watts of heat flows up the flex print cables to the CCD's flows through the standoffs to the thermal shield and up the detector housing up to the lens. 1.2 Watts of heat is conducted out the electrical cables which connect from the electronics boards to housing. 0.9 Watts of that is conducted out the cables to the camera plate while the remainder is conducted up the detector housing walls to the lens assembly. As for radiation, 3.6 watts of heat is radiated from the camera electronics boards to the detector housing, up the sides to the lens assembly. The 0.8 watts of heat dissipated in the CCD is joined by 0.2 watts of heat from the electronics boards which traveled through the flex prints and then it is conducted out the copper thermal straps to the detector housing and up to the lens assembly.

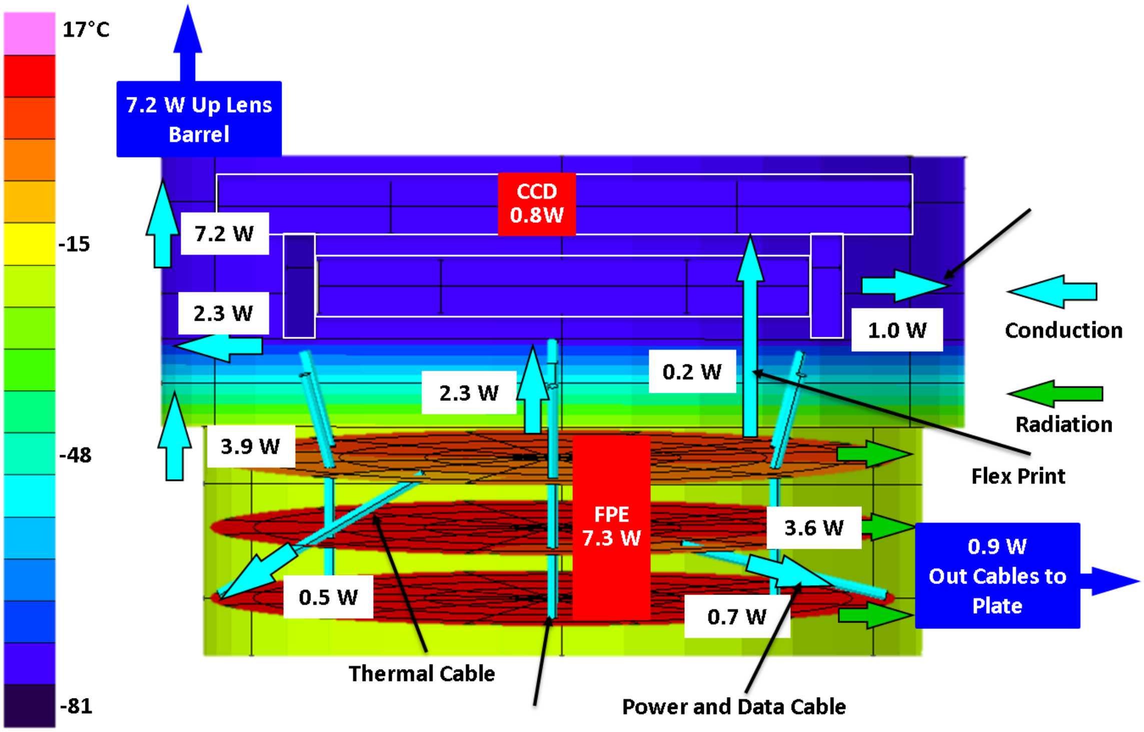


Figure 33: Detector Heat Flow Paths

8.7 System Level Heat Flow

At the system level the heat flow comes into the CSA from many different places. The dominant source is the camera dissipation at 32.4 watts. The other sources are thermal radiation from the spacecraft at 2.0 watts, 4.0 watts of conduction through the bipod struts, 4.6 watts of cable conduction from the spacecraft and 16.9 watts of solar radiation which makes it through the sunshade. All 59.9 watts of heat is then re-radiated back out through the internal surfaces of the MLI on the sunshade, the MLI on top of the camera plate as well as out through the lens hoods.

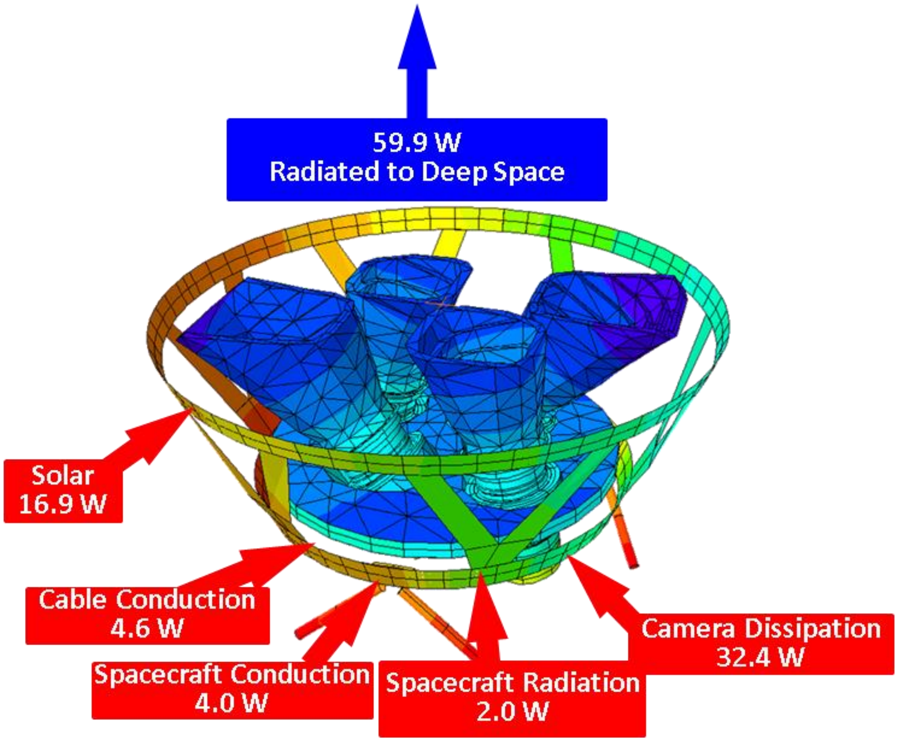


Figure 34: Instrument Heat Flow

8.8 Board Level Thermal Model

When building a system level thermal model the level of detail is usually not high enough to capture component level thermal limits on circuit boards. Detail has to be sacrificed in order to be able to run the model and iterate on design. Often for parts such as circuit boards a separate thermal model is build which captures a higher level of detail and allows the thermal engineer to certify junction temperatures against their limits. This is done for the most stressing hot case and the limits evaluated against are the ones spelled out in NASA GSFC EEE-INST-002: Instructions for EEE Parts Selection, Screening, Qualification, and Derating. This document contains instructions for derating manufacturer thermal limits in order to enhance reliability on orbit for extended life missions such as TESS.

For the TESS cameras the only parts that require a more detailed sub-model are the camera electronics boards. The model contains the detector assembly from the thermal shield and back to focal plane electronics cover. Detail has been added to the boards which are now modeled as 3D objects with three elements through the thickness and with enough fidelity to resolve the footprint of the smallest components of significant heat dissipation. In addition, the standoffs have been added as 3D objects.

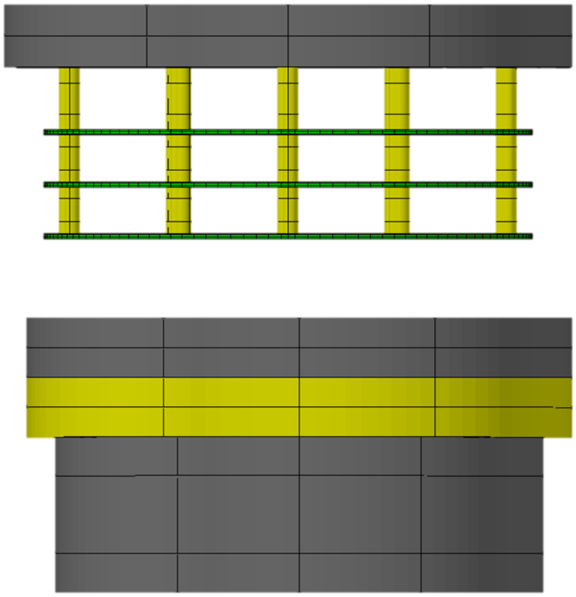
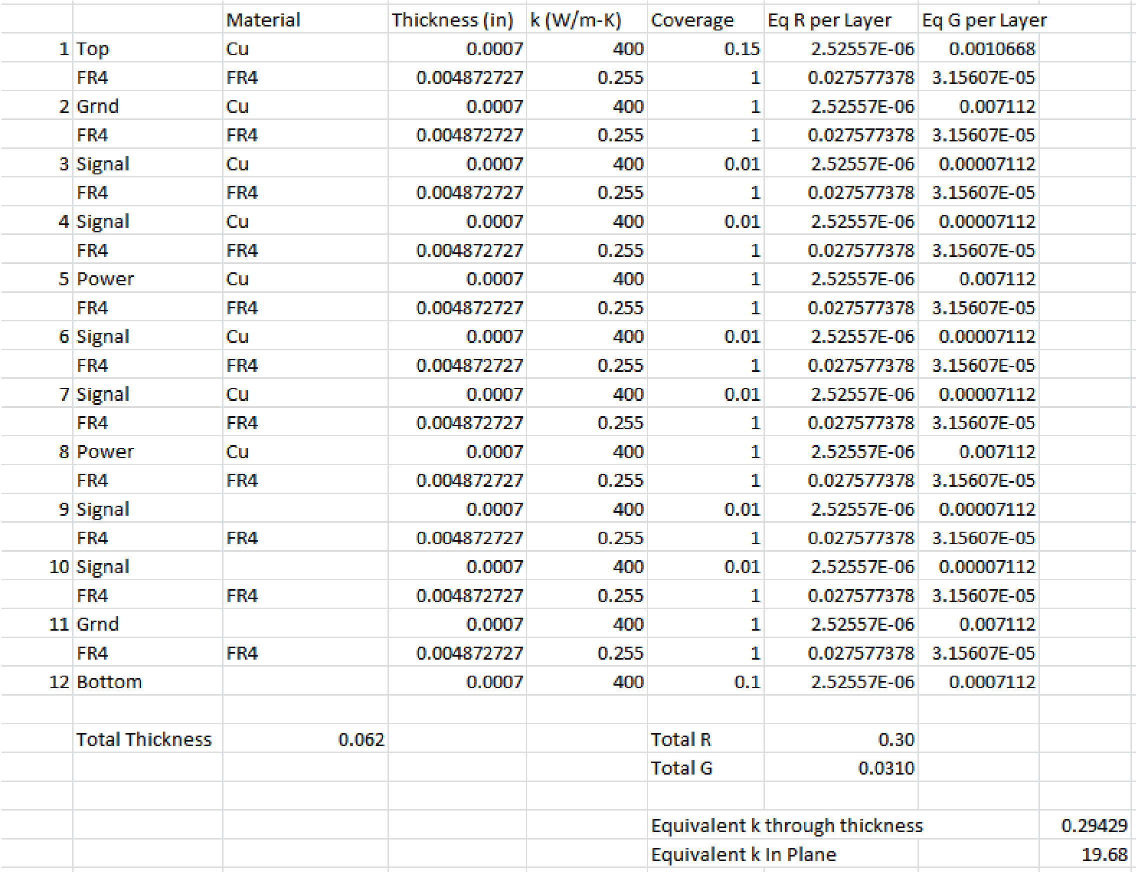


Figure 35: Detector Level Thermal Model

In order to accurately model the boards in three elements their effective properties must be calculated. The majority of the board's volume consists of FR4 with a small fraction of the volume consisting of copper. However, given copper's much higher conductivity and the nature of PCB's being a sandwich of twelve copper layers and eleven FR4 layers, the boards have thermal properties which are highly an-isotropic. In the horizontal direction, which the copper layers are oriented in, the conductivity is much higher than perpendicular to the layers. When computing the in-plane conductivity one multiplies the thickness of each layer by the conductivity and the percent coverage. Then one sums them all together and divides by the total thickness of the board. In order to find the effective through-thickness conductivity, one first finds the thermal resistance per layer which is just thickness of the layer divided by thermal conductivity of the material and the total area of the board. Then one finds the total resistance through the board by dividing the total thickness of the board by the multiple of the board area and the total resistance. As one can see from the sample calculations below the in-plane conductivity is much higher at 19.7 W/m-K compared to a through-thickness conductivity of 0.29 W/m-K.

Table 8: Sample Board Effective Properties



		Material	Thickness (in)	k (W/m-K)	Coverage	Eq R per Layer	Eq G per Layer	
1	Top	Cu	0.0007	400	0.15	2.52557E-06	0.0010668	
	FR4	FR4	0.004872727	0.255	1	0.027577378	3.15607E-05	
2	Grnd	Cu	0.0007	400	1	2.52557E-06	0.007112	
	FR4	FR4	0.004872727	0.255	1	0.027577378	3.15607E-05	
3	Signal	Cu	0.0007	400	0.01	2.52557E-06	0.00007112	
	FR4	FR4	0.004872727	0.255	1	0.027577378	3.15607E-05	
4	Signal	Cu	0.0007	400	0.01	2.52557E-06	0.00007112	
	FR4	FR4	0.004872727	0.255	1	0.027577378	3.15607E-05	
5	Power	Cu	0.0007	400	1	2.52557E-06	0.007112	
	FR4	FR4	0.004872727	0.255	1	0.027577378	3.15607E-05	
6	Signal	Cu	0.0007	400	0.01	2.52557E-06	0.00007112	
	FR4	FR4	0.004872727	0.255	1	0.027577378	3.15607E-05	
7	Signal	Cu	0.0007	400	0.01	2.52557E-06	0.00007112	
	FR4	FR4	0.004872727	0.255	1	0.027577378	3.15607E-05	
8	Power	Cu	0.0007	400	1	2.52557E-06	0.007112	
	FR4	FR4	0.004872727	0.255	1	0.027577378	3.15607E-05	
9	Signal		0.0007	400	0.01	2.52557E-06	0.00007112	
	FR4	FR4	0.004872727	0.255	1	0.027577378	3.15607E-05	
10	Signal		0.0007	400	0.01	2.52557E-06	0.00007112	
	FR4	FR4	0.004872727	0.255	1	0.027577378	3.15607E-05	
11	Grnd		0.0007	400	1	2.52557E-06	0.007112	
	FR4	FR4	0.004872727	0.255	1	0.027577378	3.15607E-05	
12	Bottom		0.0007	400	0.1	2.52557E-06	0.0007112	
	Total Thickness	0.062			Total R	0.30		
					Total G	0.0310		
					Equivalent k through thickness			0.29429
					Equivalent k In Plane			19.68

The electronics boards contain thousands of components so here again is an instance where it is important to be efficient. At Lincoln Laboratory it is general engineering practice to only analyze components which dissipate more than 100 mW. The TESS boards have components which are generally of very low dissipation with only eight components dissipating over the 100 mW threshold. The power dissipation for this case comes from the hot case for 8.1 W of focal plane electronics power which includes 1.95 W of offset heater regulator dissipation but subtracts 0.8 W of heat which is dissipated in the CCD’s. Therefor the total power dissipation over the three boards is

9.25 W. A boundary temperature of -65°C was used at the top edge of model to provide a heat sink.

According to the electrical engineers, other than the offset heater regulator power and the power from the other specific components that were looked, the power is dissipated very uniformly over three boards as well as each board individually. There are three LM195 regulators which dissipate 650 mW W at their peak located on the video board. The other specific components analyzed are three resistors counted as Fixed, Film, Chip, Electrical Resistors in EEE-INST-002 which means their de-rated limit is 70°C down from a manufacturer's rating of 150°C. This gives on a good idea of how conservative the deratings are. They dissipate only 100 mW a piece. The other two components analyzed are a transistor in the FPGA power regulation circuit as well as the FPGA itself. Both of those are on the interface board. Since they are classified as Monolithic Microcircuits their de-rated limits are 40°C below the manufacturers rated limits or 110°C, whichever is lower. The transistor dissipates 172 mW while the FPGA dissipates 244 mW.

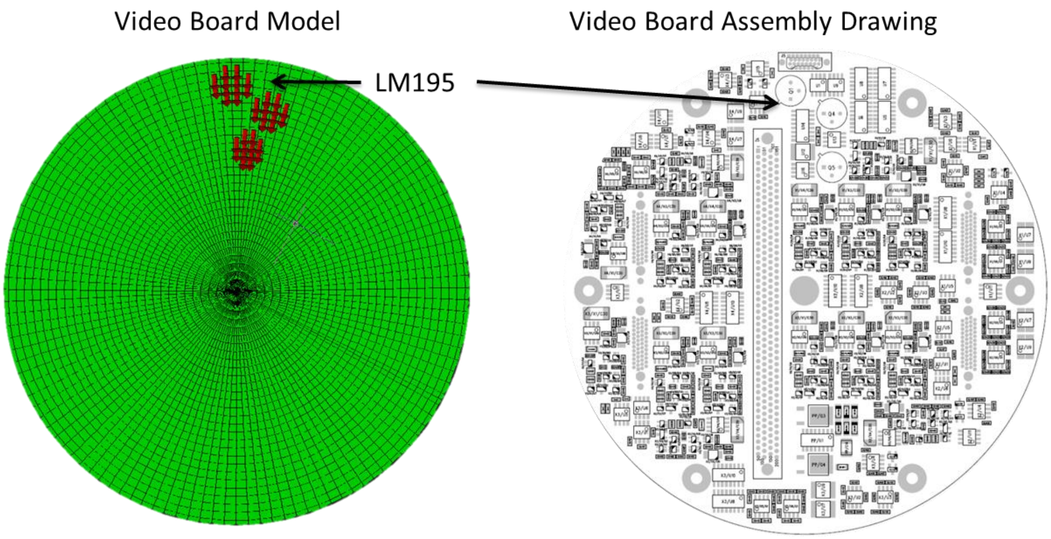


Figure 36: LM195 Heat Loads compared to Board Layout Drawing

Once the heat loads were applied, the model was run and board level temperatures were obtained. Results are shown on the next page.

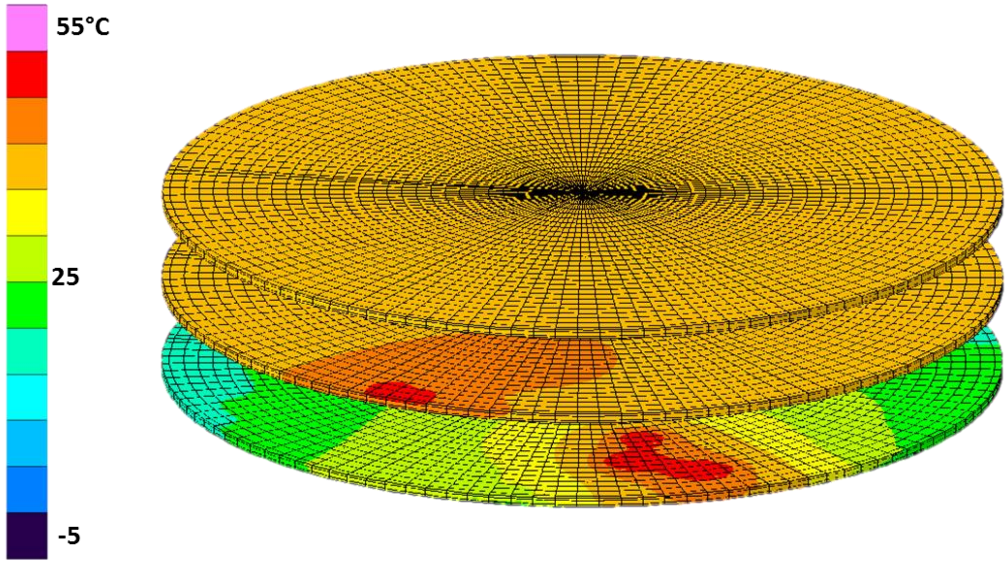
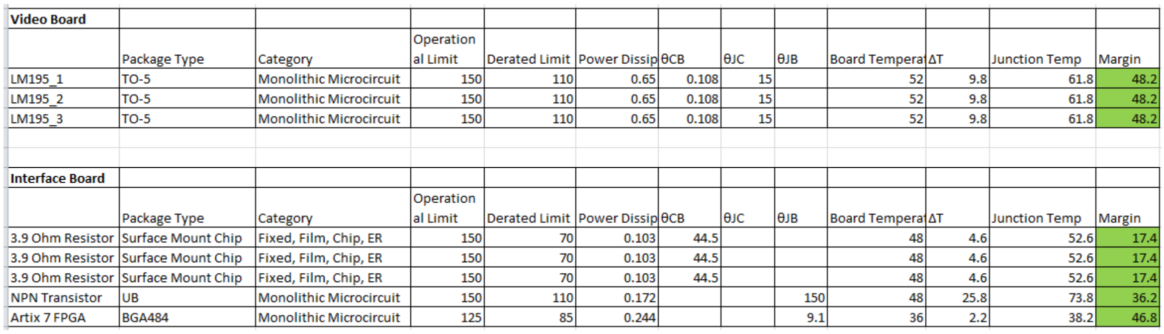


Figure 37: Board Temperature Contours

After the board temperatures were obtained, the next step was to calculate junction temperatures. When calculating junction temperatures, one finds the junction to board thermal resistance or adds the junction to case and adds it to the case to board thermal resistance and then multiplies that by the heat load. That gives the temperature rise from the board to junction. That temperature rise is added to the board temperature at the part’s location which gives the junction temperature. That junction temperature is then evaluated against the de-rated limit. All of the parts which were analyzed were shown to have at least 10°C margin against de-rated limits which is the requirement. This means that parts will be tested beyond their de-rated limit due to an additional 10°C of margin but since testing is short duration relative to mission life, the project has taken the position that this is acceptable.

Table 9: Component Junction Temperature Calculations



Video Board												
	Package Type	Category	Operational Limit	Derated Limit	Power Dissip	θCB	θJC	θJB	Board Temperat	ΔT	Junction Temp	Margin
LM195_1	TO-5	Monolithic Microcircuit	150	110	0.65	0.108	15		52	9.8	61.8	48.2
LM195_2	TO-5	Monolithic Microcircuit	150	110	0.65	0.108	15		52	9.8	61.8	48.2
LM195_3	TO-5	Monolithic Microcircuit	150	110	0.65	0.108	15		52	9.8	61.8	48.2
Interface Board												
	Package Type	Category	Operational Limit	Derated Limit	Power Dissip	θCB	θJC	θJB	Board Temperat	ΔT	Junction Temp	Margin
3.9 Ohm Resistor	Surface Mount Chip	Fixed, Film, Chip, ER	150	70	0.103	44.5			48	4.6	52.6	17.4
3.9 Ohm Resistor	Surface Mount Chip	Fixed, Film, Chip, ER	150	70	0.103	44.5			48	4.6	52.6	17.4
3.9 Ohm Resistor	Surface Mount Chip	Fixed, Film, Chip, ER	150	70	0.103	44.5			48	4.6	52.6	17.4
NPN Transistor	UB	Monolithic Microcircuit	150	110	0.172			150	48	25.8	73.8	36.2
Artix 7 FPGA	BGA484	Monolithic Microcircuit	125	85	0.244			9.1	36	2.2	38.2	46.8

9. Validation and Verification Plan

There are many parts of the validation and verification process. There are official validation and verification steps which are determined in collaboration with the systems engineers at Lincoln, NASA GSFC and OATK. Then there are unofficial validation and verification steps which take place at everywhere from the software manufacturer which validate the methods of the solver and radiation calculations among other things to validation and verification steps that happen during the modeling process. One of the things which was done as this model was being built up was check conduction between sub-components. In order to do this one places a heat load at one end of the model and a boundary node at the other end and looks at the temperature contours. If the temperature contours look symmetrical around the part then it is connected correctly, provided the part has symmetrical conduction. Other examples of model checks include checking the mass and material properties.

The official validation and verification tasks that need to be done involve tests as the system is built up. At the camera level, it will be thermally cycled 8 times. The camera will also be put through a thermal balance test which will seek to correlate the thermal model. This thermal balance test will take place within a thermal vacuum chamber and will simulate the space environment. The model will be correlated to +/-3°C and then the resulting changes will be made to the instrument level model. On-orbit temperature predictions will then be generated and margins will be tallied. After the cameras are put on the camera plate, they will be placed on the spacecraft which will form the observatory. The observatory will go through a thermal vacuum test of its own which will include a thermal balance test. After the thermal balance test, model predictions will again be updated. Finally, after the observatory is put on orbit, the instrument's RTD's will allow the model to be further validated and lessons learned will be available for future missions.

10. Summary

TESS observatory is a two year NASA Explorer mission which will use a set of four cameras to discover exoplanets. It will be placed in a high-earth orbit with a period of 13.7 days and will be unaffected by temperature disturbances caused by environmental heating from the Earth. The cameras use their stray-light baffles to passively cool the cameras and in turn the CCD’s in order to maintain operational temperatures. The design has been well thought out and analyzed to maximize temperature stability. The analysis shows that the design keeps the cameras and their components within their temperature ranges which will help make it a successful mission. It will also meet its survival requirement of sustaining exposure to a five hour eclipse. Official validation and verification planning is underway and will be performed as the system is built up. It is slated for launch in 2017.

11. References

Spacecraft Thermal Control Handbook Volume I: Fundamental Technologies, David G. Gilmore, Editor

NASA GSFC EEE-INST-002

NASA GSFC-STD-7000A