Structural, Thermal Optical Modeling of CUBESAT GEO Based Orbit Camera Payload

14th annual Advanced Maui Optical and Space Surveillance Technologies
(AMOS) Conference, September 10-13, 2013, Maui, Hawaii
Manuscript Number 1203299

Kevin R. Anderson, Matthew Devost
Mechanical Engineering Department, California State Polytechnic University at Pomona
Non-linear FEA/CFD Multi-physics Simulation Lab
Donald Edberg
Aerospace Engineering Department, California State Polytechnic University at Pomona

ABSTRACT

This paper presents the results of a team of students at California State Polytechnic University at Pomona (Cal Poly Pomona) who have been working on a multi-disciplinary team capstone senior project sponsored by Caltech's NASA Jet Propulsion Laboratory (JPL). Results obtained from Structural, Thermal Optical (STOP) Modeling of a CUBESAT GEO based orbit instrumentation payload using SIEMENS PLM NX Space Systems Thermal and NX NASTRAN Finite Element Analysis (FEA) tool suite is the focus of this paper. Results from environmental loading used to predict the thermal performance of a 4U-CUBESAT instrument payload composed of and IR camera surveillance based sub-system are presented. These thermal predictions are used to perform top-level STOP analysis in order to form an optical Figure of Merit (FOM) parameter for performance characterization.

1. INTRODUCTION

Proper modeling of Structural Thermal Optical Mechanical behavior is imperative in order to afford value added predictions to the engineering systems team. However, this STOP analysis is proven to be non-trivial and has been the nemesis of the aerospace engineering analysis team for decades. A fair amount of time has been dedicated to the area of STOP as indicated in the works of [1] and [2]. Herein, a NASA sponsored senior-level student design projects using STOP modeling focusing on thermal control technologies for compact, remote sensing instruments. This involves conceptual designs with calculations providing resource usage and, hence, a metric for feasibility. The target spacecraft is the Cubesat (3U minimum). The thermal technology needs driving the design project stem from a desire to fly detectors running well below room temperature. Cooling methods, whether active or passive, will be limited by available power and/or area for radiators. The usual paradigm of cold-biasing an instrument and then adding control heat is not to be considered due to severe power restrictions associated with Cubesats. Students were encouraged to consider design concepts such as deployable radiators, radiator turn-down devices, and duty-cycled cryo-coolers used in conjunction with phase change devices [3]. The synergy of developing a systems level thermal model which can be used to investigate various design trades while simultaneously shedding light on the details of STOP analysis are outlined in the following sections of this paper.

2. THERMAL MODEL DESCRIPTION

The Cal Poly Pomona Team was tasked with building and completing an analysis of a CubeSat using commercial off-the-shelf parts. Fig. 1 shows the thermal FEA model of the CUBESAT/Camera Payload.

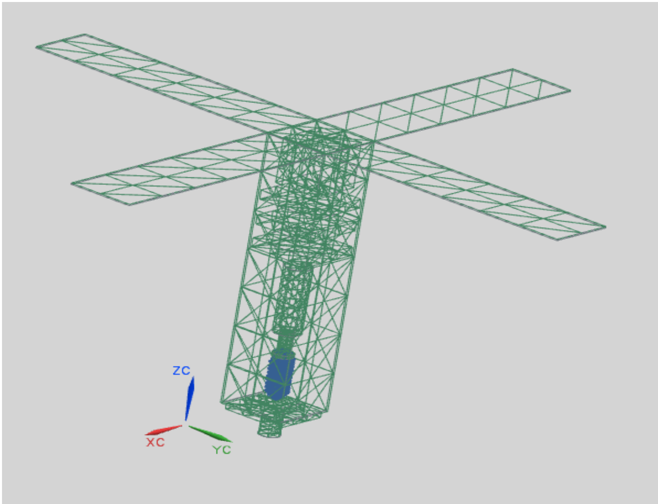

Fig. 1 Thermal Finite Element Model of Cubesat and Camera Payload

The mission of the CUIBESAT was that of a geostationary orbit (GEO), as shown below in Fig. 2. A geostationary orbit a.k.a. geostationary Earth orbit or geosynchronous equatorial orbit is a circular orbit 22,236 mi above the Earth's equator and following the direction of the Earth's rotation. An object in such an orbit has an orbital period equal to the Earth's rotational period, and thus appears motionless, at a fixed position in the sky, to ground observers. Communications satellites and weather satellites are often given geostationary orbits, so that the satellite antennas that communicate with them do not have to move to track them, but can be pointed permanently at the position in the sky where they stay. A geostationary orbit is a particular type of geosynchronous orbit.

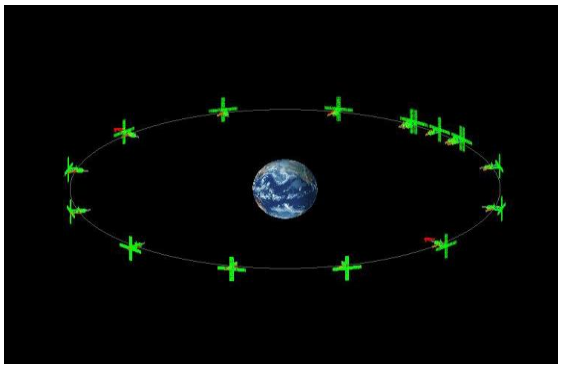

Fig. 2 GEO Orbit Cubesat and Camera Payload

The mass of the CubeSat was to be less than 3 kg and the in-flight temperature of the CubeSat was to have a 5 °C range. The maximum allowable flight temperature (AFT) was 80 °C and the minimum AFT was -35 °C. The components with all of the relevant values are displayed in Table 1.

Table 1 Properties of CubeSat Components

Part	**Mass (grams)**	**Volume (m^3)**	**Dimensions (mm)**	**Thermal Range (°C)**	**Power (W)**	**Vibration**
Chassis	580 Max Supported Mass: 6000		Outside Envelope: 100 x 100 x 340.5 Inside Envelope: 98.4 x 98.4 x 98.4	80 to -40		
Telecom	85	0.0001296	96 x 90 x 15	50 to -20 (50 degree range)	1.7	
Battery	10 Whr: 100 20 Whr: 180 30 Whr: 256	0.00019872	96 x 90 x 23		1.25	
ACS	640	0.00040558	76.2 x 76.2 x 69.85	80 to -40	8.4	> 12 g rms
SA	Standard Version: 165 Embedded MTQ option 1: 175		Standard Version: 1.6 mm PCB Embedded MTQ option 1: 1.6 mm PCB		2.1	
CPU	70	0.00013095	15 x 97 x 90	65 to -30	9	10.3 g rms
Camera	166	0.00050112	96 x 90 x 58	0 to 60	0.66	

All elements of the CubeSat were modeled using a thin shell approximation to keep the model relatively small. This was done so more components can be added to it later and to keep the solver running time short. The spacecraft was been put into a sun-synchronous orbit with the orientation of nadir being negative Z and the velocity vector being positive Y. An enclosure radiation call out was been placed on the whole model. A MLI blanket has been modeled on the +/- Y sides of the space craft to help insulate it from the environmental loads. The +/- X side of the CubeSat are being used as the radiators as these two sides are the coldest throughout orbit. The components inside the CubeSat (CPU, telecom, battery, reaction wheels, camera computer, camera) have all been modeled and placed within or on the spacecraft. Each component has been given a heat load that corresponds to the worst case heat dissipation that they will experience. These components were then tied to the radiator through modeled heat straps.

3. RESULTS

The PCMs were used as blankets to insulate the camera. For comparison two PCMS were used Water (H_2O) and Castor Oil (Ricinus communis), and two different camera lens materials were studied, Acrylic and Quartz. The results from the NX SST Thermal Model temperature fields were then mapped via interpolation to a NX Nastran Structural Model of the Camera Lens. Typical results of the PCM trade study are shown below in Fig. 3, Fig. 4 and Fig. 5 below. Fig. 3 shows the detailed NX (Space Systems Thermal) SST thermal model of the camera. Fig. 4 shows the detailed structural NX NASTRAN model of the camera lens. Fig. 5 shows transient temperature control of the camera lens, shown for H2O PCM, BETA 90 simulation, probe location is at center of camera lens.

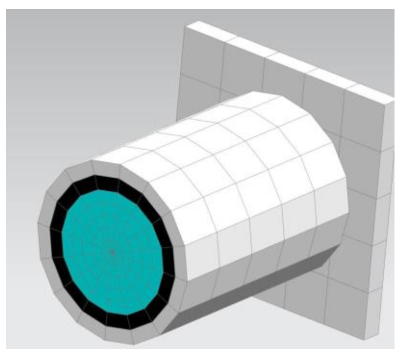

Fig. 3 NX Space System Thermal FEA Model of Camera Assembly

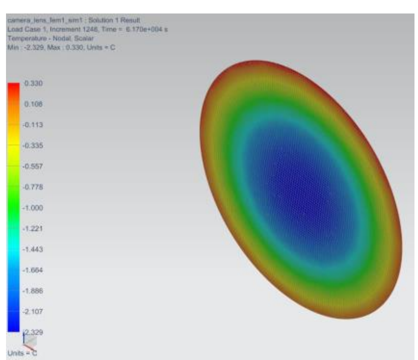

Fig. 4 Temperature Contours Mapped Onto Structural Thermal Model

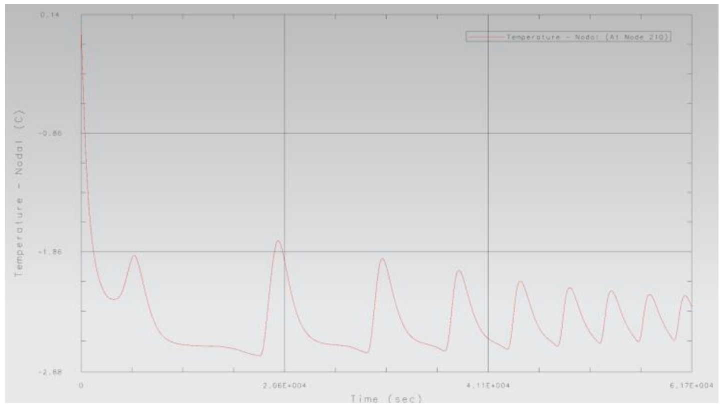

Fig. 5 Transient temperature of the Camera Lens

In order to evaluate the performance of the PCM material, the quart lens configuration was insulated first using the Water (H2O) PCM which would in practice be an "ice-bag", or a small pouch with water encapsulated within it. Next, the PCM was Castor Oil (Ricinus communis), again which upon implementation at the hardware integration level would be a pouch hermitically sealed to encapsulate the PCM material. An optical performance Figure of Merit (FOM) is used to characterize the lens performance. Herein, FOM = CTE/α, where CTE = coefficient of thermal expansion (ppm/°C), $\alpha = k/\rho C$= heat diffusivity (m^2/sec) of the optical material, k = thermal conductivity (W/m-K), ρ=density (kg/m^2) and c = heat capacity (Joules/kg-K). From the above definition of FOM, one can see that a desire optimum performance occurs when FOM < 1, i.e. large thermal diffusivity (spreading and distribution of heat, in the presence of minimal expansion/contraction of the lens material). When running the simulations, it was found that the FOM for H2O PCM was on the order of 0.53, while the FOM for Castor Oil was on the order of 0.31, as shown below in Fig. 6.

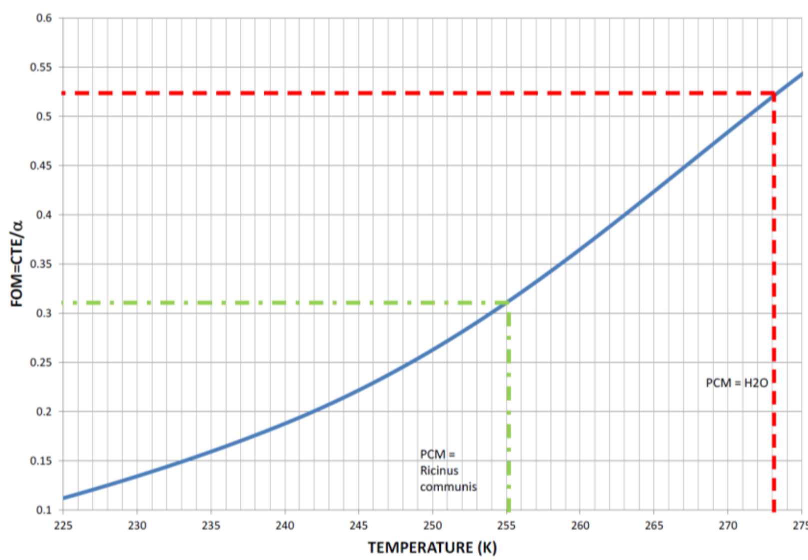

Fig. 6 – FOM for PCM Material Trade

4. CONCLUSIONS

Recall, when using the FOM the optimum design goal is to have FOM as low as possible. Evident in Fig. 5 is that the FOM increased by approximately 60% when using the Castor Oil versus the Water Phase Change Material. Thus, it has been shown by analysis, that the use of advanced PCM thermal control strategies is warranted for use in camera/optics surveillance payload applications. Future work would need to be aimed at providing the correct encapsulation of the PCMs studied. This work would need to be performed in laboratory R&D setting.

5. REFERENCES

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6. ACKNOWLEDMENTS

This project was funded under a solicitation of Caltech's NASA Jet Propulsion Laboratory's "Raise the Bar" funding. The Principal Investigator, Professor Kevin R. Anderson, Ph.D., P.E. of this project would like to thank the following individuals for their various contributions to this project.

JPL Thermal Engineering Mentor: Eric Sunada; JPL University Grant Office: Wendy Horn, Marty Herman

Cal Poly Pomona Mechanical Engineering Undergraduate Senior Project Students: Sonya Pandian, Ian Villazana, Geoff Gaw, Kevin Mayer

Cal Poly Pomona Administration Support Team: Angela Shih Chair of Mechanical Engineering,; James Cesari, Engineering Support Technician, Aerospace Engineering.

Siemens PLM Software

SIEMENS

Joel Rooks, Sr. Account Manager; , Mike Swanson, Regional Account Manager; Bijy Vattathara, Educational Grant Support Manager.

7. AUTHOR BIOGRAPHIES

Dr. Kevin R. Anderson, P.E. is a Professor of Mechanical Engineering at California State Polytechnic University at Pomona (Cal Poly Pomona). Dr. Anderson is also a Faculty Part Time Sr. Thermal Engineer for NASA JPL's Thermal and Fluids Analysis Group. Dr. Anderson received his BSME at Cal Poly Pomona in 1991 and his MSME at CU Boulder, 1994 and his Ph.D. in ME at CU Boulder in 1998. Dr. Anderson possesses over 15 years of practical experience working in the aerospace engineering thermal sector. Dr. Anderson has worked at Technology Applications, Inc. in Boulder, CO, Hughes Space & Communications El Segundo, CA, Boeing Satellite Division, El Segundo, CA, Swales Aerospace, Pasadena, CA, and ATK Aerospace, Pasadena, CA. Dr. Anderson has published several refereed journal articles regarding CFD, Numerical Heat Transfer and testing of thermal control systems hardware. Dr. Anderson can be contacted at kranderson1@csupomona.edu.

Dr. Donald Edberg is a Professor of Aerospace Engineering at Cal Poly Pomona. Dr. Edberg received his Ph.D. from Stanford University and possesses over 30 years of practical experience in the aerospace engineering sector. Prior to joining the faculty at Cal Poly Pomona, Dr. Edberg was a Boeing Fellow, and has worked and consulted on every aspect of launch vehicle design and integration, space station mission operations, satellite mission technologies, and space shuttle hardware and test development and support. Currently, Dr. Edberg is active the area of UAV design and fabrication.

Mr. Matthew Devost is a graduate student in the Mechanical Engineering Department at Cal Poly Pomona. His research interests lie within the areas of non-linear Finite Element Analysis and spacecraft control system design.