Sarah Richter

MEng Project Report

SIOS Lab, Spring 2021

STOP Analysis for a Spacecraft Camera Distortion Model

I. Abstract

In order to accurately cross calibrate a satellite swarm via image decomposition, a distortion model of the satellite's camera must be obtained. In the past, the group has assumed a radial distortion model, but this model does not accurately represent the distortions induced due to the non symmetric thermal loading on the satellite during orbit from solar radiation. To achieve a distortion model that better matches the expected deflections on orbit, STOP (Structural, Thermal, and Optical Performance) analysis shall be performed on the satellite to generate the new distortion model. This research focuses on the structural and thermal steps of this analysis, and touches briefly on the optical analysis.

II. Dynamics Overview

A dynamic model of the spacecraft is required in order to analyze the heat on each face of the satellite due to solar radiation effects. The dynamic model was formulated by Sam Feibel for his MEng report last semester (see MEng Report Model and Filtering for more information). The simulated orbit is similar to the ISS, traveling in LEO with a low inclination. The disturbances considered include non-spherical gravitational perturbations, atmospheric drag, and point-mass gravity from the moon and the sun. The formulated dynamic model iterates on the initial conditions in the form below:

$$\begin{bmatrix} \boldsymbol{r}_{G/O} & {}^{\mathcal{I}}\boldsymbol{v}_{G/O} & {}^{\mathcal{I}}\boldsymbol{\omega}^{\mathcal{B}} & {}^{\mathcal{B}}\mathbf{q}^{\mathcal{A}} \end{bmatrix}^{T}$$

The output position in addition to the solar vector $\hat{s}$ was used to formulate the heat due to solar radiation during orbit.

III.   Heat Transfer Analysis (Theory and MATLAB)

There are four different forms of radiation heat transfer that I have accounted for in my analysis: direct solar radiation, indirect (albedo) solar radiation, earth infrared radiation, and heat loss via radiation from the satellite to the environment. The first three are calculated in MATLAB for every timestep for which the dynamics analysis is run. These three heats are added and input as heat flux on each satellite face in ANSYS, and the heat loss to the environment is modeled in ANSYS as radiation with an environment temperature of -270 degrees Celsius. Each mode of radiation is outlined below.

1. <u>Direct Solar Radiation</u>

   The direct solar radiation has the largest effect on the radiation heating of the satellite. In order to calculate the direct solar radiation on the satellite, a vector indicating the sun's position must be described. **Figure 1** describes a geocentric equatorial coordinate system (GECS), where $\hat{u_3}$ points in the direction of the north pole and $\hat{u_1}$ and $\hat{u_2}$ are orthogonal and contained within the earth's equator. Specifically, $\hat{u_2}$ is in the direction of the solar vector.
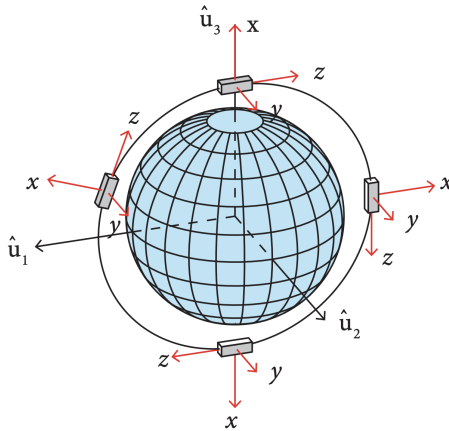
Figure 1: GECS Framework

In the figure below, the solar vector (red arrow) is shown in relation to the earth and the
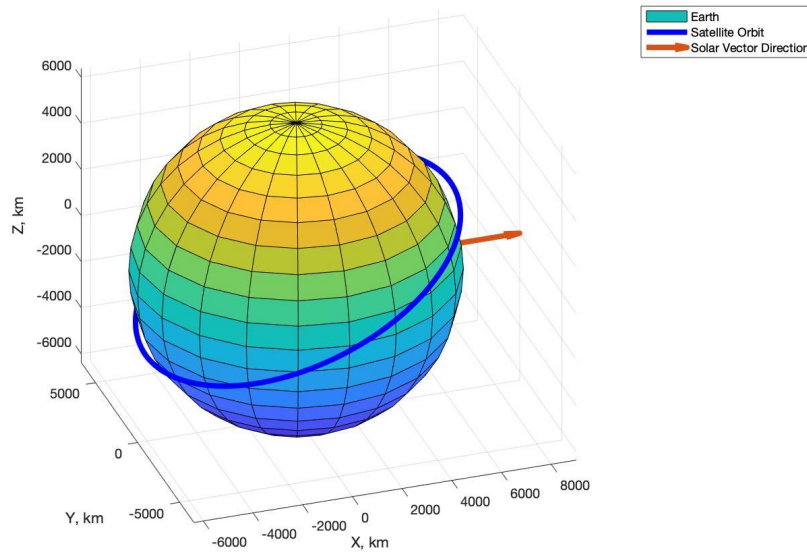
satellite's orbital path (blue line).

Figure 2: Orbital Path and Solar Vector

Outside of the eclipse zone, the direct solar radiation depends on the angle between the

normal vector to a face of the satellite and the solar vector. This can be described by the

following:

$$\cos b_i = \hat{n}_i \cdot \hat{s}$$

When $\cos(b_i)$ is negative, the sun rays do not reach the satellite face. Conversely, when $\cos(b_i)$ is positive, there will be a direct solar radiation contribution to the heating on the face. The direct solar radiation on a face i can be calculated as follows:

$$Q_{S,i} = \alpha_i A_i \cos b_i \, I_S$$

Where α_i is the face's absorptivity (between zero and one), A_i is the area of the face, and I_S is the solar irradiance. It is important to note that I_S depends on the distance between the satellite and the sun, so it varies a bit throughout orbit. However, the recommended mean value was used in my calculations ($I_S = 1367$ W/m^2). Below is the direct solar radiation heating vs. time for the model satellite.
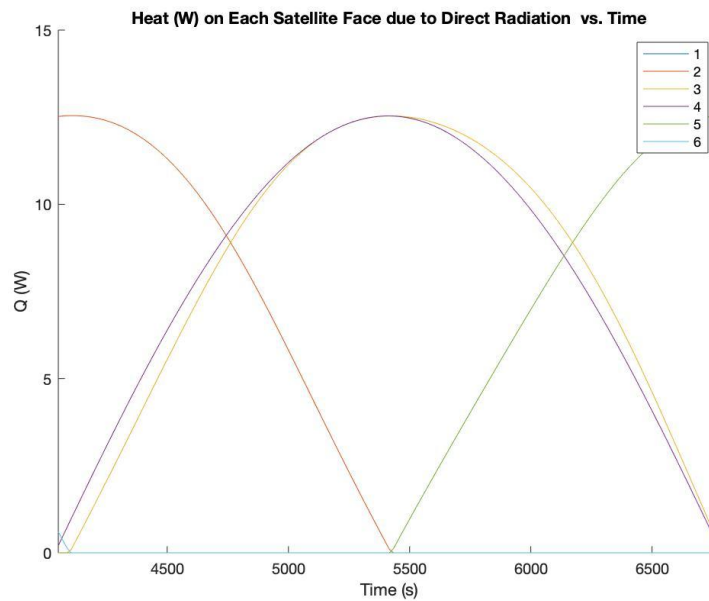

Figure 3: Direct Solar Radiation vs. Time for Each Satellite Face

2. Indirect (Albedo) Solar Radiation

The radiation from the sun reflected off of the earth onto the satellite is the Albedo solar radiation. The albedo is the reflected fraction of the incident radiation flux. We assume that this albedo is constant for simplicity, when in fact it varies due to clouds, ocean vs. land, snow and other weather conditions, deserts, and other environmental factors. The albedo (γ) used here is .273. We then can define the angle between the solar vector and an earth surface element as follows:

$$\cos(b_E) = \hat{\boldsymbol{n}}_E \cdot \hat{\boldsymbol{s}}$$

Then, the albedo heat flux from a single surface element can be calculated as:

$$dQ_{alb,i} = \alpha_i A_i \gamma I_S \frac{\cos a_E \cos a_i \cos b_E}{\pi \rho^2} dS$$

Integrating this over the whole surface of the earth, we can obtain the albedo radiation contribution on a given face of the satellite.

$$Q_{alb,i} = \alpha_i A_i \gamma I_S \tilde{F}_{iE}$$

Where α_i is the absorptivity, A_i is the area of the satellite face, γ is the albedo, I_s is the solar irradiance, and $\overline{F}_{ie}$ is the view factor given by:

$$\tilde{F}_{iE} = \int \frac{\cos a_E \cos a_i \cos b_E}{\pi \rho^2} dS$$

To evaluate the view factor integral, a new rotating coordinate system is used with an origin at the center of the earth and the third axis aligned with the position of the satellite. In this rotating system, the solar vector is given by:

$$\hat{s} = \sin v \, \hat{e}_1' + \cos v \, \hat{e}_3'$$

The view factor integral and subsequently the albedo heat flux values were evaluated in MATLAB using the **quad2d** function. I had some trouble choosing bounds on this integral, so further work will need to be done to evaluate the indirect radiation. The magnitude of this heat is expected to be roughly .3W, significantly lower than that of the direct solar radiation contribution.

3. Earth Emitted Infrared Radiation

There is also a contribution to the heat on the satellite from the radiation emitted by the earth. The earth has a radiosity that is a function of space and time, but is modeled here as constant for simplicity (213 W/m^2). The infrared heat flux from a single earth surface element is as follows:

$$dQ_{E,i} = \varepsilon_i A_i I_E \frac{\cos a_E \cos a_i}{\pi \rho^2} dS$$

The heat incident on one side of the satellite due to earth infrared radiation can be achieved by integrating over all of the surface elements:

$$Q_{E,i} = \varepsilon_i A_i I_E F_{iE}$$

For the front, rear, left and right faces of the satellite (i=2,3,5,6), the view factor is:

$$F_{iE} = -\frac{\sqrt{h^2 - 1}}{\pi h^2} + \frac{1}{\pi} \tan^{-1}\left(\frac{1}{\sqrt{h^2 - 1}}\right)$$

Where h is equal to the satellite position R divided by the radius of the earth. For the satellite surface facing the earth (i=4), the view factor is approximately equal to one over the square root of h.

4. Heat Loss to Environment

The heat lost from each face to the environment through radiation can be calculated as follows:

$$P = e\sigma A(T^4 - T_C^4)$$

This contribution to the heat on the satellite was added in during the thermal transient ANSYS, and not calculated in MATLAB along with the solar and earth radiation factors.

IV. Satellite Model

At first for simplicity, the satellite was modeled as a solid aluminum cube. This cube was later adjusted to be six bonded hollow aluminum struts, a central aluminum plate "electronics tray", and siding that included 5 aluminum sheets and one aluminosilacate glass plate to act as the camera face. The design for the satellite model is pictured below in **Figure 4** and **Figure 5**.
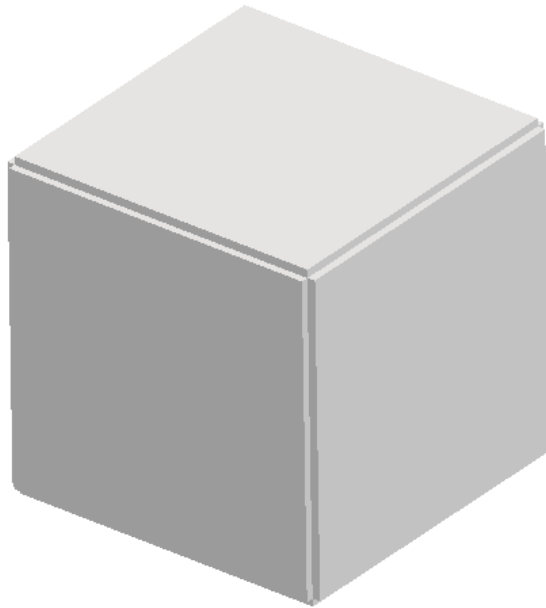
Figure 4 : Satellite Model, Aluminum and Glass Siding On
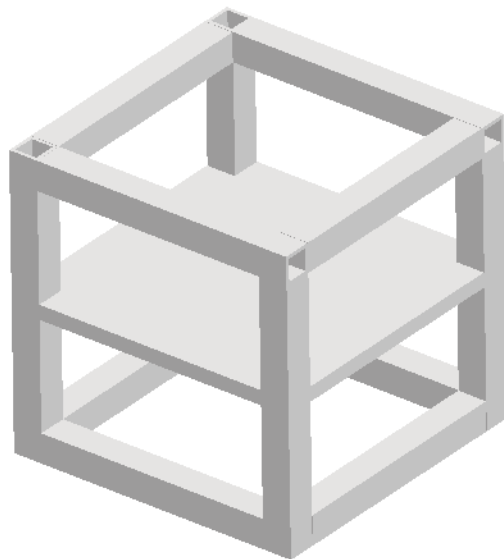

Figure 5: Satellite Model, Aluminum and Glass Siding Off

The numbering scheme used to label the faces in both the MATLAB script and ANSYS is as follows:

1. Satellite face with normal vector pointing away from the earth (in direction of r)

2. Satellite face with normal vector pointing in the direction of the velocity of the spacecraft

3. Satellite face orthonormal to faces 1 and 2

4. Satellite face with normal vector pointing towards the earth (negative r)

5. Satellite face with normal vector pointing away from the direction of spacecraft velocity

6. Satellite face orthonormal to faces 4 and 5

There were later additions to the code that accounted for the rotation of the satellite about the position axis calculated from information about the quaternion.

V.   Thermal Analysis (ANSYS)

The heat incident onto the satellite due to solar radiation effects was calculated for every timestep in MATLAB via the methods dictated in Section III. The heat incident on each of the six satellite faces was then exported from MATLAB and imported into ANSYS as heat fluxes applied to each respective face (aluminum or glass siding) in a thermal transient analysis. Then, radiation was applied to all external faces of the satellite to model the heat loss to the environment. Internal heat generation was not considered in this model, so the temperature drops drastically from the initial temperature input of -30 degrees Celsius to around -90 degrees Celsius. While this is out of the range of the operating temperatures of several components one could expect to see on these satellites, the deformation analyzed in the transient structural analysis in section VI reaches near steady state. This allows us to still analyze the non-radial deformation effects on the camera face due to solar radiation specifically. Below is a plot of the maximum, minimum, and average temperatures over the duration of 15,500 seconds (or three orbits). Maximum and average

basically align (blue and green lines). This is because the glass face is losing heat at a much

higher rate than the aluminum parts, but only accounts for a small amount of the total volume.

The minimum temperature (notably at the camera face center, seen in **Figure 7**) is the red line in
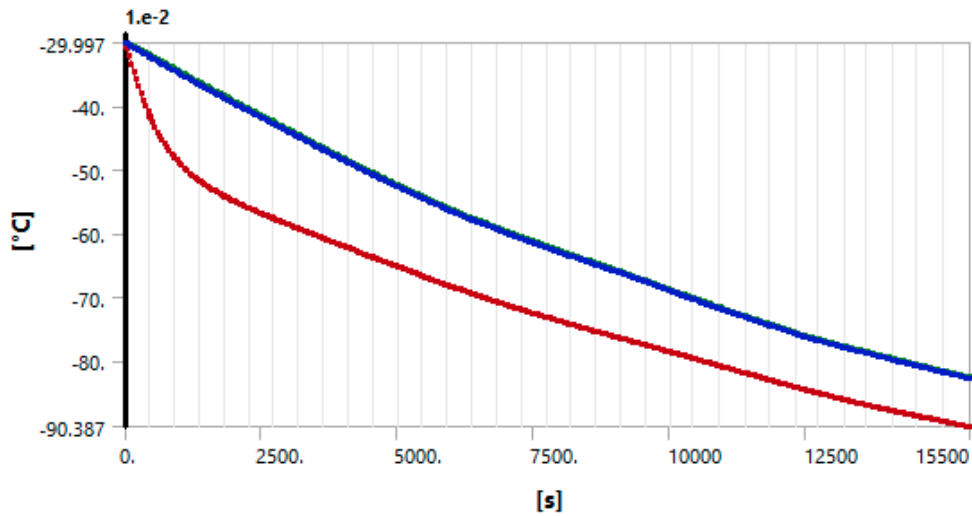
the figure below.
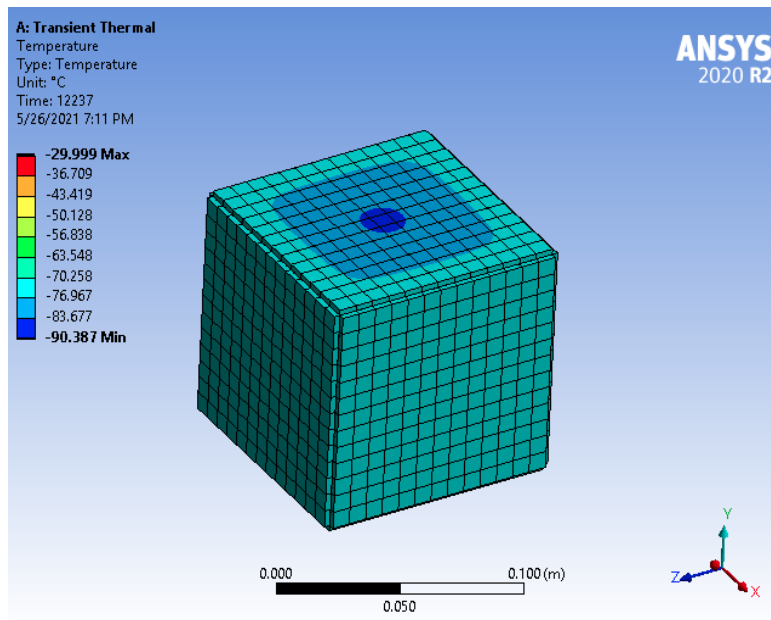

Figure 6: Temperature vs. Time

Figure 7: Temperature distribution at 12,237 seconds

VI.   Structural Analysis

The temperature distribution on the satellite throughout its orbit determined in the above section was then imported into a transient structural analysis. The satellite model was then constrained with a fixed support on an element in the center of the cube. This was the most realistic way to model the satellite's deformation while orbiting. Another method that was considered was to turn the "weak springs" setting on. However, this was less similar to how the physical satellite would behave, so the former constraint method was chosen.
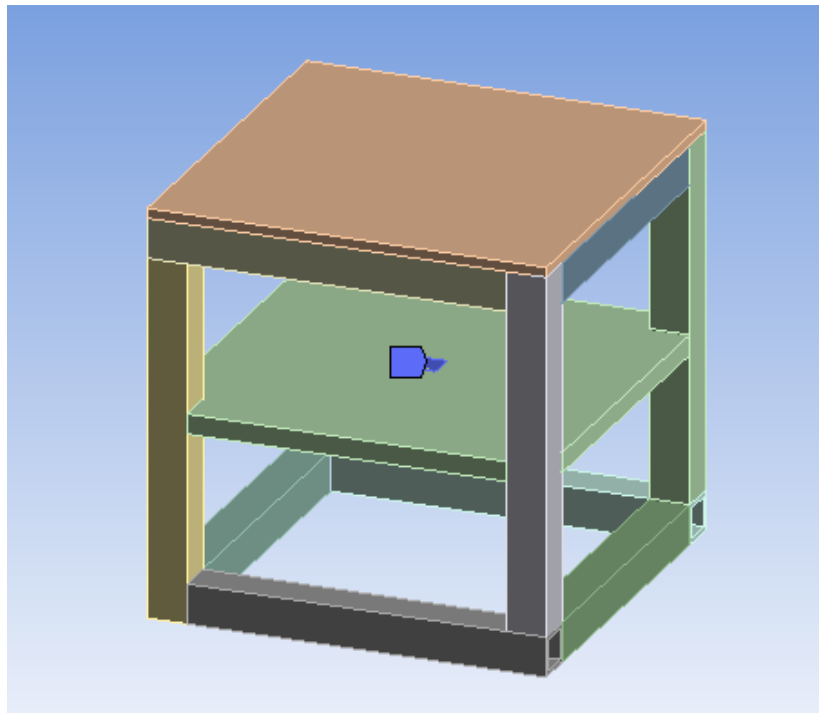

Figure 8: Fixed Element Support

Large time steps were used to force the analysis to run in a reasonable time with the maximum amount of temperature data. All of the temperature data from the thermal analysis section was used in the structural analysis. The total deformation on the whole satellite as well as the total and directional deformations on the center of the camera face were analyzed. See images below.
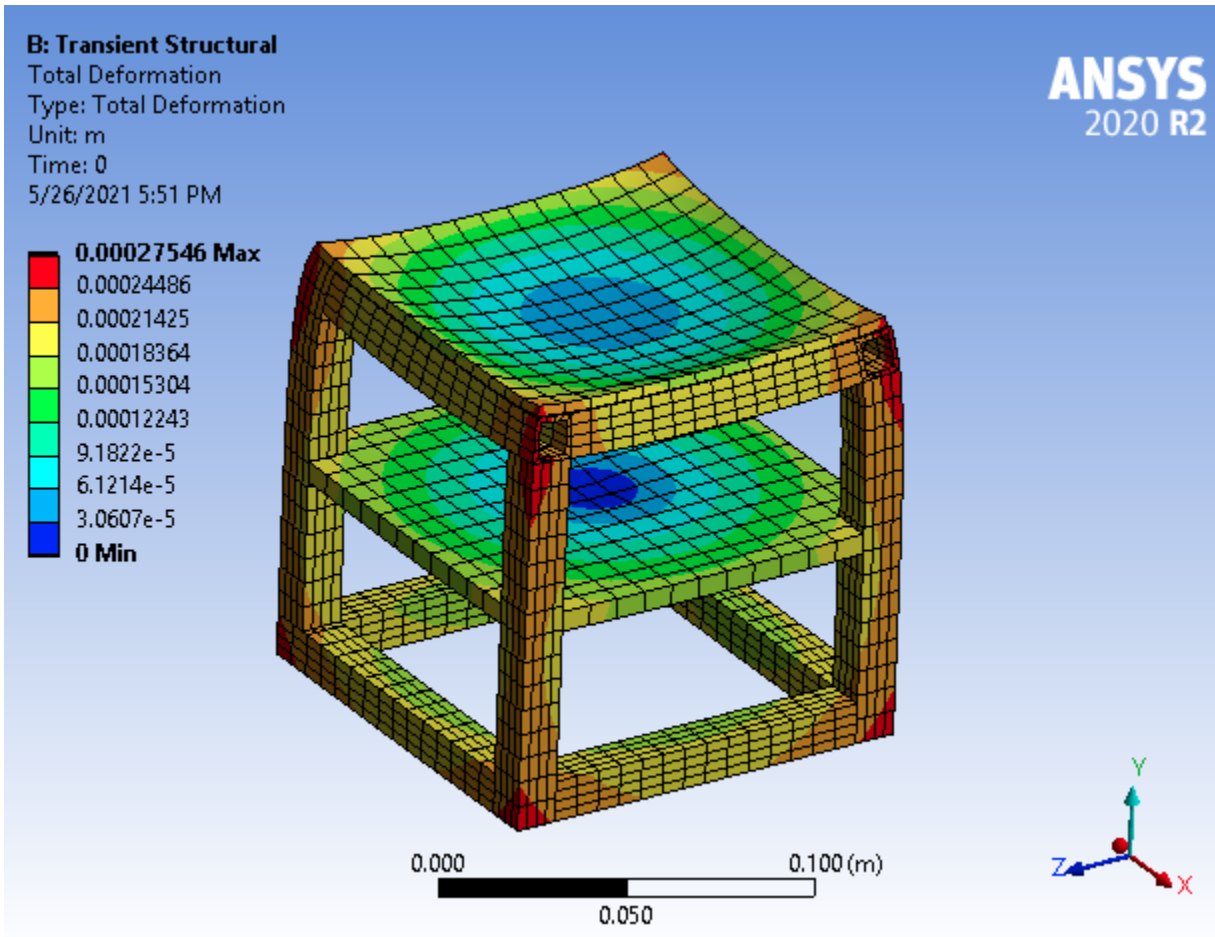
Figure : Total Deformation, t=0s

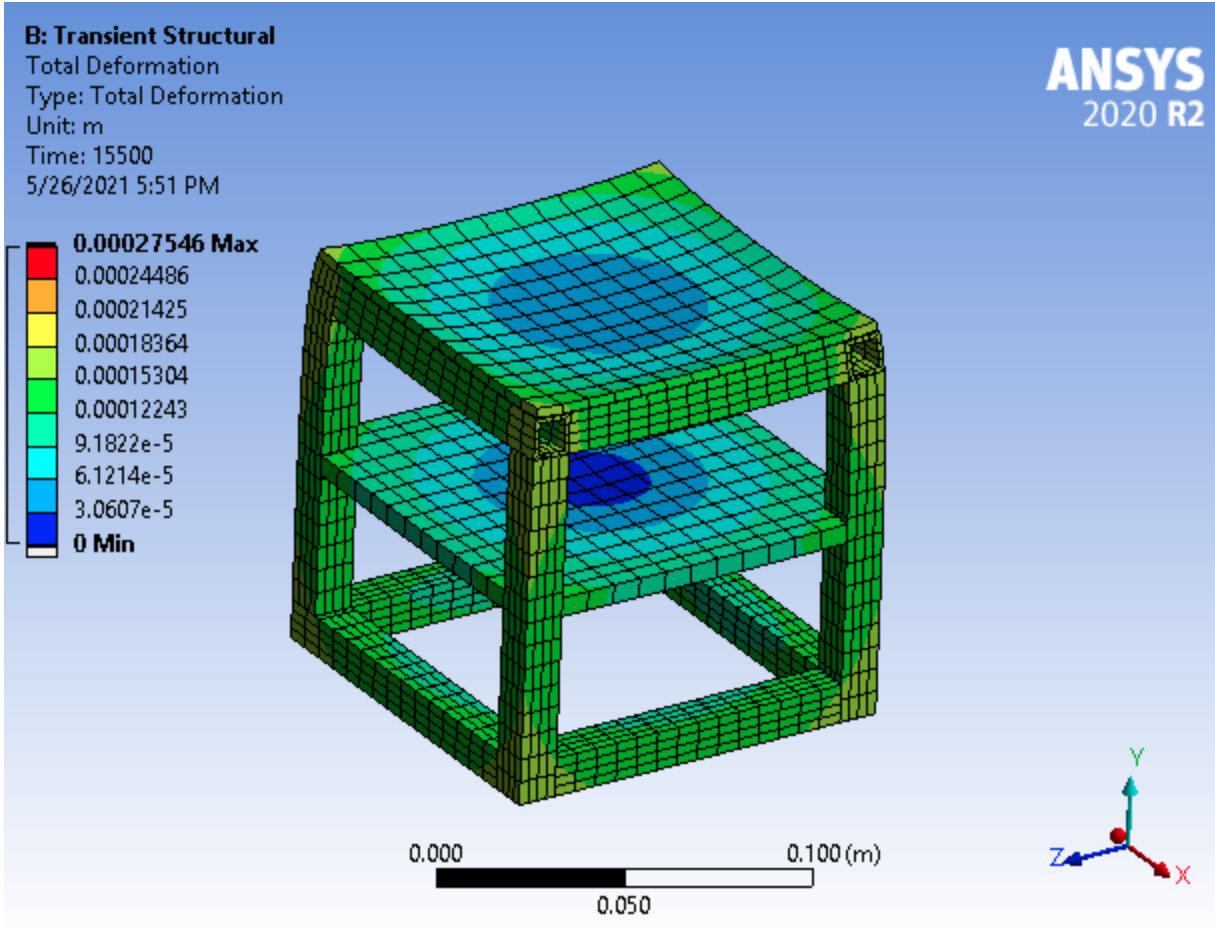**Figure 9: Total Deformation, t=0s**

Figure 10: Total Deformation t=15,500s

One of the main points of interest is the center of the camera face. The way that that point

deforms in the x y and z directions will be used to generate the camera deformation model.

Below are the plots of the camera center element deformation throughout the three orbits. The

green line is maximum, the blue line is average, and the red line is minimum deformation.
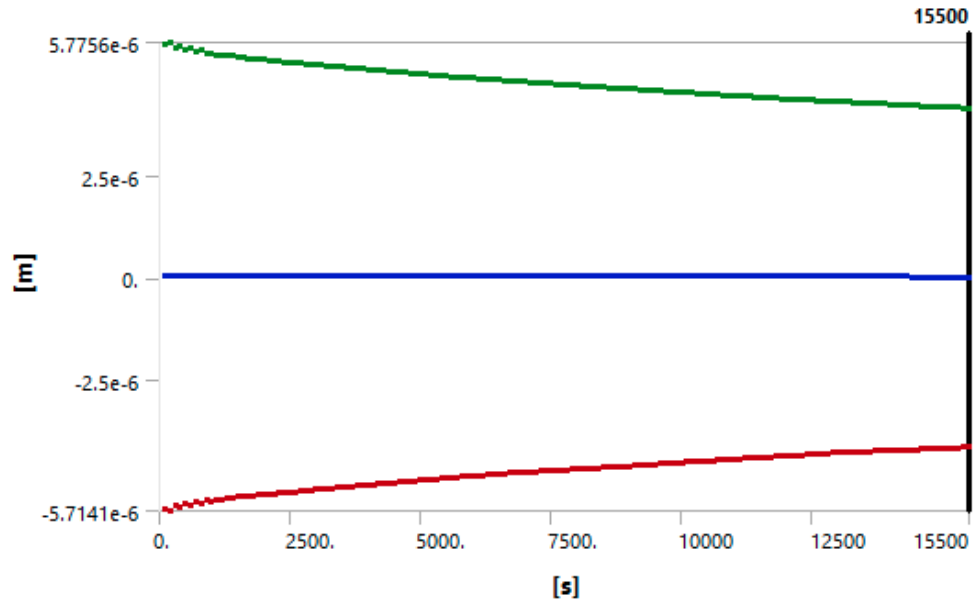
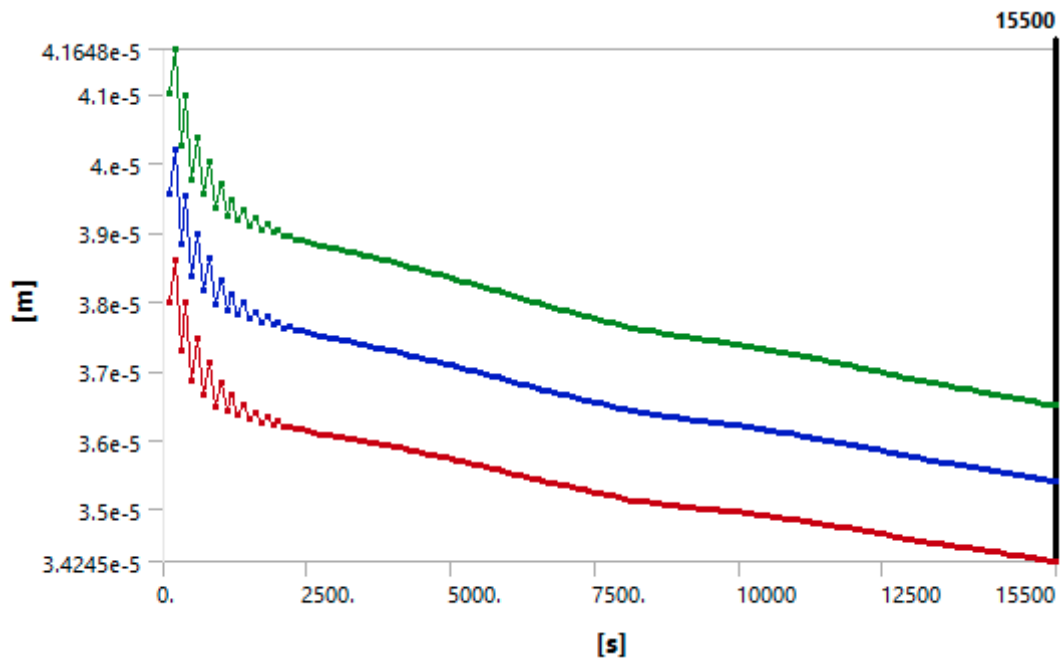**Figure 11 : Camera Center Element X axis Deformation**

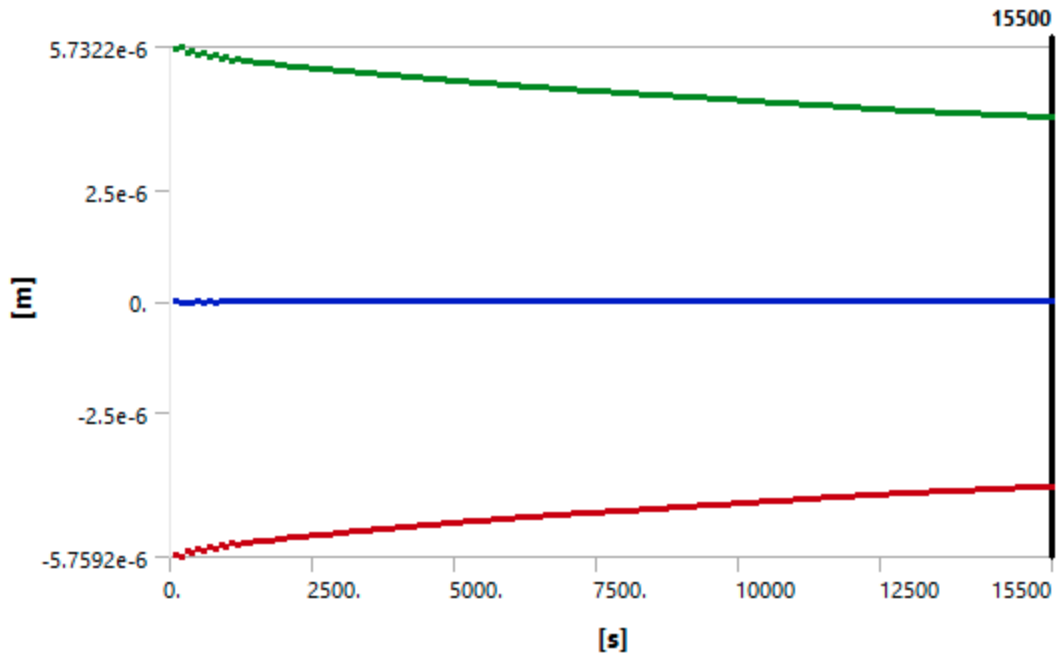**Figure 12 : Camera Center Element Y Axis Deformation**

Figure 13: Camera Center Element Z Axis Deformation

VII.   Optical Analysis Plan

The deformed geometry determined in the transient structural analysis can be further analyzed in an optical framework with ANSYS SPEOS. The deformed geometry found in the transient structural analysis must be imported into SPEOS. It appears to be a little more involved then the classic click and drag used to import solutions into analysis for other applications, I'm pretty sure the deformed geometry must be exported from the transient structural analysis and imported into SPEOS instead of connecting the geometry between the blocks (seen in **Figure 14**).
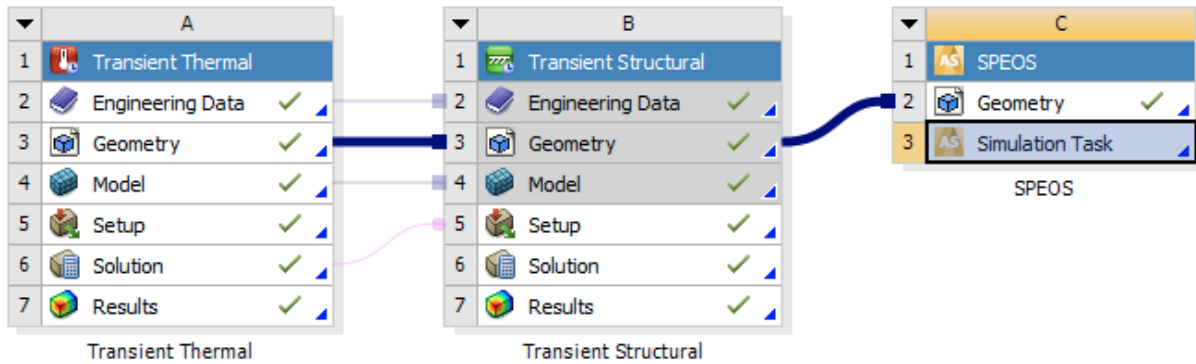
Figure 14: SPEOS, Possibly Wrong Setup

I would recommend reaching out to the ANSYS application engineers for more guidance on analyzing a deformed geometry in SPEOS, as I have been unable to find a lot about it online.

VIII.   Conclusions and Recommendations

<u>Geometry Next Steps:</u>

A good example of a satellite that could be used in the proposed constellation is the Planet Labs DoveSat. To improve the analysis, the geometry in ANSYS could be replaced with a similar model to the DoveSat, and the surface areas and materials in MATLAB could be altered to match each face.
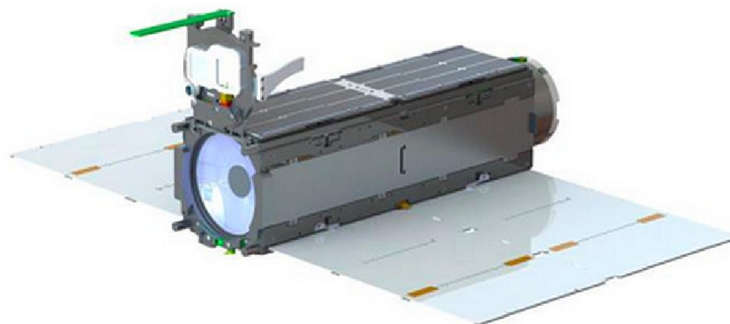

Figure 15: Planet Labs DoveSat

Thermal Next Steps:

While the deformation of the satellite reaches steady state after several simulation orbits, including internal heat would change the steady state average temperature which could result in differences in how the camera deforms. I was unsure of what form the internal heat would take (heaters in different locations, thermal controls system, what actual values to use, etc.), so more research into this and implementing it would be useful. I also opted for spending more time on figuring out my issues with ANSYS instead of focusing on fixing my indirect solar radiation calculations in MATLAB as their contribution to the total heat was fairly small, but figuring out the bounds for the double integral and evaluating it in MATLAB would be a solid next step.

Structural Next Steps:

I used pretty large time steps to make the analysis run in a reasonable amount of time (~1hr) as there was a lot of temperature data. I would recommend adding more steps once most of the changes are implemented in order to get better deformation results. I also was unable to fix the warning seen in **Figure 16** below. Reaching out to the application engineers at ANSYS would be a good idea to fix this issue. I also attempted to extend from three orbits to five orbits for the simulation but ran into issues with ANSYS crashing. Adding more orbits would better showcase when the satellite reaches steady state. The average deformation at steady state is largely due to the constant heat loss from radiation, and the deviations from that average are due to the non-symmetric heat incident on the satellite from the various forms of solar and earth radiation.

ANSYS Workbench - Warning ✕

The reference temperature for the thermal expansion coefficient differs from the reference temperature of one or more bodies. The data will be adjusted to have a zero thermal strain at the reference temperature of each body. If the number of temperature points is sparse this could cause invalid values to be used for calculations. The recommendation is to have the same reference temperature on the bodies as the thermal expansion coefficient's reference temperature in Engineering Data or a dense number of temperature points.

Figure 16: Reference Temperature Warning

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