

# A FINITE ELEMENT THERMAL SIMULATION OF A MICROWAVE BLACKBODY CALIBRATION TARGET\*

*Derek A. Houtz<sup>1,2</sup>, David K. Walker<sup>1</sup>*

<sup>1</sup>National Institute of Standards and Technology, Boulder, Colorado 80305, USA

<sup>2</sup>Department of Aerospace Engineering Sciences, University of Colorado, Boulder, CO

## ABSTRACT

We introduce a method to determine the gradient between measured physical temperature and true radiating surface temperature of a passive microwave calibration target (load or blackbody). An empirical cooling-curve fit is employed to determine heat-transfer coefficients that then allow commercial finite-element software to solve for the physical temperature at the surface of the target. Only gradients in the direction parallel to the target's pyramidal structures are determined. Two target insulation thicknesses are investigated and a mean surface radiating temperature is determined. This surface temperature differs from the internally measured physical temperature by a maximum of 0.3 K in an ambient environment. Use of a thicker insulation assembly decreases this temperature bias by 0.1 K.

**Index Terms**—Passive microwave remote sensing, Microwave radiometry, Calibration, Blackbody characterization

## 1. INTRODUCTION

The National Institute of Standards and Technology (NIST) is developing brightness temperature standards for passive microwave remote sensing radiometers. The standards will serve as absolute references allowing traceability and consistency amongst brightness temperature measurements. Accurate characterization of microwave blackbody targets is imperative to achieve predictable and accurate standards [1].

Typical blackbody microwave calibration targets consist of a heated metal base with absorber-coated pyramidal arrays. The physical temperature of the target is monitored with thermometers embedded into the metal base. The temperature at the location of the thermometers is not the same as the temperature of the radiating absorber surface. This study aims to understand the temperature gradients present on the calibration target surface and to determine an average radiating surface temperature for brightness temperature quantification. We measured the target surface temperature directly using a platinum resistance thermometer (PRT), but these data are questionable because of difficulty in repeatedly measuring a specific spot on a pyramid and error from imperfect thermal contact between the PRT and the surface.

We present a two-step method: the first step consists of target cooling-curve measurements that allow us to determine heat-transfer coefficients. The second step uses these heat-transfer coefficients as constants in a commercial software finite-element steady-state thermal simulation of the target surface temperature.

The target under investigation is 33 cm in diameter and has four-to-one height-to-base pyramid aspect ratio. The base is made from aluminum and the absorber coating is iron-loaded epoxy. When the target is heated, the average of three embedded PRTs is about 352 K with less than 0.1 K deviations.

The study investigates two target insulation assemblies consisting of different thicknesses of Zotefoam<sup>1</sup> HD30, a polyethylene foam material with low loss in the 18 to 26.5 GHz frequency range. The

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two insulators extend beyond the sides of the target by about 2.5 cm and 10 cm, respectively. The radiating surface is covered with a sheet of HD30 of about 2.5 cm thickness for both assemblies. We attempted to evaluate whether the use of thicker insulation decreases the temperature gradients on the target surface.

## 2. COOLING-CURVE FITTING

A challenge in the computational modeling of the target system was to determine of the heat transfer coefficients such as the convection coefficient and emissivity. The air velocity, direction, temperature, and humidity within the measurement environment, an anechoic chamber, are not constant and are unknown. The convection coefficient is a function of all of these parameters and for this study is assumed not to be a function of time or temperature. The ambient background temperature of the chamber is recorded but this is not enough information to fully characterize the convection present on the target and insulation system. A method has been developed that uses a cooling-curve fit and lumped-capacitance approximation to solve for the heat-transfer constants to be input to the finite-element computation.

An empirical way to determine the convection coefficient is to measure the temperature-versus-time curve of the target and fit this to the transient spatially uniform heat equation. This lumped capacitance method makes a few assumptions about the thermal system. First, it assumes that temperature gradients within the system are small. This assumption contradicts the overall goal of the analysis but it is actually not a bad assumption since the system is well insulated, and the temperature gradients within the target compared to the temperature difference between target and ambient are small. The target-to-ambient gradient is more than 50 K, while the gradients within the target are on the order of a few degrees. For this study, the aluminum target and the absorber coating are defined within the control volume, and the surrounding insulation material is considered outside the control volume. This is because the target is surrounded by insulating foam that has a much smaller heat capacity and mass than the aluminum or absorber and the temperature gradients within the insulation cannot be considered small.

The mechanisms that cool the target are radiation, conduction to the surrounding insulation, and

convection to the surrounding air. Convection and conduction are both proportional to the temperature difference across the boundary, so the convection and conduction heat-loss mechanisms can be grouped into one term with a single heat-transfer coefficient,  $h_c$ . The effective emissivity is a lumped term that accounts for the total energy out of the target due to radiation. This includes effects due to thermal energy reflected by the insulating foam, the thermal emissivity of the foam, and the temperature gradients within the insulation, so this value could be quite different from simply the thermal emissivity of the target surface or insulation material. For the lumped-capacitance model with radiation and no internal heat generation, the rate of temperature change can be described by a transient energy balance of the following form [2]:

$$mc \frac{dT}{dt} = -A[h_c(T - T_\infty) + \varepsilon_{eff}\sigma(T^4 - T_\infty^4)], \quad (1)$$

where  $\varepsilon_{eff}$  is the effective thermal emissivity of the target,  $\sigma$  is the Stefan-Boltzmann constant,  $T$  is the target temperature as a function of time,  $T_\infty$  is the ambient temperature,  $m$  is mass,  $c$  is specific heat capacity, and  $A$  is area. The specific heat capacity used is a mass-weighted average of the base and absorber materials. Note that the effective thermal emissivity here is unrelated to the microwave emissivity that makes the target essentially a blackbody in the microwave spectrum.

We performed a nonlinear sum of absolute-error optimization to determine values of  $h_c$  and  $\varepsilon_{eff}$ , fitting equation 1 to the experimental average PRT temperature data. Figure 1 shows the measured target cooling curves for both insulators plotted with the corresponding fitted theoretical model. Standard errors of the optimized values are computed with numerical estimation of the Jacobian matrix. Optimal values of  $h_c$  and  $\varepsilon_{eff}$  were determined to be  $0.5112 \pm 0.0016$  W/(m<sup>2</sup>K) and  $0.04618 \pm 0.00022$ , respectively, for the 2.5 cm thick insulator, and  $0.2319 \pm 0.0011$  W/(m<sup>2</sup>K) and  $0.04583 \pm 0.00017$  for the 10 cm insulator. The larger insulator decreases heat loss due to conduction and convection but has no significant effect on the heat loss due to radiation.

The fitted constants now quantify the physical mechanisms of heat transfer from the system and can be used in a finite-element simulation to determine the resulting temperature gradients when the target is kept at a steady state.

### 3. THERMAL FINITE ELEMENT MODEL

A computer-aided design (CAD) representation of the calibration target is created as an input geometry to the commercial finite-element modeling software ANSYS<sup>1</sup>. A simplified target geometry is created including the aluminum base and Eccosorb<sup>1</sup> coating as separate materials with their associated material properties. The CAD model is meshed and imported to a steady-state thermal analysis in ANSYS<sup>1</sup>. The resistance heater on the baseplate of the target is modeled as an isothermal surface on the back of the plate and is assigned a temperature equal to the average of the embedded PRT readings. The convective and radiative heat transfers were applied uniformly with the fitted coefficient values over the target surface. Figures 2 and 3 show the resulting surface temperature contours plotted on the blackbody geometry for the two insulation assemblies. An area-averaged temperature is calculated from the finite-element surface temperature output. For PRT average heater temperature of 351.0 K the resulting averages over the coating area for the 2.5 cm and 10 cm foam insulation assemblies are 350.70 K and 350.80 K. These are 0.30 K and 0.20 K below the average internal PRT reading. The added insulation measurably and significantly changes the average physical temperature of the radiating surface. Blackbody insulation is an important consideration in radiometer design, considering that modern radiometers quote absolute accuracies of less than 1 K [3, 4].

To investigate the effect of uncertainty in the fitted parameters a similar simulation is run with heat-transfer coefficients of plus- and minus-one-standard deviation. A one-standard deviation increase in  $h_c$  and  $\epsilon_{\text{eff}}$  showed an overall decrease in the average surface temperature of 0.0022 K for the 2.5 cm thick insulation case and smaller for the 10 cm insulation.

### 4. CONCLUSIONS

The nature of the lumped-capacitance assumption in this study eliminates the spatial variation of heat transfer and creates a gradient only in the direction away from the heater. Direct measurements of the surface temperature reveal that there is also a

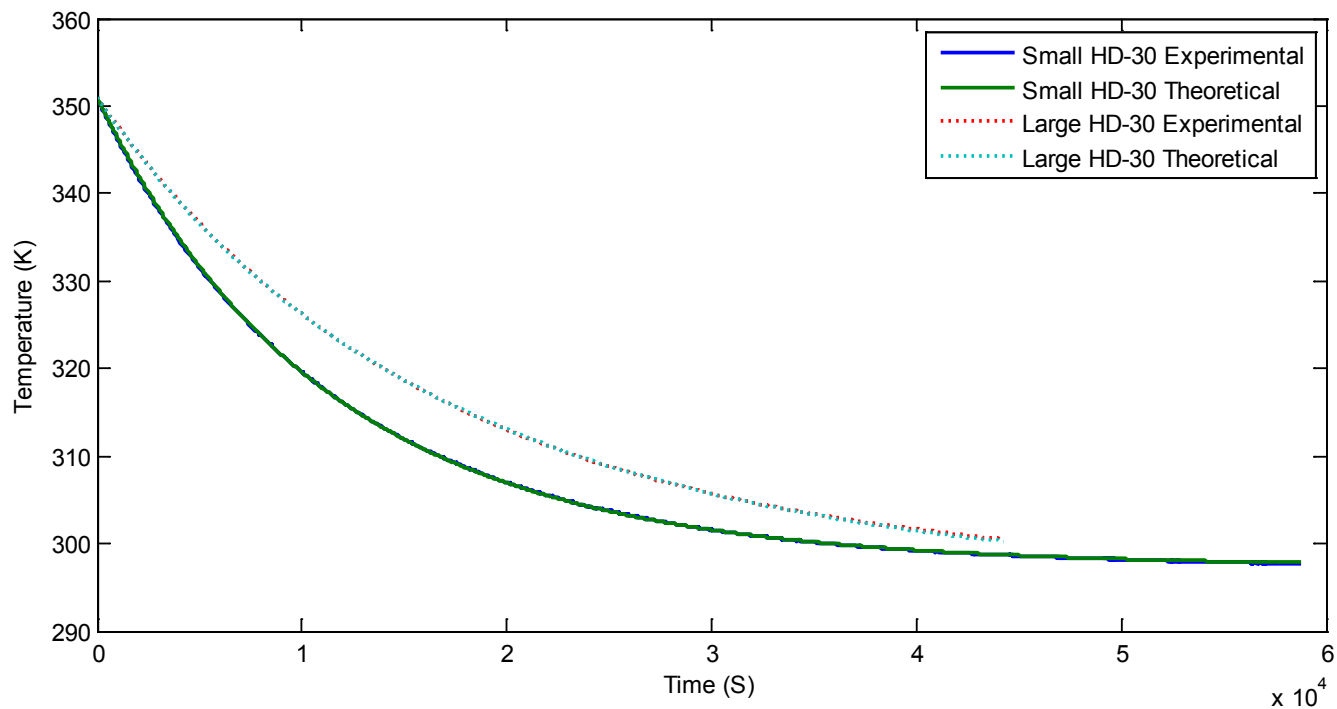
considerable temperature gradient in the plane of the heater on the order of about 2 K. The center and top of the vertically oriented target are generally hotter while the bottom and sides are cooler. Future investigations will attempt to incorporate these temperature gradients into the theoretical model and computational simulation.

The method introduced here is as equally applicable for a space-based calibration standard as it is for the ground-based case, the main difference being that radiation would be the only heat-loss mechanism in space and the ambient temperature would be much lower.

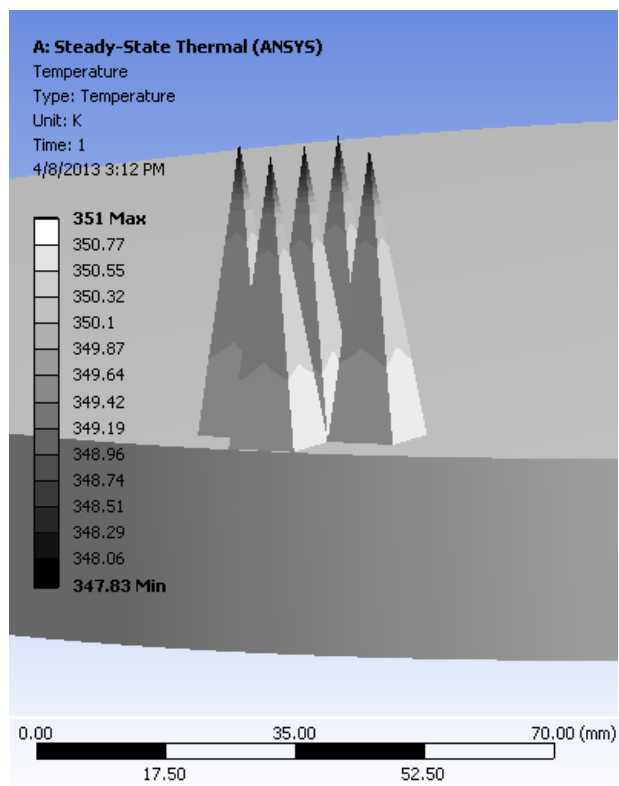
A tradeoff when adding insulation to the calibration target is the effect on the microwave power transmitted through the insulation. It was mentioned that the Zotefoam HD30 is essentially transparent to microwaves, but the material does exhibit a small frequency-dependent deviation from unity relative permittivity. Though the insulation maintains the physical temperature of the target, it also slightly decreases the transmitted microwave power because of the reflection back into the target. Different microwave frequencies would experience slightly different brightness temperatures depending on the properties of the insulation at the measured frequency.

### 5. REFERENCES

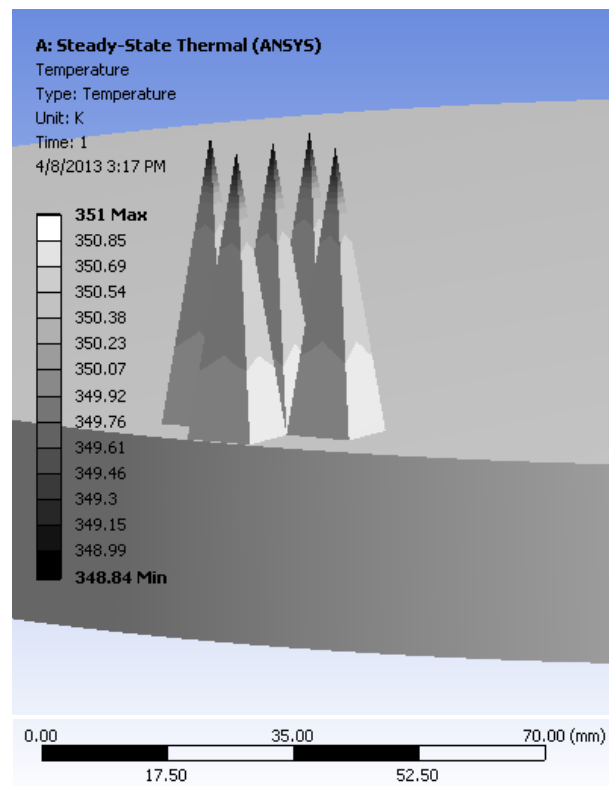
- [1] J. Randa, A.E. Cox, and D.K. Walker, "Proposal for Development of a National Microwave Brightness-Temperature Standard", *Proc. of SPIE*, vol. 6301, 630105, September 2006.
- [2] Moran, Michael J. et al. Introduction to Thermal Systems Engineering. John Wiley & Sons. 2003.
- [3] Twarog, Elizabeth M. et al. "WindSat On-Orbit Warm Load Calibration" *IEEE Transactions on Geoscience and Remote Sensing*, vol. 44, no. 3, pp. 516-529, March 2006.
- [4] Draper, David and David Newell. "Global Precipitation Measurement (GPM) Microwave Imager (GMI) Pre-flight Calibration Performance" *Microwave Radiometry and Remote Sensing of the Environment (MicroRad) Conference Proc.* Rome, March 2010.



**Fig. 1.** Target cooling curves with small (2.5 cm thick) and large (10 cm thick) surrounding insulators.



**Fig. 2.** 2.5 cm insulation target temperature gradient



**Fig. 3.** 10 cm insulation target temperature gradient