Thermal Modeling and Testing of the Edison Demonstration of Smallsat Networks Project

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NASA's Edison program is intending to launch the Edison Demonstration of Smallsat Networks (EDSN) project, a swarm of 8 1.5U cubesats in the fall of 2014 to demonstrate intra-swarm communications and multi-point in situ space physics data acquisition. Due to late changes in the duty cycles of various components, potential overheating issues appeared. In addition, it was determined that capacity loss due to the coldness of the batteries was unacceptable, so mitigation was required. This paper will discuss the thermal modeling, testing, and results of the EDSN mission.

Nomenclature

Al	=	Aluminum
ADCS	=	Attitude Determination and Control System
ARC	=	Ames Research Center
BOM	=	Bill of Materials
BTU	=	British Thermal Unit
ºC	=	Degrees Celsius
CAD	=	Compute Aided Design
CDR	=	Critical Design Review
CONOPS	=	Concept of Operations
EDSN	=	Edison Demonstration of SmallSat Networks
EDU	=	Engineering Development Unit
EPISEM	=	Energetic Particle Integrating Space Environment Monitor
EPS	=	Electrical Power System
FLUINT	=	Fluid Integrator
GPS	=	global positioning system
LV	=	launch vehicle
MAPTIS	=	Materials and Processing Information System
MC	=	minor cycle
MEL	=	master equipment list
MSFC	=	Marshall Space Flight Center
MT	=	magnetorquer
NASA	=	National Aeronautics and Space Administration
NIST	=	National Institute of Standards and Technology
PCB	=	Printed Circuit Board
PDR	=	Preliminary Design Review
RBF	=	Remove Before Flight
SC	=	Spacecraft
SINDA	=	Systems Improved Numerical Differencing Analyzer
SS	=	Stainless Steel
TD	=	Thermal Desktop
TM	=	tape measure
TVAC	=	thermal vacuum
VR	=	voltage regulator
W	=	Watt
WD	=	Watch Dog

I. Summary

NASA's Edison program is intending to launch a swarm of at least 8 small satellites the fall of 2014. 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 EDSN project, a geometrically accurate thermal model has been constructed. Due to the low duty cycle of most components, no significant overheating issues were found for nominal operation and orbital parameters, although there is little margin. The predicted mininum temperatures of the batteries are low enough, however, that some mitigation may be in order. The development and application of the model is discussed in detail. Further, if extended (~4 hr) detumble operations are required, overheating of some components may occur. This report should be considered supplemental to the CDR thermal analysis[1] and addresses changes in the design and operations that have occurred after CDR.

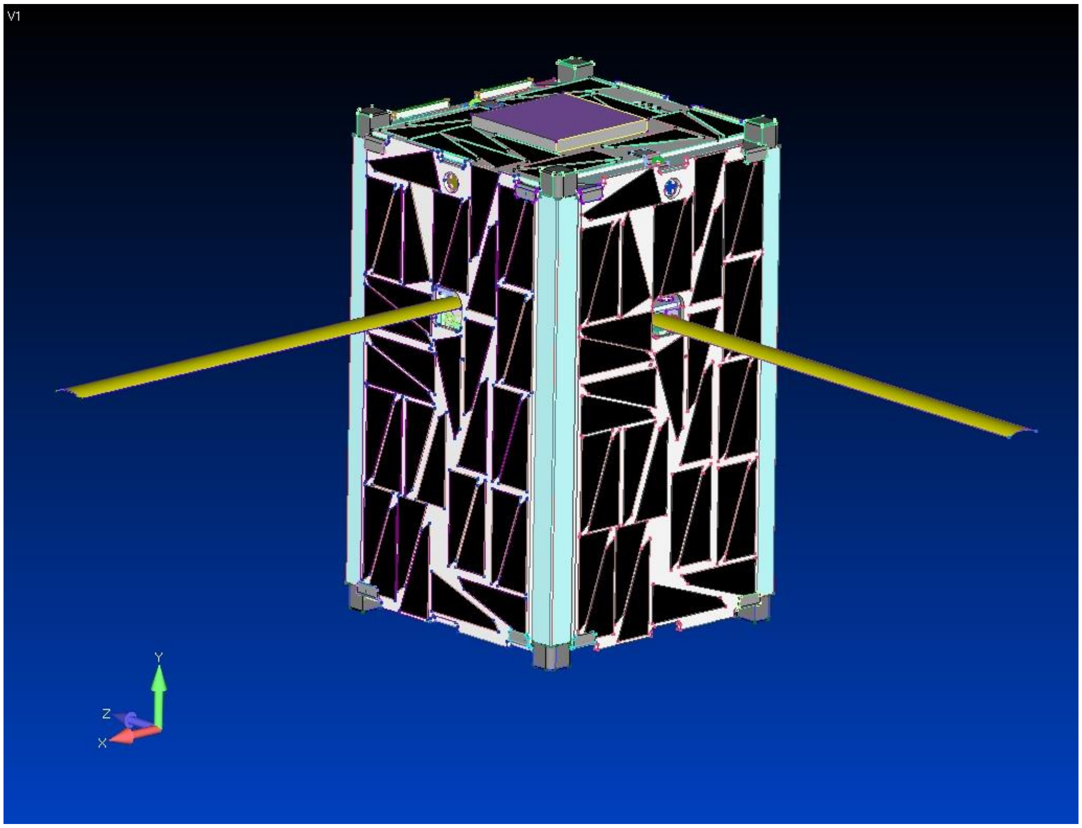

Figure 1. CAD representation of an individual EDSN Satellite.

II. Introduction

The EDSN mission will deploy a swarm of 8 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 10x10x17 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 the fall of 2014. The spacecraft will be placed into nominal 500 km high orbits with an inclination of 94.8º. Note that the precise launch time determines the orbital sun angle, β, of the final orbit and this has a significant impact (of up to 15ºC) on nominal EDSN temperatures. With the present launch window of 2 hrs starting at local noon, this results in β=0º for a 'cold nominal' orbit and a β=30º for a 'hot nominal' orbit.

Figure 1 shows a CAD illustration of a single EDSN satellite. The Pumpkin chassis is made of aluminum (Al), with the four sides being Al 7075-T7351 and the top and bottom endcaps being Al 5052. Further, the 4 exposed corners are Anodized while the rest of the surfaces are clear Alodined. The inside surfaces of the chassis are rough while the outer Alodined surfaces are smooth. The exterior is covered with photovoltaic panels (consisting of cells soldered to a PCB backing) to generate electrical power and magnetorquers are imbedded in the PCB to help control the attitude of the spacecraft; the PCB is attached to the chassis with clips visible in Fig. 1. The yellow extensions are self-deployed tape-measure radio antennas. The square patch on the 'top' of the spacecraft is a Taoglas patch GPS antenna; another patch antenna, modified for S-Band, is located on the 'bottom' of the spacecraft. Inside each spacecraft is a Nexus phone for processing and an Energetic Particle Integrating Space Environment Monitor (EPISEM) as a payload.

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 2011 and should be completed in about four 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 redesign of the EDSN spacecraft, a thorough thermal analysis was conducted as an update to the PDR and CDR analyses[1,2]. Using a Computer Aided Design (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 with SINDA/FLUINT (version 5.5) in order to predict minimum and maximum temperatures and compare them to expected hardware limits.

III. Model Details

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)
- Power System:
  - Battery assembly with 4 Li-ion cells
  - 154 2.63 cm2 solar cells mounted on a PCB backing
- Communications System:
  - 2 patch Antennas (GPS and S-Band)
  - 1 Novatel OEMV-1 GPS Receiver
  - MicroHard (MHX) 2420 Ground-link Transceiver
  - StenSat Beacon
  - 2 Tape Measure Antennas
- Attitude Control System:
  - 154 Magnetorquers in the PCB backing under the solar cells
  - 3 Reaction Wheels
- Data System:
  - Router
  - Nexus phone
- Structure:
  - 10x10x17 cm solid Al Pumpkin chassis (including endcaps)
  - 2 Steel boards bracketing the batteries
  - 7 PCB boards (one of which is the EPS)
  - 2 Al heat sinks (one each for the MHX 2420 and the GPS)
  - 4 threaded SS rods
  - Assorted SS 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, β, and attitudes compatible with bracketing expected mission values were used, while the onboard heat dissipation values due to on/off duty cycles were based on representative 'minor cycles'. Although not every possible combination of orbit, orientation, and power was explored, the 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 12/20/13, with the caveat that the solar panels, which now number 170 and are 2.3cm^2 in area each, were not adjusted from the CDR CAD; the total solar panel surface area is different by less than 5%. 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 the embedded MTs, 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 contact with adjacent parts. The tape measure (TM) antennas extend 12.5cm from the SC. For the purposes of thermal modeling, the SC are greatly simplified: no clips, spacers, standoffs, nuts, pins, or switches were included in the Thermal Desktop model. Also, the RBF plug is not included. The only screws explicitly included are those that mount the GPS reciever and the router board assembly. The EPISEM was modeled as various subcomponents: the UMHV power, the gchip, the 2 coilcrafts, and the Geiger counter housing. The Nexus phone, patch antennas, StenSat, tape measure antenna holders, backplane holders, and Novatel were modeled as single simple bricks. The reaction wheel component was split into 6 bricks (3 reaction wheels and their holders), while the MHX2420 was split into 4 bricks and the Lithium radio into 2 bricks. The batteries were modeled as finely resolved cylinders, while the battery casing and backplane were imported in detail from the CAD file. The resulting shapes of all these components are shown in Fig. 3 for comparison to the CAD file; note the boards are not shown in Fig. 3. Some of the bricks (e.g., the MHX2420) consist of multiple nodes, while the smaller ones that are expected to be isothermal (e.g., the patch antennas at the top and bottom) are a single node. The TM antennas (not shown in Fig. 3) are modeled as massless rectangles that are thermally connected to their holders (via contacts with a 0.003 Thickness/Length) and the chassis (via 5678 W/m^2/°C conductors). Four Arduino chips (EPS/WD, sensors, GPS,

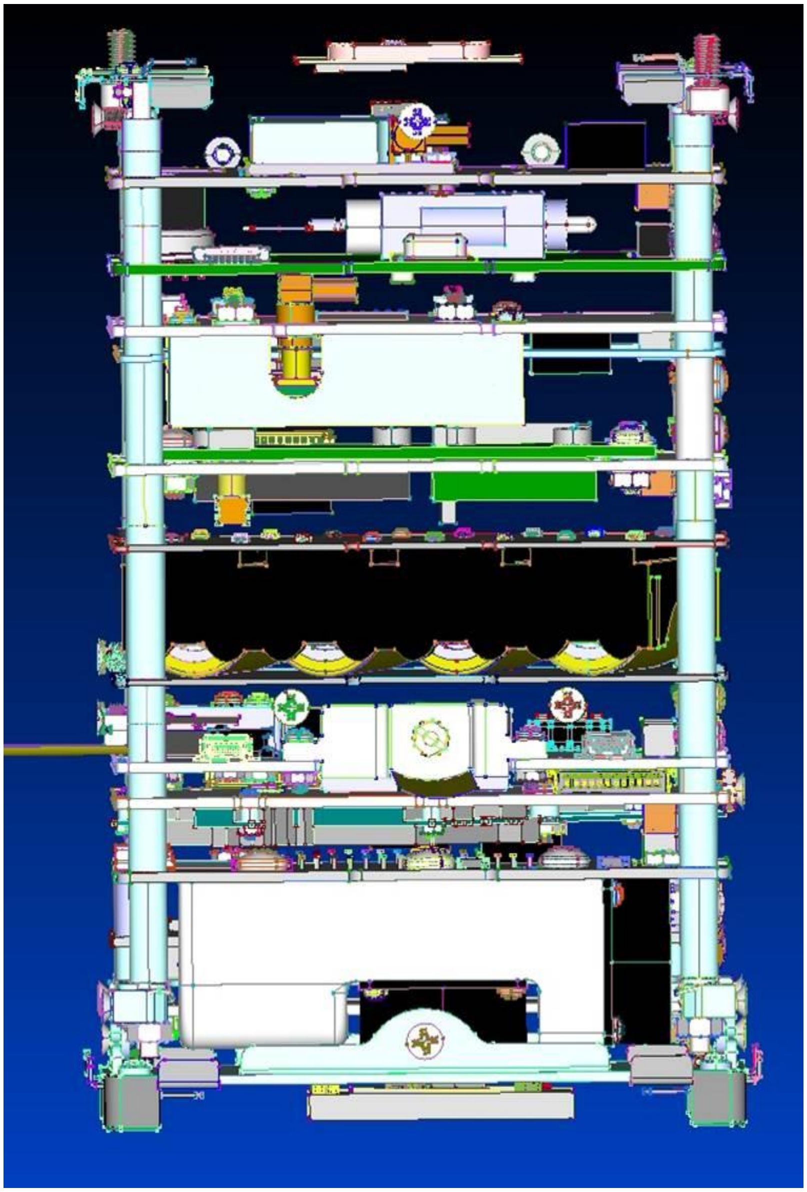

Figure 2. Display of the recently updated EDSN CAD file.

and ADCS), the parallax chip on the router board, and five voltage regulators (Nexus, MHX2420, EPS/WD, Beacon, and GPS) are also included as bricks.

The subsystem surface optical properties are listed in Table 1, while the thermophysical properties are listed in Table 2. Quantities marked with an asterisk in Table 2 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 ('1') scaling factors. Due to geometric simplification, some objects do not match the expected mass. For example, the modeled mass of the chassis is 25% too high due to not including the cutouts in the sides which were added later in the design process. However, the total mass in the model is within 7% of the present predicted actual SC mass[3]. The omitted ~100g from the model is in screws, standoffs, wires, pins, switches, etc., so that the thermal capacitances (mass times specific heat) for each component should match the final EDSN hardware. The possible exceptions to this are the generic 'silicon' components listed in Table 2: the heat capacity of silicon is relatively low compared to plastic (though high compared to metal), so this may result in somewhat higher and more rapid temperature excursions for these components in the model than in reality.

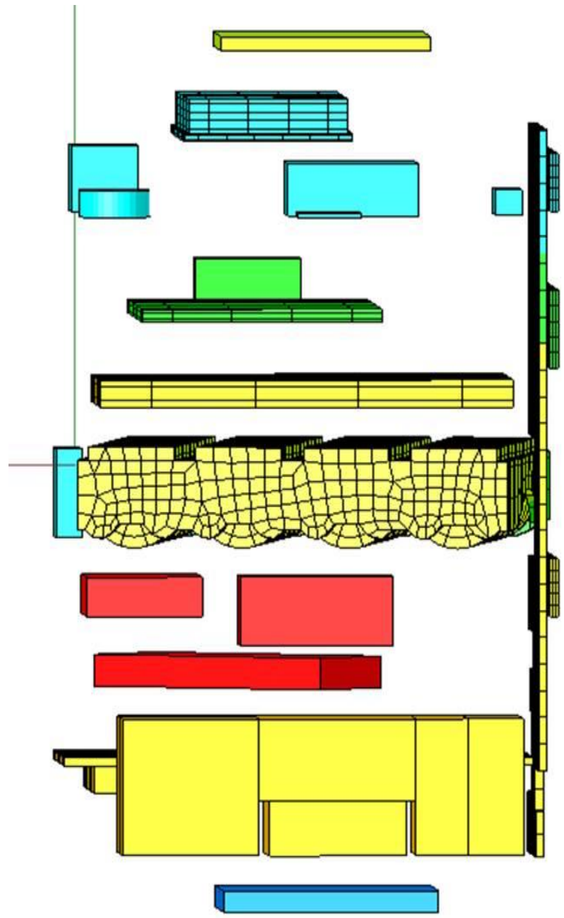

Figure 3. EDSN Components in the TD model.

Some exposed interior surfaces (the TM holders) are set to the relatively high (0.87) IR emissivity typical of white colored objects, while most large electrical components were modeled as bricks of silicon with the optical properties labeled 'component' in Table 1 that has a slightly lower (0.75) emissivity. The optical properties of the boards (labeled 'PCB' in Table 1) were determined by measurements of uncoated white PCB at MSFC using typical flight methods[4]; although the properties vary depending on the circuitry extent, a rough average is used for all PCB in the model. It is assumed there is no conformal coating on the SC; this would not change the optical properties much, but might impact thermal contact values (see blow). The optical properties of the chassis (excluding the Anodized corners), endcaps, batteries, and battery plastic coatings were also determined using flight-like hardware at MSFC. For higher model fidelity, measured values of optical and thermophysical properteis of all as-built components would be required; note that this is a requirement of APR 8070.2[9] that the project has chosen to waive in the face of budget and schedule issues. Optically, since these surfaces are internal and not exposed to sunlight, it is, strictly speaking, only the IR emissivity which is important, not the solar absorptivity.

Any thermal effects of wiring and cable bundles have been ignored, since their thermal mass is small and their resulting thermal flux between components is estimated to be negligible for EDSN. However, it was noticed during assembly of the EDU that will be used in qualification TVAC testing, that there are possible significant heat paths via cabling from the antennas to internal components that have been ignored. Most of the thermophysical properties in Table 2 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. The active solar panel emissivity, used for the cold case, is angularly dependent with a hemispherical value of 0.726, while the green plastic of the battery wrapping was deemed to have 5% transmission; these are marked with an asterisk in Table 1. Note the flight batteries will be wrapped in a salmon-colored plastic; it is assumed the optical properties will be the same as the measured green plastic.

Table 1. Subsystem Surface Optical Properties

Component	Material	Absorptivity	Emissivity
9 Screws	SS machined	0.47	0.14
3 backplane holders	SS machined	0.47	0.14
3 backplane holders (inside)	Kapton (1 mil)	0.37	0.44
2 Battery heatsinks (B2a,b)	SS machined	0.47	0.14
Solar cells (active)	Active Panel	0.726*	0.83
Solar cells (inactive)	Inactive Panel	0.92	0.83
PCB backing of solar cells	PCB	0.49	0.90
wrapped batteries	Green plastic	0.93*	0.85
Battery tips	Al	0.15	0.11
Battery casing	PE black plastic	0.93	0.92
Chassis (external surfaces)	Alodined (7075, smooth)	0.35	0.09
Chassis (internal surfaces)	Alodined (7075, rough)	0.35	0.22
Chassis Endcaps	Alodined (5052)	0.23	0.115
Chassis Corners	Anodized (7075)	0.68	0.82
2 patch antennas	Component	0.25	0.75
MHX2420 transceiver	Component	0.25	0.75
GPS receiver	Component	0.25	0.75
Grounding unit	Alodined (6061)	0.44	0.14
MHX&GPS heatsinks, GPS housing	Alodined (6061)	0.44	0.14
EPISEM payload	Component	0.25	0.75
TM antenna holders	White plastic	0.25	0.87
Tape measure antenna	Yellow Polyester	0.52	0.82
Router board (B6)	PCB	0.49	0.90
Backplane	PCB	0.49	0.90
GPS Switch	PCB	0.49	0.90
Reaction wheels and holders	Component	0.25	0.75
Boards (B1,3-5,7-9)	PCB	0.49	0.90
Lithium Radio	Component	0.25	0.75
Lithium Housing	Al (buffed, 30% specular)	0.16	0.03
4 threaded rods	Al (buffed, 30% specular)	0.16	0.03
StenSat radio	Component	0.25	0.75
Nexus phone	Component	0.25	0.75
Arduinos, VRs, parallax	Component	0.25	0.75

For simplicity, and in the absence of any other information, most thermal contact conductance values between most touching components were assumed to be a constant 568 W/m^2/ºC (100 BTU/hr/ft^2/ºR). The uncertainty in this thermal connectivity value, which is a low value for solid (e.g. soldered) metal-metal contacts but a high value for glued-together plastic components in a vacuum, results in roughly a few ºC uncertainty in most components; this uncertainty is larger for the chips, since that is where most of the power dissipation is assumed to occur (see below). Contact values between the VRs and chips and their respective boards were estimated based on the number of pins and soldered contact area.

Specifically, all chip pins were assumed to have the dimensions of the parallax chip pins: 0.1mm thick, 0.35mm wide, and 1.0mm long. Since the parallax has 44 pins, the ATMEGA2560 Arduinos (used on the ADCS and GPS/PL boards) have 100 pins, and the ATMEGA328P Arduinos (used on B3 for the WD/EPS and SI/Sensors) have 32 pins, this gives Area/Thickness values of 1.54mm, 3.5mm, and 1.12mm, respectively. The 20 pins for the MHX2420 are 0.025" on a side and 0.215" long, giving an Area/Thickness for that contact of 1.5mm. All pins were assumed to have the high conductivity of Al 6061-T6. Note that since the pins are soldered, they are not likely to be made of Al, but this assumption is not critical as long as they are of a highly conductive material. The VRs' soldered fractional contact area to their boards was estimated to be ~25%, so a low (for soldering) conduction coefficient of 2839 $W/m^2/°C$ was used. Due to expected close contacts, the endcaps to the chassis, the grounding unit to the chassis, the TM holders to B3, the MHX2420 board to its housing and legs, and the contacts between the solar panels and their PCBs were set to 5678 $W/m^2/°C$. In contrast, the solar panel PCB to chassis contacts were set to 57 $W/m^2/°C$, due to only being clipped on. Similarly, the pressure contact between the backplane and the boards and router is fairly weak, so a conductance per area of 57 $W/m^2/°C$ was used there as well. Since the threaded rods are loose in their holes through the boards, under vacuum they will have a poor thermal contact with all the boards and chassis. However, they are encased in Al standoffs (not included explicitly in the model, but indirectly included by using Al optical properties for the rods, as listed in Table 1), so their conductance per area to the boards and chassis was set to a moderate 57 $W/m^2/°C$. Since the GPS housing is well screwed to the board, and it was modeled as a 1mm thick shell, a high edge conduction coefficient value of 1 W/m/°C was used there. Since Kapton was added between the backplane and the backplane holders, that contact was reduced to 6 $W/m^2/°C$. During EDU assembly, it was observed that the contact between the MHX2420 and its heatsink was only 'hand tight', so under vacuum that will be a very weak contact. However, in the model these surfaces are coincident, so to approximate radiative transport, a weak contact of 6 $W/m^2/°C$ was used. The contact between the phone and its board, B4, was estimated, based on the results of TVAC testing, to be 284 $W/m^2/°C$. However, that test was not done 'as flight' and indicated the contacts may be very sensitive to thermal cycling effects (to a factor of ~5x). Finally, with the addition of 3M 2216 "Scotchweld" potting, the thermal contact between the batteries and their casing was changed to the nominal specified value[5] of 1.3 $W/m^2/°C$. However, the contact between the tips of the batteries and the casing was reduced to 0.6 $W/m^2/°C$, due to inspection of the flight hardware showing those contacts to be low pressure line contacts.

Table 2. Subsystem Thermophysical Properties (@25°C)

Components	Material	Conductivity (W/m/C)	Density (kg/m^3)	Heat capacity (J/kg/C)
9 Screws and 4 long rods	Steel AISI 316	13.5*	8027	460*
Solar cells	Tedlar	0.2	1390	1010
boards(B1,3-5,7-9), router board, GPS switch, backplane	PCB (0.2% Cu)	1.12	1952	1598
batteries	LiH	100	3085	553
Chassis	Al 7075-T7351	180*	2796	1140*
Chassis Endcaps	Al 5052	142	2685	921
Grounding unit, GPS heatsink and housing	Al 6061-T6	150*	2707	870*
MHX heatsink	Al 6063	212*	2712	850*
2 patch antennas, MHX, GPS receiver, Beacon, Nexus, RWs and holders, VRs, chips, EPISEM, lithium module and housing	Silicon	125.5	2330	702.9
TM antenna holders	DELRIN 500	0.33	1429	1214
TM antenna	Steel A286, 33-1033K	12*	7913	460*
Battery casing	PP copolymer	0.1255	910	2343
Heatsink Shelves (B2a,2b), backplane holders	SS 304	704*	8009	480*

The peak power dissipation assumed for each subsystem is listed in Table 4. These heat loads were smeared equally over the entire volume for each brick or geometric object making up the various components. The battery dissipation was found via testing to be ~2.5% of the total power being drawn; it is more than this when the draw is low and the batteries are cold as well as when the batteries are warm and the draw is high, so 2.5% is a slightly conservative value for both cases. Note however there is considerable uncertainty in this value due to non-linearities. For the Lithium radio, average values for the modes Crosslink Captain, when a SC is primarily receiving, and Crosslink Lieutenant, when a SC is primarily sending, are listed. This power is put into B9 and the Lithium module, but not the Lithium housing. It has been assumed that 1W of radiated radio power is produced by the StenSat and MHX2420; this is not included in the thermal dissipation values in Table 4. It is assumed that if a SC is not in one of the operational states (see below), it is in a quiescent state, where the beacon is on for 5 s out of every 90 s. The average dissipation values for the EPS, the router parallax chip, and VCC5 (the router VR) in this quiescent state are listed in parentheses in Table 4. Components that are not listed in Table 4 are assumed to have no dissipation. Note the dissipation values given in Table 4 are in many cases significantly different than was used in the CDR analysis.

Table 3. EDSN Subsystem Mass Scaling

Component	Density Scaling Factor	Modeled Mass (kg)
Solar cells	3.072	0.033
SP PCBs (chassis + endcaps - cells)	1.274	0.259
Batteries	1.00	0.182
Battery Casing	0.92	0.028
Battery heatsinks (B2a,b)	1.00	0.128
4 Arduinos (total)	1.532	0.00182
Parallax	1.863	0.00061
2 T/6 VRs	0.644	0.0032
3 T/3 VRs	0.747	0.0048
Backplane	1.44	0.0237
3 backplane holders	1.00	0.0294
Chassis	1.00	0.219
Endcaps	1.00	0.093
2 TM holders	1.18	0.016
2 TMs	1.00	0.0025
GPS heatsink	1.00	0.0104
GPS housing (1mm thick)	1.00	0.021
EPISEM (including B8)	1.00	0.047
MHX2420 transceiver	0.631	0.0438
GPS receiver	0.966	0.0183
MHX heatsink	1.00	0.014
GPS patch antenna	0.686	0.007
Lithium radio (module + housing)	0.734	0.0258
Router board (2mm thick, B6)	1.00	0.019
Reaction wheels and housing	0.831	0.0964
MHX patch antenna	1.103	0.018
StenSat radio	0.471	0.020
Nexus phone	0.8594	0.013
GPS switch	1	0.00126
Grounding unit	1	0.0032
Other PCB boards (B1, 3-5, 7, 9)	1	0.165
9 Screws and 4 rods	1	0.042
Total		**1.589**

Since the previous power dissipation modeling was deemed overly conservative, it was decided to use actual on-orbit power profiles. Thus, it was necessary to find the duty cycle of each component during each state. Figure 4 lists the operational states and which components are on during each of them. Also listed is the duration of each state and the estimated power draw during each state. The latter, taken from the Master Equipment List (MEL), is then used to estimate the power dissipation in the batteries during each state. For simplicity, this ignores the fact that at times ~0.2W of the total power draw may be directly delivered by the solar panels to components. Next, a representative on-orbit sequence was constructed using minor cycle 176 for SC#1[10]. This minor cycle was picked since it exercises most of the hardware. Note that to capture an entire minor cycle, 17 orbits were required in the time dependent model. The start time for each state used for SC1MC176 is listed in Table 5. This then gives the power dissipation as a function of time for each component. Since it was requested by the project to remove conservatisms, the hot and cold cases use the same component dissipation values; only the orbital plane, fluxes, and solar panel behavior are changed (see below). For the cold cases, 0 time refers to near the start of eclipse, while for the hot cases it refers to just after the beginning of sunlight (see Figs. 5 and 6 below). The results of these analyses depend somewhat on this choice of phasing.

Table 4. EDSN Subsystem Heat Dissipation (mW)

Component	Dissipation (mW)
Batteries	11.5-232.6 (2.5%)
EPISEM Components	131
Lithium (Captain)	381
Lithium (Lieutenant)	540
MHX2420	5190
MHX2420 VR	200
Nexus phone	518
Nexus VR	200
Novatel GPS Receiver	1427
GPS Controller Arduino	124
GPS VR	200
Reaction Wheels	627
Router Parallax chip	294(16)
VCC5 (Router VR on EPS)	162(9)
EPS/WD Arduino	316(201)
Sensors Arduino (on B3)	160
ADCS Arduino (on B5)	414
Magnetorquers	104
StenSat Beacon	122
StenSat VR	200

	State									
	Planning	EPISEM	Crosslink Captain	Crosslink Lieutenant	Alignment Downlink	Pointing Propagation	Pointing Demo	Magnetic Alignment	Alignment GPS	Quiescent
Component Name										
EPISEM		on								
Torque Coils					on	on	on	on	on	
ACS Controller					on		on	on	on	
Reaction Wheels							on			
GPS Receiver									on	
GPS/PL Controller		on							on	
Smartphone	on	on	on	on	on	on	on	on	on	
Router Board		on	on	on	on	on	on	on	on	on
Sensors						on	on			
EPS board	on	on	on	on	on	on	on	on	on	on
VCC 5		on	on	on	on	on	on	on	on	on
Beacon										on
S-Band Radio					on					
UHF Radio, Hub Avg			on							
UHF Radio, Node Avg				on						
Duration (s)	300	600	2650	2650	672	60	300	3600	1320	remainc
Power draw (W)	1.146	1.933	2.073	2.249	9.305	1.943	3.097	2.225	4.166	0.

Figure 4. Table of EDSN Components and State durations and power draws.

The hot cases use combined maximum 3.3σ 90 minute environments for high inclination orbits from Table 2.2 in Reference 6. The solar flux value is thus 1414 W/m^2 and the Earth IR flux is 240 W/m^2. The orbit-averaged albedo correction for β=30º (the angle between the SC orbital plane and the sun) was found to be 6%, for a total albedo of 32%. Again, at project request, this orbit is the maximum nominal hot orbit and is thus not conservative. The maximum possible β of 30º assumes the present EDSN launch window of noon to 2pm local time and results in an orbit that is in eclipse 36% of the time. An orbit of 430x505 km was used for both the hot and cold cases. The spacecraft are assumed to be either tumbling rapidly in all 3 axes or 3-axis stabilized with the GPS patch antenna pointing towards earth. For radiation purposes, the solar panels were taken as 'inactive', with an angularly constant high absorptivity, conservatively determining, i.e. overestimating, the amount of heat due to incoming solar radiation. Two hot cases were run, one with the SC stabilized and one with it tumbling.

Table 5. State start times for SC1MC176

State	Start Time (s)
Quiescent	0
EPISEM	4163
Pointing Propagation	6059
Pointing Demonstration	6120
EPISEM	6525
Crosslink Captain	14400
Magnetic Alignment	30195
Alignment Downlink	33796
Crosslink Captain	43200
Crosslink Captain	57600
Magnetic Alignment	73772
Alignment Downlink	77373
Magnetic Alignment	80504
Alignment GPS	84105
Planning	85426

The cold cases use combined minimum 3.3σ 90 minute environments for high inclination orbits from Table 2.1 in Reference 6. This gives a solar flux value of 1322 W/m^2 and an Earth IR of 218 W/m^2. The orbit-averaged albedo correction for a β=0º orbit is 4%, for a total albedo of 23%. This orbit is in eclipse 38% of the time. Models using a circular orbit of 450x450 km result in less than ~1º C change for all components (hot or cold); such models are not discussed here any further. The solar panels, for radiation, were taken as 'active', conservatively determining, i.e. underestimating, the amount of radiation captured as heat by the spacecraft solar panels. That is, an angularly dependent absorptivity is used such that solar radiation perpendicular to the solar panels is less likely to be 'thermally adsorbed', and thus converted to thermal energy, but rather is converted directly to electricity and does not heat the SC. Two cold cases were run, one with the SC stabilized and one with it tumbling. The high and low solar flux values used here correspond to near northern hemisphere winter (in January) and summer solstice (in July), respectively. Thus, they should appropriately bracket a launch near the fall equinox, with the hot values becoming more appropriate late in the mission.

Each model was run in steady-state, using orbital averages, to obtain initial conditions. The models were then run for 17 orbits, using the power dissipation as a function of time discussed above, to determine the thermal response over an entire minor cycle; as can be seen in Figures 5-7 below, due to the relatively short duty cycles determined above, in no case do the models obtain a quasi-steady result. Although the SC will be tumbling initially, the MTs will assist in aligning them with the Earth's magnetic field. However, here we discuss models that are either 3-axis stabilized, with the side with the reaction wheels (the top side of Figs. 1 and 2) pointing towards nadir or rapidly tumbling in all 3 directions; spinning tends to reduce thermal gradients so most temperature extrema occur when 3-axis stabilized (see Table 7). Various yaw rotations were not explored. The presented chosen orientation results in enveloping the mininum 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. Still, the four cases discussed here probably represent component temperature extremes to within a few degrees C for the most critical components.

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.

Table 6. EDSN Thermal Limits

Component	Min/Max Thresholds (ºC)	
	Nominal	Survival
GPS Receiver	-30/+85	-30/+85
Backplane	-25/+105	-25/+105
GPS patch Antenna	-40/+85	-40/+100
S-Band patch Antenna	-50/+150	-50/+150
Router board	-10/+70	-40/+85
MHX2420 Transeiver	-40/+85	-40/+85
Reaction Wheels	-25/+80	-25/+80
StenSat Beacon	-30/+80	-30/+80
EPISEM	-30/+30	-40/+50
PCB Components	-40/+85	-55/+85
Nexus Phone	-25/+65	-40/+85
Lithium	-30/+70	-30/+70
EPS	-30/+78	-30/+78
ADCS	-30/+85	-30/+85
LEDs	-20/+80	-30/+85
Arduinos & VRs	-40/+85	-40/+85
Parallax router chip	-55/+125	-65/+150
Batteries	-20/+60 (discharging) 0/+45 (charging)	-20/+60

IV. 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 exceptions are the Nexus phone, with an upper limit due to an internal thermal reset switch of ~+65 ºC, the router board, due to an oscillator with a limit of +70°C, and the EPISEM with a tested upper limit of only +30 ºC. The thermal limits expected for various components, as taken from Ref 7, are listed in Table 6. Some, such as the StenSat Beacon, assume the industry standard, while others, such as the EPISEM, are based on testing. For the batteries, the 'charging' state limits will likely apply while in full sunlight (i.e., the hot case) while the 'discharging' state limits will likely apply in eclipse (i.e. the cold case). The "PCB Components" include connectors, sensors, resistors, etc. The nominal upper limit for the Nexus phone is the tested temperature at which the phone begins to reset (which eventually causes performance problems, so is undesirable).

The model results, listed in Table 7, show there are no overheating issues with any components, neither when the SC are tumbling for extended periods nor when stabilized. Component cases that may have minor nominal performance issues are high-lighted in yellow in Table 7. On the cold side, the batteries are cold enough to lose significant performance and the router board and the GPS patch antenna are close to their lower nominal operating temperatures. On the hot side, the phone and the router board are within 10°C of their nominal operating limits; any extended detumbling will further erode this margin at a rough estimate of 5°C/hr of continuous detumbling. Recently, the temperature limits of the router (B6) were significantly tightened to those listed in Table 6. As a result, both the cold and hot predicted limits of the router board are now within the ±5 ºC uncertainty band (see below) of the router nominal operating thresholds. The router board reaches its nominal cold limit when the SC is in a Quiescent state for more than ~3 orbits, while it reaches its hot limit when the SC is in a Magnetic Alignment state for more than ~1 hr.

Table 7. EDSN Worst Case Temperature Predictions

	Temperature (ºC)			
Component	**Cold Case (minimum)**		**Hot Case (maximum)**	
	Stabilized	**Tumbling**	**Stabilized**	**Tumbling**
Batteries	-4	+1	+20	+18
Solar Cells & MTs	-37	-32	+34	+26
Shelves (B1-2AB, 4-5,7,9) & heatsinks	-15	-10	+62	+60
EPS Board (B3)	-3	+2	+57	+56
Chassis & Endcaps	-35	-30	+25	+21
Router (B6)	-7	-2	+69	+68
EPISEM & board	-13	-7	+20	+18
Patch Antennas	-38	-31	+22	+22
StenSat Beacon	-8	-2	+25	+23
Router Parallax	-5	0	+69	+68
Nexus S Phone	0	+6	+59	+58
MHX2420	-4	+1	+60	+58
GPS Receiver	-10	-5	+41	+39
Reaction Wheels	-4	+1	+44	+42
TM Antennas	-69	-86	+45	+23
Arduinos	-11	-5	+62	+60
VRs	-10	-4	+60	+58
Lithium Radio	-14	-8	+19	+17

The temperatures of all internal components (plus the external patch antennas) for the stabilized hot case are shown in Fig. 5. The hottest components are the phone and MHX2420 at ~60 ºC when those components are on for extended periods and in sunlight. The hot extrema are determined by the modulation of internal heating due to dissipation when components are on and external heating as the SC comes out of eclipse. It can be deduced from Fig. 5 near 90k seconds that if the phone were left on for ~4hrs, as would be needed in an extended detumble (which is a Magnetic Alignment state), then its temperature would continue to climb above 60°C; in addition, the temperature of the router board (not shown in Fig. 5) would be over 70°C. Similarly, if Alignment Downlink were significantly longer, the MHX2420 might have overheating issues.

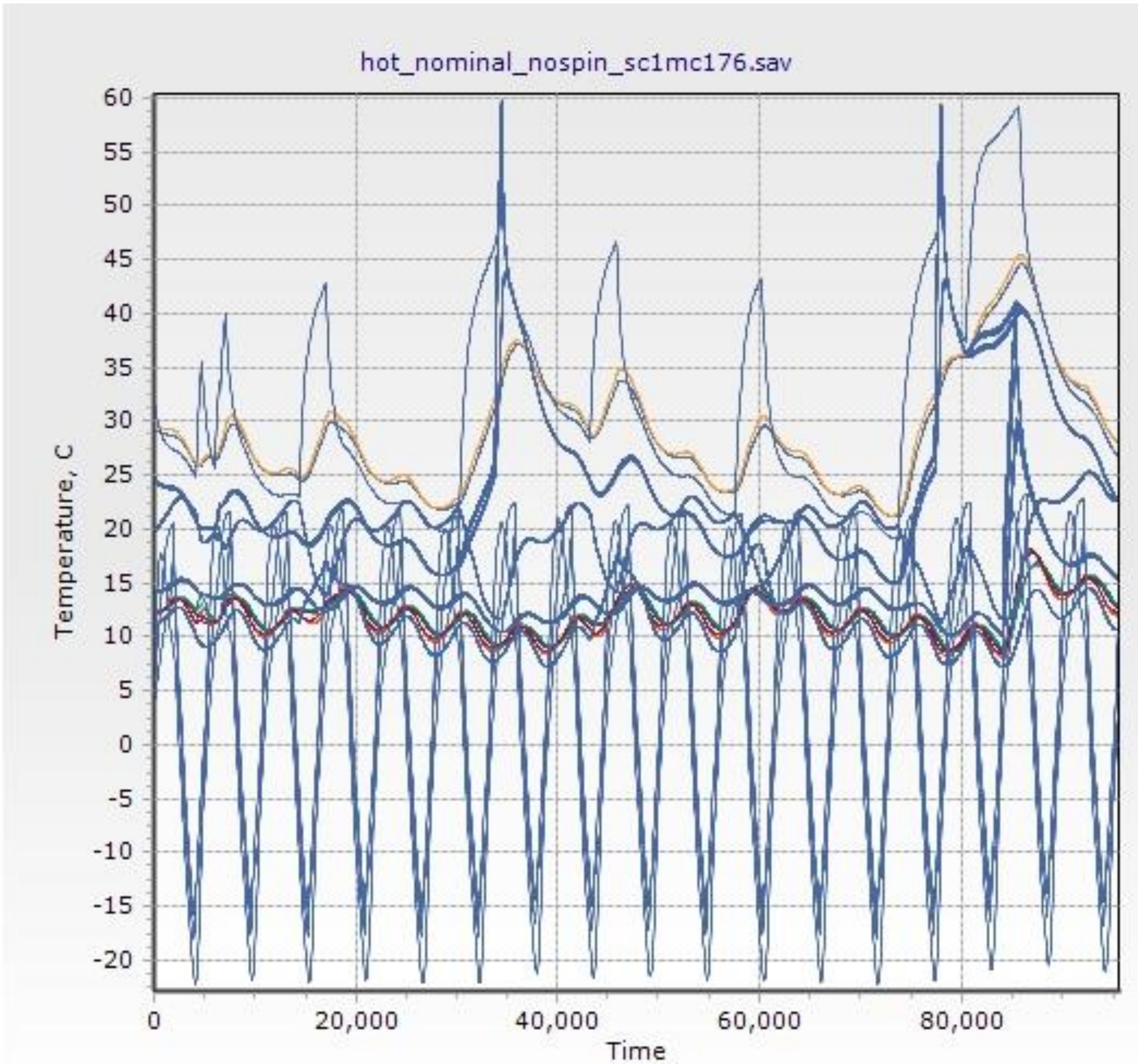

Figure 5. Temperatures of internal EDSN components (plus the patch antennas) for the stabilized hot case.

The temperature results for the internal components (plus the external patch antennas) for the stabilized cold case are shown in Fig. 6. No components ever get colder than -40 ºC, although the patch antenna shielded from the earth IR flux (the GPS) gets close. Since no internal components operate at less than -20°C, even the LEDs, which are not included in the model, with nominal cold limits of -20ºC, should operate nominally. Figure 7 shows the temperature results for the external components for the cold stabilized case. The TM antennas, due to their very low thermal mass, swing from nearly +45 ºC hot to -85 ºC cold during an orbit and may thus have thermal cycling lifetime issues. In addition, when the TM antennas, which are stored bent across the rest of the SC, are released via a burn wire 30 minutes after SC deployment from the launch vehicle (LV), they may have embrittlement issues related to bending in cold conditions, although tests for the TM antenna on PhoneSat 1 at -40 ºC showed no issues. The chassis, MTs, and solar panels on the shielded end of the SC (the bottom edge in Figs. 1 and 2) get as cold as -35 ºC. However, being designed for space applications, they are expected to not have any issues at those temperatures, with the possible exception of any thermo-couples on the external SC surfaces (they may have expansion issues related to thermal cycling).

An illustration of how the temperature at a single point in time is distributed across the SC for the hot stabilized case is shown in Fig. 8. The point in time is picked to be near the peak temperature of the phone. The phone and the MHX2420 are the hottest components, with the StenSat Beacon close behind. Note that +z corresponds to Earth-pointing in Fig. 8.

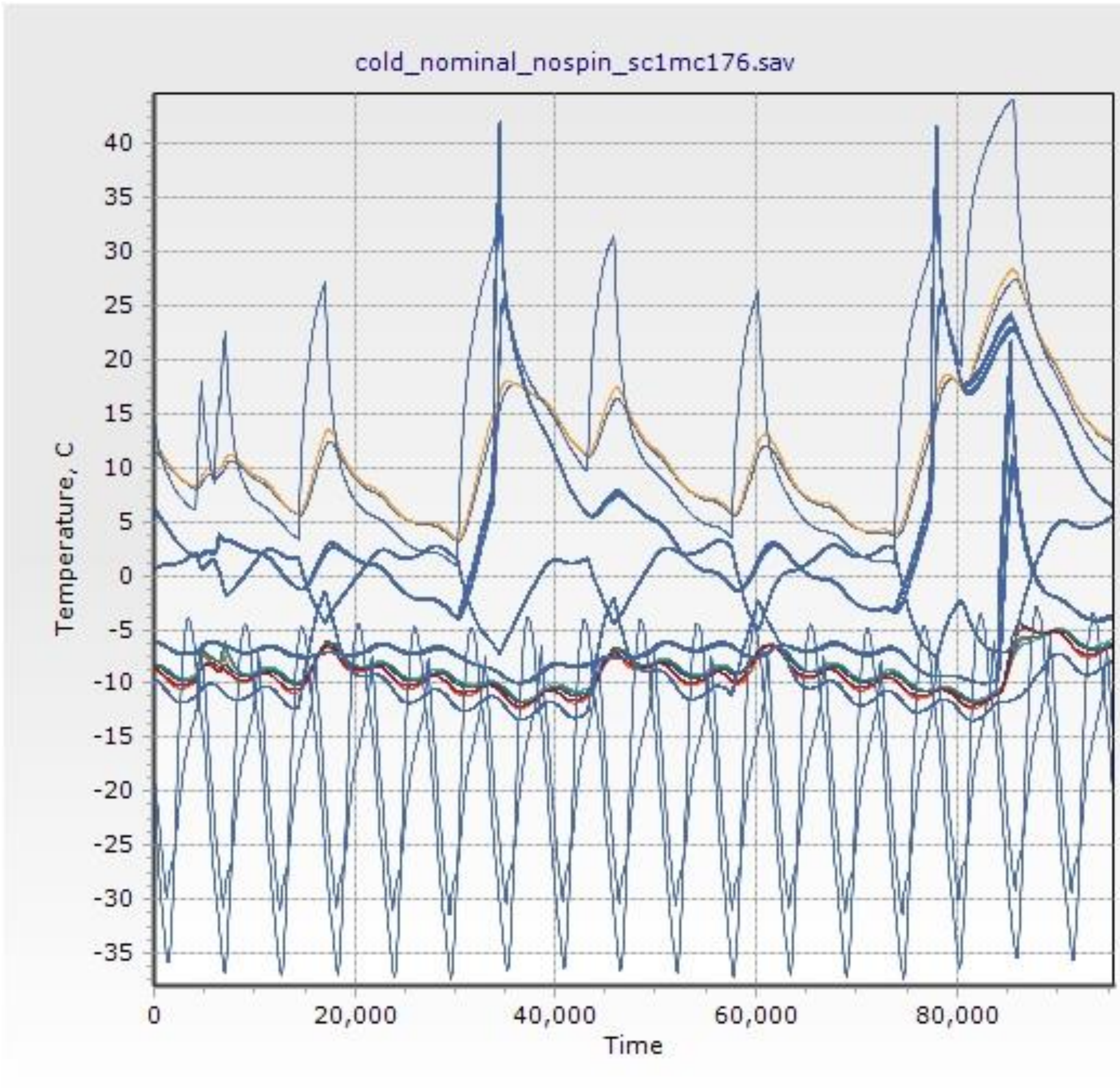

Figure 6. Temperatures of internal EDSN components (plus the patch antennas) for the cold stabilized case.

No active component gets hotter than +70 ºC or colder than -40 ºC. However, there are a number of uncertainties in the analysis. The geometry has been greatly simplified, particularly for the StenSat and the phone. The thermal coupling between components used an assumed nominal value for most connections. Perhaps most importantly, values for the optical and thermophysical properties for many components had to be assumed; it is critical that actual values from the as-built components be measured to determine the accuracy of the values used in this analysis. Due to these assumptions, the estimated 2σ uncertainties in the final temperature extrema are ±5 ºC. Note this is an uncertainty estimate, not an estimate of margin; no explicit margin is included in these analyses. That is, the hot and cold cases are 'nominal', not conservative. The only inherent 'conservatism' is in the assumed bracketing low and high limits for the solar and earth IR fluxes seen by the SC discussed above. Of the ~15°C differences seen in the hot and cold results (compare Figs. 5 and 6), the majority is due to the differences in the fluxes, with roughly one third being due to the different orbits (β=0° versus 30°). That is, using mean fluxes, the hot and cold cases are ~5°C colder and warmer, respectively.

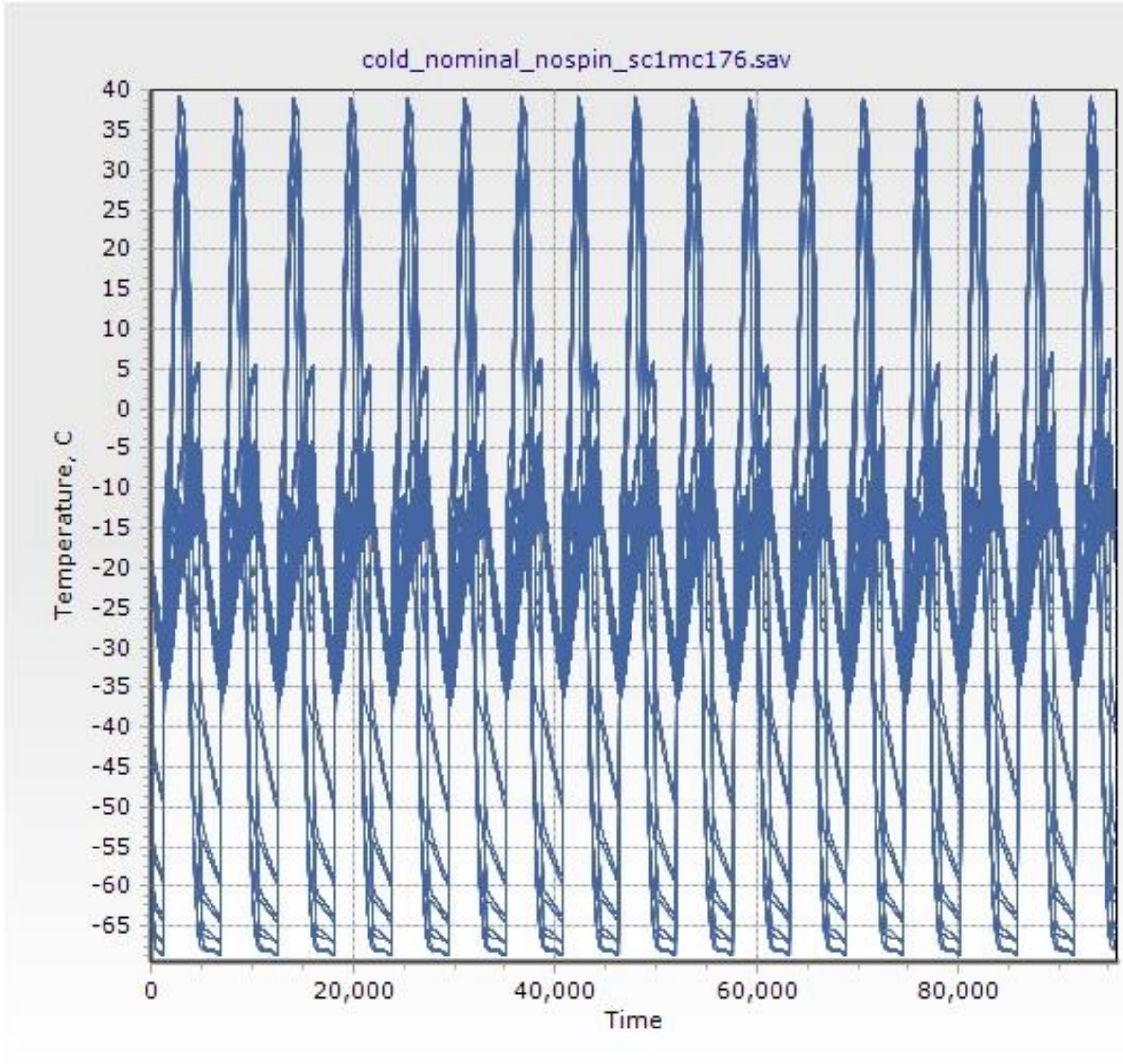

Figure 7. Temperatures of solar panels, their PCBs, the chassis, and the TMs for the cold stabilized case.

Although the patch antennas, phone, and router are predicted to get close to their nominal operating limits, the most significant thermal problem for the EDSN SC is predicted to be the batteries: since the cold case in practice will occur while in eclipse, the batteries will be discharging, so the worst nominal cold case, as shown in Table 7, marginally violates the lower limit of the nominal specification. The batteries are not predicted to fail, but they will be operating at the cold end of their range and thus are likely to be inefficient. The end result will be less power delivered to the SC components than anticipated. Since the SC is already power strapped, this could cause significant mission concerns. That is, although the batteries are predicted to be above their operating limits, they are below the recommended charging temperature of 0 ºC, and thus the batteries are expected to lose up to ~10% of their capacitance[8].

The temperature of the insides of the chassis varies from about +25°C to -35°C, depending on the orbit and fluxes, with a temperature swing of ~40°C as the SC goes in and out of eclipse. The thermal response of the SC as a whole, with all components off, is ~10C/hr across this temperature range. Thus, since the thermal timescale of the SC is longer than an orbit (~90 mins), the internal components never see a constant 'temperature bath'. Figure 9 shows the temperature of everything inside the SC for a few orbits of the hot stabilized case, but with no heatloads on any components. For TVAC testing, the peaks of Fig. 9, at 5°C, should be the chamber set point on the hot side.

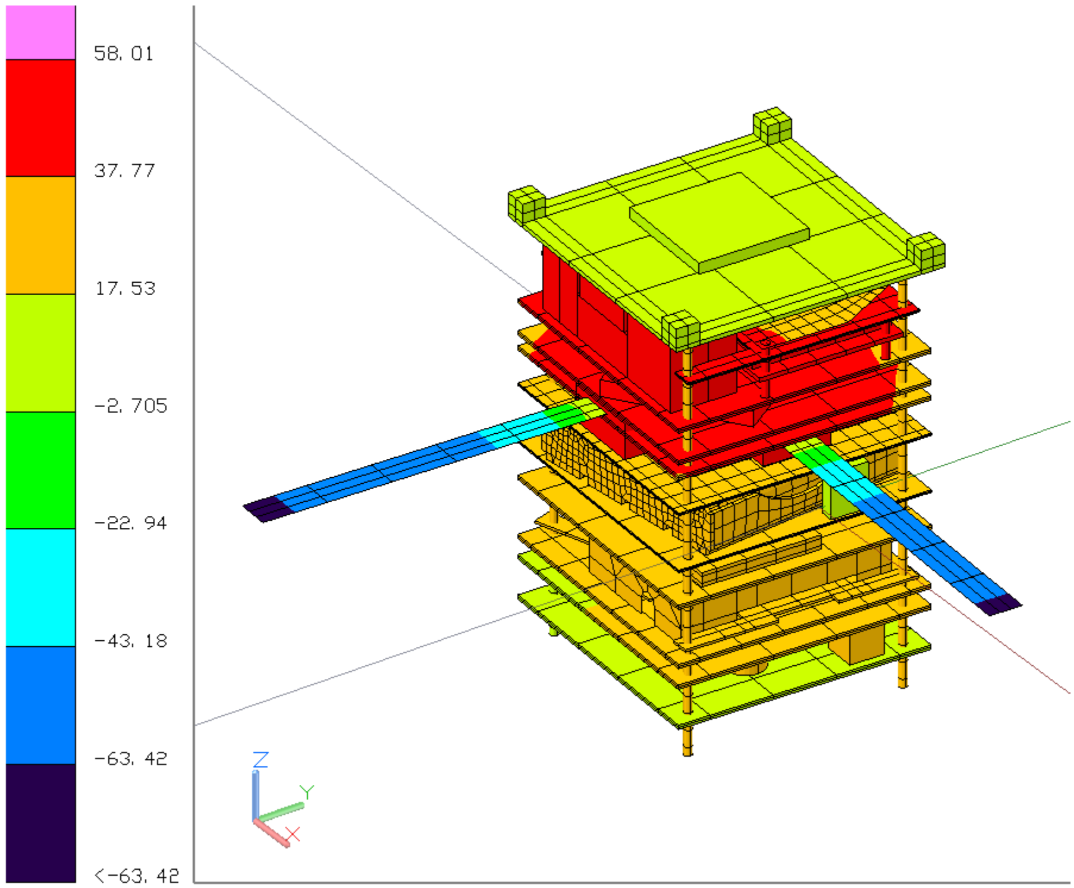

Figure 8. Snapshot of temperatures (in ºC) of EDSN components for the hot stabilized case at the hottest point for the phone (bottom and sides of chassis not shown).

However, when including the additional 5°C model margin and 10°C required by APR 8070.2[9] for qualification testing, and if TVAC testing follows 'test as you fly' and thus uses the states in Fig. 4, this would result in the router and phone getting hotter than their nominal operating limits. This would occur during a Planning state that follows an Alignment GPS state (as occurs during a GPS activity). A set point of 5°C would avoid these overheating issues, but would not meet testing requirements, so a waiver would be required. Similarly, for the cold side, models suggest a TVAC set point of -27°C (not including the required APR 8070.2 margin), but that would cause issues for the router as well as the batteries. The router will only permit a -10°C TVAC set point, so a waiver on the cold side is also required. It may be possible to test on the cold side at -20°C with the SC always in at least the Quiescent state, so that the batteries and router board keep themselves sufficiently warm; this is suggested below. Note that when the SC are jettisoned from the LV, they are inert for 30 minutes with all components off. Over this time period, particularly if the SC are in eclipse and tumbling, the SC, including the router, will cool. The final minimum temperature will depend on the initial conditions inside the LV when the SC are jettisoned. If it is less than ~-5°C, the router will reach -10°C and thus may pose a significant issue for SC start up. For TVAC testing, it is suggested that the hot nominal threshold values listed in Table 6 be used as redlines and the values in Table 7 plus 5°C be used as yellow lines. For thermal cycle testing, the requirement is ±10°C of model predictions9. Thus, from Table 7 (and ignoring external components) a range of -25°C to +80°C would be required. However, this would violate the survival limits of the batteries and EPISEM. Note that the latter may be +60°C for relatively short durations. Again a waiver would be required, but set points of -25°C and +60°C are therefore suggested for the thermal cycle testing.

Since EDSN is a cubesat mission, the project has deemed it acceptable to take risks by waiving a number of APR 8070.2 requirements (qualification limits, acceptance limits, margin limits, subsystem testing, number of TVAC cycles, TVAC duration, chamber heating and cooling rates, and component measurements). In an attempt to balance those 'requirements' with testing cost and schedule, a TVAC test plan that includes some thermal balance testing as well as thermal cycle testing was developed. Figure 10 is a schematic of the test plan while Table 8 lists

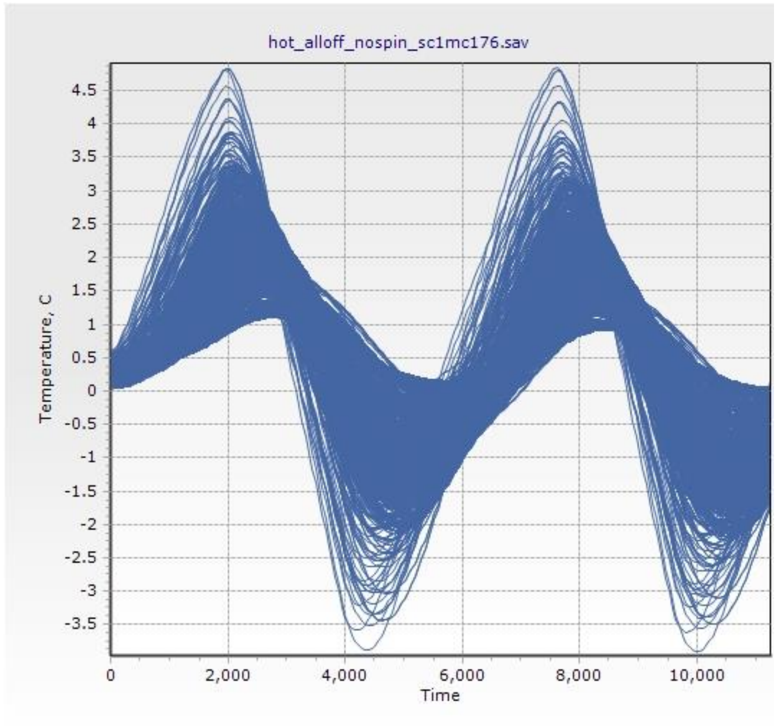

Figure 9. Temperatures of all internal objects for the stabilized hot case with no heatloads.

the activities and states and their durations. It is essential that the EDUs used in the TVAC testing be well instrumented, so one can look for unexpected temperature excursions due to, e.g., weakened thermal contacts. The extended Detumble activity listed in Table 8 is needed only on the first hot thermal balance test sequence, so that sequence is 9.8 hrs long, while other thermal balances are only 5.3 hrs long. It may be necessary to recharge the batteries after the extended Detumble. This 'custom' Detumble is different from what was recently decided to do on orbit (8 cycles of 30 minutes detumble and 2 hrs of battery charging) and is thus more for thermal validation than qualification testing; this Custom Detumble is done at -5°C to avoid possible overheating issues. The hot side of one of the thermal cycling sequences may qualify for the bake out requirement if extended in duration so that the whole SC soaks for 6 hrs at +60°C; this should be verified with the LV. During the thermal balance testing, one SC should be a Captain and one a Lieutenant and this should switch between different hot thermal balance tests. The 30 minute Quiescent states between other activities are the minimum required for the SC components to cool back down to near 'background' levels (see, e.g., Fig. 5). In some cases (e.g., after Crosslink), less time is used since that mimics on-orbit operation. The thermal cycling testing is, at a minimum, 8x4 or 32 hrs long. Given the thermal response time of the SC, the duration of each thermal cycle should not be shortened and in fact may need to be increased to more than 9 hrs in order for the SC to properly soak. Note the thermal cycle limits were picked to have some margin for hot and cold survivial limits of some components (e.g., reaction wheels and EPISEM); they do not meet the -34°C to +71°C thermal cycling requirement of APR 8070.2. After the final hot thermal cycle, battery recharge can be combined with the dwell to get to +5°C for the hot thermal balance test (which takes ~5 hrs), since the batteries generate very little heat while charging. Total minimum test time (and it must be emphasized that Fig. 10 represents a minimum level of testing and it still does not meet APR 8070.2 requirements), including a recharge after Detumble and assuming recharging the batteries takes 4 hrs, is estimated to be ~80 hrs. If as-flight Detumble is added to the testing, this would add another 24 hrs, though perhaps only a single cycle is needed for qualification. Also, the chamber can take ~1 hr to heat and ~3 hrs to cool to the set points (at roughly 5°C/hr depending on whether overshooting is used), significantly adding to the test time required.

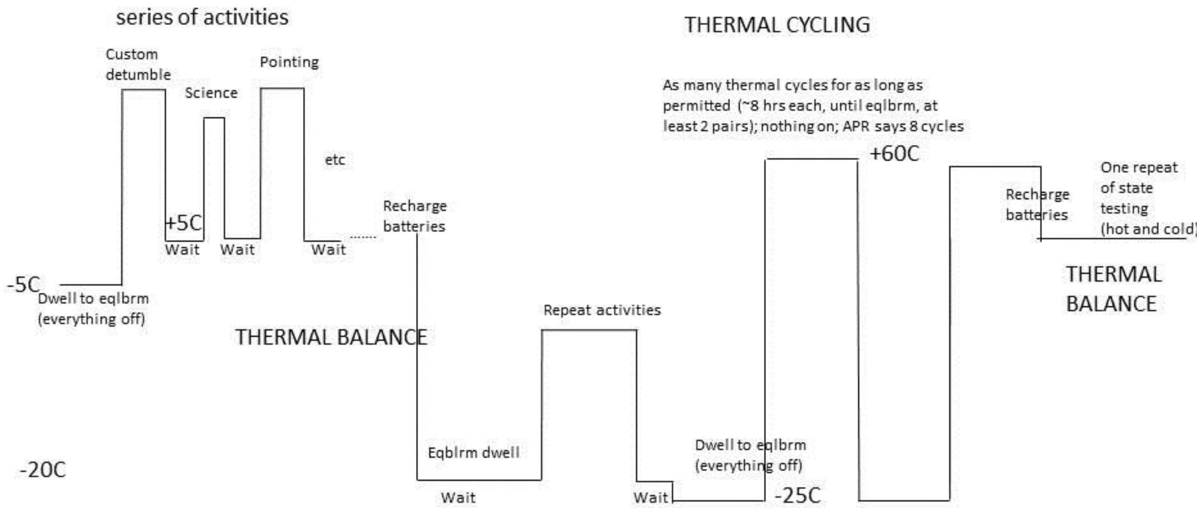

Figure 10. Schematic of suggested TVAC testing plan.

V. Conclusions

A detailed thermal analysis was conducted for the EDSN Cubesat mission. Although there are many uncertainties in the analysis (such as unknown thermal contacts, absorptivities and emissivities, and thermal masses) and a number of components (batteries, phone, router board) are predicted to be close to impacting system availability, a nominal analysis shows that there are no significant thermal issues that threaten minimum mission success[11]. 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 overheating issues. However, this is unlikely due to total power constraints on the small SC. The patch antennas, if shaded for long periods, may have cold issues. The TM antennae get very cold and cycle over 100 ºC every orbit, so they may have deployment or cycle fatigue issues. However, they are made of SS, so failure is considered to be unlikely. Of more concern is the router: it has no margin on either the hot or cold end, particularly considering model uncertainties. The router oscillator loses stability outside its nominal operating temperature limits; this is deemed by the project to be an acceptable risk. Of greatest concern are the batteries: depending on their efficiency curves as a function of temperature, they may store and discharge more than 10% less than is expected due to being too cold. That is, in the cold stabilized case, the batteries continuously operate at less than 0 ºC and thus will underperform, particularly when charging. Other than this, the EDSN SC seem very robust to thermal issues, both hot and cold. It must be cautioned, however, that these final analyses are based on a single nominal minor cycle, SC1MC176. For example, a minor cycle that has a Planning activity immediately followed by a Downlink activity might result in higher tempreatures (and thus overheating since they are at their limits) for the phone and/or router board. Any power dissipation or CONOPS changes or vastly different minor cycles will have a direct impact on temperature extrema. Further, the Nexus TVAC test results suggest the possibility that EDSN SC thermal contacts – and thus their temperature extrema – are sensitive to thermal cycling; upcoming full SC TVAC testing should shed light on this. In addition, any change in the launch window will have a significant impact: a $\beta>30°$ will result in overheating of the router while a launch date closer to the summer solstice will result in the batteries getting to colder than -5°C.

The results discussed here are significantly different (in general, warmer) than in the CDR report[1]. A number of the assumptions made and enumerated in the CDR analysis turned out to be incorrect due to a combination of last minute design changes, inaccurate CAD files, unupdated BOM and MEL files, and a lack of communication between the analyst and the project. For example, it was assumed the interior of the chassis was black coated and the exterior white coated, as is typical for smallsats. In reality, no color coatings at all were applied and the optical properties of the Al alloys undetermined. This discrepancy was only caught after the analyst was able to be present at the assembly of an EDU. These types of issues should be taken as a lessons learned for future smallsat thermal analysis.

Table 8. Suggested TVAC Thermal Balance Test Plan

Activity	**STATE**	**Duration**
Detumble	Detumble	4 hrs
	Quiescent	30 minutes
Science	EPISEM	600 s
	Quiescent	30 minutes
Pointing	Pointing Prop	60 s
	Quiescent	1 s
	Pointing Demo	300 s
	Quiescent	30 minutes
Collect/Provide Crosslink	Crosslink Captain/Lt	2650 s
	Quiescent	10 minutes
Downlink	Magnetic Alignment	3600 s
	Quiescent	10 s
	Alignment Downlink	672 s
	Quiescent	30 minutes
GPS	Magnetic Alignment	3600 s
	Quiescent	10 s
	Alignment GPS	1320 s
	Quiescent	10 s
	Planning	300 s
TOTAL TEST DURATION		**9.8(5.3) hrs**

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[11]Paragraph 2.3 Requirements as stated in “P01.BRD.EDSN Baseline”, the EDSN Baseline Requirements Document, August 13, 2013.