Thermal Modeling in Support of the Edison Demonstration of Smallsat Networks Project

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NASA's Edison program is intending to launch a swarm of at least 8 small satellites in 2013. This swarm of 1.5U Cubesats, the Edison Demonstration of Smallsat Networks (EDSN) project, will demonstrate intra-swarm communications and multi-point in-situ space physics data acquisition. In support of the design and testing of the EDSN satellites, a geometrically accurate thermal model has been constructed. Due to the low duty cycle of most components, no significant overheating issues were found. The predicted mininum temperatures of the external antennas are low enough, however, that some mitigation may be in order. The development and application of the model will be discussed in detail.

Nomenclature

Al	=	Aluminum
ARC	=	Ames Research Center
BTU	=	British Thermal Unit
ºC	=	Degrees Celsius
EDSN	=	Edison Demonstration of SmallSat Networks
EPISEM	=	Energetic Particle Integrating Space Environment Monitor
EPS	=	Electrical Power System
LV	=	launch vehicle
MSFC	=	Marshall Space Flight Center
MT	=	magnetorquer
PCB	=	Printed Circuit Board
SC	=	Spacecraft
SINDA	=	Systems Improved Numerical Differencing Analysier
SST	=	Stainless Steel
TM	=	tape measure
W	=	Watt

I. Introduction

THE Edison Demonstration of Smallsat Networks (EDSN) mission will deploy a swarm of at least eight cubesats into a loose formation orbiting more than 400 kilometers above Earth. EDSN will demonstrate the potential value of multiple small satellites as tools for a wide array of scientific, commercial, and academic space research. The EDSN mission will demonstrate new communications capabilities, including satellites sending data, as needed, amongst themselves. Each EDSN satellite is 10 by 10 by 15 cm in size and weighs less than 2 kg. This size is equivalent to 1.5 cubesat units (1.5U). Each satellite carries an identical sensor to measure space radiation in Earth orbit. Each of the satellites can communicate with a ground station and can relay all information from the entire network of satellites, so that the sensor data from separate locations can be collected and combined to provide an extended picture of the space environment as a function of time. The EDSN swarm is expected to operate for at least 60 days in orbit and will remain in orbit for up to three years. The present plan is to launch all of the spacecraft together as secondary payloads on a Super Strypi launch vehicle from Kauai, Hawaii in late 2013. The spacecraft will be placed into nominally circular orbits with an altidude of roughly 490 km and an inclination of 97º.

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Figure 1 shows an illustration of a single EDSN satellite. The Pumpkin chassis is made of aluminum (Al). The exterior is covered with photovoltaic panels to generate electrical power and magnetorquers to help control the attitude of the spacecraft. The yellow extension is a self-deployed tape-measure radio antenna. The square patch on the 'top' of the spacecraft is a Taoglas patch GPS antenna; another is located on the 'bottom' of the spacecraft. Inside each spacecraft is a Nexus phone and an Energetic Particle Integrating Space Environment Monitor (EPISEM) as payloads.

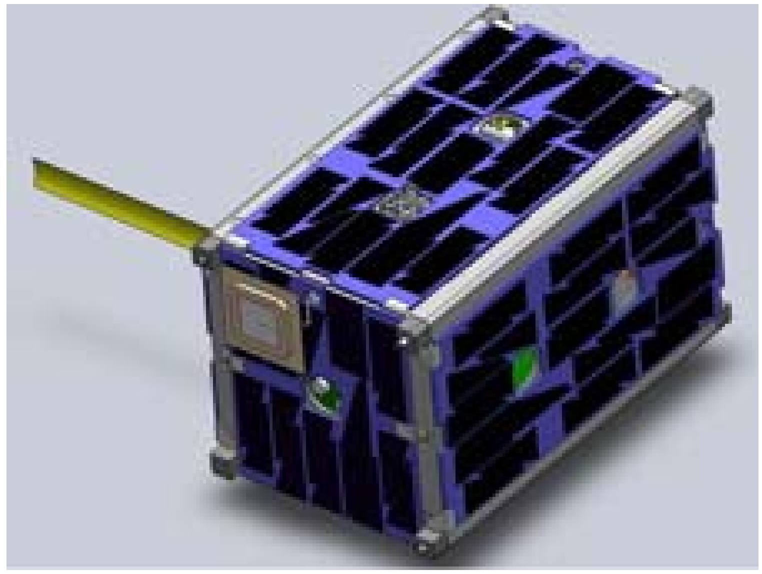

Figure 1. An individual EDSN Satellite.

The EDSN project is managed and conducted by a team at the NASA Ames Research Center (ARC), Moffett Field, California, and is funded by the Small Spacecraft Technology Program in NASA's Office of the Chief Technologist. The project began in October 2012 and should be completed in a little over two years from start. Other team members on the EDSN project are the NASA Marshall Space Flight Center (MSFC), Montana State University in Bozeman, which is providing the EPISEM radiation sensors under contract to NASA, and Santa Clara University, California, which is providing the ground tracking station and operations.

In support of the design and testing of the EDSN spacecraft, a thermal analysis was conducted. Using a CAD file and a mass and power spreadsheet provided by ARC, a geometric and thermal model was constructed using Cullimore and Ring Technologies' Thermal Desktop® (www.crtech.com) code in order to predict minimum and maximum temperatures and compare them to expected hardware limits.

II. Modeling Procedure

Thermal analyses of EDSN were performed to assess component temperatures for the spacecraft (SC) design. These analyses assumed the EDSN SC houses the following elements:

- Payload:
  - Particle detector (EPISEM)
  - Nexus Camera
- Power System:
  - Battery Box with 4 Li-ion cells
  - 170 1.9 cm^2 solar clips mounted on a PCB backing
- Communications System:
  - 2 Taoglas GPS Antennas
  - 1 GPS Receiver
  - MicroHard MHX2420 Ground-link Transceiver
  - StenSat Beacon
  - Tape Measure Antenna
- Attitude Control System:
  - 154 Magnetorquers in the PCB backing under the solar clips
  - 3 Reaction Wheels
  - 3-axis Gyroscope
- Data System:
  - Tyvak Intrepid System Board
- Structure:
  - 10x10x15 cm solid Al Pumpkin chassis

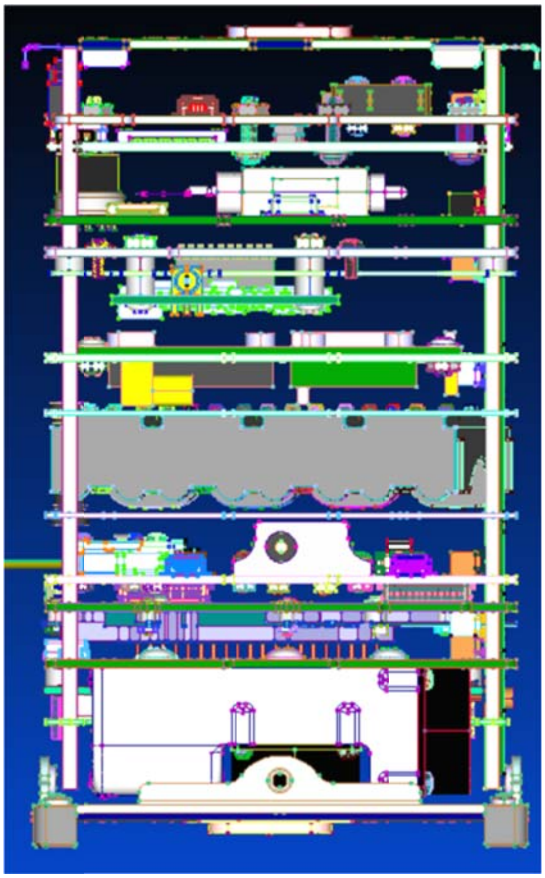

Figure 2. Display of the updated EDSN CAD file.

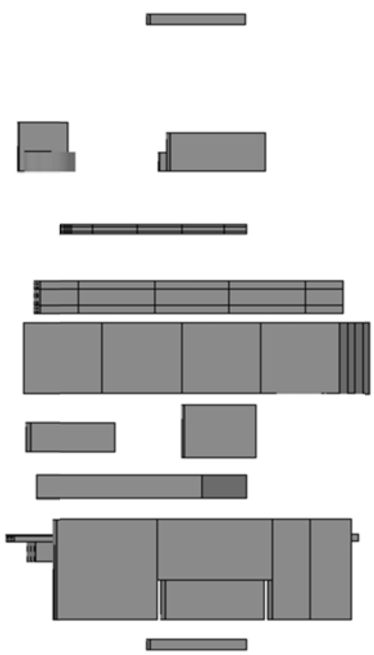

Figure 3. EDSN Components in the Thermal Desktop model.

- 2 Steel boards bracketing the batteries
- 7 PCB boards (one of which is the EPS)
- 2 Al heat sinks (one each for the MHX2420 and the GPS)
- 4 threaded SST rods
- Assorted SST screws

On-orbit thermal analyses of the EDSN mission were performed to determine the range of temperatures that are to be expected during the course of the mission. Hot and cold case simulations were performed, varying the external environmental parameters and onboard heat dissipation. Specifically, a range of beta angles and attitudes compatible with expected mission values were used, while the onboard heat dissipation values due to on/off duty cycles were varied and scaled. Analytical results presented herein are expected to bound conditions experienced during the actual flight. No analyses were done for pre-flight or ascent environments.

The model is based on a CAD file received from ARC on 11/13/12, with the added change of moving both Taoglas patch antennas to the middle of the their respective surfaces. Figure 2 shows the components in the CAD file, excluding the external chassis, solar panels, and magnetorquers (MTs). The solar cells are mounted to a PCB backing with embedded magnetorquers, which in turn is mounted on the Al chassis. Those parts of the backing and chassis that are exposed to space are radiative surfaces, while those that are not, are in full contact with adjacent parts. The extended tape measure (TM) antenna extends 12.5cm off to the left of the figure. For the purposes of thermal modeling, the SC is greatly simplified: no clips, spacers, standoffs, nuts, pins, or switches were included in the Thermal Desktop model. Also, the RBF plug and PCB backplane are not included. The only screws explicitly included are those that mount the GPS reciever and the Intrepid board. The EPISEM was modeled as various subcomponents: the UMHV power, the gchip, the 2 coilcrafts, and the Geiger counter housing. The Nexus phone, Taoglas antennas, StenSat, tape measure antenna holder, camera and holder, batteries and housings, and Novatel were modeled as single simple bricks. The gyro component was split into 6 bricks (3 reaction wheels and their holders), while the MHX2420 was split into 3 bricks. The resulting shapes of all these components are shown in Fig. 3 for comparison to the CAD; note the boards are not shown in Fig 3. Some of the bricks (e.g., the batteries) consist of multiple nodes, while the smaller ones (e.g., the Taoglas patch antennas at the top and bottom) are a single node. The TM antenna (not shown in Fig. 3) is modeled as a massless rectangle that is thermally connected to its holder (via a contact) and the chassis (via a conductor).

The subsystem surface optical properties are listed in Table 1, while the thermophysical properties are listed in Table 2. Latter quantities marked with an asterisk are temperature dependent. Due to the simplicity of the Thermal Desktop model, as well as uncertainty in the composition of various components, density scaling factors had to be applied to the densities listed in Table 2 for some components to get the expected mass. These factors, along with the resulting masses, are listed in Table 3; the actual component mass is unknown for components with unity scaling factors. However, the total mass in the model is within 1% of the present predicted actual SC mass, so that the thermal capacitances (mass times specific heat) for each component should closely match the final EDSN hardware. Some exposed interior surfaces (the boards, chassis, and batteries) are set to the relatively low (~0.2) absorptivity to emissivity ratio of that of high quality white paint, while most electrical components were modeled as single bricks of silcon with optical properties (labeled 'component' in Table 1) resulting in a slightly higher (~0.3) ratio. In reality, the optical properties of the boards will be determined by a conformal coating, such as Urethane, but the emissivity of such a coating is expected to be fairly high. Any thermal effects of wiring and cable bundles have been ignored. Further, for simplicity, contact conductance values between all touching components were assumed to be a constant 568 $W/m^2/^{o}C$ (100 $BTU/hr/ft^2/^{o}R$). Note that the thermo-physical properties were taken from various sources including MAPTIS-II (Materials and Processes Technical Information System-II), NIST (National Institute of Standards and Technology) Cryogenics Database, and vendor data. The optical properties were also taken from various sources, including the Spacecraft Thermal Control Handbook and NASA Spacecraft Thermal Coatings Reference.

Table 1. Subsystem Surface Optical Properties

Component	Material	Absorptivity	Emissivity
10 Screws and 4 long rods	SST machined	0.470	0.140
Solar cells (active)	Active Panel	0.925	0.830
Solar cells (inactive)	Inactive Panel	0.920	0.830
PCB backing of solar cells	PCB	0.850	0.900
batteries	White paint	0.200	0.880
Chassis (external surfaces)	White paint	0.200	0.880
Chassis (internal surfaces)	Black Anodized	0.860	0.860
2 Taoglas antennas	Component	0.250	0.750
MHX2420 transceiver	Component	0.250	0.750
GPS receiver	Component	0.250	0.750
GPS housing	PCB	0.850	0.900
EPISEM payload	Component	0.250	0.750
Tape measure antenna holder	White Paint	0.200	0.880
Tape measure antenna	Yellow Anodized	0.470	0.870
Intrepid board	PCB	0.850	0.900
2 Heat sinks	Alodyne Al 6061	0.440	0.140
Camera and holder	Component	0.250	0.750
Reaction wheels and holders	Component	0.250	0.750
Boards (B1,3-5,7-9)	PCB	0.850	0.900
Shelves (B2a,2b)	White Paint	0.200	0.880
StenSat radio	Component	0.250	0.750
Nexus phone	Component	0.250	0.750

The power dissipation and duty cycles assumed for each subsystem are listed in Table 4. These heat loads were smeared equally over the entire volume for each brick making up the various components. Note that B3 is the electrical power system (EPS) board and thus has an explicit power dissipation, while the other boards do not. All sources are turned on at a time that is centered at 50% of the orbital period and left on for the specified fraction of an orbit. Thus, half-way through each orbit is the largest power dissipation, since everything will be on at that point. For example, for the MTs in the hot case, peak heat is only applied for 1.4% of each orbit; the rest of the time it is at stand-by power levels. Only the EPISEM payload and EPS board are run at full power continuously. Note the camera and the Taoglas antennas are assumed to dissipate no power. The percentage of time for components to be at peak power is limited by the total power available to the spacecraft; the values in Table 4 drain the batteries in a few dozen orbits. If significantly different power duty cycles are used, a re-analysis will be required.

The hot case uses combined maximum 3.3σ 90 minute environments for high inclination orbits from Table 2.2 in Reference 1. The solar flux value is thus 1414 W/m^2 and the Earth IR flux is 241 W/m^2. The orbit-average albedo correction for $\beta=49^{o}$, the maximum possible angle between the SC orbit plane and the sun, for the present EDSN orbit and launch date and window (noon to 2pm on September 1, 2013), was linearly interpolated and found to be 9%, for a total albedo of 35%. An orbit of 450x600 km, representing the worst (hottest) case orbit scenario, was used. This orbit is in eclipse 36% of the time. Full subsystem heat loads were applied with, for example, the Intrepid board operating at 0.84 W for 15.6% of each orbit and in stand-by mode, using only 0.21 W, for the rest of each orbit. The batteries were assumed to dissipate 10% of the 1.81 W generated by the solar panels at beginning of life. For radiation purposes, the solar panels were taken as 'inactive', with reduced absorptivity, conservatively determining the amount of trapped heat. Two hot cases were run, one with the MHX2420 in normal mode and one in search mode. In the latter case, the power dissipation is less, but the transceiver is on for longer. The hot case heat loads listed in Table 4 represent conservative high values; in flight not all components will be on at the same time and they will more often be at lower power levels. For example, the Nexus phone is not likely to be on for as much as 4% of the time due to power depletion issues.

The cold case uses combined minimum 3.3σ 90 minute environments for high inclination orbits from Table 2.1 in Reference 1. This gives a solar flux value of 1322 W/m^2 and an Earth IR of 218 W/m^2. The orbit-average albedo correction for a β=0º orbit is 4%, for a total albedo of 23%. An orbit of 450x450 km, representing the worst (coldest) case orbit scenario, was used. This orbit is in eclipse 38% of the time. A "cold nominal" case was performed using component heat dissipation rates that were 50% of the hot case power levels for the EPS board, the MTs, and the Intrepid board. All other components, including the payload and batteries, were assumed to have no heat load at all, so the heat loads listed in Table 4 for the cold case represent conservative low values. The solar panels, for radiation, were taken as 'active', conservatively determining the amount of heat radiated away from the spacecraft.

Table 2. Subsystem Thermophysical Properties (@25ºC)

Component	**Material**	**Conductance (W/m/C)**	**Density (kg/m3)**	**Heat capacity (J/kg/C)**
10 Screws and 4 long rods	Steel A286, 33-1033K	11.766*	7913.12	456.696*
Solar cells	Tedlar	0.2	1390	1010
PCB backing of solar cells	PCB (0.2% Cu)	1.12	1951.99	1597.57
batteries	G10	0.857657*	1790	991.336*
Chassis	Al 6061-T6	151.193*	2707.12	872.194*
2 Taoglas antennas	Silicon	125.5	2330	702.9
MHX2420 transceiver	Silicon	125.5	2330	702.9
GPS receiver	Silicon	125.5	2330	702.9
GPS housing	PCB (0.2% Cu)	1.12	1951.99	1597.57
EPISEM payload	Silicon	125.5	2330	702.9
Tape measure antenna holder	Al 6061-T6	151.193*	2707.12	872.194*
Tape measure antenna	Steel A286, 33-1033K	11.766*	7913.12	456.696*
Intrepid board	PCB (0.2% Cu)	1.12	1951.99	1597.57
2 Heat sinks	Al 6061-T6	151.193*	2707.12	872.194*
Camera and holder	Silicon	125.5	2330	702.9
Reaction wheels and holders	Silicon	125.5	2330	702.9
Boards (B1,3-5,7-9)	PCB (0.2% Cu)	1.12	1951.99	1597.57
Shelves (B2a,2b)	Steel A286, 33-1033K	11.766*	7913.12	456.696*
StenSat radio	Silicon	125.5	2330	702.9
Nexus phone	Silicon	125.5	2330	702.9

Each model was run in steady-state, using orbital averages, to obtain initial conditions. The models were then run for 5 orbits to determine quasi-steady temperature cycles; in no case did it take very long to obtain a quasi-steady result, with the results of the 1st orbit generally not deviating more than a few degrees from the 5th orbit. Although the SC will be tumbling initially, the MTs will assist in aligning them with the Earth's magnetic field. However, for simplicity, here we discuss models that are 3-axis stabilized, with the side with the reaction wheels (the bottom side of Figs. 1 and 2) pointing towards nadir; any spinning will tend to reduced thermal gradients. Various yaw rotations were not explored. That is, the presented chosen orientation results in enveloping the maximum extreme spacecraft temperatures as a whole, but not for specific subsystems. The hottest and coldest orbit case for each component depends on its location on the bus and relative area presented to the Sun or deep space. Thus, a particular spacecraft orientation may result in more extreme temperatures for a specific component than are given here. However, a smattering of runs (not further discussed here) exploring a variety of orientations and spins suggests this effect will not be more than a few degrees, with the largest impact being on the external Taoglas antennas due to their low thermal mass.

Table 3. EDSN Subsystem Mass Scaling

Component	Density Scaling Factor	Modeled Mass (kg)
Solar cells	3.072	0.033
batteries	1.500	0.330
MHX2420 transceiver	0.7925	0.055
GPS receiver	1.1351	0.021
GPS housing	1	0.024
EPISEM payload	1	0.021
Intrepid board	1	0.021
Reaction wheels and housing	0.793	0.092
StenSat radio	0.375	0.026
Nexus phone	0.8594	0.013
Taoglass antennas	3.134	0.025
chassis	1.043	0.319
Heat sinks	1	0.024
SST shelves	1	0.126
PCB boards	1	0.193
Screws and rods	1	0.037
Camera and holder	1	0.005
Tape measure and holder	1	0.012
PCB backing of solar cells	1	0.203
Total		1.580

Table 4. EDSN Subsystem Heat Dissipation (W)

Component	Hot Case			Cold Case		
	Peak	Off-peak	% of orbit on at peak	Peak	Off-peak	% of orbit on at peak
Magnetorquers (PCB backing)	0.357	0.027	1.4	0.179	0.014	1.4
batteries	0.181	0	100	0	0	N/A
MHX2420 transceiver	8.160	0	1.1	0	0	N/A
MHX2420 transceiver (searching)	2.750	0	6.3	0	0	N/A
GPS receiver	1.155	0	4.4	0	0	N/A
EPISEM payload	0.105	0	100	0	0	N/A
Intrepid board	0.840	0.210	15.6	0.420	0.105	12.6
Reaction wheels	0.663	0	7.1	0	0	N/A
StenSat radio	3.400	0	2.2	0	0	N/A
Nexus phone	2.748	0	4	0	0	N/A
EPS board (B3)	0.117	0.063	100	0.058	0.031	100

The EDSN SC do not have any stand-alone thermal control systems. The thermal control is entirely passive, relying on structural elements and equipment layout. There are no heaters and no separate radiators; however, the solar panels are attached to the structure and act as efficient radiators when faced away from the Sun. Internal components are cooled via radiation and conduction, and mostly have high emissivity exterior surfaces.

III. Results

The standard thermal limits for industrial electronic parts are -40 ºC to +85 ºC. Most components on the EDSN spacecraft are expected to have limits better than or equal to these. The significant exception is the Nexus phone, with an upper limit due to an internal thermal reset switch of ~+55 ºC. However, the results show there are no overheating issues with any components. The temperatures of all internal components (plus the patch antennas) for the hot case with the MHX2420 in search mode are shown in Fig. 4. The hottest component is, as expected, the phone, and even it only reaches 42 ºC. With a reduced duty cycle, it will not even get that warm. The external components (the chassis, MTs, solar panels, and TM antenna) reach peak temperatures of ~30 ºC. Note that the difference between having the MHX2420 in search mode or not is negligible for all components other than the transceiver itself, which goes from a peak of ~21 ºC to ~26 ºC when it is searching.

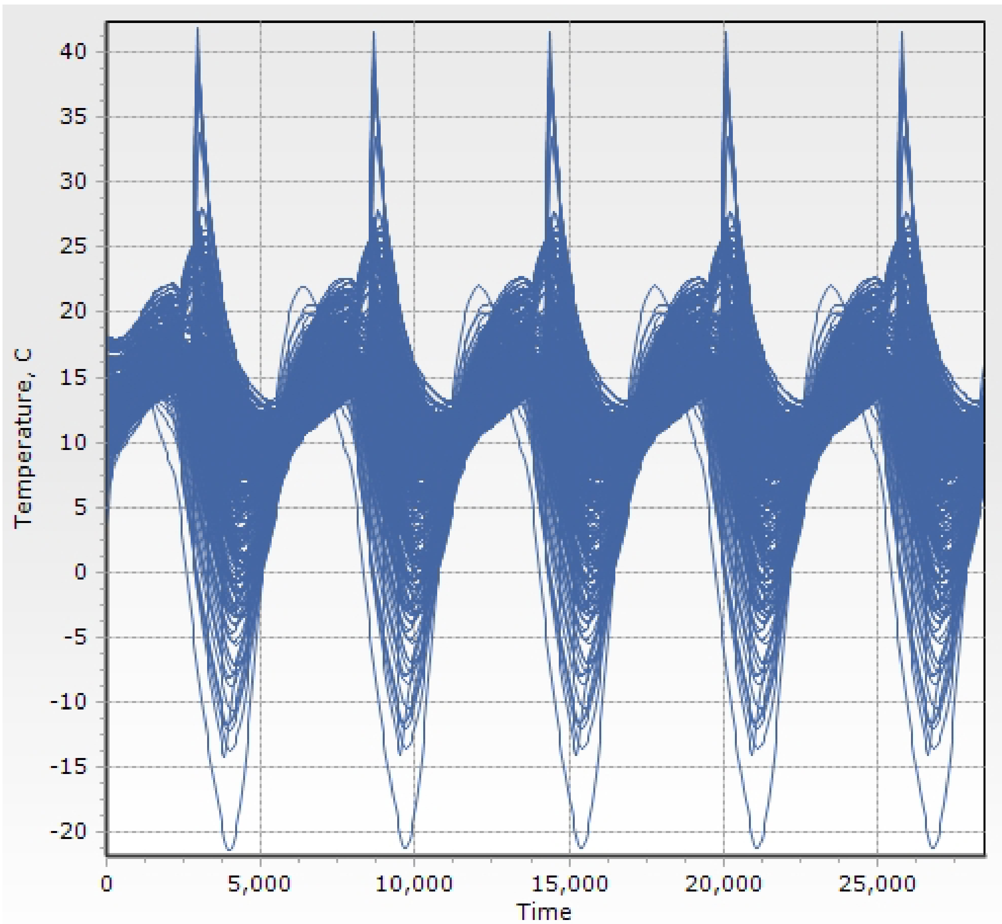

Figure 4. Temperatures of internal EDSN Components for the hot search mode case.

The temperature results for the internal components (plus the patch antennas) for the cold case are shown in Fig. 5. Only the patch antenna that is shielded from Earth IR flux is colder than -40 ºC. However, the EDSN flight antennas will be conformally coated with an acrylic seal which may improve the thermal characteristics of the patch antennas. Thus, -43 ºC is not a concern for them. Figure 6 shows the temperature results for the external components. The TM antenna, due to its very low thermal mass, swings from +40 ºC hot to -70 ºC cold and may thus have thermal cycling lifetime issues. In addition, when the TM antenna is released 30 minutes after SC deployment from the launch vehicle (LV), it may have embrittlement issues related to bending in the cold. The chassis, MTs, and solar panels on the shielded end of the SC (the top edge in Figs. 1 and 2) also get as cold as -43 ºC. However, being designed for space applications, they are expected to not have any issues at those temperatures. An illustration of how the temperature at a point in time is distributed for the hot searching case is shown in Fig. 7. The point in time is picked to be near the peak temperature of the phone. The phone, the MHX2420, and the Intrepid board are the hottest components. Note that +z corresponds to Earth-pointing in Fig. 7.

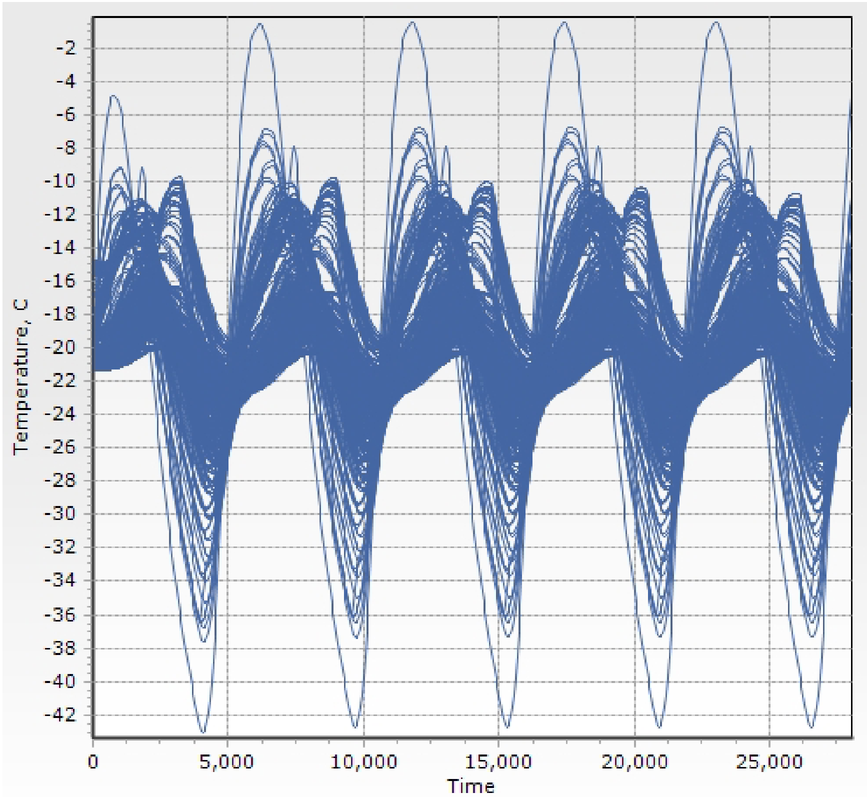

Figure 5. Temperatures of internal EDSN Components for the cold case.

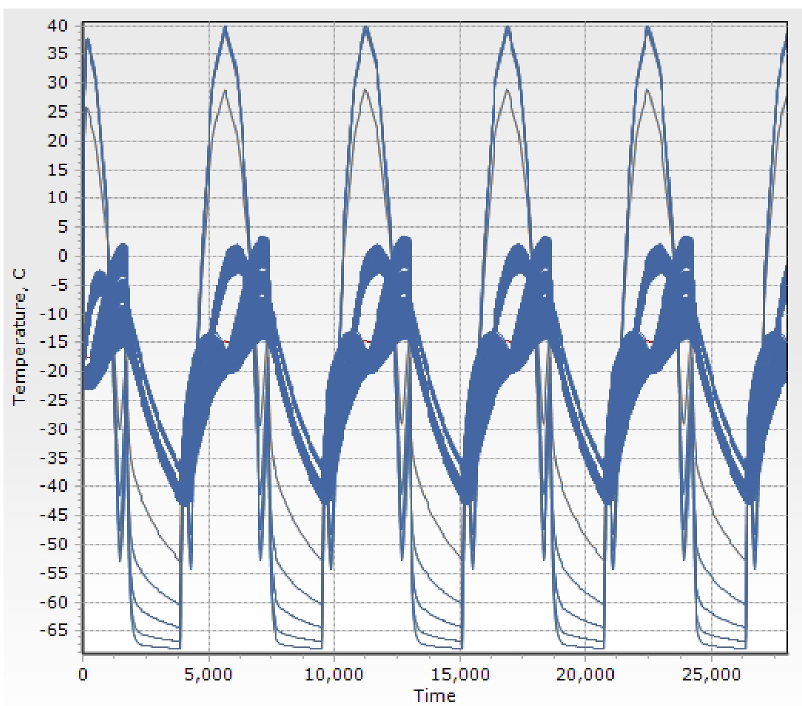

Figure 6. Temperatures of external EDSN Components for the cold case.

IV. Summary

A thermal analysis was conducted for the EDSN Cubesat mission. Although there are many uncertainties in the analysis, a conservative approach shows that there are no significant thermal issues. If the MHX2420 transceiver or the Nexus phone have a significantly longer duty cycle or more power dissipation than was used in the analysis, they may have heating issues. However, this is unlikely due to total power constraints on the small SC. One of the patch antennas may have cold issues, but a conformal coating should address it. The TM antenna gets very cold and cycles over 100 ºC every orbit, so it may have deployment or cycle fatigue issues. However, it is made of SST, so failure is considered to be unlikely. In summary, the EDSN SC seem very robust to thermal issues, both hot and cold.

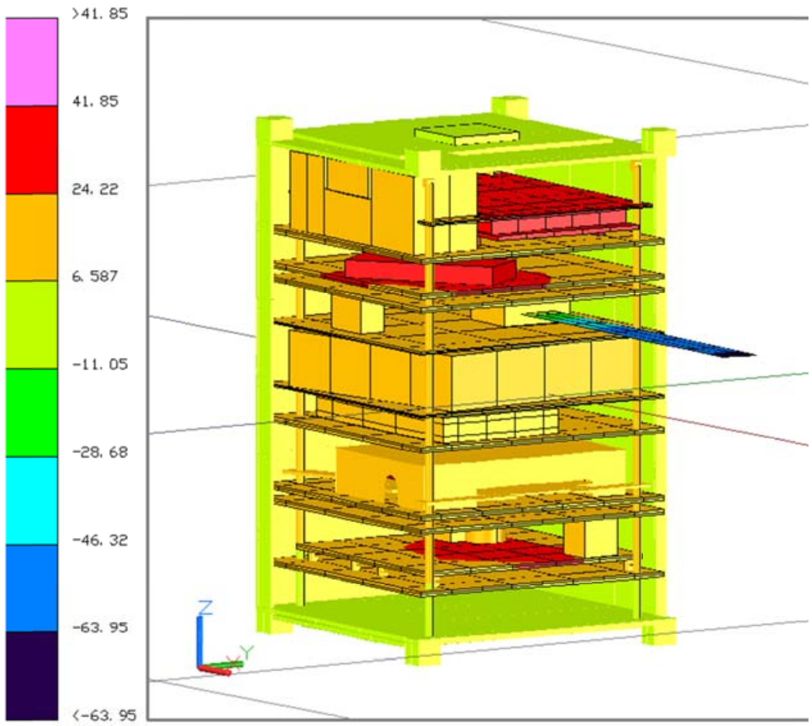

Figure 7. Snapshot of temperatures (in ºC) of EDSN Components for the hot searching case.

References

[1]Anderson, B. J., Justus, C. G., and Batts, G. W., "Guidelines for the Selection of Near-Earth Thermal Environment Parameters for Spacecraft Design," NASA TM-2001-211221, Oct. 2001.