Enabling High-Power SmallSats with Advanced Thermal Management

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ABSTRACT

High-power Small Satellites have the potential to provide new and advanced capabilities; however, significant challenges prevent wide-spread use. Of these, thermal management of high-heat loads is significant. Although advances in thermal acquisition, transport, and storage are available; thermal dissipation technologies for high-power systems are lacking. Several design concepts are presented focused on high-efficiency, lightweight deployable radiating technologies. Analysis showed that realistic deployable radiator designs offer 220% more thermal dissipation than body-mounted radiator designs, which directly correlates to the same amount of increase in feasible total bus power. Using deployable radiators, a nominal 6U Small Satellite can realistically dissipate around 200 W.

INTRODUCTION

The United States has enjoyed unimpeded freedom of action in the space domain delivering intelligence collection, missile warning, weather monitoring, satellite communications, and precise position, navigation, and timing. Small Satellites (SmallSats) have shown promise to provide similar capabilities at lower cost. For example, constellations of SmallSats in low Earth orbit might one day replace larger satellites in geosynchronous orbit. In addition, the National Security Space might benefit from SmallSats. Spreading systems across multiple satellites makes it economically and logistically infeasible for adversaries to attack. Rather than having to shoot down one satellite to destroy a capability, an enemy would now have to shoot down dozens or hundreds of satellites. With respect to the types of missions being considered across various private/government entities such as NASA, constructs are desired to support capabilities related to:

- high power radio frequency mapping of the Lunar surface,

- ground penetrating radar for investigating outer planet moon ocean habitability, and

- laser communication missions.

Examples like these have focused attention to SmallSat capabilities. These advantages can only be realized through cutting-edge systems, especially power and thermal subsystems. Recent developments in solar energy acquisition systems and energy storage systems have led the way. Solar panel technology is one example of progress made in solar energy acquisition systems, with advancement in photovoltaics and concentrated solar power affording the ability to generate kilowatt-level power in a SmallSat. Advancements in energy storage systems, such as increasing battery capacities and using several small-cell batteries with minimized volume, have provided the ability to store high levels of power within a SmallSat. These improvements in acquiring and storing energy in space have opened the door for high-capability and high-power systems in SmallSat packages, such as: electric propulsion, higher power imaging payloads, or higher power communications payloads, just to name a few examples. The primary challenge then becomes managing significant heat loads in a small package and effectively dissipating excess heat. Unfortunately, traditional thermal management techniques, especially those typical of SmallSats, are not sufficient to handle these heat loads. Challenges include acquiring thermal energy, effectively transporting thermal energy with minimal losses,

energy storage, and effectively dissipating thermal energy to the surrounding environment.

This paper describes thermal design considerations that need to be taken to maximize high-power SmallSats full potential. Specific emphasis was given to outlining state-of-the-art thermal control systems that address the challenges of thermal acquisition, transport, storage, and dissipation for high-power SmallSats, along with the power generation requirements and limits of these systems. Most of the paper will focus on a detailed discussion that addresses the use of deployable radiators as the best option to deal with the challenge of thermal dissipation and finally realize all of the capabilities that high-power SmallSats can provide.

SMALLSAT THERMAL DESIGN

Conventional SmallSat Thermal Design

SmallSat thermal control is typically an afterthought within the bus architecture and is therefore not allocated much of the mission's volume or mass budget. As a result, conventional SmallSat thermal control designs often include the simple use of optical coatings and tapes on small body-mounted radiators, along with insulation and survival heat. Conventional high-emissivity coatings can be employed on SmallSat radiating surfaces to help increase the radiating heat transfer. Insulation (e.g. MLI blankets) and insulating standoffs amongst the structure and components can be used for temperature control for tight temperature tolerance components; this can limit the necessary use of heater power or phase change materials that are prone to become more massive and require large volumes for global SmallSat thermal control. As the demand for SmallSats grows, component capabilities will continue to increase, requiring more power and more improvements to thermal control systems.[1] Body-mounted radiators and other conventional thermal design approaches simply will not be able to provide enough thermal dissipation to keep up.

High-power SmallSat Thermal Design

In order to meet these increasing power demands, several companies are developing miniaturized thermal control components specifically for SmallSat thermal control, such as LoadPath's high thermal conductance, flexible thermal straps (Figure 1), thermal louvers, and ISIS' CubeSat heat pipe (Figure 2), to name a few.[2] These technologies are at various levels of technology readiness level (TRL) for SmallSat purposes, but all aim to address the challenges of advanced high-power SmallSat thermal control that include thermal acquisition, thermal transport, and thermal storage.[2]

High-power SmallSats will inevitably use high-power components such as Gallium Nitride (GaN) devices, which present thermal acquisition problems due to their high-powered nature. Recent advances have ushered in new technologies to overcome these challenges. One example is GaN-on-Diamond wafer technology. By using CVD diamond with thermal conductivities >1200 W/m-K, GaN heat can be effectively spread to a thermal transport system.[3] Regardless of the effectiveness of thermal acquisition device, thermal bottlenecks still remain including transport, storage, and dissipation.

Figure 1: LoadPath's High Thermal Conductance, Flexible Thermal Strap

To enable heat load sharing amongst SmallSat components and address the thermal transport challenge from heat source to heat sink, there are various forms of advanced technologies being developed. These technologies act to reduce temperature gradients. Annealed pyrolytic graphite is a material with high in-plane thermal conductivity that can be encapsulated into aluminum, providing thermal spreading throughout a SmallSat structure or utilized within a thermal strap component for transport to deployable radiators.[4] Various forms of heat pipes, such as conventional heat pipes, flat heat pipes, and oscillating heat pipes, can also be used to provide relatively high heat load and flux transport across SmallSats. Brouwer studied the use of water heat pipes for SmallSat applications and the effects of bending on performance.[5] In general, thermal transport components must be scaled down and conformable for integration into the small, crowded volumes of a SmallSat. Examples include heat pipe heat spreaders, flat and flexible heat pipes, and miniature loop heat pipes.[6,7] Due to the small size of a SmallSat and the microgravity environment of space, heat pipe solutions have the potential to provide cost-effective thermal transport.

Figure 2: ISIS' CubeSat Heat Pipe

Thermal storage devices are an important consideration for high-power SmallSats, because they offer the ability to more effectively manage the heat loads involved, especially for Low Earth orbits and low duty cycle components. Thermal energy storage such as phase change materials (PCMs) can be used to reduce the size of the radiator by reducing peak loads. This has direct application to a majority of SmallSat missions and components like propulsion systems, radios, avionics, and most payloads that do not need to be continuously running at full capacity. Consequently, PCMs are currently a popular focus of thermal subsystem advancement efforts. Thermal Management Technologies and Roccor have both created PCM panels that are of the CubeSat form factor allowing them to be easily stacked in between critical components.[8,9] LoadPath has an approach for thermal storage that also includes thermal spreading features (Figure 3). Regardless of the effectiveness of thermal storage devices, a thermal bottleneck still exists for SmallSat thermal control without a complimentary high-quality thermal dissipation technology.
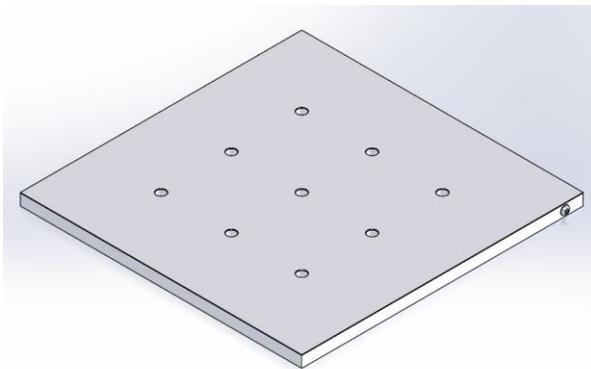

Figure 3: LoadPath's Phase Change Panel with Thermal Spreading

Therefore, the largest challenge facing high-power SmallSat thermal designs is thermal dissipation. One method for increasing dissipation is by taking advantage of the $q \sim T^4$ relationship, where $q =$ dissipated heat and $T =$ rejection temperature. A recent study was conducted to evaluate this approach.[10] In this work, a vapor compression system was used to increase heat rejection capacity for a given/fixed radiator area. It was found that the necessary compressor work was equal to or greater than the additional heat rejection capacity. Not only does the additional heat load need to be pumped through the vapor compression cycle but also the original heat load. Hence, even a small increase in heat dissipation requires significantly higher heat rejection temperatures. The increasing condensation temperatures with increasing additional component loads decrease the COP.[10]

A more practical way to meet this challenge is by increasing the radiating surface area by means of deployable radiators. Body-mounted radiators for SmallSats provide limited cooling, simply because their surface area is heavily restricted and severely limited. An ideal body-mounted radiator analysis was conducted to demonstrate these limitations. The radiating area required to dissipate a certain power level at a given temperature was obtained as shown in Figure 4 shows radiator areas from 0 to 2 m².
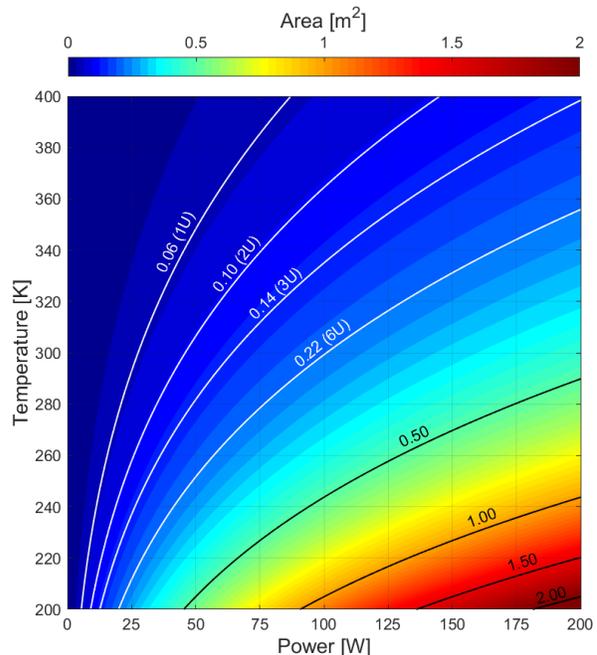

Figure 4: Ideal Radiator Areas (0 to 2 m²) with $\varepsilon =$ 0.9 as a Function of Power and Temperature

Figure 4 includes maximum body-mounted radiating area curves for typical CubeSats. For example, a 3U

CubeSat has a maximum surface area of 0.14 m² (assuming flat body-mounted radiators). Given a radiating temperature of 300 K, a 3U body-mounted design can dissipate at most ~60 W of heat assuming every external surface is designed as a body-mounted radiator. A 6U CubeSat has a maximum surface area of 0.22 m². Under similar conditions, it can dissipate at most ~90 W, again assuming that every external surface is acting as a body-mounted radiator. This is much less than next-generation high-powered SmallSat needs. Therefore, deployable radiators are imperative, and provide the best solution to solve the thermal dissipation challenges of high-power SmallSats, and finally make high-power SmallSats possible for future missions.

A deployable radiator analysis was developed from Mackay and Leventhal for a thin rectangular radiator radiating to free-space (Figure 5) with the following assumptions:[11]

- Steady-state and constant properties

- Radiation is the only heat loss from the plate

- Constant thermal properties

- No conduction in the y-direction

- Radiator temperature is assumed constant across the thickness, t, and at all x positions. This is valid for thin radiators ($t \ll W$ and $t \ll 1$), where t = thickness and W = radiator width.

- Heat loss from edges is negligible. This is valid for thin radiators ($t \ll W$ and $t \ll 1$)

- $T_{space} = 0$K, where T_{space} = deep space temperature.
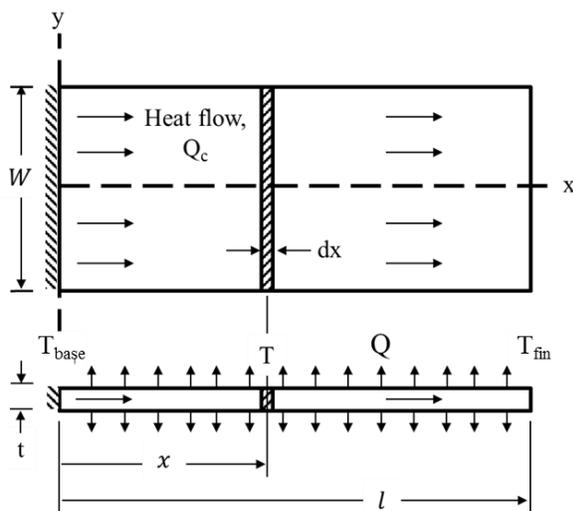

Figure 5: Coordinate system and definition for a radiating longitudinal fin

The fin receives no heat input on its faces from other bodies in space. Heat enters uniformly at the fin base at $x = 0$ and passes from the fin faces by radiation. The heat dissipated by the fin is obtained from:

$$q = -ktW \frac{dT}{dx}\bigg|_{x=0} \tag{1}$$

where q = dissipated heat; kt = conduction term; T = temperature; and x = position.

Using the temperature gradient at $x = 0$ where $T = T_{base}$ gives

$$q = 2ktW \left(\frac{\sigma \varepsilon}{5kt}\right)^{1/2} \left(T_{base}^5 - T_{tip}^5\right)^{1/2} \tag{2}$$

where σ = Stefan-Boltzmann constant; ε = emissivity; T_{base} = temperature at base of the fin; and T_{tip} = temperature at the tip of the fin. For heat dissipated per width,

$$\frac{q}{W} = 2kt \left(\frac{\sigma \varepsilon}{5kt}\right)^{1/2} \left(T_{base}^5 - T_{tip}^5\right)^{1/2} . \tag{3}$$

Figure 6 and Figure 7 provides a contour plot of length based on the conduction term (kt) and dissipation per unit width (Q/W).
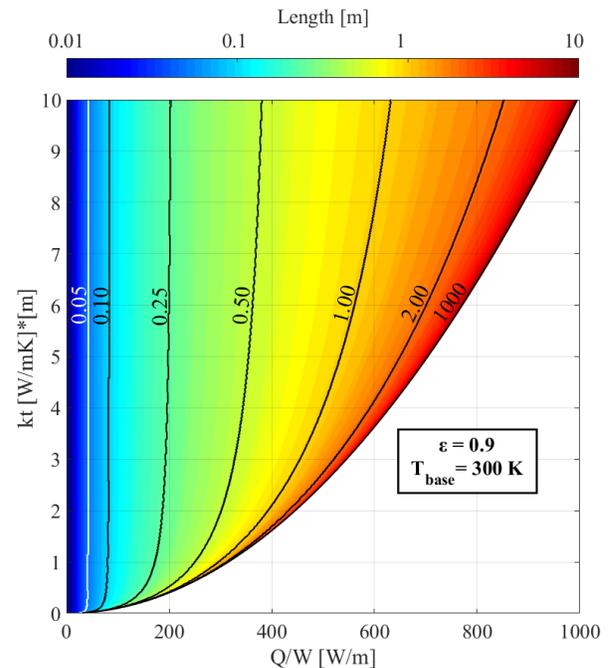

Figure 6: Contour plot of non-ideal radiator dissipating to free space (0 to 10 m in length)
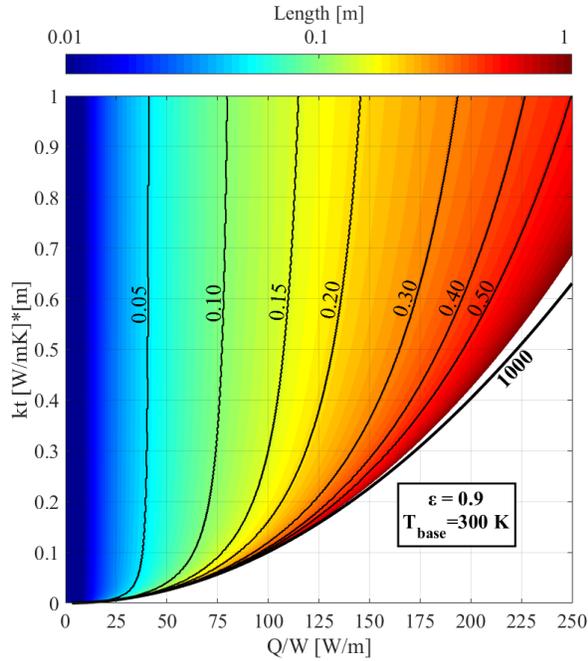
Figure 7: Contour plot of non-ideal radiator dissipating to free space (0 to 1 m in length)

The conduction term is the thermal conductivity of the radiator, k, multiplied by the thickness of the 'thin' radiator, t. This data was validated using Thermal Desktop to within 0.5% error. The Thermal Desktop model also neglected heat dissipating from the edges; therefore, as the thickness increases the error increases. The analytical model and plot can be applied for a wide range of values to use as an early thermal design tool. It was used to initially evaluate the validity of using a deployable radiator.

After analytically validating the utility of a deployable radiator, the design of a practical approach to implementing a deployable radiator within a SmallSat architecture was initiated. Figure 8 and Figure 9 show a 6U SmallSat design with some generic components, including antennae, batteries, two payloads, a radio, a propulsion component, avionics, and an attitude determination and control component. This is the 6U SmallSat bus used for the deployable radiator concepts and thermal analysis discussed throughout the rest of this paper.
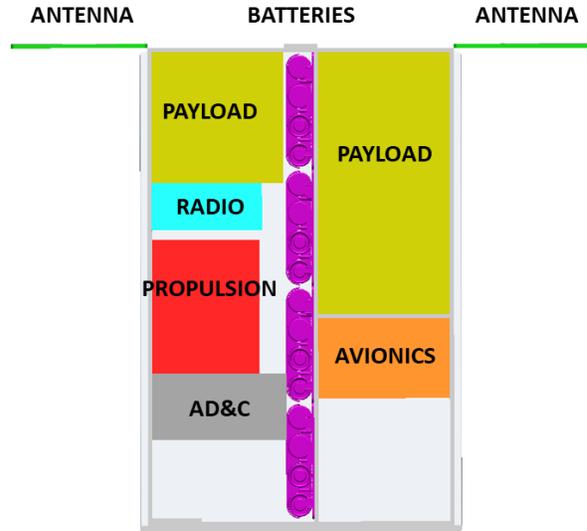

Figure 8: Generic 6U SmallSat Bus (Component View)
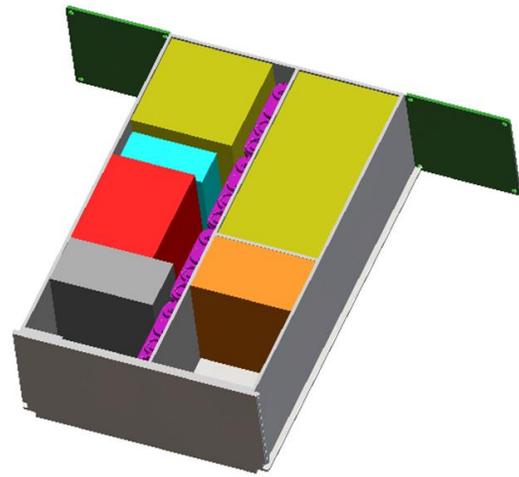

Figure 9: Generic 6U SmallSat Bus (Isometric View)

The following figures show different deployable radiator design concepts. Figure 10 illustrates a radial design with highly-efficient packing. Figure 11 and Figure 12 show a two-sided deployable radiator concept under development by LoadPath.
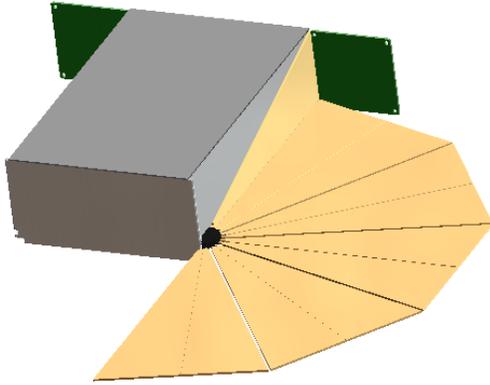
Figure 10: 6U SmallSat Radial Deployable Radiator Concept

These examples bring up several design considerations for deployed radiators. First, increased heat dissipation can be achieved with increases in *kt* and radiator length. However, increased length has diminishing returns. For a small increase in length (at a given *kt*), heat dissipation increases significantly; further increases in length provided less significant results. This non-linear nature is an important design consideration as length also impacts overall radiator mass.

Realizing an effective deployable radiator system is a significant challenge as there are many options and design considerations. For example, deployable effectiveness can partially be characterized by the stowage volume versus deployable area. A deployable thermal radiator could be deployed from the side of a bus to provide additional area; but they must be sized based on their conductance to provide a mass efficient solution. Options include: 1) a radial deployable (Figure 10) made up of high thermal conductivity materials/connections and motor driven deployment which requires mass, volume and power; and 2) novel uses of passive deployment mechanisms. For example, a composite radiator (Figure 11 and Figure 12) could be designed to utilize its strain energy in the stowed state to deploy from the SmallSat. Composite panels often have poor thermal characteristics, therefore, doping or impregnating highly conductive materials should be considered for thermal performance.

Deployable radiator effectiveness will depend on the ability to transport heat to the radiator or through the radiator. A passive two-phase thermal solution could provide this quasi-constant boundary temperature through a condensing fluid along the base section. Additionally, it could replace the need for a high conductance connection between the deployable
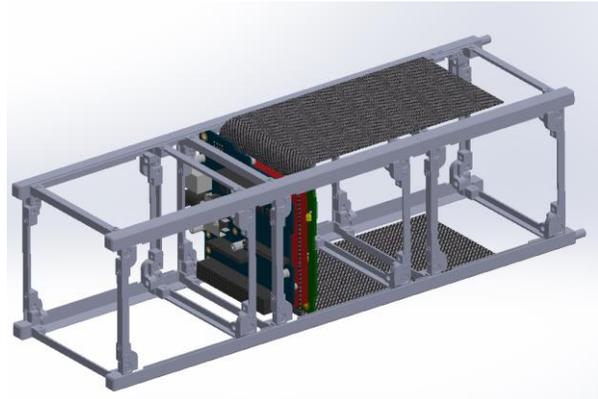

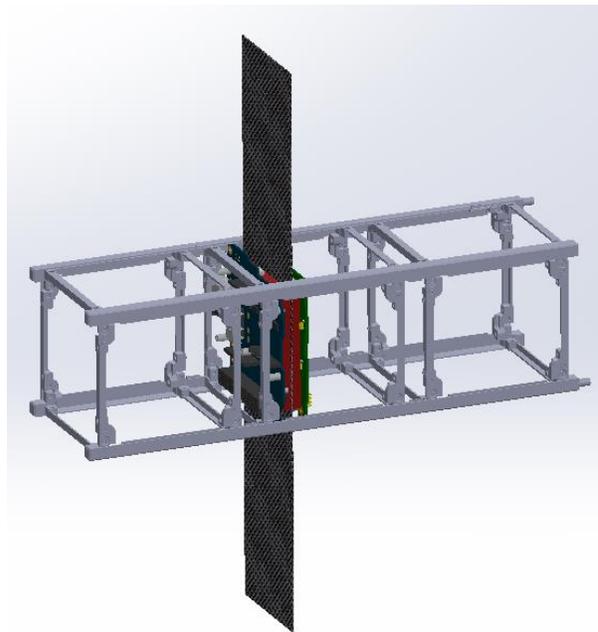**Figure 11: LoadPath Deployable Radiator (stowed)**

Figure 12: LoadPath Deployable Radiator (deployed)

Miniature loop heat pipes can manage up to 500 W and transport up to 3 m with a conductance up to 25 W/K.[7] Additionally, some miniature loop heat pipe evaporators are square with dimensions very close to the CubeSat form factor (i.e. ~10 x 10 cm^2).[12] If there is an appropriate heat load, additional deploying radiator area could be deployed. Volume will be the limiting factor for the necessity of radiator area. Both the solar arrays and radiators must be stowed within the available volume; the solar arrays must produce enough power to drive the need for additional radiating area.
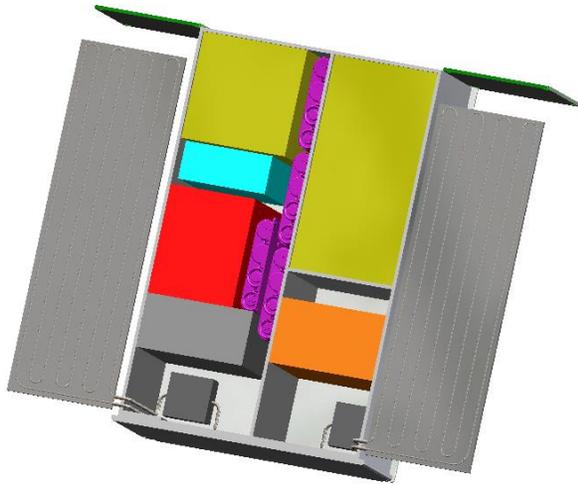
Figure 13: Double-Sided Deployable Radiator with Miniature Loop Heat Pipe

ANALYSIS

Thermal analyses were performed using the same nominal 6U SmallSat bus architecture and components shown in Figure 8. More optimal component layouts are likely, but not considered in the current work. A list of the generic components, along with their associated temperature ranges and average power levels, can be seen in Table 1.

Table 1:   List of Component Temperature Ranges and Power Levels

Component	General Vendor	Min Temp [°C]	Max Temp [°C]	Average Power [W]
Battery	GOMSpace	-20	40	2
AD&C	Blue Canyon	-30	50	3
Payload	---	-40	50	22
Propulsion	VACCO	0	60	1
Radio	Innoflight	-15	50	3
Avionics	---	-40	60	6

The generic components decided upon came from a combination of several SmallSat missions (i.e. GOMspace GOMX-3, NASA Inspire, and MIT ExoplanetSat), in order to develop a generic and nominal 6U satellite. The thermal model shown in Figure 14 was used to characterize the thermal performance of this nominal design and observe the significance of deployable radiators. First, the nominal 6U SmallSat bus with nominal power values as described in Table 1 was performed; followed by several other analysis runs that consisted of simply sweeping through increasing power values and observing the resultant component temperatures.

Increasing the component power values was intelligently determined in order to realistically represent a high-powered bus, since there are not any high-powered SmallSat components to baseline. For example, the propulsion component's power was not increased, whereas the batteries, avionics, and payload components' power values were heavily increased with increasing overall bus power. All component powers were not increased equally, but separate scaling factors were used for each component based on the total power for the entire bus.
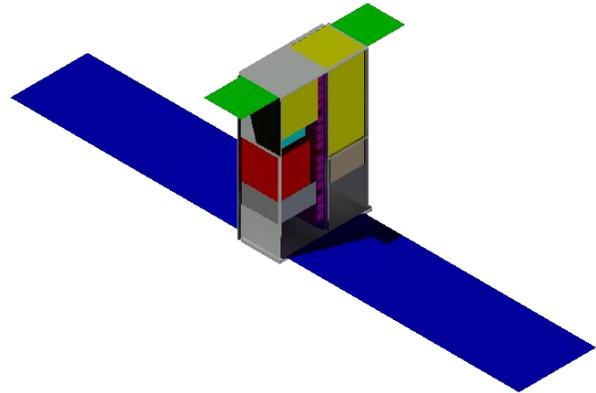

Figure 14: Thermal Desktop® Model for a Standard 6U SmallSat with a Nominal Component Layout

For each analysis, both a hot- and a cold-case orbit were run to determine measured T_{min} and T_{max} values for the components and associated nodes of interest. A 5-orbit transient analysis was run with the 3rd, 4th, and 5th orbits showing quasi-static equilibrium and thus being used to obtain the measured results. Details on the parameters used for these cases are shown in Table 2. It is important to note that yearly averages were used for the solar flux, earth IR, and albedo values in order to keep the environment as generic as possible. There was not a specific mission being targeted, and so only the beta angle and altitude were varied to differentiate between a hot and cold-case orbital environment.

Table 2:   Summary of Orbit Parameters for Nominal 6U SmallSat Thermal Model

Orbit	Beta Angle	Altitude [km]	Orientation	Inclination	Solar Flux [W/m²]	Earth IR [W/m²]	Albedo
Cold-case	46°	850	Nadir	23.44°	1354	221.5	0.35
Hot-case	0°	400	Nadir	23.44°	1354	221.5	0.35

The intent of the thermal analysis was to validate a high-power SmallSat thermal design using deployable radiators, to ensure that all components stayed within

operating temperatures throughout the satellite's nominal mission. In order to aid this SmallSat design, a few standard thermal management design features were implemented to include within the analysis. These thermal design features are summarized below:

- Using all external surfaces as a Body-mounted Radiator – The entire 6U SmallSat was enclosed by an Aluminum 5052 structure. The external surfaces of this structure were coated with a low absorptivity (0.10) and high emissivity (0.75) optical material, in order to make all surfaces body-mounted radiators based on the material ATU9193 from Astral Technology Unlimited, to dissipate heat from the 6U SmallSat.

- High number of bolted connections – A high number of bolted connections was used throughout this 6U SmallSat design. The structure contained many bolted pieces, and each component was bolted to the structure in several places, so as to provide the best possible conduction path from the components to the external body-mounted radiator surfaces.

- Thermally isolate the propulsion component – this was due to its high minimum operating temperature requirement as shown in Table 1.

A brief description of the different design revisions is provided below, and each of these design revisions was thermally analyzed and compared in order to show the validity of utilizing deployable radiators in SmallSats.

- REVA is the nominal 6U thermal model as shown in Figure 9 with power values described in Table 1. From the REVA design, advancements and extrapolations to the component power levels were made to analyze high-powered SmallSats. It is important to note that the REVA results are not included in Figure 18 because this design did not completely represent even a conventional SmallSat thermal design.

- REVB is the first advancement from the REVA design simply consisted of spacing all the components out as much as possible and represented a conventional SmallSat thermal design approach with the thermal design features that are summarized above. This REVB was the basis against which all other thermal design feature ideas were compared. The REVB design was analyzed in the hot-case environment shown in Table 2 and only the maximum temperature of components was tracked so as to try and determine the maximum amount of power that the SmallSat bus could contain. It is important to note that analyses for all design revisions and models were

conducted with the same parameters and in the same manner, for a direct comparison of thermal designs.

- REVC is the next design revision built on the REVB design, but integrated high-conductance thermal technologies in order to represent a high-power SmallSat thermal design without the use of deployable radiators. The technologies used could include high conductivity inserts, oscillating heat pipes, embedded heat pipes, or thermal ground planes, but still only consisted of body-mounted radiators for thermal dissipation. The REVC design did not look any different from REVB. The only difference was the thermal conductivity value of all body-mounted radiator panels was increased to represent a state-of-the-art conduction value (k = 600 W/m/K and panel thickness of 4 mm), which represents a radiator consisting of k-Core of 1.5 mm thickness embedded into aluminum, as opposed to a standard aluminum body-mounted radiator (k = 150 W/m/K) which was used in REVA and REVB.

- REVD consisted of three different iterations: REVD1, REVD2, and REVD3. Each of these iterations consisted of a high-fidelity model with current state-of-the-art conduction values (k = 600 W/m/K and panel thickness of 4 mm) for the body-mounted and deployable radiator panels. REVD1 contained a single deployed radiator; REVD2 contained a double deployed radiator whose deployed radiating surface area was twice that of REVD1; and REVD3 contained a double deployed radiator with a realistic maximized surface area that could be developed with state-of-the-art technology with a deployed radiating surface three times that of REVD1. Each of these different REVD design configurations can be seen in Figure 15 through Figure 17.
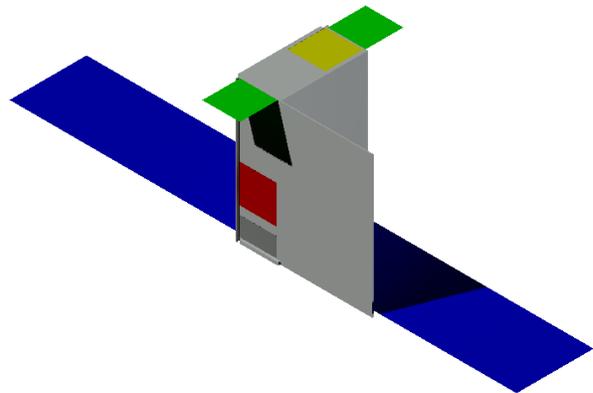

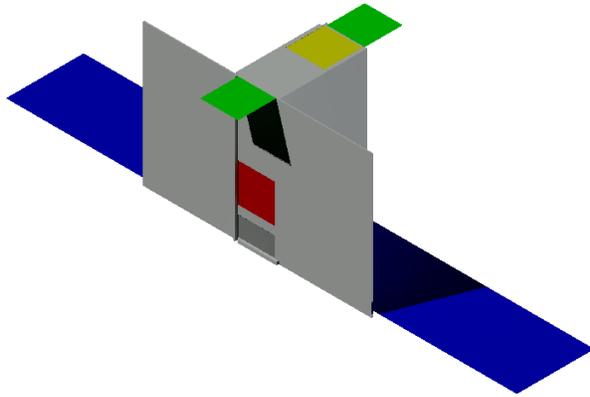**Figure 15: REVD1 - 6U SmallSat Radial Deployable Radiator**

Figure 16: REVD2 – Double-Sided Deployable Radiator Deployed via Strain Energy Composite Panel
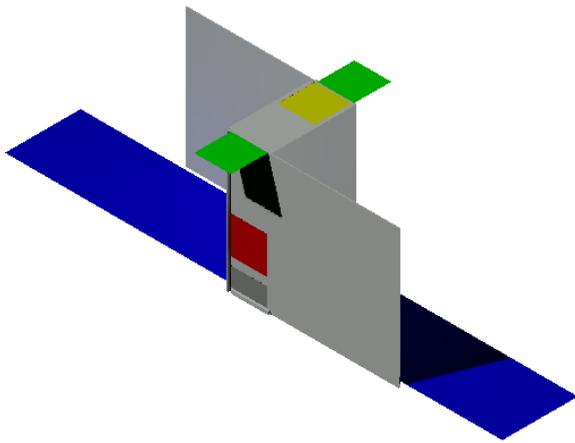

Figure 17: REVD3 - Double Sided Deployable Radiator Deployed via Strain Energy Composite Panel

A summary of the analyses run for the 6U SmallSat designs REVB, REVC, and REVD is shown in Figure 18. Again, it is important to note that the maximum temperature of components was tracked so as to try and determine the maximum amount of power that the SmallSat bus could contain. The Maximum Allowable line is based off of the minimum value for the maximum temperature of the nominal SmallSat components shown in Table 1. In many cases, batteries are the limiting components as far as temperature, as most SmallSat batteries cannot exceed temperatures of 40°C. Therefore, a baseline for the thermal analyses performed was that the total bus power could not exceed a value that causes temperatures higher than this limiting factor.

These results show that deployable radiators drastically increase the amount of heat that can be dissipated from a SmallSat, especially compared to a nominal SmallSat architecture with body-mounted radiators and even

compared to a SmallSat architecture with state-of-the-art thermal control systems and high thermal conductivity body-mounted radiators. It can be seen, that for a nominal 6U SmallSat, using deployable radiators can result in a realistic dissipation of around close to 200 W compared to only 90 W of dissipation using state-of-the-art thermal control techniques and state-of-the-art body-mounted radiators (like that of k-Core embedded aluminum radiator). This correlates to a realistically achievable 220% increase in allowable bus power for SmallSats. Using deployable radiators will lead to an increase in feasible total bus power, simply because more heat can be effectively dissipated, which validates deployable radiators as a crucial part of the future of high-powered SmallSats. As a result, pursuing development in maximizing the radiator surface area with this technology is of high interest.
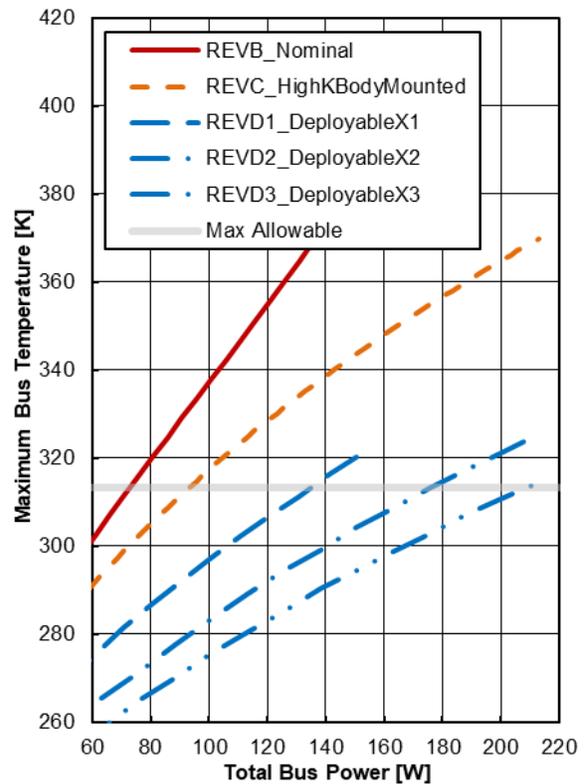

Figure 18: 6U High-Powered SmallSat Design Comparison

The effectiveness of passive thermal control solutions for high-powered SmallSats will depend on the ability to maintain component temperatures throughout the mission's orbit. The advantage of miniature loop heat pipes (mini-LHPs) is the high conductance and heat load dissipation capabilities; however, the high conductance during a cold orbit can lower the temperatures of the components far below their minimum temperatures. There are several flight-proven

methods to halt operation with very small (e.g. heating the compensation chamber) or even with zero power input (e.g. pressure regulating valve). Both methods risk the freezing of the working fluid maintained in the radiator during the cold cases. Transient thermal control issues during the thawing process could result while transitioning from cold cases to hot cases. Once the potential issues are resolved, high-power SmallSat thermal control could be modularized. The same basic deployable radiator design could be used for sun-synchronous missions, which utilizes the bus structure as additional radiator area, and missions with cold cases utilizing a completely insulated bus. Therefore, the temperature ranges for missions with cold cases would be solely maintained by the operation of the mini-LHPs.

Fine tuning the thermal control for critical components may require additional design considerations. Sparse heating or PCMs may be necessary for the tightest temperature range components (i.e. batteries). Another option for taking advantage of the bus radiating area for orbits with cold cases, could be thermal louvers or emerging technologies such as a jumping droplet vapor chamber, which can both act to provide a passive turn-down ratio. These could be applied to regions of the bus where the highest heat loads reside. These are a good potential addition to maintain modularity throughout the thermal design.

CONCLUSIONS AND FUTURE WORK

High-power Small Satellites have the potential to provide new and advanced capabilities to a wide-variety of missions; however, significant design challenges are currently preventing high-power SmallSats from being readily utilized. Of these, thermal management of high-heat loads is most significant. Although options for advanced technologies in thermal acquisition, transport, and storage are currently available, thermal dissipation technologies for high-power systems are lacking. This has created a thermal bottleneck in the high-power SmallSat domain as an effective technology is not being used to dissipate the excess heat that comes with the increased power levels. Deployable radiating technologies are the future for high-power SmallSats as they offer a solution to the thermal dissipation challenges. Several design concepts were presented that focused on high-efficiency, lightweight deployable radiating technologies specifically for SmallSat architectures. Analysis showed that realistic deployable radiator designs offer 220% more thermal dissipation than state-of-the-art body-mounted radiator designs, which directly correlates to the same amount of increase in feasible total bus power. Using deployable radiators, a nominal 6U SmallSat can realistically dissipate around 200 W;

as a result, pursuing development in maximizing the radiator surface area with this technology is of high interest and should be continued further.

As the 6U SmallSat deployable radiator analysis yielded a lot of intrigue regarding the future of high-power SmallSats, future work will involve expanding this analysis beyond the 6U domain. Some preliminary analysis has gone into observing bus power versus maximum bus temperature for 3U and 12U SmallSats as well. Nominal 3U, 6U, and 12U SmallSats with varying deployable radiator sizes were analyzed to observe the effect that deployable radiator size has on the allowable bus power values for future high-power SmallSat architectures. Results from this general analysis can be seen in Figure 19.

A brief description of the different design revisions is provided below, and each of these design revisions was thermally analyzed and the results were compared.

- 3U_RadX1: This design was of a 3U CubeSat architecture with a single deployable radiator.

- 3U_RadX2: This design was of a 3U CubeSat architecture with a single deployable radiator that had twice the length of the 3U_RadX1 design.

- 3U_RadX4: This design was of a 3U CubeSat architecture with a single deployable radiator that had four times the length of the 3U_RadX1 design.

- 6U_RadX1: This design was of a 6U CubeSat architecture with a single deployable radiator.

- 6U_RadX2: This design was of a 6U CubeSat architecture with a single deployable radiator that had twice the length of the 6U_RadX1 design.

- 6U_RadX4: This design was of a 6U CubeSat architecture with a single deployable radiator that had four times the length of the 6U_RadX1 design.

- 12U_RadX1: This design was of a 12U CubeSat architecture with a single deployable radiator.

- 12U_RadX2: This design was of a 12U CubeSat architecture with a single deployable radiator that had twice the length of the 12U_RadX1 design.

- 12U_RadX4: This design was of a 12U CubeSat architecture with a single deployable radiator that had four times the length of the 12U_RadX1 design.

It is important to note that nominal characteristics of these thermal models consisted of an isothermal bus, radiator thermal conductivity of 600 W/m/K, radiator panel thickness of 4 mm, and an orbital environment representative of the hot-case orbit described in Table 2. In addition, the deployable radiator sizes were scaled

in integers. The thermal analysis runs were similar to those performed and described earlier in the paper, except that only a single node was used for the isothermal bus. A heat load was applied to this node and was swept through a range of power values, and this node temperature was tracked and used in the plot for Figure 19. Future work may include more detailed analysis for SmallSats of different sizes, in an effort to focus on the benefits of deployable radiators for a wide scope of SmallSat architectures.
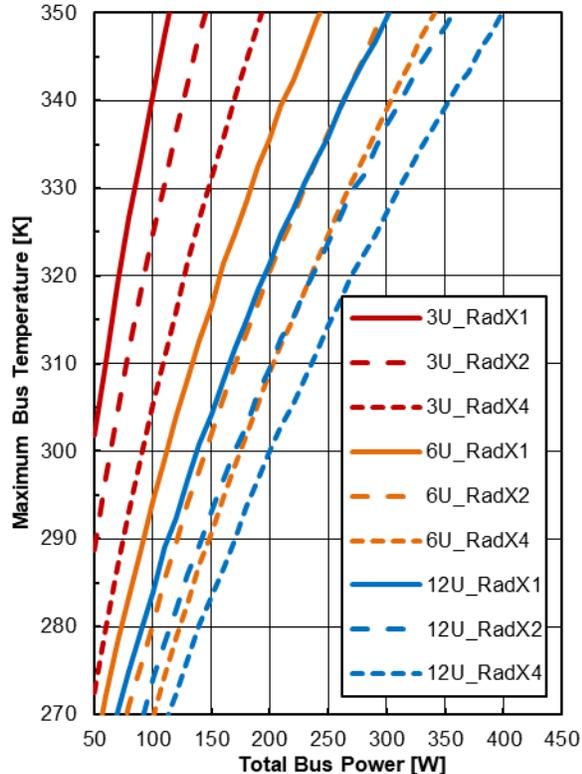

Figure 19: High-Power SmallSat Analysis with Different Sized Bus Architectures and Varying Deployable Radiator Sizes

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