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Advanced SmallSat Thermal Analysis Using Reduced-Order Models

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ABSTRACT

High-power Small Satellites (SmallSats) have the potential to provide new and advanced capabilities for missions beyond low Earth orbit; however, certain challenges prevent wide-spread use. Of these, thermal management of high-heat loads is significant. Therefore, efficient and effective thermal modeling and analysis methods are becoming increasingly more important, as reliable predictions of thermal behavior in SmallSat components and systems can significantly drive key design and mission-operation parameters. Thermal modeling and analysis efforts have traditionally relied on computer simulations that are often complex and computationally expensive. When properly developed, reduced-order models (ROMs) can overcome these challenges by providing a computationally efficient surrogate that accurately captures the behavior of an underlying high-fidelity thermal model (e.g., Thermal Desktop®) while significantly reducing computational expense. In response to this, a reduced-order modeling approach based on intelligent sampling and robust regression data-fitting methods was developed to predict a SmallSat thermal model's behavior as a function of a user-defined set of input factors. Multiple use cases are provided, showing reduced-order model efficacy in SmallSat thermal uncertainty quantification, thermal sensitivity studies, and rapid thermal model correlation to thermal balance TVAC test data. Results of the reduced-order model created in these use cases are shown and compared strongly to the underlying Thermal Desktop® models, showing that ROMs are an innovative software technology that can provide significant advancement in Small Satellite missions by providing unique and advanced thermal analysis results to reduce design margin and further enable higher power SmallSats.

INTRODUCTION

Thermal control for small satellites has become a SmallSat design driver, because it can limit the overall design and performance of a small spacecraft [1]. As such, the Thermal Control System (TCS) for small satellites is being given more attention earlier on in a program's project cycle. This is also due in part to notorious thermal design challenges of concurrent designs, schedule and cost impacts, high power density with limited radiator area, and maintaining traditional thermal margins for SmallSats. While advancements in thermal control hardware can help with some of these challenges, advancements in thermal modeling and analysis methodology are also crucial to high-power SmallSat success. With more heat becoming more prevalent in smaller form factors, the accuracy of thermal models and thermal analysis efforts is increasing in importance as well; resulting in higher fidelity thermal models, more severe analysis margins, longer model run times, and less timely and more costly thermal analysis efforts. Utilizing significantly faster thermal model processing software is directly beneficial to small satellite thermal analyses, where thermal design time is limited. Since mechanical, electrical, and system engineering decisions need to be made quickly, Reduced Order Modeling (ROM) allows the thermal engineering inputs to keep pace [1]. Not only can ROMs assist in reducing the time it takes to complete traditional thermal analysis efforts, but they can also be used to reinvent the way thermal designs are analyzed. Using ROMs as a statistical predictor of a high-fidelity thermal model, more sophisticated analyses can be performed. Rather than a traditional approach of running a few worst-case simulations and bounding the design with significant margin, due to time constraints, ROMs can be used to generate a complete understanding of a SmallSats thermal design space using uncertainty quantification, sensitivity studies, rapid model correlation, and more. This greater understanding of a SmallSats thermal design space can reduce analysis timelines which saves schedule, while also providing enough justification to reduce the necessary thermal margins on the design which saves cost.

REDUCED-ORDER MODELING

Spacecraft TCS are commonly evaluated using high-fidelity, powerful modeling tools. Capable of simulating a near limitless range of conditions, these tools enable thermal engineers to examine a broad trade space. However, these computer experiments can be computationally expensive. Nominal thermal models, taking days to months to develop, can have run times on the order of hours. Comparing and evaluating multiple TCS design parameters amplifies these timelines. When built to evaluate several variables, these costs can become challenging. ROMs have the potential to help alleviate this burden. When properly developed, ROMs provide a computationally efficient surrogate that accurately captures the effects of an underlying high-fidelity model (e.g., Thermal Desktop®). ROMs can then provide thousands of simulation results in seconds which enables evaluation of large design spaces consisting of several variables.

Redwire Space's Veritrek software builds and leverages ROMs built from Thermal Desktop® models to provide accurate thermal model surrogates. Veritrek uses a statistical scheme based on sampling and data fitting an underlying Thermal Desktop® model [3]. This approach is considerably different than nodal reduction methods in that it relies on training data (i.e., high-fidelity simulations). The first step in developing a ROM is carefully selecting sampling points. Full-factorial approaches examine all combinations of variables; however, only at extreme values. As a result, space-filling designs were utilized to efficiently identify and evaluate interior points. The second step uses regression data-fitting methods to interpolate between the training data truth results, in a robust fashion, to finalize the ROM equation. This ROM generation is provided in the Veritrek Creation Tool. The ROM can then be utilized in the Veritrek Exploration Tool to perform rapid thermal analyses.

Reduced-order modeling has been successfully implemented for a broad range of spacecraft thermal analysis applications [2-6]. The developed approach creates surrogate models by accurately mapping (i.e., data fitting) select input factors to output responses. Leveraging the speed of ROMs, thermal analysis teams have access to rapid optimization, sensitivity studies, rapid model correlation, and uncertainty quantification to name a few. These methods have been successfully applied to such applications as the Mars 2020 Helicopter [7], Dream Chaser, and Vigoride programs to name a few. In addition to the speed of the ROMs, another advantage of the developed approach is its relative robustness.

EXAMPLES AND APPLICATIONS FOR SMALLSATS

Veritrek's ROM approach was implemented for multiple SmallSat models and applications, to perform some of the advanced analyses that are going to become more prevalent and necessary as the high-power SmallSat trend continues. Veritrek was used to perform a thermal uncertainty quantification on a 6U SmallSat's payload and battery temperatures, a thermal sensitivity study on a 3U CubeSat's PCB component temperature, and a rapid model correlation campaign on a 6U SmallSat.

Advanced SmallSat Thermal Uncertainty Quantification Analysis

For this application, a 6U SmallSat thermal model was analyzed and included the following characteristics. The model (depicted in Figure 1) included several isothermal components (such as antennae, batteries, attitude determination and control, propulsion, payloads, radios, avionics, and solar arrays), along with a deployable radiator. In total, this Thermal Desktop® model contained 1795 nodes and the model runtime was ~15 min. per run.

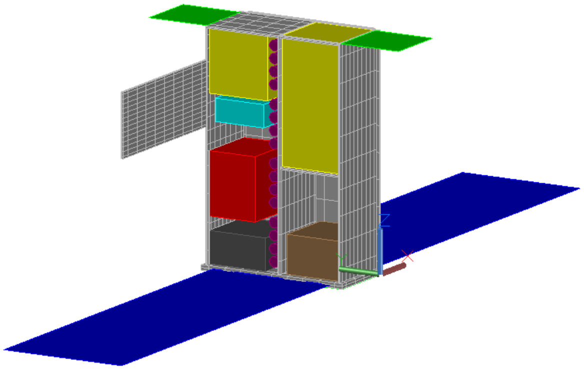


Figure 1: Thermal Desktop® model for 6U SmallSat

Symbols that were included as input factors for this reduced-order model included conductance values between various components and the bus structure, total conductance value of the deployable radiators hinge, conductivity values for all the PCB boards, and sensitivity factors for the optical properties associated with all radiating surfaces. In addition to symbols, there were also multiple sets used to simulate hot and cold orbital environments.

1024 training runs were used to create this ROM, and this took about 5 days of actual time to complete. This ROM was performed in parallel to help reduce ROM creation time, and Thermal Desktop® licenses were used over nights and weekends to avoid interrupting other workflows. Of the ten temperature output responses tracked, the worst performing output response had a mean of residual error of 0.5 °C and a standard deviation residual error of 2.1 °C.

Upon completion of the ROM creation, the Veritrek Exploration Tool was used to perform thermal uncertainty quantification analyses to understand how uncertain thermal inputs propagate to a range of possible output response values. A user defines a design space range that Veritrek will explore and plot out a histogram of possible output response values based on the range of input values provided. For this ROM, conductance values for the mounting of components to the bus structure were allowed to vary a maximum of 4 W/C, the total conductance of the radiator hinge varied from 0.8 to 2.4 W/C, the thermal conductivity was allowed to vary a total of 10 W/m/C and the optical property values were allowed to vary +/- 0.08. Veritrek explored 10,000 different design points within this specified design space and generated the histogram plots for payload temperature in cold and hot orbital environments (Figure 2 and Figure 4), and battery temperature in hot orbital environments (Figure 3).

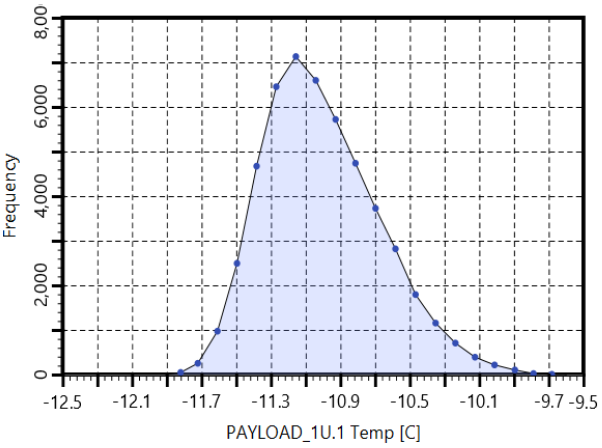


Figure 2: Uncertainty Quantification results for Payload Temperature in Cold Environment

For the cold orbital environment, based on the design space range defined above, this plot shows that even with varying input conditions, the payload temperature will never drop below -12 °C. The most likely minimum temperature of the payload is shown to be about -11 °C., with a possible variation of a few degrees being likely.

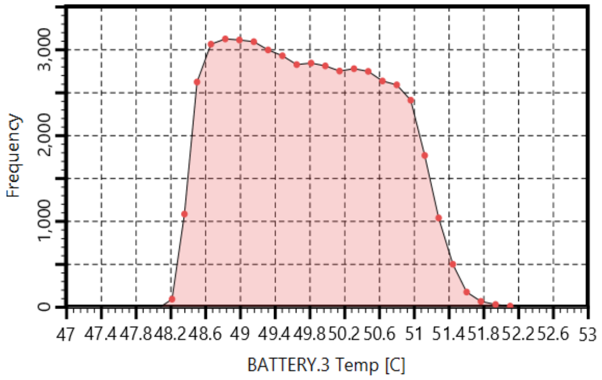


Figure 3: Uncertainty Quantification results for Battery Temperature in Hot Environment

For the hot orbital environment, the battery temperature is shown to potentially climb up to 52 °C, although it is more likely that the battery temperature will fluctuate between 49 °C and 51 °C.

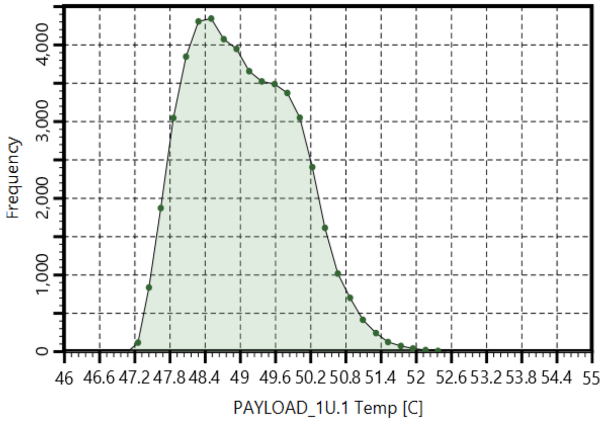


Figure 4: Uncertainty Quantification results for Payload Temperature in Hot Environment

For the hot orbital environment, the payload temperature also shows it has potential to reach 52 °C, although the most likely temperature is 48 °C across a potential 5 °C spread.

Veritrek's Uncertainty Quantification Analysis feature allows users to analyze stochastic relationships between the input factors and output responses of a reduced-order model, to make statistically based conclusions about the uncertainty of a model. Understanding how uncertain thermal inputs propagate to uncertainty in output parameters can help give thermal teams more confidence in tightening design margins and requirements, further assisting in allowing higher power SmallSats to become more realistic.

Advanced SmallSat Thermal Sensitivity Analysis

For this application, a 3U SmallSat thermal model with a primary PCB-based component was analyzed. A ROM was built from the higher fidelity Thermal Desktop® model and was used to perform a thermal sensitivity study to better understand how sensitive the primary PCB-based component's temperature was to a handful of input parameters: PCB component power, emissivity of the SmallSat's body-mounted radiator, conductance values associated with mounting and thermally controlling the PCB component, and the in-plane thermal conductivity of the component. Results from this sensitivity analysis are shown below for hot operating conditions (shown in red) and cold operating conditions (shown in green) in Figure 5. Veritrek's Sensitivity Analysis is based on Monte Carlo methods of rapidly interrogating a design space and visualizing output responses from the several thousand ROM simulations that are performed. The result is a visualization of Pareto bar graphs that depict the on-average impact individual input parameters have on a given output response. The larger the bar graph, the more of an impact on-average that input has on the output response shown on the y-axes.

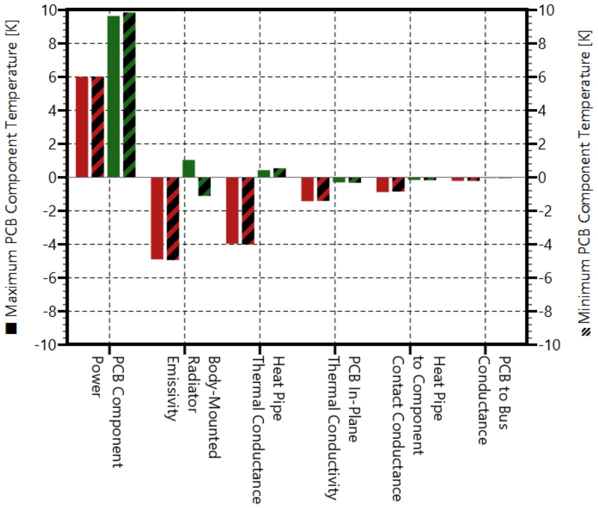


Figure 5: Sensitivity Study results for PCB Component temperature on-board a 3U SmallSat

These Sensitivity Analysis results show that the PCB Component Power is the biggest driver for the temperature of the PCB-based component, which is not surprising. More interestingly, the results show that the emissivity of the body-mounted radiator has a larger impact on reducing the maximum temperature of the PCB-based component than any of the mounting conductance or component conductivity inputs investigated. This information can then be used to focus design optimization efforts on the heat dissipation system of the SmallSat, instead of optimizing internal mounting designs or material properties, as this is a bigger design driver.

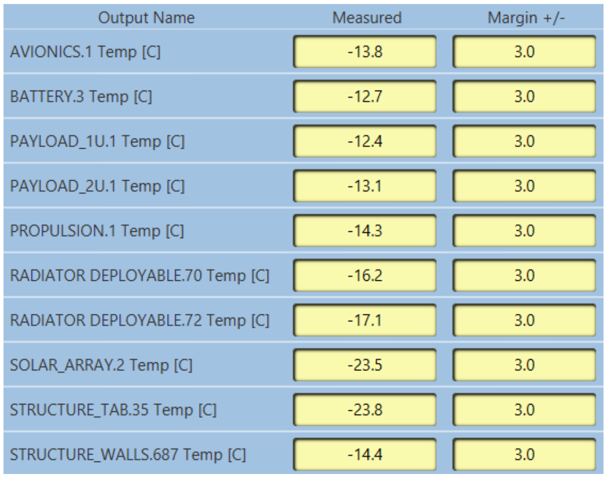
Veritrek's Sensitivity Analysis feature uses statistical methods to identify key design drivers in a thermal model and quantify the impact that varying input parameters have on output responses. This information can then be used by design teams to more efficiently optimize their TCS, and provides enough information to do this confidently and in a much shorter time frame that typical thermal modeling and analysis approaches.

Advanced SmallSat Rapid Thermal Model Correlation

For this application, the same 6U SmallSat Thermal Desktop® model and ROM that were discussed previously were used. Two different case sets were included, which replicated a hot and cold TVAC environment to match thermal balance test data obtained in the lab.

Upon completion of this ROM creation, the Veritrek Exploration Tool was used to perform rapid model correlation. A user defined the output response values they were trying to correlate to by inputting the node temperatures they want into Veritrek, based on thermocouple readouts from their thermal balance test. This rapid model correlation effort consisted of correlating two thermal balance tests at the same time, with ten thermocouple readings per test.

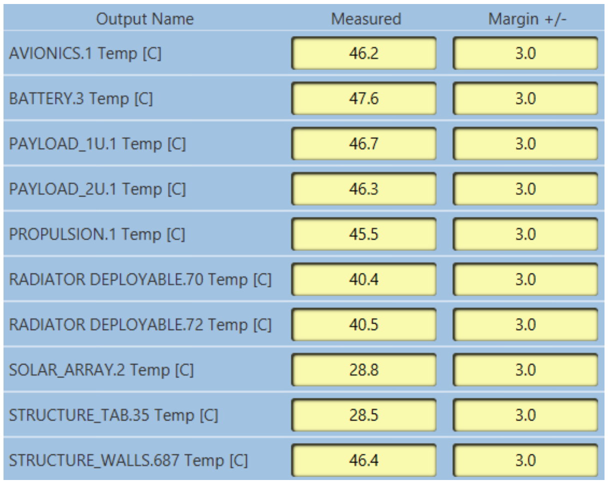
For the Cold TVAC test, the values that Veritrek was correlating to are shown below, along with a user-defined allowable margin of +/- 3 °C.



Output Name	Measured	Margin +/-
AVIONICS.1 Temp [C]	-13.8	3.0
BATTERY.3 Temp [C]	-12.7	3.0
PAYLOAD_1U.1 Temp [C]	-12.4	3.0
PAYLOAD_2U.1 Temp [C]	-13.1	3.0
PROPULSION.1 Temp [C]	-14.3	3.0
RADIATOR DEPLOYABLE.70 Temp [C]	-16.2	3.0
RADIATOR DEPLOYABLE.72 Temp [C]	-17.1	3.0
SOLAR_ARRAY.2 Temp [C]	-23.5	3.0
STRUCTURE_TAB.35 Temp [C]	-23.8	3.0
STRUCTURE_WALLS.687 Temp [C]	-14.4	3.0

Figure 6: Thermal balance test results imported into Veritrek for correlation of a Cold TVAC Test

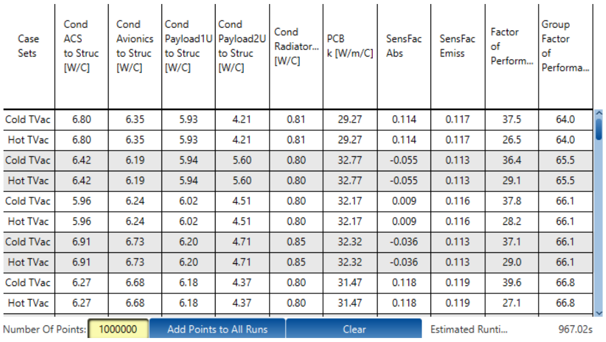
For the Hot TVAC test, the values that Veritrek was correlating to are shown below, along with a user-defined allowable margin of +/- 3 °C.



Output Name	Measured	Margin +/-
AVIONICS.1 Temp [C]	46.2	3.0
BATTERY.3 Temp [C]	47.6	3.0
PAYLOAD_1U.1 Temp [C]	46.7	3.0
PAYLOAD_2U.1 Temp [C]	46.3	3.0
PROPULSION.1 Temp [C]	45.5	3.0
RADIATOR DEPLOYABLE.70 Temp [C]	40.4	3.0
RADIATOR DEPLOYABLE.72 Temp [C]	40.5	3.0
SOLAR_ARRAY.2 Temp [C]	28.8	3.0
STRUCTURE_TAB.35 Temp [C]	28.5	3.0
STRUCTURE_WALLS.687 Temp [C]	46.4	3.0

Figure 7: Thermal balance test results imported into Veritrek for correlation of a Hot TVAC Test

After specifying the thermal balance thermocouple values to correlate to, Veritrek explored the user-defined design space to find combinations of inputs that correlated the model effectively within the allowable margin range. For this effort, the user asked Veritrek to explore 1,000,000 combinations of input parameter combinations (e.g., conductance values, thermal conductivity values, and optical property values). Leveraging the power of the ROM, this investigation of 1,000,000 design points occurred in ~16 minutes and Veritrek found 40 possible solutions. Some of these results are shown below.



Case Sets	Cond ACS to Struc [W/C]	Cond Avionics to Struc [W/C]	Cond Payload1U to Struc [W/C]	Cond Payload2U to Struc [W/C]	Cond Radiator... [W/C]	PCB k [W/m/C]	SensFac Abs	SensFac Emiss	Factor of Perform...	Group Factor of Performa...
Cold TVac	6.80	6.35	5.93	4.21	0.81	29.27	0.114	0.117	37.5	64.0
Hot TVac	6.80	6.35	5.93	4.21	0.81	29.27	0.114	0.117	26.5	64.0
Cold TVac	6.42	6.19	5.94	5.60	0.80	32.77	-0.055	0.113	36.4	65.5
Hot TVac	6.42	6.19	5.94	5.60	0.80	32.77	-0.055	0.113	29.1	65.5
Cold TVac	5.96	6.24	6.02	4.51	0.80	32.17	0.009	0.116	37.8	66.1
Hot TVac	5.96	6.24	6.02	4.51	0.80	32.17	0.009	0.116	28.2	66.1
Cold TVac	6.91	6.73	6.20	4.71	0.85	32.32	-0.036	0.113	37.1	66.1
Hot TVac	6.91	6.73	6.20	4.71	0.85	32.32	-0.036	0.113	29.0	66.1
Cold TVac	6.27	6.68	6.18	4.37	0.80	31.47	0.118	0.119	39.6	66.8
Hot TVac	6.27	6.68	6.18	4.37	0.80	31.47	0.118	0.119	27.1	66.8

Number Of Points: 1000000

Estimated Runti... 967.02s

Figure 8: Rapid model correlation test results from Veritrek

Veritrek automatically sorts the found solutions, such that the closest fitting solution appears at the top of the list. In some cases, it can be advantageous to select this single top solution as the best solution to use. However, Veritrek users at NASA Goddard and Ball Aerospace have found other ways of analyzing the solutions that Veritrek finds, using histograms to choose the most likely value for each given input parameter [8,9].

Veritrek's Correlation Analysis feature allows users to rapidly correlate their Thermal Desktop® models to thermal balance test data, leveraging the power of the ROM to investigate millions of combinations of inputs to find those combinations that most closely or most accurately match results obtained in the lab.

CONCLUSIONS

When properly developed, reduced-order models (ROMs) can overcome challenges by providing a computationally efficient surrogate that accurately captures the effects of an underlying high-fidelity model (e.g., Thermal Desktop®). ROMs can then provide thousands of simulation results in seconds which enables evaluation of large design spaces and previously infeasible advanced analysis methods. A ROM scheme was developed in combination with Thermal Desktop® and includes the Veritrek Creation Tool and Veritrek Exploration Tool. Together, this software suite enables end-users to develop and use ROMs from Thermal Desktop® models. The tools provide a semi-automated method for generating ROMs and provide users with seven analysis features including: point analysis, factor sweeps, surface plots, screening, optimization studies, rapid model correlation, and uncertainty quantification. This approach was successfully applied to three applications. Results compared favorably to the underlying Thermal Desktop® model.

When properly developed, ROMs can overcome several of the key challenges inherent with high-power SmallSats by providing a computationally efficient surrogate of a high fidelity SmallSat thermal model, while significantly reducing computational expense. With the use cases shown being just a few examples, ROMs have already proven to be an innovative software technology that can provide significant advancement in Small Satellite missions.

ACKNOWLEDGEMENTS

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