Structural-Thermal Optical Performance Analysis of Small Satellite Payloads

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Overview

Thermal expansion governs the optical performance of the Spectral Ocean Color (SPOC) satellite's adjustable multispectral payload. Due to the dynamic thermal environment of low earth orbit (LEO), rapid temperature fluctuations will induce deformation in the structure. Additionally, the refractive properties of the optical lenses require them to be placed in very specific and precise positions. As the structure deforms due to thermal expansion, these positions will change in orbit, causing image quality to fluctuate as well. While this is an unavoidable effect, it can be calibrated for by using predictions from simulation, and careful selection of material coefficients of thermal expansion. A structural-thermal optical performance (STOP) analysis uses combines all three phenomenon to determine how the image quality relates to temperature change.

Optics Setup

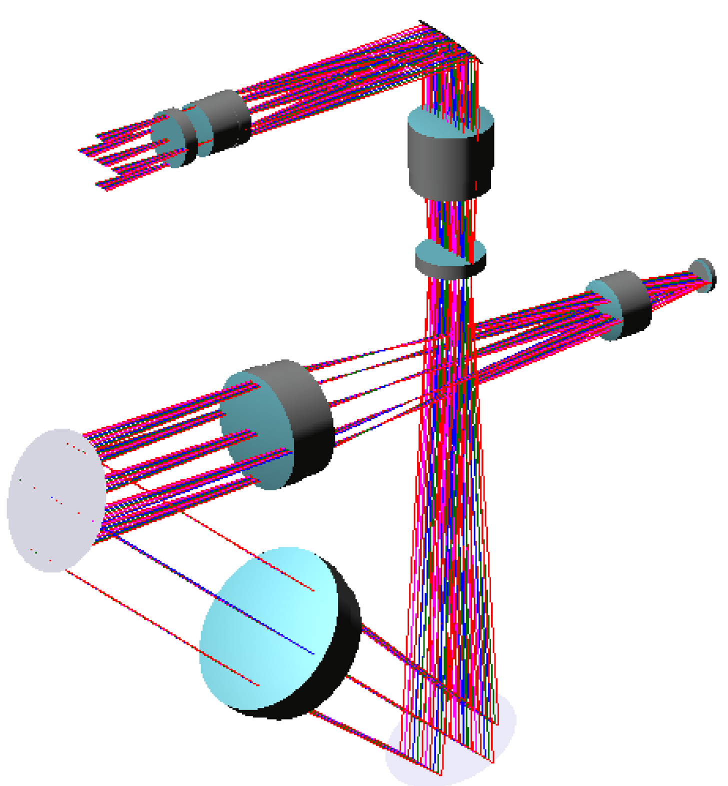

Figure 1: SPOCeye optical layout

The SPOCeye payload has a 130m resolution (GSD) with 16 adjustable multispectral bands. It will gather remote sensing data in the 450 to 820nm range. The optics consist of a telescopic portion and a camera portion for focusing light on the CMOS sensor, and a diffraction grating for separating the spectrum.

Analysis

The optical performance of SPOCeye is quantified in terms of the contrast (in %) it can produce at a certain spatial frequency, measured in line-pairs per millimeter (lp/mm). The CMOS sensor on SPOCeye has $6\mu m$ pixels, meaning the image-space sampling frequency is bound by the Nyquist sampling limit:

$$f_s = \frac{1}{d_{\text{pixel}}} \geq 2f_N \tag{1}$$

For a $6\mu m$ pixel size, the Nyquist frequency is 83.3lp/mm.

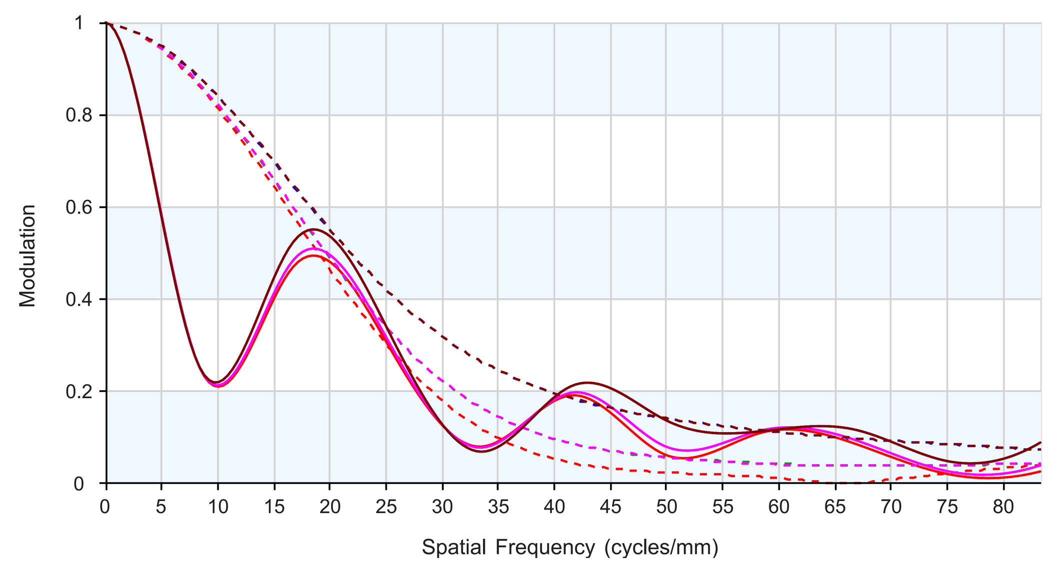

Figure 2: MTF Graph at nominal lens spacing

A first-order STOP analysis was completed, which finds the MTF (a measure of contrast) range over a temperature change observed at a given beta angle. The temperature change is applied as a step, assuming the optics were calibrated to perfect alignment at room temperature (20°C). The thermal expansion is modeled as aluminium rods between the elements. After applying the step temperature change, the new distances between the lenses are given by

$$L_1 = (1 + \alpha \Delta T)L_0 \tag{2}$$

Where α is the coefficient of linear thermal expansion ($\approx 23.6\mu\text{m/m}\cdot\text{K}$ for aluminium)

Beyond this type of first-order analysis, Code V offers the ability to do a tolerancing analysis on the optical system. This will perform a Monte Carlo simulation, moving and adjusting all lenses at the same time. This gives a statistical likelihood of achieving a certain MTF value, partially accounting for thermal expansion.

Results

The analysis applying a step temperature change produced the graph shown in Figure 3 below. The results include the temperature ranges expected in the interval where imaging would be ideal and the thermal strain induced by the temperature change. The thermal strain–which moves the lenses–affects the optical performance of the entire system, which is captured in the MTF values plotted as well. The data is gathered over multiple beta angles, which affect the heating of the satellite, and thus the temperatures expected.

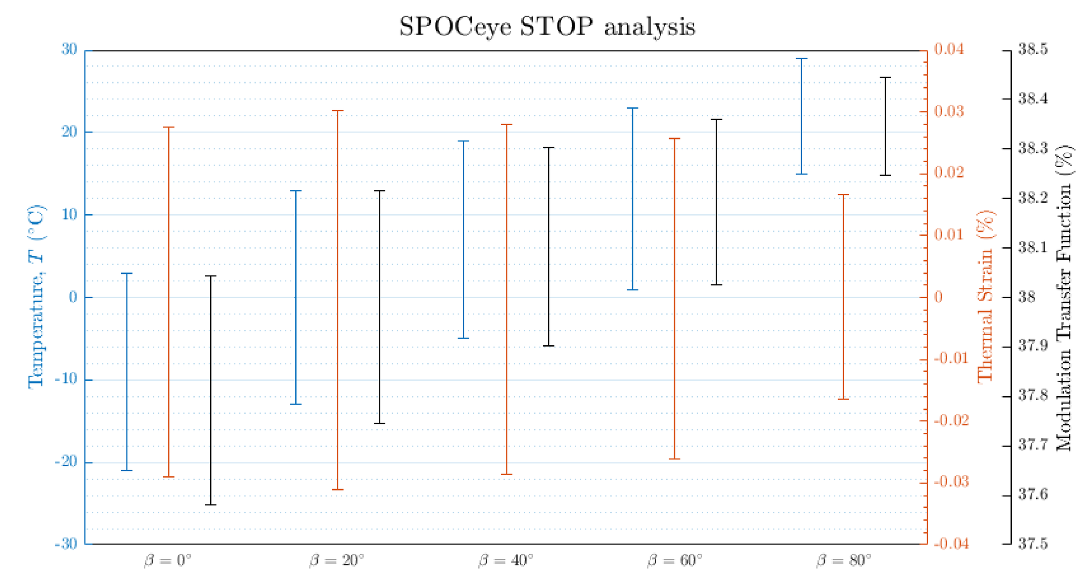

Figure 3: First-order STOP analysis results

In general, fluctuations away from the 20°C mark have a tendency to negatively affect the optical performance, as this shifts the focus of the system to either in front or behind the CMOS sensor, reducing the image quality. These first-order results give initial insight into the sensitivity of the optics to temperature changes, and will help determine how accurately the system will need to be calibrated.

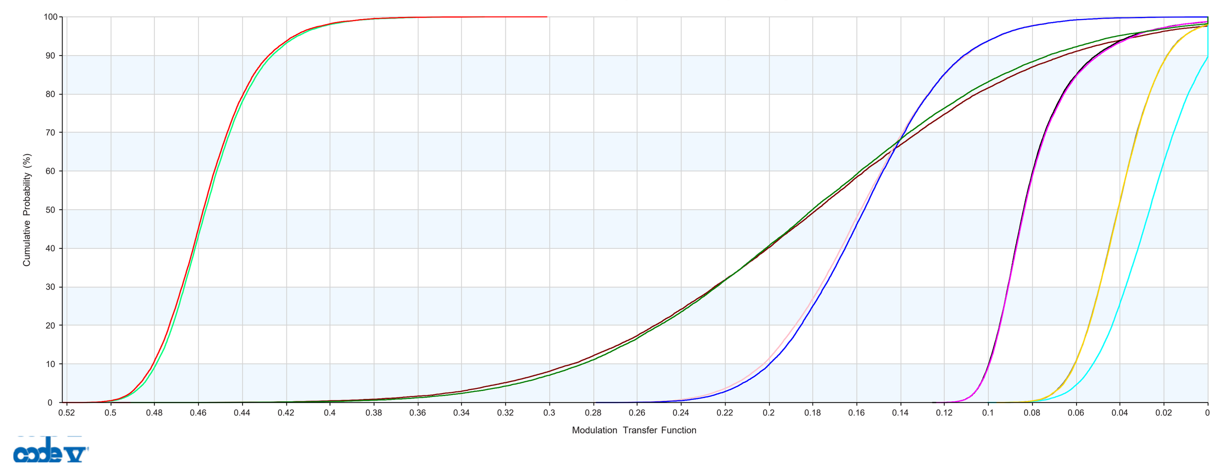

Figure 4: Tolerancing analysis results

The tolerancing analysis results are included in Figure 4, which show that most fields have a relatively low probability of having an acceptable MTF of above 30%.

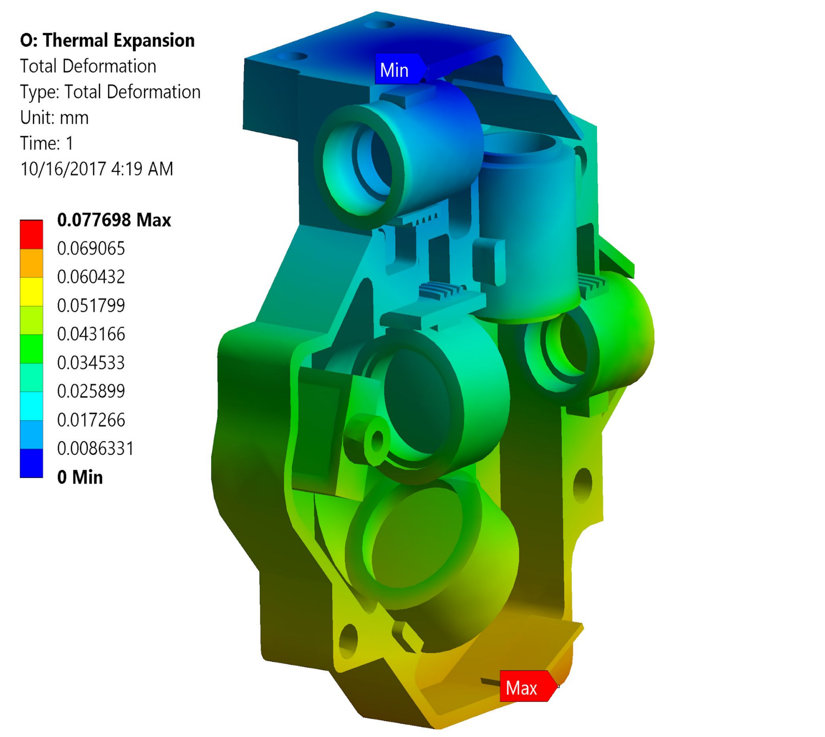

Figure 5: Finite element thermal expansion analysis

Figure 5 above shows a finite element thermal expansion model based on a 50°C step temperature change, based on the total temperature swing on orbit. More sophisticated models will include a finite element portion to more precisely determine the impact of thermal expansion on optical performance.

Future Work

The next step in this research will include a complete finite element analysis of the entire optical payload to get a complete idea of the temperature profile, and thus the thermal expansion of the payload. This will give a better idea of how to adjust the lenses, and therefore how a temperature change influences the optical performance.

There is built-in functionality to integrate the analysis softwares Nastran, Thermal Desktop and Code V with the express purpose of doing structural-thermal optical performance analyses.

Acknowledgments

All authors would like to thank Brandon Zimmerman, PhD. at NASA Goddard Spaceflight Center, for his help in understanding optical transfer functions.