California State Polytechnic University, Pomona

Mechanical Engineering Department

MEMORANDUM

To: Professor McNamara **Date:** Apr. 2, 2025

From: Chiara Wu

Subject: Low Earth Orbit Satellite Analysis

A one-dimensional transient thermal model of a Low Earth Orbit Satellite was designed to accommodate the hardware units housed within it. The model consists of a combined thermal and radiative circuit capturing interactions between the units, the satellite chassis, and the environment for 15 100-minute orbital periods. The model is simulated for a hot case, a cold case, and a survival case to ensure the design closes.

The parameters used in the analysis can be summarized as follows:

- Hardware requirements according to Table 1

Table 1: Satellite Hardware Requirements

Unit Name	Unit Mnemonic	Footprint (in)	Height (in)	Survival Range (K)	Operating Range (K)	Dissipation Level (W)
Power Distribution Unit	PDU	10 x 10	8	239 to 344	249 to 334	30
Heater Control Unit	HCU	6 x 6	4	239 to 344	249 to 334	15
Flight Computer Module	FCM	12 x 9	7	239 to 344	249 to 323	88
Low Data Rate Ratio	LDRR	5 x 3	2	239 to 344	249 to 313	10
High Data Rate Radio	HDRR	6 x 8	4	239 to 344	249 to 308	10
Inertial Measurement Unit	IMU	3 x 3	9	239 to 344	249 to 343	44
Image Control Manager	ICM	4 x 7	4	239 to 344	73 to 313	4
Cryocooler	CC	2 x 3	3	239 to 344	263 to 318	95

- Unit mass must equal approximately 15% of its completely solid mass

- DEU must capture accurate heat spreading within the PCB and the JESD51 models of the IC's it houses and must be connected to a radiator
- Three units are to have time variable dissipation:
    - LDRR must elevate to 30 W for 10 minutes as soon as the satellite enters eclipse.
    - HDRR must elevate to 90 W for 5 minutes as soon as the satellite exits eclipse.
    - FCM must elevate to 120 W any time that the LDRR or HDRR are elevated.
- In addition to its nominal dissipation, the hot side of the CC must also experience the absolute value of the heat load removed from the ICM
- The cold side of the CC that is in contact with the ICM must be maintained at 70 K
- One side of the ICM must be exposed to the environment such that it can always face the Earth
- The satellite must be oriented such that one direction of the satellite always faces the Earth, another will always face the Sun, and the rest will always see deep space, neglecting the effects of orbital mechanics
- The satellite must experience 35% of its time in eclipse for 15 100-minute orbital periods
- Assume an initial temperature across the satellite of 20˚C
- Assume deep space temperature of 2.73 K
- Case assessment constants according to Table 2

Table 2. Case Assessment Constants

	Solar (W/m^2)	Albedo	Earthshine (W/m^2)	Units Operation
Hot Case	1414	0.36	201	ON
Cold Case	1322	0.12	98	ON
Survival Case	1322	0.12	98	OFF

To make the model more manageable, additional assumptions used in its design include:

- Each unit excepting the DEU is approximated as thin-walled
- All units are constructed of aluminum unless otherwise specified
- Conduction within each individual unit is negligible

Each unit is modeled as an independent subsystem as to ensure the accuracy of its behavior. Then, these subsystems are integrated together with environmental inputs to accurately model the thermal behavior of the overall satellite. This method allows for more efficient troubleshooting to ensure at each step of integration the temperature ranges remain compliant. At the very core, each unit is modeled as a circuit containing a thermal mass, a dissipation, and a temperature sensor to ensure compliance with the acceptable temperature ranges. Figure 1 shows this generic template implemented for the PDU subsystem.

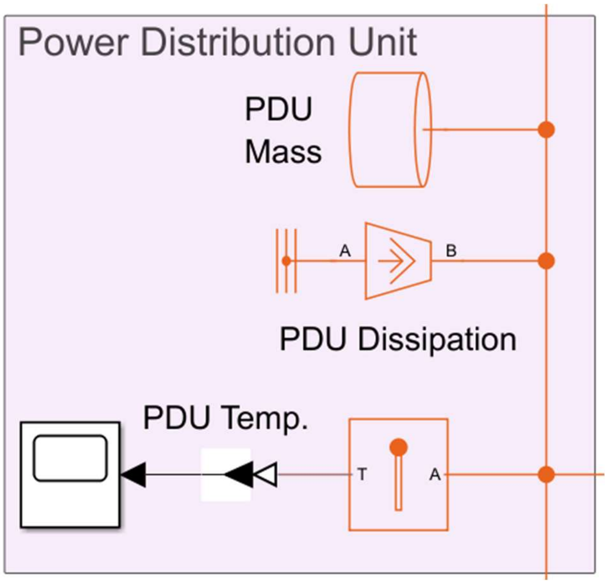

Figure 1. Power Distribution Unit Model

After applying this template to each unit, we find that a few units require a few modifications. For example, Figure 2 shows the ICM, which is coupled to the CC via its hot side and the cold side maintained at 70 K. The connection to the hot side fulfils that the CC must experience the ICM dissipation in addition to its nominal dissipation.

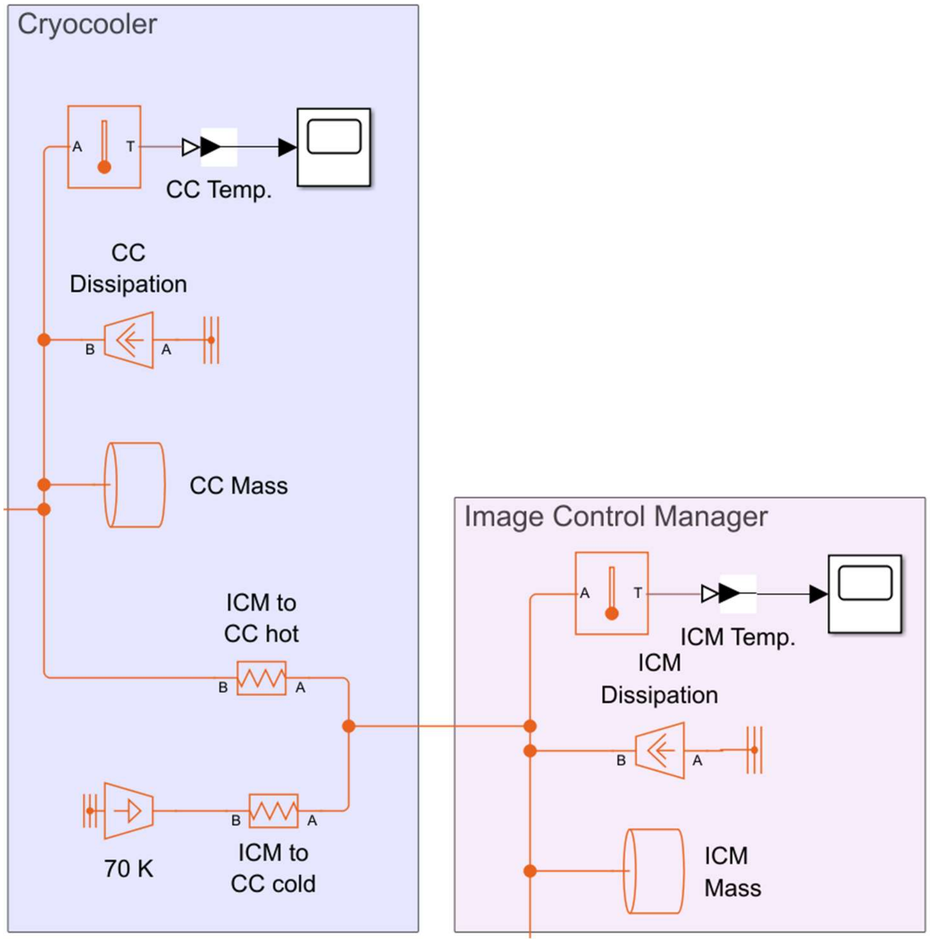

Figure 2. CC and ICM Models

Another unit that requires more attention is the DEU. The PCB behaves as an extended surface [1], so it accounts for the heat spreading in the in-plane direction as well as the dissipation from the IC's. The limiting temperatures in this case are that of the junctions, so the temperature sensors are placed at the junctions of the IC's. Each IC dissipates 5 W and have specifications such that $T_{J,max}$ = 110˚C and R_{JB} = 3.4 K/W. The PCB is constructed from 22% copper which results in the following effective thermal conductivities.

$$k_{in\ plane} = 88.0280 \frac{W}{m * K}$$

$$k_{throu\quad plane} = 0.7689 \frac{W}{m * K}$$

The dimensions of the PCB are shown in Figure 3.

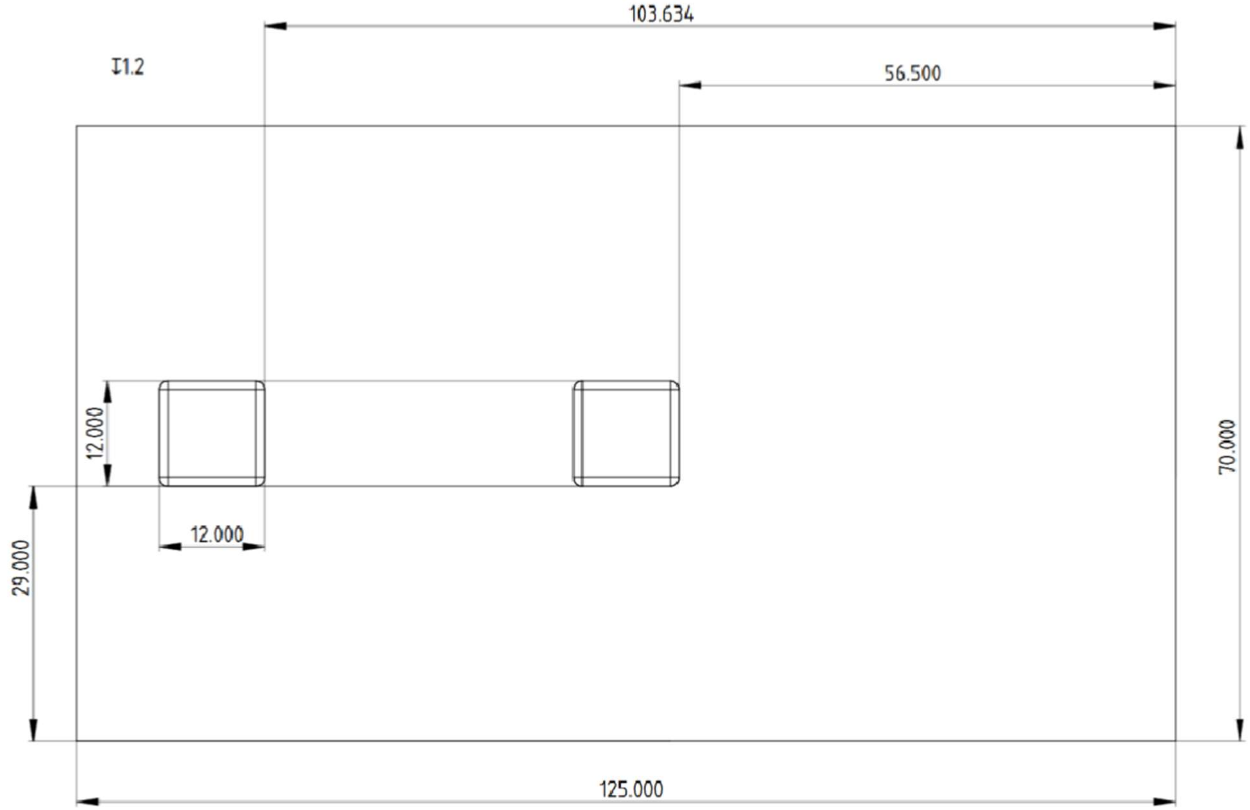

Figure 3. PCB Diagram (mm)

The in-plane resistances of the PCB can be calculated using the definition of conductive resistance, and the dimensions in Figure 3 which results in:

$$R_{PCB1} = 2.0781 \frac{K}{W}$$

$$R_{PCB2} = 6.3743 \frac{K}{W}$$

$$R_{PCB3} = 8.4524 \frac{K}{W}$$

Ice-Lok card locks with R = 0.15 K/W [2] are placed on each end of the PCB to mount it to its housing. The left card lock is coupled with the wall of the enclosure, which is designed as a 1 mm thick wall with outer wall dimensions of 127 x 72 x 6.5 mm. Heat conducts through the smallest wall (A = 6.5 x 72 mm) then through a Laird Tflex thermal gap pad of the same area with k = 6 W/m/K and t = 1.27 mm [3] to a radiator. This results in the following resistances:

$$R_{CL} = 0.15 \frac{K}{W}$$

$$R_{side\ wall} = 0.0097 \frac{K}{W}$$

$$R_{pad} = 0.4523 \frac{K}{W}$$

Figure 4 shows this conduction path not including the radiator below.

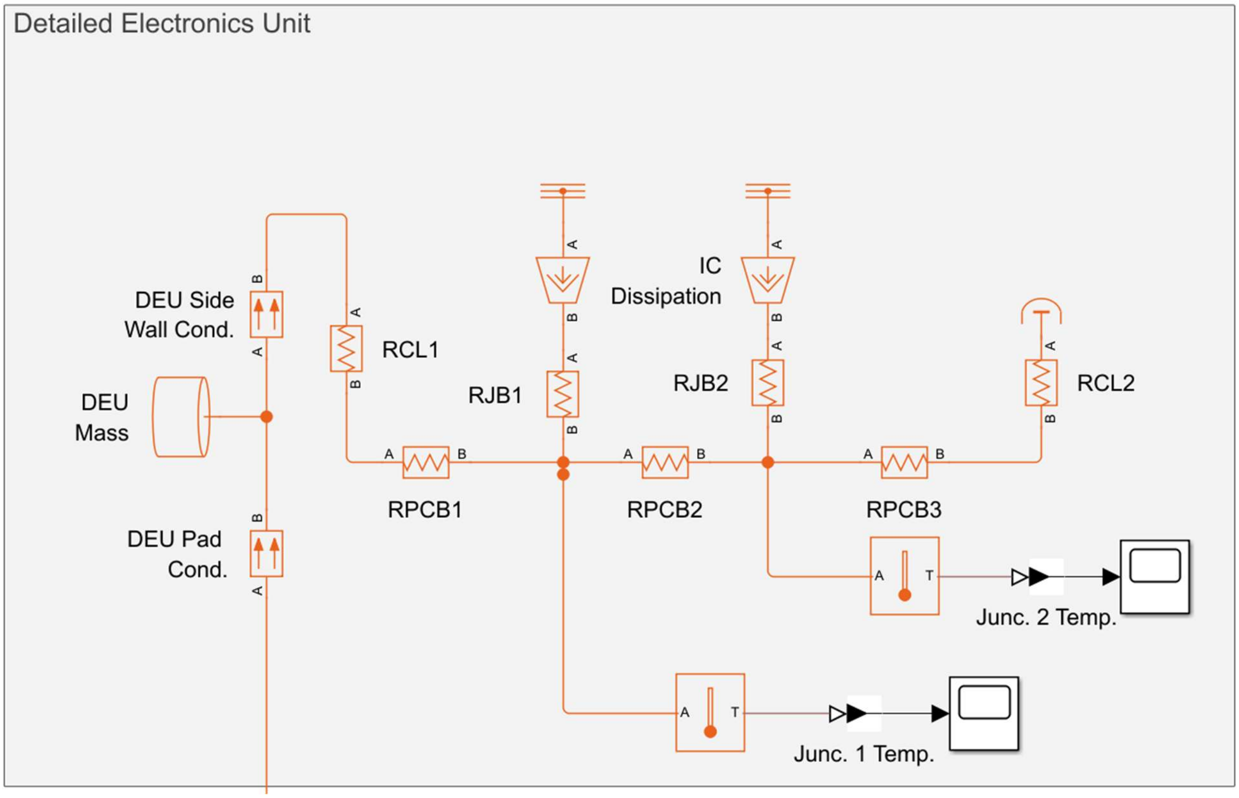

Figure 4. DEU Model

The card lock to the right is connected to an insulator, as the right side of the DEU is to be surrounded by insulation which will stop it from interacting with any surrounding units. The heat transfer in the through-plane direction is not modeled, as the conduction in this direction is negligible. To justify this, the PCB was modeled with conduction to the top and bottom walls of the enclosure, as shown in Figure 5. The temperature of the top and bottom walls was graphed in Figures 6 and 7, showing an indistinguishable difference of temperature behavior, thus proving that through-plane conduction could be disregarded.

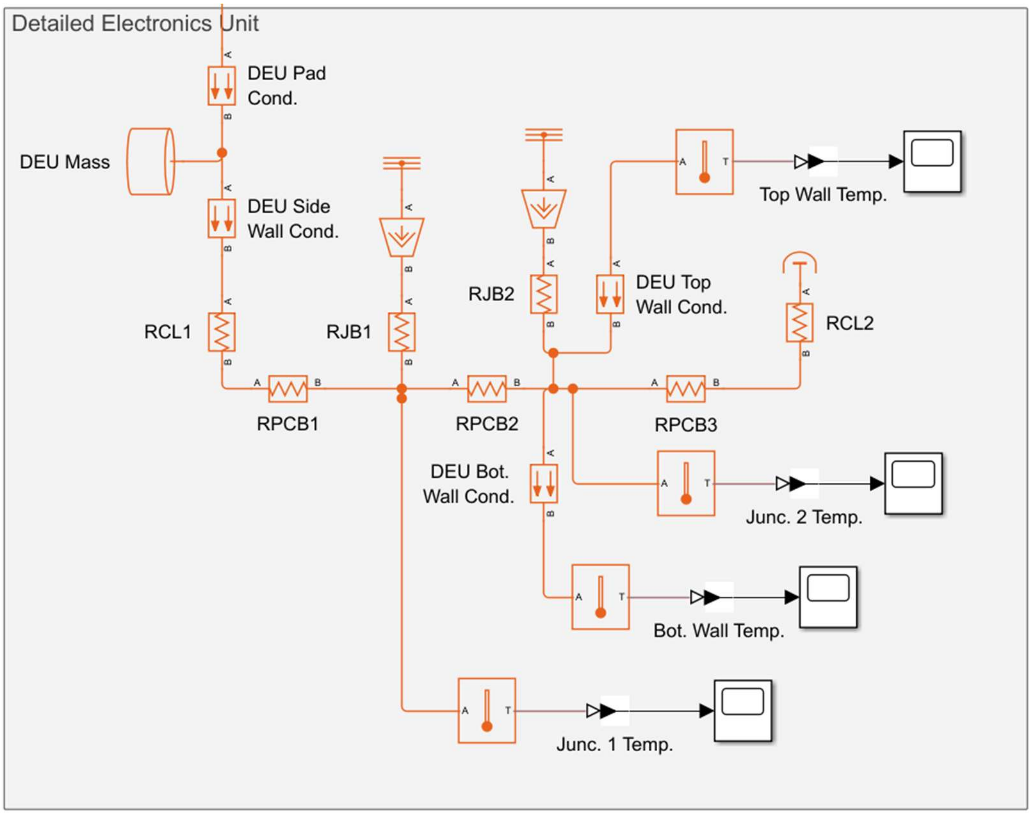

Figure 5. PCB Model with Through-Plane Conduction

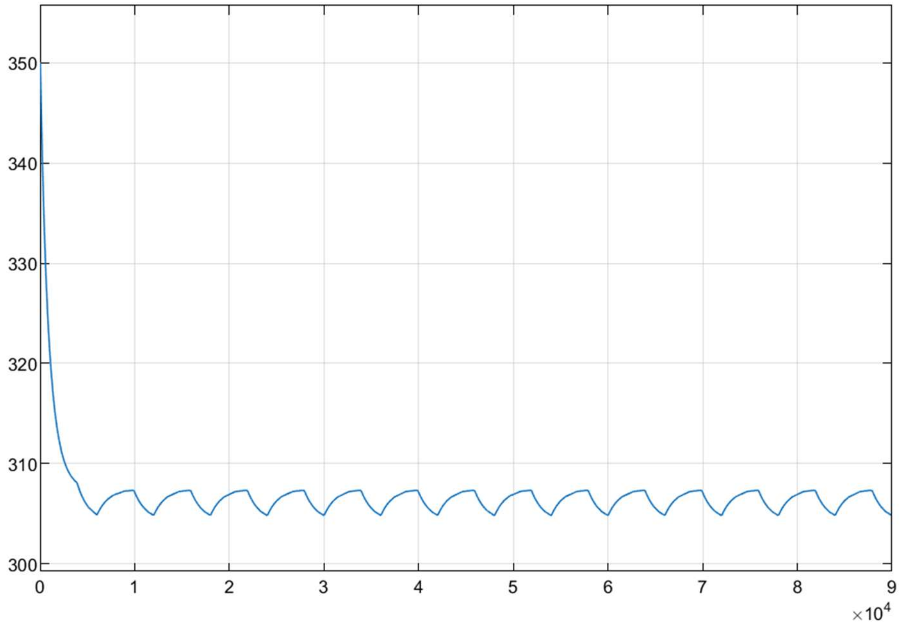

Figure 6. PCB Model with Through-Plane Conduction: Top Wall Temperature

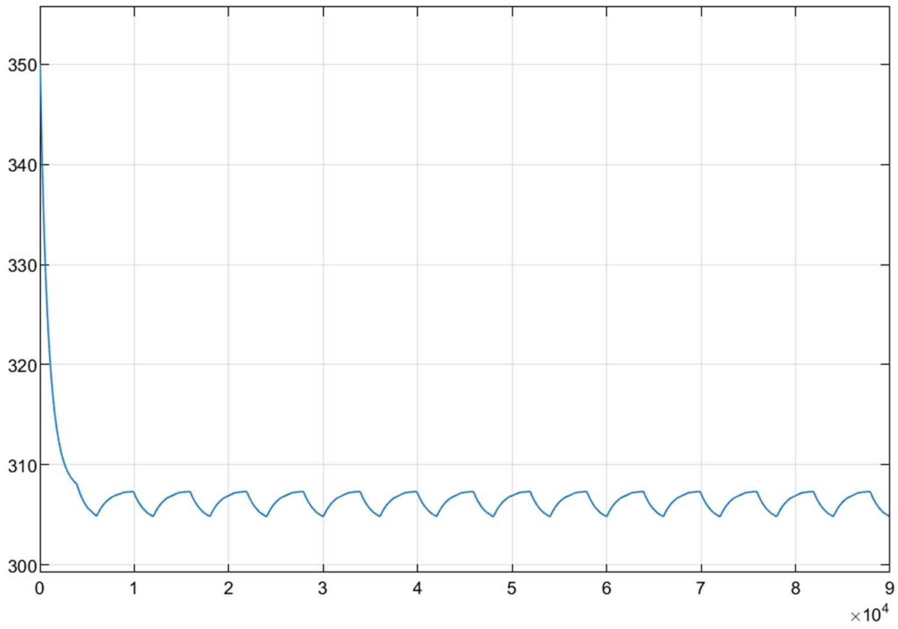

Figure 7. PCB Model with Through-Plane Conduction: Bottom Wall Temperature

To model the time-varying dissipation of the LDRR, HDRR, and FCM, the eclipse time is modeled to switch the dissipation value according to the time each unit will be elevated. All three models appear identical with the only difference being the period of elevation modeled in the Eclipse OFF/ON block. The setup for the LDRR dissipation is shown in Figure 8.

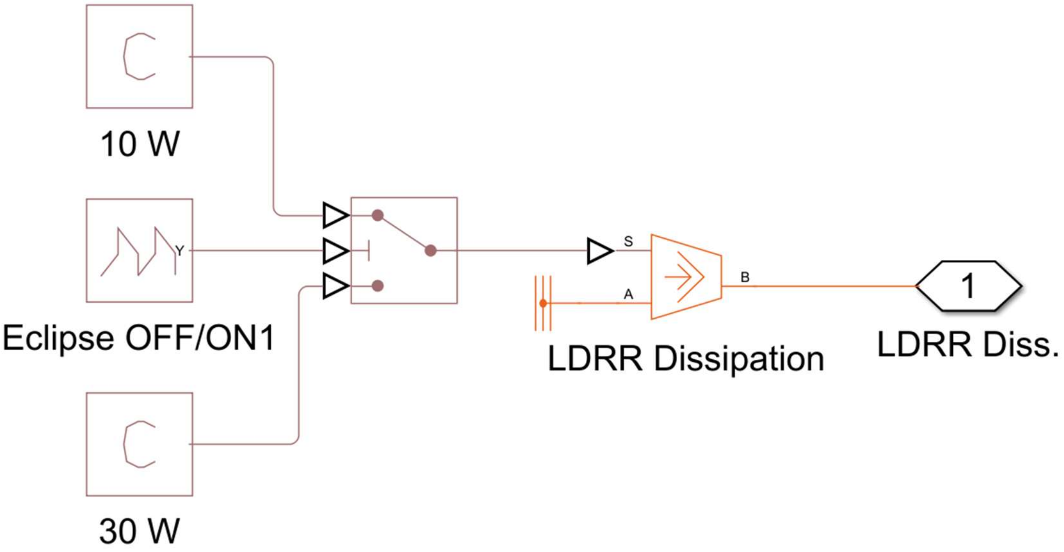

Figure 8. LDRR Time-Varying Dissipation Model

Each subsystem was then connected to the environment to generate an approximate operating temperature range. The units were oriented, grouped, and attached to radiators as necessary to achieve compliance with their respective temperature ranges. The CC was found to benefit from a space-facing radiator due to its high dissipation and relatively limited temperature range. The proposed 3D internal layout of the units is shown in Figures 9 and 10. The top-down view of this layout can be seen in Figure 10. Note that from this view, the front and back surfaces are space-facing.

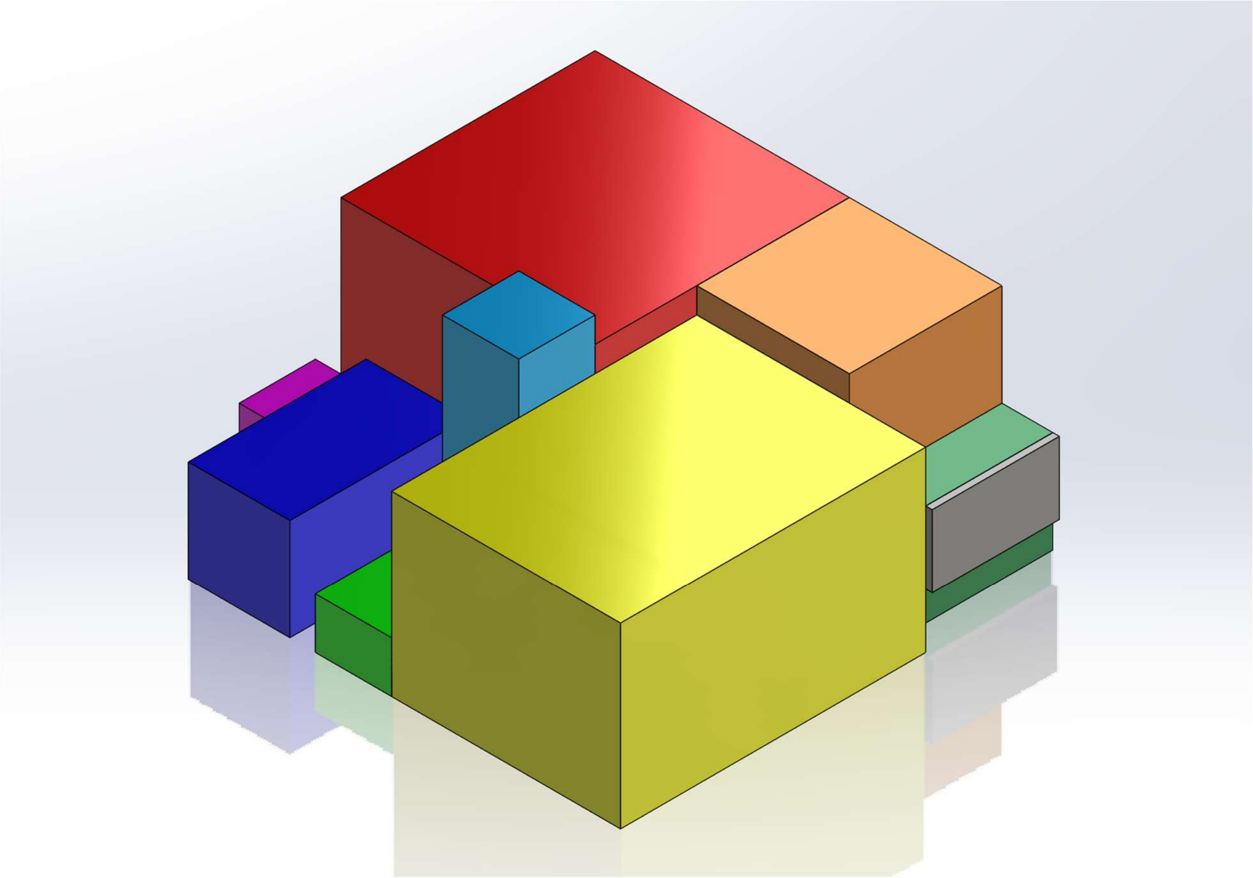

Figure 9. 3D Internal Layout of Satellite, Isometric View

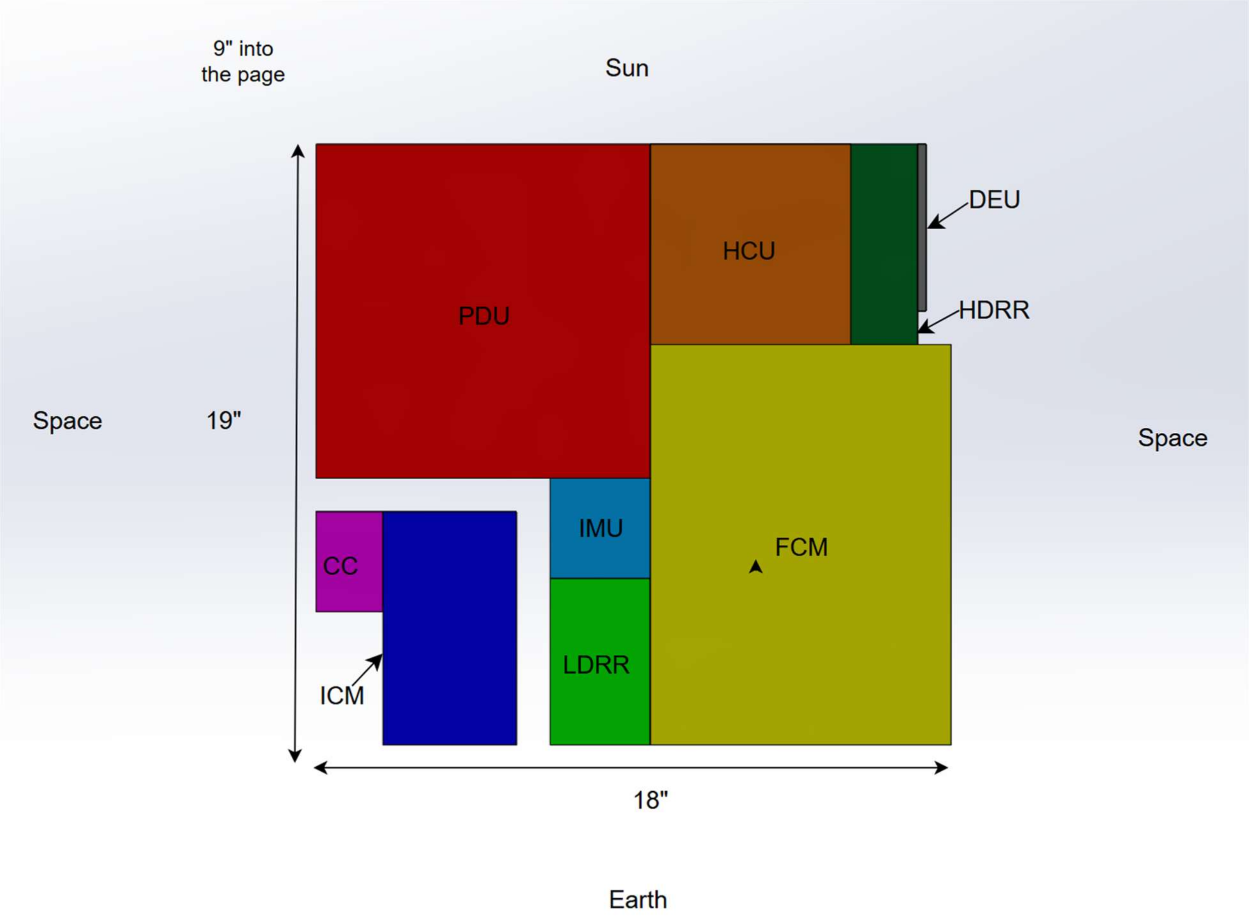

Figure 10. 3D Internal Layout of Satellite, Top View

Using this layout and assuming the thickness of the overall satellite enclosure to be 0.5 in, this results in outer dimensions of 19 x 20 x 10 in, which results in the following areas available to install radiators within:

$$A_{\infty,top/bottom} = 380\ in^2$$

$$A_{\infty,left/right} = 200\ in^2$$

$$A_{Sun/Eart} = 190\ in^2$$

To derive a starting value for the space and Sun-facing radiator areas, the fluxes must first be corrected to account for the elevation of the 750 km orbit using the Inverse Squares Law [4] and the hot case values of the fluxes.

$$G_E = G_{E,hot}\left(\frac{R}{R+h}\right)^2 \tag{1}$$

$$G_\rho = \rho G_{S,hot}\left(\frac{R}{R+h}\right)^2 \tag{2}$$

Then the temperatures required can be calculated using the following equation, where T_{hi} is the upper limit of the unit's temperature range, Q is the dissipation of the unit, R_{cont} is the resistance between the unit and the radiator, and ΔT is the radiator temperature margin of 11˚C [5]. The intermediate resistance is taken as the conductive resistance through a Laird Tflex thermal gap pad with k = 6 W/m/K and t = 1.27 mm [3]. The area is taken as the area in contact with the radiator.

$$T = T_{hi} + QR_{cont} - \Delta T \tag{3}$$

Then the radiative heat transfer formulas can be reorganized to solve for area of the radiators, respectively [1].

$$A_{rad,\infty-facing} = \frac{\sum Q}{\varepsilon\sigma(T^4 - T_\infty^4)} \tag{4}$$

$$A_{rad,Sun-facing} = \frac{\sum Q}{\varepsilon[\sigma(T^4 - T_\infty^4) - G_E] - \alpha G_\rho} \tag{5}$$

Silvered Teflon is chosen as the radiator coating for both radiators, which has an emissivity of 0.88 and an absorptivity of 0.09 [6]. Assuming that only the CC and DEU are interacting with their respective radiators due to insulation of the radiator to other units, the following preliminary radiator areas are calculated. Note that the area of the space-facing radiator is similar to the preliminary dimension of the space-facing enclosure walls, so this area will likely need to be reduced during the modeling stage to achieve a more realistic size.

$$A_{rad,\infty-facing} = 0.1238\, m^2 = 191.9\, in^2$$

$$A_{rad,Sun-facin} = 0.0107\, m^2 = 16.58\, in^2$$

Then assuming the radiator thickness is equal to the wall thickness of 0.5 in, their masses are calculated to be:

$$m_{rad,\infty-facing} = 4.0879\, kg$$

$$m_{rad,Sun-facing} = 0.3533\, kg$$

Next, the walls of the satellite enclosure can be modeled by calculating their mass (subtracting areas reserved for radiators and ICM surface) and accounting for conduction through the wall from inside to outside. The following masses and areas are calculated and tabulated into Table 3 using the density of aluminum and volume of each wall, assuming uniform wall thickness of 3.18 mm.

Table 3. Areas and Masses of Satellite Enclosure Walls

	Left	Right	Front (Earth-facing)	Back (Sun-facing)	Top/Bottom

Area (m^2)	0.0581	0.0561	0.100	0.0996	0.245
Mass (kg)	0.4801	0.4641	0.8268	0.8237	2.0270

The last subsystems to model are the environmental effects. Space is modeled as a temperature source of 2.73 K with an emittance of 1 and an area of 10^6 m^2 to simulate deep space as a black body that is relatively large compared to the satellite. Earth load is modeled as the sum of Earthshine and albedo load when the satellite is not experiencing eclipse. Sun load is modeled as Solar when the satellite is not experiencing eclipse and Earthshine when experiencing eclipse.

Now that all units have been modeled, the conduction paths throughout the satellite can be modeled according to the preliminary layout established in Figures 9 and 10. The temperature ranges will be calibrated at this stage rather than after adding radiative heat transfer to simplify the process, as conduction heat transfer is much more efficient than radiative heat transfer. The contact resistances between surfaces will also be neglected, as they will be assumed to be much larger than the bolt resistances.

Assuming all units are polished aluminum with emittance 0.05, the heat transferred via radiation throughout the inside of the satellite is relatively insignificant and therefore disregarded in the model. Radiation from the outer walls to deep space was assumed to have a view factor of 1 from the satellite to space as space is relatively very large. Heat transfer between the walls was considered negligible since the walls are 3.18 mm thin. Using this thickness, the conductive resistances were taken from tabulated TRW and Lockheed Martin Bolted-Joint Resistance Data [7].

Figure 11 shows the resulting overall hot case model of the satellite.

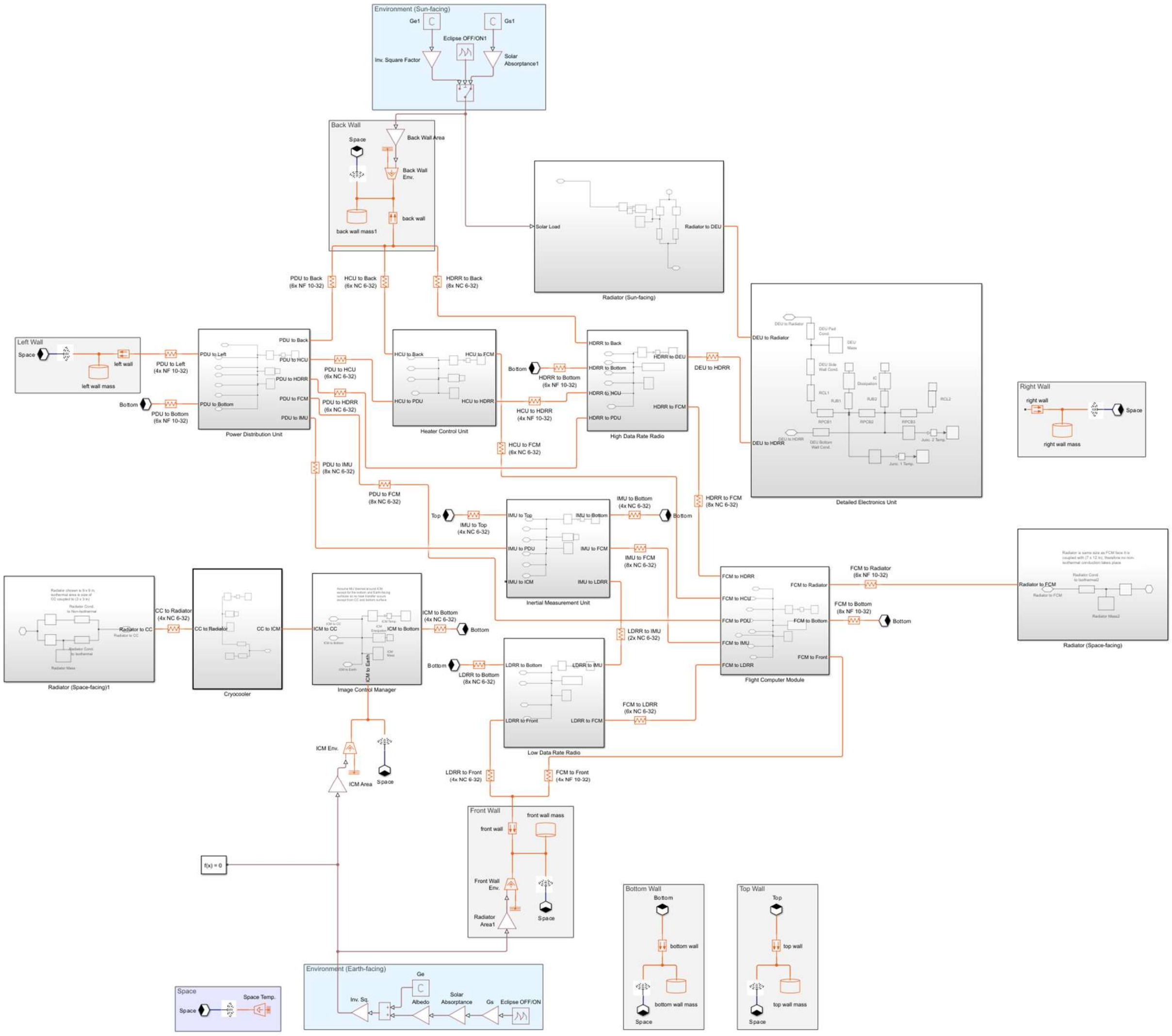

Figure 11. Overall Hot Case Model of Satellite

Table 4 tabulates the actual temperature ranges of each unit according to their corresponding scopes.

Table 4. Temperature Requirements Met for Hot Case

Unit Name	Unit Mnemonic	Operating Range (K)	Actual Range (K)
Detailed Electronics Unit	DEU	233 to 383	J1: 305 to 362, J2: 294 to 323
Power Distribution Unit	PDU	249 to 334	262 to 294
Heater Control Unit	HCU	249 to 334	263 to 296
Flight Computer Module	FCM	249 to 323	263 to 296
Low Data Rate Ratio	LDRR	249 to 313	260 to 294

High Data Rate Radio	HDRR	249 to 308	260 to 294
Inertial Measurement Unit	IMU	249 to 343	264 to 293
Image Control Manager	ICM	73 to 313	108 to 293
Cryocooler	CC	263 to 318	296 to 311

To run the cold case simulation, the environmental constants are first replaced with the cold case constants. This results in the following preliminary temperature ranges in Table 5.

Table 5. Preliminary Temperatures for Cold Case

Unit Name	Unit Mnemonic	Operating Range (K)	Actual Range (K)
Detailed Electronics Unit	DEU	233 to 383	J1: 305 to 353, J2: 278 to 315
Power Distribution Unit	PDU	249 to 334	247 to 294
Heater Control Unit	HCU	249 to 334	248 to 295
Flight Computer Module	FCM	249 to 323	247 to 294
Low Data Rate Ratio	LDRR	249 to 313	246 to 294
High Data Rate Radio	HDRR	249 to 308	245 to 293
Inertial Measurement Unit	IMU	249 to 343	250 to 297
Image Control Manager	ICM	73 to 313	103 to 293
Cryocooler	CC	263 to 318	294 to 311

Evidently, the PDU, HCU, FCM, LDRR, HDRR, and the IMU are slightly close to the lower range of desired temperature, so require light heating. Since these units are all bolted to the bottom wall of the enclosure, a 10 W constant heater is coupled to the bottom wall to bring the temperatures into compliance. Table 6 shows the compliant temperature ranges that result.

Table 6. Temperature Requirements Met for Cold Case

Unit Name	Unit Mnemonic	Operating Range (K)	Actual Range (K)
Detailed Electronics Unit	DEU	233 to 383	J1: 305 to 353, J2: 285 to 316
Power Distribution Unit	PDU	249 to 334	253 to 294
Heater Control Unit	HCU	249 to 334	254 to 295
Flight Computer Module	FCM	249 to 323	254 to 295
Low Data Rate Ratio	LDRR	249 to 313	252 to 294
High Data Rate Radio	HDRR	249 to 308	252 to 294

Inertial Measurement Unit	IMU	249 to 343	252 to 297
Image Control Manager	ICM	73 to 313	104 to 293
Cryocooler	CC	263 to 318	295 to 311

To run the survival case, the environmental constants are left at the cold case values, and the dissipations of each unit are set to 0 W. Table 7 shows the resulting preliminary temperatures.

Table 7. Preliminary Temperatures for Survival Case

Unit Name	Unit Mnemonic	Survival Range (K)	Actual Range (K)
Detailed Electronics Unit	DEU	239 to 344	J1: 100 to 290, J2: 90 to 290
Power Distribution Unit	PDU	239 to 344	90 to 290
Heater Control Unit	HCU	239 to 344	90 to 290
Flight Computer Module	FCM	239 to 344	90 to 290
Low Data Rate Ratio	LDRR	239 to 344	90 to 290
High Data Rate Radio	HDRR	239 to 344	90 to 290
Inertial Measurement Unit	IMU	239 to 344	90 to 290
Image Control Manager	ICM	239 to 344	75 to 290
Cryocooler	CC	239 to 344	75 to 290

To achieve compliant temperature ranges for all units in the survival case, different iterations of constant heater power were tested until a 300 W constant heater on the bottom wall yielded mostly acceptable ranges, shown in Table 8.

Table 8. Preliminary Temperatures with Constant Heater for Survival Case

Unit Name	Unit Mnemonic	Survival Range (K)	Actual Range (K)
Detailed Electronics Unit	DEU	239 to 344	J1: 288 to 304, J2: 282 to 296
Power Distribution Unit	PDU	239 to 344	279 to 294
Heater Control Unit	HCU	239 to 344	280 to 294
Flight Computer Module	FCM	239 to 344	279 to 294
Low Data Rate Ratio	LDRR	239 to 344	279 to 295
High Data Rate Radio	HDRR	239 to 344	279 to 294
Inertial Measurement Unit	IMU	239 to 344	279 to 294

Image Control Manager	ICM	239 to 344	105 to 290
Cryocooler	CC	239 to 344	105 to 290

To raise the temperatures of only the ICM and CC, a heater of 1800 W is coupled to the ICM and the 300 W heater on the bottom wall is removed. T able 9 shows the results of the survival case with a 1800 W constant heater coupled to the ICM.

Table 9. Temperature Requirements Met for Survival Case

Unit Name	Unit Mnemonic	Survival Range (K)	Actual Range (K)
Detailed Electronics Unit	DEU	239 to 344	J1: 275 to 300, J2: 268 to 293
Power Distribution Unit	PDU	239 to 344	266 to 293
Heater Control Unit	HCU	239 to 344	266 to 293
Flight Computer Module	FCM	239 to 344	266 to 293
Low Data Rate Ratio	LDRR	239 to 344	266 to 293
High Data Rate Radio	HDRR	239 to 344	266 to 293
Inertial Measurement Unit	IMU	239 to 344	266 to 293
Image Control Manager	ICM	239 to 344	252 to 293
Cryocooler	CC	239 to 344	252 to 293

The following references were used in the preparation of this report.

1. Bergman, T. L., et al. *Incropera's Principles of Heat and Mass Transfer.* Wiley, 2017.
2. *ICE-Lok*, Advanced Cooling Technologies, https://www.1-act.com/wp-content/uploads/2018/05/ICE-Lok4.24.18.pdf
3. *Tflex HD80000 Data Sheet*, Laird, https://www.laird.com/sites/default/files/2023-06/A18003-00%20Tflex%20HD80000%20Data%20Sheet%2011-07-22.pdf
4. Wikipedia Contributors. *Inverse-Square Law.* Wikipedia, Wikimedia Foundation, 14 Apr. 2019, en.wikipedia.org/wiki/Inverse-square_law.
5. Christopher McNamara, *10. ME 4271 Radiator Design*
6. J. H. Henninger*, Solar Absorptance and Thermal Emittance of Some Common Spacecraft Thermal Control Coatings*, NASA Reference Publication 1121 (1984)
7. Christopher McNamara, *03. ME 4271 Contact Resistance & Electronics Cooling*