SatTherm: A Thermal Analysis and Design Tool for Small Spacecraft

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ABSTRACT

Small spacecraft have become an attractive alternative for a significant class of space missions. They have the potential to provide valuable science data with shorter development times and at a reduced cost over traditional multi-instrument spacecraft. However, many of the legacy tools used for spacecraft design and analysis have considerable cost and complexity that are not suited to small spacecraft and their associated short development cycles. SatTherm is an alternative thermal analysis tool specifically developed for small spacecraft as a collaborative effort between the Mission Design Center at NASA Ames and San Jose State University. It is intended to be available to the small spacecraft community. SatTherm consists of an easy to use, Microsoft Excel user-interface coupled to a suite of Matlab routines that determine the time dependant temperature solution for spacecraft components. This paper presents a comparison that includes the accuracy of results and the ease of use between SatTherm and the commercially available Thermal Desktop software by Cullimore & Ring Technologies. A benchmark case of a model of the small spacecraft, PharmaSat, is presented. The time-dependant temperatures predicted by the SatTherm model agree with those predicted by the Thermal Desktop model within 4 Degrees Celsius or less. Both models are also validated by the flight data, recorded after the spacecraft was launched in May 2009. This demonstrates that SatTherm can be a useful tool for the early design stage of a small spacecraft.

INTRODUCTION

Proper temperature control within a spacecraft is critical to the success of a mission. Every component of the payload and spacecraft bus has required temperature limitations. These requirements may include an operational and a survival temperature range, which, if exceeded, may result in reduced performance and/or permanent damage to the component. Electrical devices will not work properly or may have a shortened life span if they overheat. Battery efficiency decreases if the temperature is off nominal or if there is a significant temperature difference between battery cells. Liquid hydrazine will freeze in the fuel lines if it gets too cold, making it impossible to get fuel to the thrusters. Large temperature gradients can also deform the spacecraft structure, possibly leading to significant pointing errors. These are just a few of the problems that may prematurely end a mission if temperatures are left uncontrolled.[1]

The Thermal Control System of a spacecraft is responsible for maintaining temperatures within the required limitations. Throughout the various stages of the spacecraft design process, a thermal analysis, or prediction of key component temperatures, should be performed. There are a variety of commercially available software programs, such as Thermal Desktop by Cullimore & Ring Technology and Thermica by Network Analysis Inc., which can be used to create detailed thermal models and predict the temperature of a spacecraft in orbit. While the complexity of a model may increase its ability to accurately predict temperatures at precise locations within a spacecraft, it can also become a hindrance. Detailed spacecraft models are difficult and time consuming to build without human error. Although software programs, such as Thermal Desktop and Thermica, are very powerful for a wide range of situations, they require a significant investment of time to learn how to use.

The Mission Design Center (MDC) is a branch within the Small Spacecraft Division at NASA Ames Research Center. One goal of the MDC is to streamline the small spacecraft design process. It is currently creating a set of tools to accomplish this. In collaboration with the Mission Design Center and San Jose State University, a tool has been developed to simplify the process of small spacecraft thermal analysis and thermal control system design. This thermal analysis program is called SatTherm and it can be used to quickly approximate the average temperature of spacecraft components, which is especially useful in the early design stages of a spacecraft mission.

THE SATTHERM PROGRAM

SatTherm uses the finite difference method to solve for the time-dependant temperature of spacecraft components. A collection of Matlab scripts performs the calculations and is coupled to a Microsoft Excel user-interface. Matlab and Excel are connected using the Matlab toolbox called Excel Link, which allows Microsoft's Visual Basic (VBA) to execute commands in Matlab.

SatTherm was designed for small thermal models, with the total number of nodes being on the order of tens, not hundreds or thousands, as may be the case for more complex models. It was designed such that each spacecraft component, such as a wall, battery, or circuit board should be modeled by a single node, not split into a number of nodes. The results found are the average temperatures for individual components.

Inputs

The Excel based user-interface has four pages of inputs, in which the user can fully define the thermal model. Example screen shots of these four pages are displayed in Figure 1-Figure 4. In general blue cells are inputs that the user must define, and green cells are calculated

based on these inputs. These green items are displayed for use in the temperature calculations and/or for the user's reference, to double check that the model has been accurately defined.

Figure 1: Screenshot of the First Page of SatTherm Inputs. This is where the Program Controls, Orbital Elements, Spacecraft Orientation, the Body that is Orbited, and the Solar Position are Defined.

transtemp1_cube.xls

	A	B	C	D	E	F	G
3							
4							
5	# of nodes	6					
6							
7	Node Properties						
8	Node Index	1	2	3	4	5	6
9	Name	surface 1	surface 2	surface 3	surface 4	surface 5	surface 6
10	Surface Area (m^2)	1	1	1	1	1	1
11	Thickness (m)	0.01	0.01	0.01	0.01	0.01	0.01
12	Material Thermal Properties	Aluminum	Aluminum	Aluminum	Fr4	Aluminum	Aluminum
13	Density Multiplyer	1	1	1	1	1	1
14	Material Optical Properties	Alodine	Alodine	Alodine	Alodine	Alodine	Alodine
15	Initial Temperature (K)	293	293	293	293	293	293
16	Internal Heat Load (W)	0	0	0	0	0	0
17							
18							
19							
20							
21							
23							
24							
25	Program Calculations (Do not change):						
26							
27	Node Index	1	2	3	4	5	6
28	Density (kg/m^3)	2770	2770	2770	1360	2770	2770
29	Specific Heat (J/kg/K)	961	961	961	600	961	961
30	Solar Absorbtivity	0.35	0.35	0.35	0.35	0.35	0.35
31	IR Emissivity	0.1	0.1	0.1	0.1	0.1	0.1
32	Volume (m^3)	0.01	0.01	0.01	0.01	0.01	0.01
33	Mass (kg)	27.7	27.7	27.7	13.6	27.7	27.7
34							
35	Total Spacecraft Mass (kg)	152.1					
36	Total Power (W)	0					
37							

Input 1 | **Input 2** | Input 3 | Input 4 | Output Data

Ready — Sum=6

Figure 2: Screenshot of the Second Page of SatTherm Inputs. This is Where the Nodes and Their Properties are Defined.

transtemp1_cube.xls

	A	B	C	D	E	F	G	H
7								
8								
9	Radiation View Factors between nodes. **Note: A_i*F_ij = A_j*F_ji							
10			j:					
11			1	2	3	4	5	6
12	i:		surface 1	surface 2	surface 3	surface 4	surface 5	surface 6
13	1	surface 1	0	0	0.2	0.2	0.2	0.2
14	2	surface 2	0	0	0.2	0.2	0.2	0.2
15	3	surface 3	0.2	0.2	0	0.2	0	0.2
16	4	surface 4	0.2	0.2	0.2	0	0.2	0
17	5	surface 5	0.2	0.2	0	0.2	0	0.2
18	6	surface 6	0.2	0.2	0.2	0	0.2	0
19								
20								

Input 1 | Input 2 | **Input 3** | Input 4 | Output Dat

Ready — Sum=0

Figure 3: Screenshot of the Third Page of SatTherm Inputs. The Radiation View Factors Between All Node Pairs are Defined Here.

transtemp1_cube.xls

	A	B	C	D	E	F	G	H
13								
14					**Note: This matrix should be diagonally symmetric,			
15	Conductance between nodes (W/K)				with the diagonal line values equal to zero.			
16								
17			1	2	3	4	5	6
18			surface 1	surface 2	surface 3	surface 4	surface 5	surface 6
19	1	surface 1	0	1	1	1	1	1
20	2	surface 2	1	0	1	1	1	1
21	3	surface 3	1	1	0	1	1	1
22	4	surface 4	1	1	1	0	1	1
23	5	surface 5	1	1	1	1	0	1
24	6	surface 6	1	1	1	1	1	0
25								
26								

Input 1 | Input 2 | Input 3 | **Input 4** | Output Dat

Ready — Sum=0

Figure 4: Screenshot of the Fourth Page of SatTherm Inputs. The Absolute Contact Conductances Between All Node Pairs are Defined Here.

The following is a brief description of each of the inputs that must be defined by the user. A more detailed description is available in the SatTherm User's Manual.[2]

- Program Controls: Length of simulation and time-step.

- Spacecraft Configuration: The cross-sectional shape of the external walls of the spacecraft. The user can choose from three options in the pull-down menu for this cell: Rectangle, Hexagon, or Octagon.

- Orbital Elements

- Spacecraft Orientation and Rotation

- Properties of the Orbiting Body (default for Earth)

- Solar Position, with respect to the center of the Earth

- Node Properties: Area, thickness, material properties, initial temperature, and internal heat load for each node.

- Radiation View Factors between Nodes, where the view factor F_{ij} is the fraction radiated from surface i, that is absorbed by surface j.

- Contact Conductance between Nodes

Finally, after all the inputs have been defined, the program can be run. The red cell, labeled "To Run:" at the top of the first page (Figure 1) acts as a button to execute the unsteady temperature calculations. After all the inputs have been entered, the user should select the red cell, hit the F2 key, and then hit Return. This will cause the VBA module to feed the inputs to Matlab, run the Matlab script, and display the temperature data as a function of time for each of the nodes.

Program Structure

The SatTherm Matlab code consists of a large loop, performing the necessary calculations for each point in time, then incrementing forward by one time-step and repeating the process.

First the program calculates the spatial position of the spacecraft, assuming that the spacecraft is at periapsis at time t=0 s. Next, the orientation of the spacecraft determines the local axes, defined in the Geocentric-Equatorial Coordinate System. For example, if the spacecraft local +Z axis is chosen to be Sun facing, the local +X axis will be set in the plane of the orbit (in the

direction of the spacecraft motion), and the local +Y axis will complete the right-handed three-axis system.

The initial normal vector of each of the exterior surfaces is defined in the Spacecraft Local Coordinate System, as shown in Figure 5. If the user specified an additional rotation, the normal vectors are then rotated accordingly. Finally, the normal vectors are converted from the Spacecraft Local Coordinate System to the Geocentric-Equatorial Coordinate System using the necessary rotation matrix.
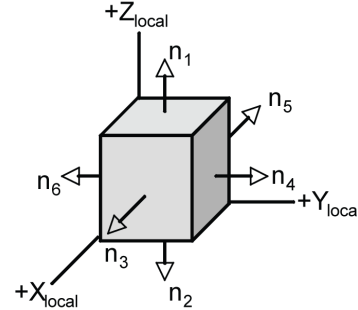
Figure 5: If the Rectangle Configuration is Chosen, the First Six Nodes will be Assigned to the Exterior Walls of the Spacecraft as Shown.

Once the orientation of the external surfaces is known, the environmental radiation heat flow into each of the nodes is calculated. This includes direct solar, reflected solar (or albedo), and Earth infrared radiation, as follows:

$$q_s = G_s \alpha_s \cos \psi \qquad (1)$$

$$q_e = \sigma T_e^4 \alpha_{IR} F_e \qquad (2)$$

$$q_a = G_s (AF) \alpha_s F_e \cos \theta \qquad (3)$$

where the subscripts s, e, and a represent solar, Earth, and albedo, respectively, q is radiation flux, G is the solar constant, α is absorptivity, ψ is the angle between the solar rays and the spacecraft surface normal, σ is the Stephan Boltzmann Constant, T is temperature, F is view factor, AF is albedo factor, and θ is the angle between the solar rays and the Earth-to-spacecraft vector.

The net heat flow through each node due to conduction is calculated using a sum of each of the node's contacts, and the net heat flow through each node due to the radiation network between all the components on the inside the spacecraft is also calculated.[3]

Next, the program calculates the furture temperature, T', of each node, based on the temperature at the current time-step, T, such that

$$T_i' = T_i + \frac{\Delta t}{C_i}\left(\sum_j \dot{Q}_{ij-net} + \dot{Q}_{i-int}\right) \qquad (4)$$

where the subscript i refers to the current node, and j refers to other nodes, Δt is the time-step size, C is the thermal capacity, the first term in the parentheses refers to the net heat flow through node i, due to other spacecraft nodes and space (both conduction and radiation), and the second term in the parentheses is the internal heat load of node i.[4]

Before incrementing forward in time, the program checks that the time-step size will lead to a stable solution, by checking that

$$\sum_j \frac{\Delta t}{R_{ij}C_i} \leq 1 \qquad (5)$$

where Δt is the time-step size, R_{ij} is the thermal resistance between node i and j, and C is the thermal capacity.[4] If the time-step does satisfy this requirement, the program goes on using this time-step, but if the time-step is too large, it will be reset to 0.9 times the value of the maximum allowable time-step, and that will be used in the next loop.

The program continues looping through time, until it reaches the end time specified by the user. The outputs are the temperatures of each node at each of the time points. This data is automatically plotted in a Matlab figure, and is also listed in the Outputs page of the Excel file.

SATTHERM VALIDATION

To verify the accuracy of the SatTherm program, a number of benchmarking cases were established, comparing SatTherm to the commercially available Thermal Desktop program by Cullimore & Ring Technologies. Thermal Desktop is a well-established, CAD-based, thermal analysis tool, which is capable of both Finite Difference and Finite Element Analysis. While numerous benchmarking scenarios were examined during the writing of the SatTherm code, only one is described here. Equivalent models were built in both SatTherm and Thermal Desktop, with identical, orbits and external environments. Ideally the two programs would produce matching results. Additionally, the results from both programs are compared with actual flight data.

PharmaSat Spacecraft

PharmaSat is a small satellite, built at the NASA Ames Research Center, and launched in May 2009. It carries a biological experiment to study the effects of microgravity on yeast and its ability to fight an antifungal agent. A picture of PharmaSat is shown in

Figure 6. It is approximately 35 cm long and amasses 5 kg. GaAs solar panels are body mounted to four of the side panels of the spacecraft. PharmaSat flies in a Low Earth Orbit, at an altitude of 460 km, and at an inclination of 40.5°. The spacecraft is oriented by a set of magnets, which align the +Z axis of the spacecraft with the Earth's magnetic field lines. The spacecraft spins about the +Z axis. The temperature requirements for several of the spacecraft bus components are given in Table 1.
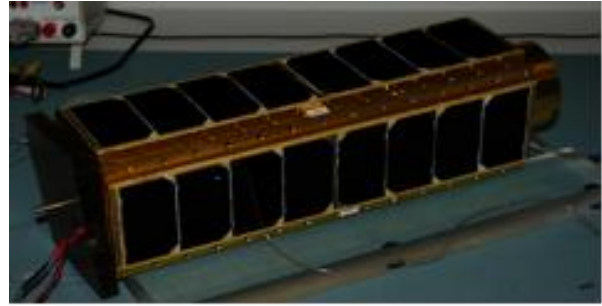
Figure 6: The PharmaSat Spacecraft During Preparation for Thermal Vacuum Testing.

Table 1: Bus Component Temperature Requirements

	Operational Range		Survival Range	
	T_{min} °C	T_{max} °C	T_{min} °C	T_{max} °C
Beacon	-15	85	-40	85
PCB Boards	-40	85	-40	85
Batteries	0	45	-10	60

SatTherm PharmaSat Model

A thermal model of the PharmaSat spacecraft was created in the SatTherm program. A single node was defined for each bus component and wall, coming to a total of 20 nodes. The spacecraft configuration option was set as a rectangular cross-section, and for simplicity the spacecraft orientation was modeled with the +Z axis nadir pointing (toward the center of the Earth). The rotation was set to 3600 degrees per orbit, which corresponds to 10 rotations per orbit.

The four long side panels (as seen in Figure 6) each consist of one node, which must combine the aluminum substrate panel and the thin solar cells. To model this combination, the thermal properties of aluminum were chosen, since most of the mass consists of the aluminum substrate. However, because two thirds of the surface area is GaAs solar cells (α=0.67 and ε=0.85) and one third of the area is gold coated aluminum (α=0.23 and ε=0.03), an area-weighted

average emissivity and absorptivity were calculated (α=0.509 and ε=0.588) and added to the optical properties database for these nodes.

Each of the four batteries also consists of a single node, with the physical and optical properties of aluminum. Because the batteries are three-dimensional cylinders and SatTherm is limited to two-dimensional nodal regions, the size must be approximated such that they have roughly the same surface area as the cylinders and the same volume (and therefore the same mass) as the cylinders. These nodal regions were chosen to be 6.5 cm long (the same length as the cylinders) and 1.85 cm wide (the diameter of the cylinders), making the input area 0.00121 m^2. Then the thickness was chosen to be 1.45 cm, so that the volume of the nodal region (area $\times$ thickness) is 1.75×10^{-5} m^3 (the same volume as the cylinders). The batteries are surrounded by a two-piece battery case, each of which was modeled with their own nodes.

There are also five printed circuit boards (PCBs) in the PharmaSat bus. Each of these was easily modeled as a two-dimensional nodal region with appropriate surface area and thickness, and with the material properties of Fr4 (a fire resistant material used to make PCBs). The spacecraft's micro-hard processor was also modeled as a single node. The material properties of aluminum were used, but because the micro-hard is not actually a solid block of aluminum, a density multiplier of 0.5 was defined so that the node had the correct mass.

Because the focus of this model was limited to the spacecraft bus, the entire payload was modeled as a single node with the properties of aluminum, an appropriate density multiplier to adjust the node mass, and the total internal heat load of all the payload components.

With knowledge of the bus layout and how each component is oriented with respect to the others, the radiation view factor between each node was approximated. The contact conductivity was also approximated, knowing the contact areas between each component and using Gluck & Baturkin as a guide.[5]

After the model was built, it was run for a short period of time, with a first estimate of the time-step of 60 s. The program output showed that this time-step was too large, and recommended a maximum time-step of 2.2 s. The time-step was then reset to 2.1 s and run for a full analysis, which produced stable results.

As mentioned above, there were a total of 20 nodes in the model. It took the author approximately two 8-hour days to build the model in SatTherm and takes approximately 3.5 minutes to run a simulation of 20 orbital periods, or roughly 30 hours, with a time-step of 2.1 seconds.
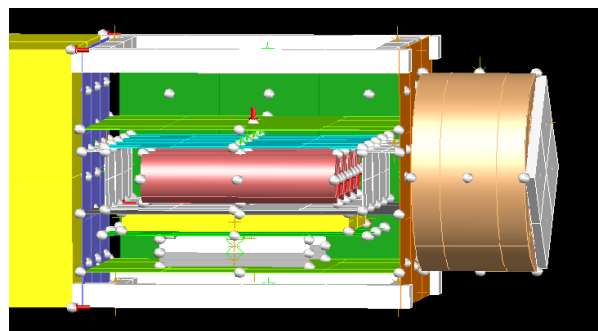
Thermal Desktop PharmaSat Model

A finite-difference thermal model of the PharmaSat spacecraft was also created with the Thermal Desktop program. Thermal Desktop has an advantage over SatTherm in that it offers a visualization of the model, as it is being built. An example of this is shown in Figure 7. Thermal nodes appear in the image as rectangles with small white spheres at the center.
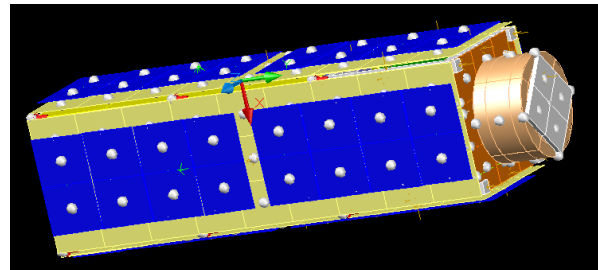
Figure 7: An Outside View of the PharmaSat Thermal Model in Thermal Desktop.

The contents of the Thermal Desktop model are very similar to the model built in SatTherm (described above). However, in the Thermal Desktop model, each bus component was divided into several nodes, and Thermal Desktop can have three-dimensional nodal regions, unlike SatTherm, which is limited to two-dimensional nodal regions. In this model, the side panels (shown in yellow in Figure 7) and the solar cells (shown in blue) are modeled as separate pieces, as opposed to the SatTherm model, which combined them.

With the outside panels removed, and the image zoomed in, one can see the details of the spacecraft bus in Figure 8. The cylinders in the center are batteries, each of which was split into 12 three-dimensional nodal regions. Many of the flat plates in Figure 8 are PCBs for the command and data handling system, electrical power system, and communications system.

Figure 8: An Inside View of the PharmaSat Bus Thermal Model in Thermal Desktop.

The material properties and internal heat loads were defined similarly to those in the SatTherm model. The contact conductance was defined for each pair of surfaces or edges that touch. Thermal Desktop calculates the radiation view factors between nodes using a random ray tracing technique.

Altogether the Thermal Desktop model has a total of 461 nodes. It took approximately two full work weeks to build, and about 2.5 minutes to run a simulation of 20 orbital periods, or roughly 30 hours.

Simulation Cases

Before a spacecraft is launched, the environment that it will encounter while in orbit cannot be known exactly. The external heat loads on a spacecraft vary over some range, depending on time of launch, exact orbit details, mission phase, and natural variations in the solar output and Earth atmospheric conditions. The internal heat loads of the electronics may vary as well. To assure that a spacecraft will work properly in orbit, thermal analysis is done for a hot case (in which all heat loads are assumed to be on the high end of their range) and a cold case (in which all heat loads are assumed to be on the low end of their range). The spacecraft should be able to survive both of these extreme cases; all spacecraft components should stay within their temperature requirement ranges.

To demonstrate the accuracy of the SatTherm software the SatTherm and Thermal Desktop PharmaSat models were both run though identical hot and cold case simulations. Table 2 lists some of the conditions used for the different cases.

**Table 2: Conditions Chosen for the Hot and Cold Case Analyses.**

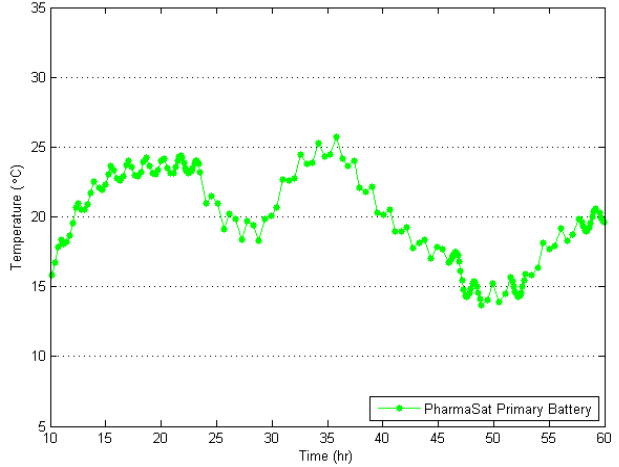|	Hot Case	Cold Case
Solar	1414 W/m^2	1322 W/m^2
Earth IR	257 W/m^2	218 W/m^2
Albedo	0.26	0.19
Orbit Inclination	40.5°	40.5°
RAAN	60°	0°
Argument of Perigee	270°	270°
RA Sun	247°	247°
Dec. Sun	-21.7°	-21.7°
Altitude	460 km	460 km
Eccentricity	0	0

Validation Results

For both the hot and cold case, a time-dependent thermal analysis of the SatTherm PharmaSat model was run (with initial conditions starting at room temperature) for a length of 20 orbit periods. This is a sufficient amount of time for the spacecraft temperature to reach steady state conditions. The predicted temperatures of several spacecraft components were examined and compared to the results given by the Thermal Desktop model. For additional validation, the results of both models were also compared to some of the initial flight data from the PharmaSat Spacecraft, which was recorded after its May 2009 launch.

The predicted battery temperatures for the hot and cold case analyses are displayed in Figure 9 (A). The solid lines are the results found by SatTherm, showing that the battery temperature levels off at 34 °C for the hot case and 8 °C for the cold case. Figure 9 (A) also shows that the battery temperature predicted by the Thermal Desktop analysis (dashed lines) is 33 °C and 10 °C for the hot and cold case respectively. The battery temperatures found by the two models agree within approximately 2 °C. Figure 9 (B) shows PharmaSat's battery temperature, as recorded during flight. Though the time scales of (A) and (B) are different, it can be seen that the flight data falls within the extreme hot and cold range predicted by the models, as expected. One can also see that the short-term wobble in the temperature, which is due to the orbital variation of going in and out of eclipse, is approximately 2 °C in both (A) and (B).

The temperature of one of the side panels of the bus is shown for the hot and cold cases in Figure 10 (A) and (B), respectively. The solid lines are the SatTherm results and the dashed lines are the Thermal Desktop results. The temperatures predicted by SatTherm match those from Thermal Desktop within a few degrees Celsius. Figure 10 (C) shows the side panel temperature recorded during flight. While the flight data stays within the predicted lower limit, it does slightly exceed the predicted upper limit. This emphasizes the need to hold some margin between predicted temperatures and absolute temperature requirements, when designing a thermal control system. The side panel temperature varies more within each orbit than the battery temperature because it is directly exposed to the varying external environment as the spacecraft goes in and out of eclipse.
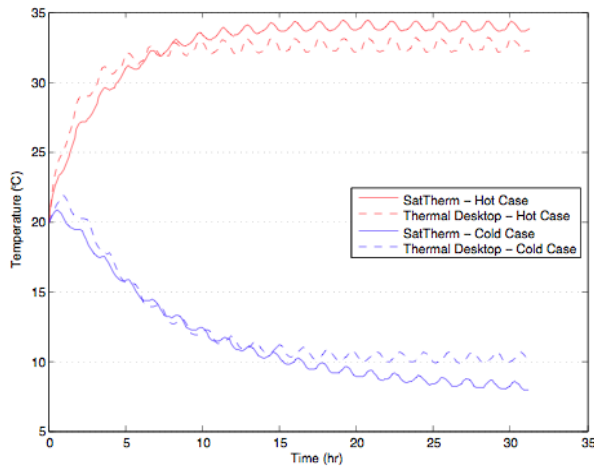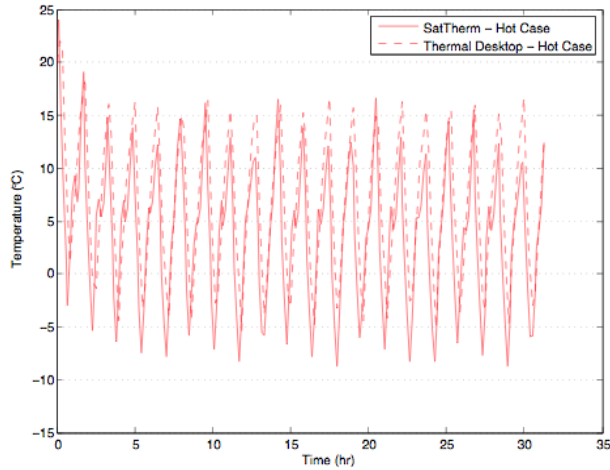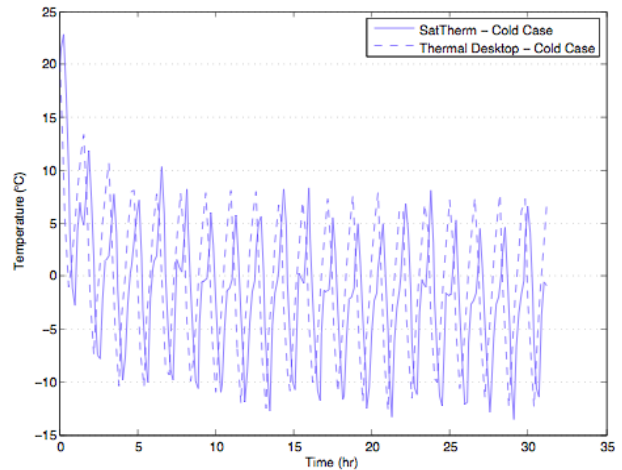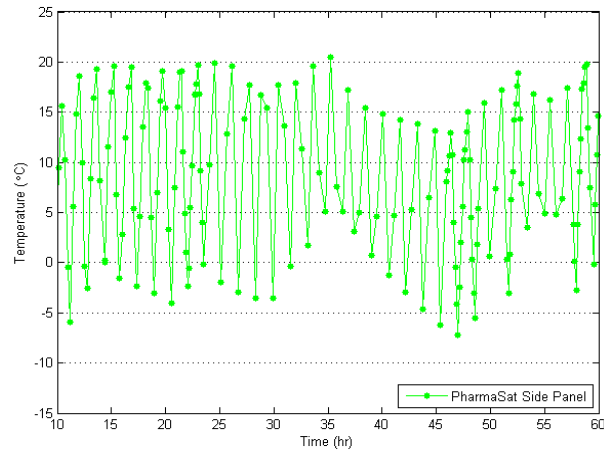
(A)   (B)

Figure 9: PharmaSat Battery Temperature (A) for the Hot and Cold Cases, as Predicted by the SatTherm and Thermal Desktop Models, and (B) Recorded During Flight.

(A)   (B)

(C)

Figure 10: PharmaSat Side Panel Temperature Predictions for the (A) Hot Case and (B) Cold Case, as Predicted by the SatTherm and Thermal Desktop Models, and (C) Recorded During Flight.

CONCLUSION

SatTherm is a simple, easy to use thermal analysis software tool designed for the early stages of small spacecraft mission design. The discussion of the PharmaSat model, above, demonstrates that SatTherm accurately calculates the environmental radiation that a spacecraft encounters while in orbit. It shows that SatTherm is a useful tool for creating a simple thermal model of a small spacecraft, and that such a simple model can produce accurate predictions of spacecraft component average temperatures. The temperatures predicted by the SatTherm model agree with those predicted by the Thermal Desktop model within 4 °C or less. Even for the lowest temperature examined in these cases, which is less than 2%, if considered in the absolute Kelvin scale.

There is no indication that the results found by SatTherm tend to be on the cooler or warmer side of those found by Thermal Desktop. The uncertainty should be thought of as +/- 4 °C. When making a Thermal Model of a spacecraft there are numerous sources of error, including error in the mathematical calculations as well as error due to the simplifications made to approximate reality. For example: three-dimensional objects were modeled as two-dimensional flat surfaces, and the radiation view factors were calculated using the approximations for simplified geometries.

The discussion of the PharmaSat model also demonstrates the time-saving value of a simple thermal model built in SatTherm compared to a complex model built in Thermal Desktop. Though the SatTherm PharmaSat model takes slightly longer to complete one run than the Thermal Desktop model (3.5 minutes compared to 2.5 minutes), the real time saved is in how long it takes to learn the program and build a model (on the order of days compared to weeks).

In its current form, SatTherm is a useful thermal analysis tool for small spacecraft. It does have its limitations, though. In the future, it may be expanded to include:

- More complex spacecraft geometry, such as solar panels on booms extending away from the spacecraft body, or payload components attached to the outside of the body walls.
- More complex orientation control, such as aligning the spacecraft with Earth's magnetic field lines, instead of only having the choice of Sun facing, Nadir facing, or setting a constant right ascension and declination.
- The ability to model interplanetary trajectories.

- The ability to define different optical properties on different sides of a single surface.
- A more efficient check and reassignment of the time-step if the initial time-step is too large, which can cause an unstable solution.

REFERENCES

1. Gilmore, D. G., Hardt, B. E., Prager, R. C., Grob, E. W., & Ousley, W., Thermal. In W. J. Larson & J. R. Wertz (Eds.), Space Mission Analysis and Design (3rd ed.). Microcosm Press, El Segundo, CA, 2006.

2. VanOutryve, C., A Thermal Analysis and Design Tool for Small Spacecraft. MS Dissertation, San Jose State University. United States - CA. Dissertations and Theses: Full Text Database (Publication No. AAT 1463378), 2008.

3. Cengel, Y. A., Heat transfer: A practical approach, McGraw-Hill, San Francisco, 1998.

4. Chapman, A. J., Fundamentals of Heat Transfer, MacMillan Publishing Co, New York, 1987.

5. Gluck, D. F., & Baturkin, V. Mountings and Interfaces. In D. G. Gilmore (Ed.), Spacecraft Thermal Control Handbook. Vol. I: Fundamental technologies, The Aerospace Press, El Segundo, CA, 2002.