



A passive thermal analysis of a small satellite by **Wyatt Hurlbut**

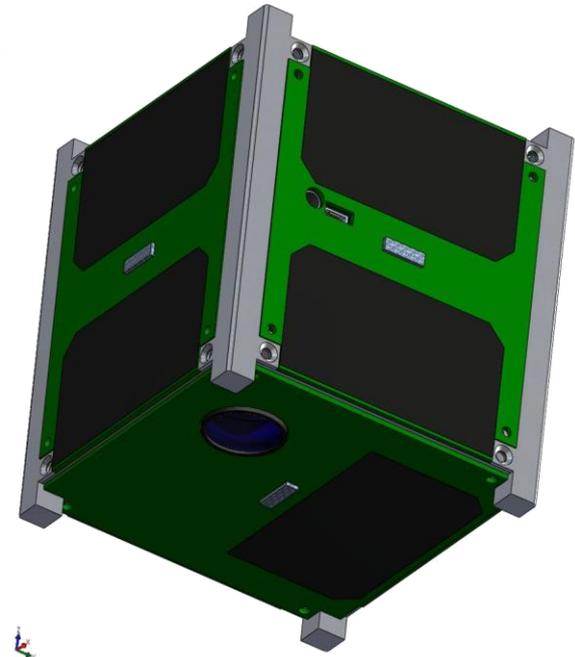
Presented By
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Houston, TX





- **CubeSat Design Specifications, www.cubesat.org**
 - Begun as a collaboration in 1999 between Stanford University and California Polytechnic State University (CalPoly)
 - 1U CubeSat: 1.33 kg, 10x10x10 cm³
 - 2U is 2.66 kg, 20x10x10 cm³; 3U is 4.00 kg, 30x10x10 cm³
 - Center of Mass: 2 cm from Geometric Center
 - Secondary payload for launch vehicles
- **Unique design challenges**
 - Very short build time, low budgets
 - Student-run development teams
 - Existing power limitations
 - Extreme thermal environments
- **“Failure is an option.”**
 - *Professor Jordi Puig-Suari*





CubeSat Mission Objectives



- Educational hands-on design process
 - Mostly students and volunteers
 - Highlights student research and interests
 - Conception to completion: two to three years
- Launch vehicle requirements
 - Cannot impact primary payload
 - Compliant with ITAR, FCC, CubeSat specs, et cetera
 - Launch costs \$40-80k, not inclusive of testing
- University budget **\$500k-\$1000k**
 - No space-hardened equipment
 - Commercial off-the-shelf components
 - Machining and fabrication costs prohibitive
 - Power constraints impact potential



Solar Power Constraints



- Approximate average solar power: www.spectrolab.com
 - Two space-rated panels per face, ~ 1 W per cell
 - Transmission needs: 500-2000 mW
- Design considerations
 - Location; Quantity
 - Deployment angle; Orientation
 - Total # axis stabilization
 - Orbital launch parameters
- Requires attitude control system
 - Considerable technical knowledge
 - Machining / fabrication challenges
 - Nontrivial mass cost
 - Average case: 5 degrees accuracy





Extreme Thermal Environment



- Secondary payload
 - Launch vehicle often unknown
 - Average lifetime 6-60 months
- Low Earth Orbit (LEO)
 - Reduced radiation exposure from Van Allen belt
 - Allows amateur “ham” radio contact
 - Sun synchronous temperature – 295 K
 - Eclipsed temperature – 158 K

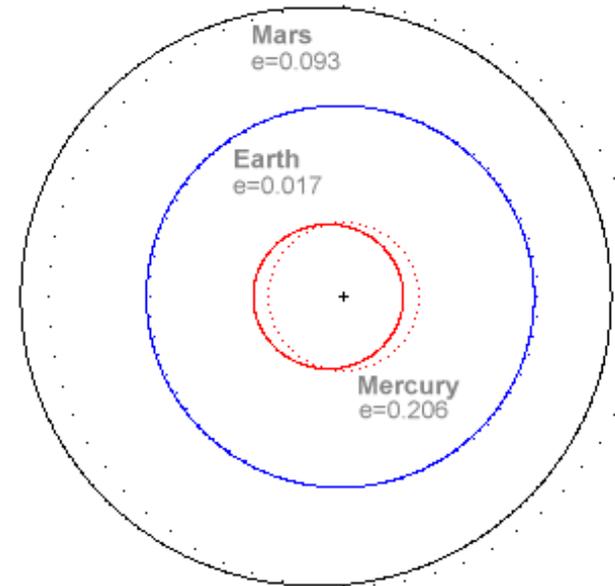
Altitude	Velocity	Orbit	Sunlight	Cooling	Avg Temp
[km]	[km/s]	[min]	[% Orbit]	[min]	[K]
300	7.73	90.37	59.58%	36.53	236.56
400	7.67	92.41	61.00%	36.05	238.40
500	7.62	94.47	62.22%	35.69	240.00
600	7.56	96.54	63.30%	35.43	241.41
700	7.51	98.62	64.28%	35.23	242.69
800	7.46	100.72	65.18%	35.07	243.86



Worst Case Conditions



- Solar flux
 - Summer Season 1393 W/m^2
 - Winter Season 1305 W/m^2
- Hot condition
 - Sun-synchronous, summer orbit
- Cold condition
 - Sun-asynchronous, winter orbit
- Initial assumptions
 - Constant velocity, circular orbit, precise axis control
 - Altitude 300km, no atmosphere or atmospheric friction
 - Ambient temperature 4 K, No reflection from Earth or Moon
 - Material properties: 1 kg aluminum 6061-T6
 - Internal component block produces 2 watts





Hot Condition Model



Boundary Settings - General Heat Transfer (htgh)

Equation

$$-\mathbf{n} \cdot (-k \nabla T) = q_0 + h(T_{\text{inf}} - T) + \epsilon \sigma (T_{\text{amb}}^4 - T^4)$$

Boundary Condition: Heat flux

Quantity	Value/Expression	Unit	Description
q_0	1414	W/m ²	Inward heat flux
h	0	W/(m ² ·K)	Heat transfer coefficient
T_{inf}	294.5	K	External temperature
Radiation type:	Surface-to-ambient		
ϵ	.85		Surface emissivity
T_{amb}	4	K	Ambient temperature
J_0	epsilon_htgh*sigma_htj	W/m ²	Surface radiosity expression

Member of group(s):

Subdomain Settings - General Heat Transfer (htgh)

Equation

$$\rho C_p \partial T / \partial t + \nabla \cdot (-k \nabla T) = Q + q_s T$$

T = temperature

Library material: Aluminum Solar

Quantity	Value/Expression	Unit	Description
k	201[W/(m·K)]	W/(m·K)	Thermal conductivity
ρ	2700[kg/m ³]	kg/m ³	Density
C_p	900[J/(kg·K)]	J/(kg·K)	Heat capacity at constant pressure
q_s	0	W/(m ³ ·K)	Production/absorption coefficient
Q	6420	W/m ³	Heat source

COMSOL Multiphysics - Geom1/Heat Transfer Module - General Heat Transfer (htgh) : Cold_Sat_2Wa

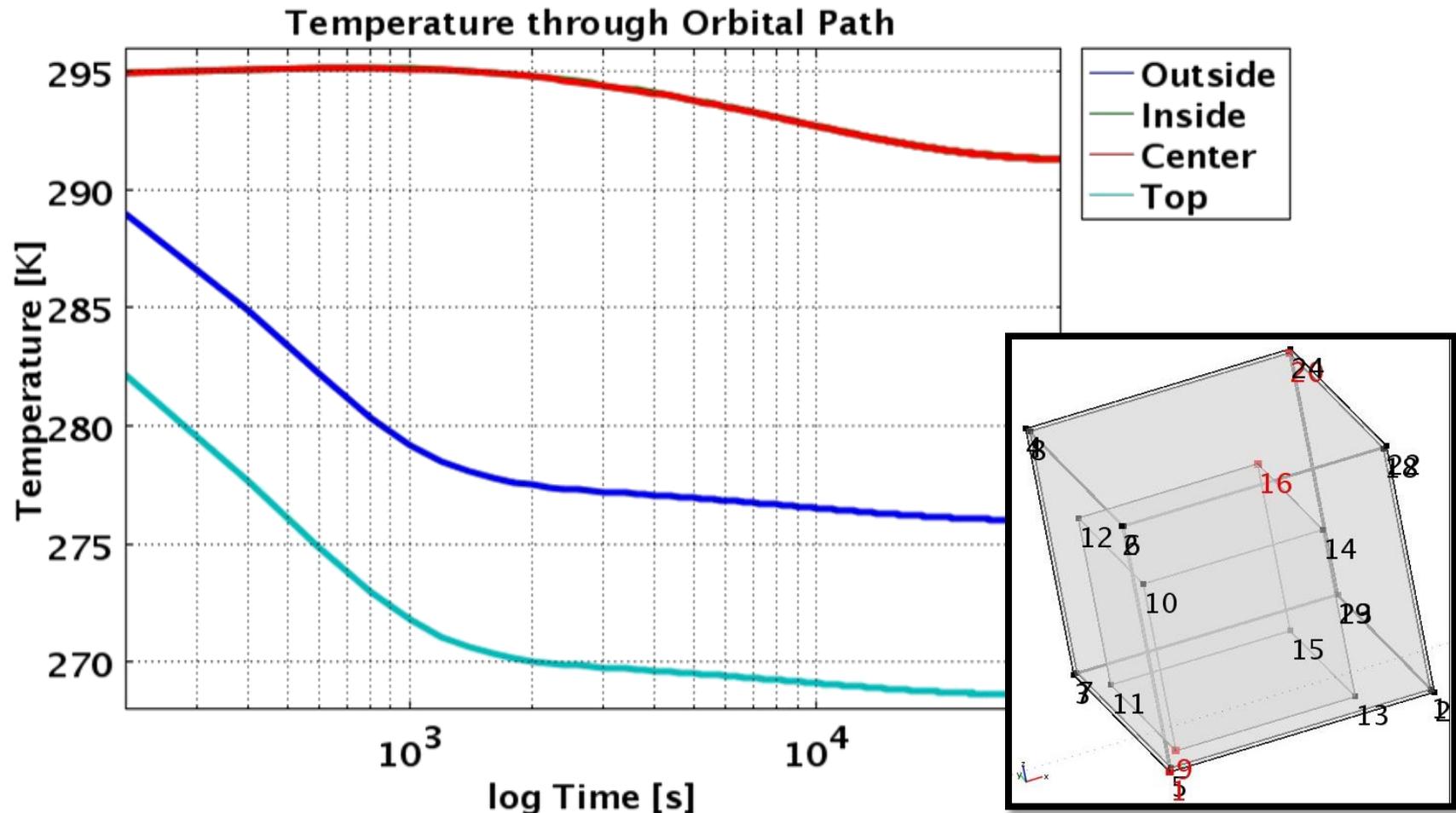
Model Tree

- Geom1
 - General Heat Tr

Value: 219.7322578025876 [K], Expression: T, Point: 9
Value: 219.73038111236855 [K], Expression: T, Point: 16
Value: 161.86256481319526 [K], Expression: T, Point: 20



Hot Condition Results





Cold Condition Model



The screenshot displays the COMSOL Multiphysics interface for a "Cold Condition Model". Two dialog boxes are open over a 3D model of a satellite component.

Boundary Settings - General Heat Transfer (htgh)

Equation:
$$-\mathbf{n} \cdot (-k \nabla T) = q_0 + h(T_{inf} - T) + \epsilon(G - \sigma T^4)$$
$$(1 - \epsilon)G = J_0 - \epsilon \sigma T^4$$

Boundary Condition: Highly Conductive Layer

Boundary sources and constraints

Library coefficient: Load...

Boundary condition: Heat flux

Quantity	Value/Expression	Unit	Description
q_0	0	W/m ²	Inward heat flux
h	0	W/(m ² ·K)	Heat transfer coefficient
T_{inf}	294.5	K	External temperature

Radiation type: Surface-to-surface

ϵ	0.85		Surface emissivity
T_{amb}	4	K	Ambient temperature
J_0	J	W/m ²	Surface radiosity expression

Member of group(s): 1

Name: Interior
Type: Boundaries

Buttons: New, Delete, OK, Cancel, Apply, Help

Subdomain Settings - General Heat Transfer (htgh)

Equation:
$$\rho C_p \partial T / \partial t + \nabla \cdot (-k \nabla T) = Q + q_s T$$

T = temperature

Subdomains: General | Convection | Ideal Gas | Infinite Elements | Init | Element | Stabilization | Color

Thermal properties and heat sources/sinks

Library material: Aluminum Solar

Quantity	Value/Expression	Unit	Description
k	201 [W/(m·K)]	W/(m·K)	Thermal conductivity
ρ	2700 [kg/m ³]	kg/m ³	Density
C_p	900 [J/(kg·K)]	J/(kg·K)	Heat capacity at constant pressure
q_s	0	W/(m ³ ·K)	Production/absorption coefficient
Q	0	W/m ³	Heat source

Opacity: Opaque

Name: Exterior

Buttons: New, Delete, OK, Cancel, Apply, Help

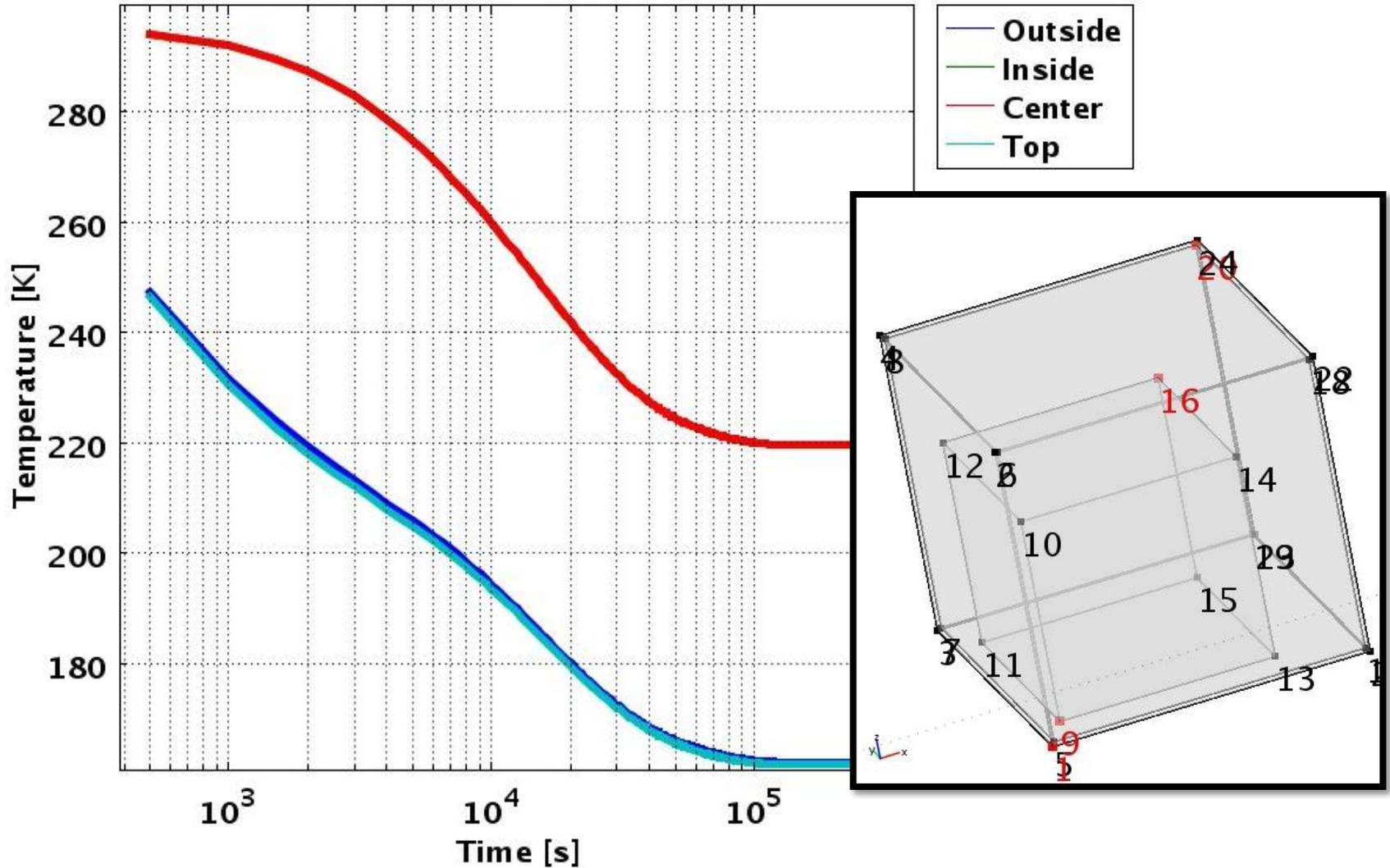
The 3D model shows a rectangular satellite component with a red mesh. The background features a view of Earth from space.



Results of First Orbit

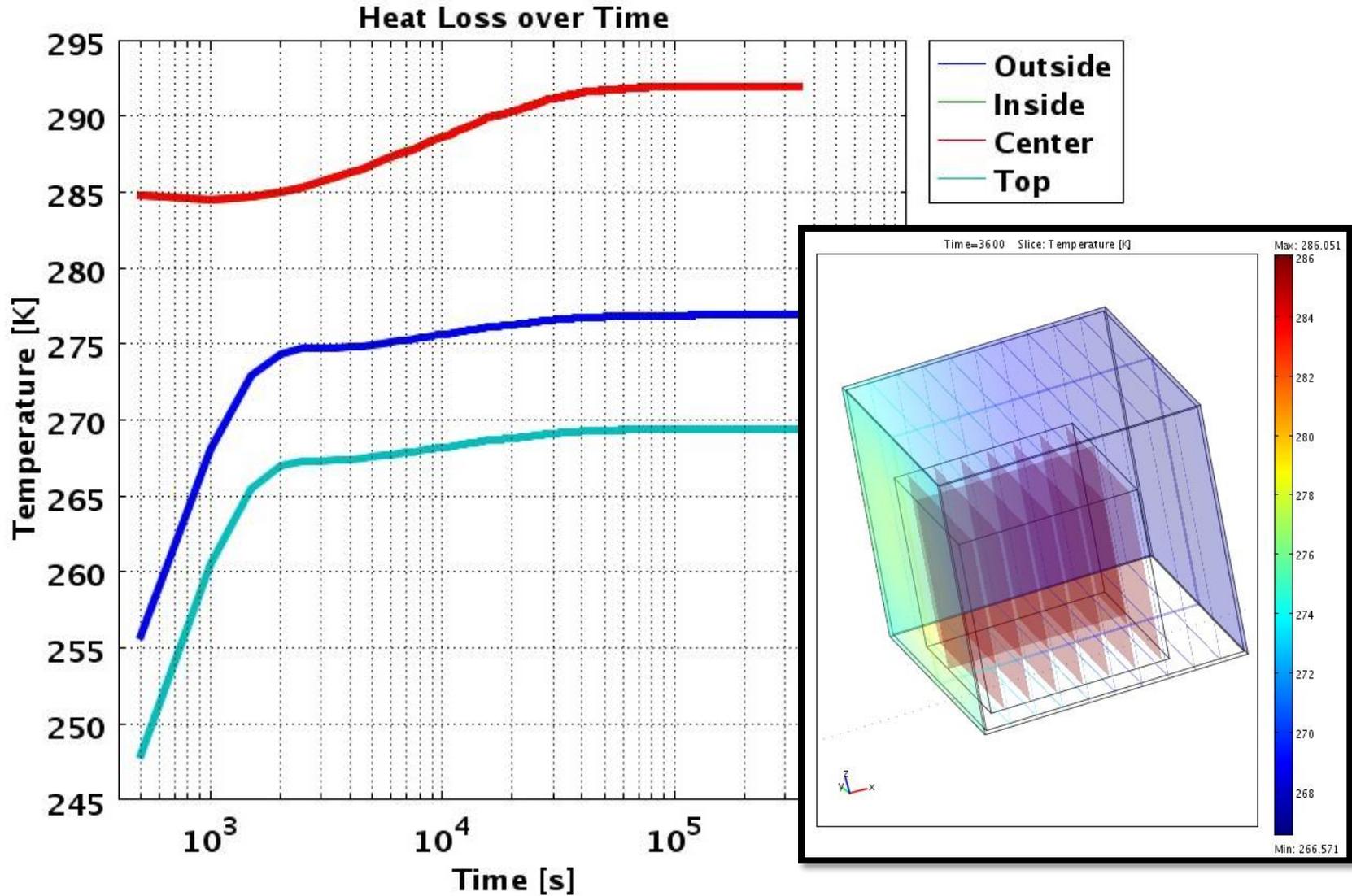


Heat Loss over Time



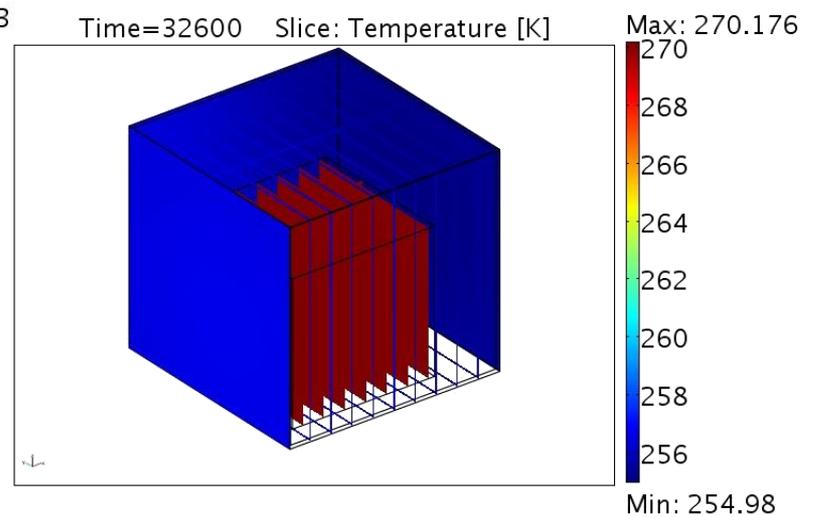
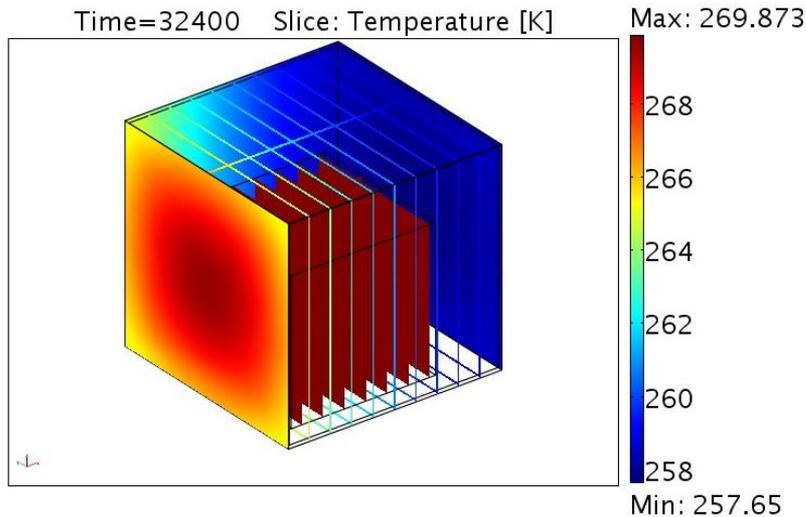
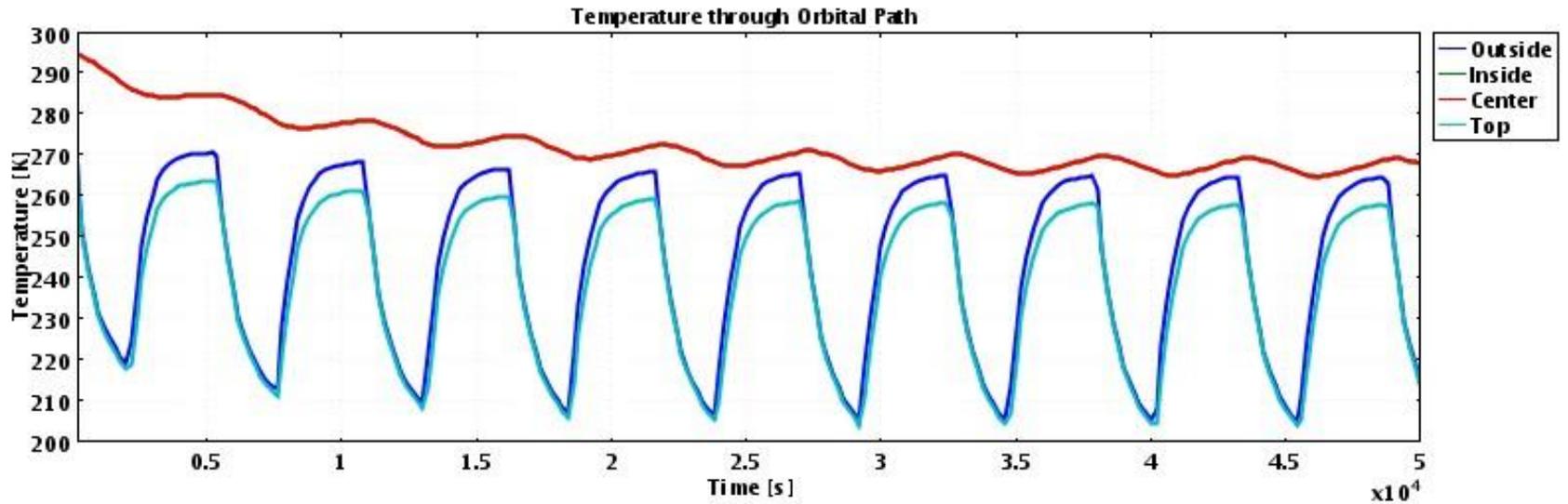


Results of First Orbit, Cont.





Orbit Comparison, cont.





Summary



- Model results corroborate rough experimental data
 - Depends on ideal conditions
 - No knowledge of specific design
- Advantages to CubeSats:
 - Inexpensive, low-cost research
 - Excellent educational platform
- Disadvantages:
 - Challenging development environment
 - Continually reinventing wheel Sputnik
- Unanswered questions:
 - Thermal characteristics of CubeSats with deployed solar panels?
 - Overall accuracy of model that indicates thermal conditions?
 - Critical variables for deployable solar panel designs?
 - Should CubeSat teams consider this as a viable option at all?



Future Improvements



- Expand initial literature review
 - Designs often poorly documented
 - ITAR regulations prohibit releasing specific details
- Identify critical design constraint variables
 - Deployment angle; Orientation; Location; Quantity
 - Orbital launch parameters; Total # axis stabilization
- Determine thermal characteristics of detailed model
- Create detailed energy balance and thermal model
 - Used for the Alaskan Research CubeSat
 - Will be made available for future CubeSat teams
- Answer questions posed by CubeSat community
 - Are power issues best solved by simply increasing size?
 - How does each design variable impact a CubeSat?
 - Where do we start?



Acknowledgements



**UAF CubeSat Team: Left to right: Samuel Vanderwaal , Donald ‘Crank’ Mentsch, Greg Geiger, Alex Arneson, Andrew Paxson, Marco Ulloa, Ben Montz, Wyatt Rehder, Dustin Olson, Robert Schnell, Heather Havel, Dr. Joseph Hawkins - Professor, Wyatt Hurlbut, Jesse Frey, and Steven Kibler.
Not pictured: Dr. Denise Thorsen – Director of ASGP, Dr. Rorik Peterson – Advisor, Gregg Christopher, Morgan Johnson, James Peters, and Scott Otterbacher.
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Thank you for your attention! Questions?