A Spreadsheet for Preliminary Analysis of Spacecraft Power and Temperatures

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Abstract

Low cost design requires the timely analysis of multiple spacecraft configurations. This paper presents a rapid spreadsheet approach for thermal and electrical power analysis of thirteen basic configurations typical of small satellites. The spreadsheet "Solver" routine can be used to adjust temperature limits, by automatic iteration of absorptivity and emissivity subject to user imposed constraints. The program also estimates the maximum power load supportable by body fixed solar panels. The program assumes a circular orbit and fixed vertical or horizontal attitude. Orbit average solar direction cosines, earth view factors and albedo are evaluated for each surface to calculate the total heat load. Program Inputs include: altitude, mass, surface dimensions, thermal properties, electrical power system parameters (efficiencies, degradation, battery depth of discharge and solar cell packing factors), solar position (beta angle) and intensity, planet IR, albedo and equipment power dissipation during sunlight and eclipse. Thermal outputs include upper, average and lower temperatures. Power outputs include required battery capacity and maximum supportable power load. The power output feature also allows optimum placement of solar panels.

The outputs are shown simultaneously for a sphere, cylinder, and five regular prisms (triangle, square, pentagon, hexagon and octagon) in both vertical and horizontal attitudes. Comparisons of the spreadsheet approach with detailed simulation show an <u>exact</u> match for maximum supportable electrical power load and orbit average temperature and a 0.2 ºC match for upper and lower temperatures. The program is intended for use by Systems Engineers and students as an aid in establishing viable baseline configuration options. The program also serves as a "reality check" on complex thermal analysis programs. The rapid analysis of body fixed solar panel capability in combination with judicious power budgets might avoid (or justify) the expense and risk of deployable solar arrays.

Nomenclature

a = albedo coefficient
A_t = total external area ~ m^2
c_p = specific heat capacity ~W.s.kg^{-1}.K^{-1}
C(.) = cosine of angle (.)
O.D. = diameter ~m
E = Earth's IR intensity ~ W/m^2
G = solar flux intensity ~ W/m2
h = altitude km
L = length ~m
m = nodal mass ~kg
P_d = daylight period ~ s
P_e = eclipse period ~ s
P_o = orbit period ~ s
Q_{al} = heat rate from albedo ~ W
$\mathbf{Q_{eq}}$ = ave. heat load from equipment ~ W
Q_{IR} = heat load from Earth ~ W
Q_{sun} = heat load from Sun ~ W
$\mathbf{Q_e}$ = average heat load in eclipse~ W
$\mathbf{Q_d}$ = average heat load in daylight~ W
s.i = surface **i** to sun direction cosine
SSP = point in orbit closest to sun
S(.) = sine of angle (.)
T(.) = tangent of angle (.)
T_L = lower temperature
T_U = upper temperature
x_o , y_o , z_o = SC orbit reference frame (LVLH)
α = solar absorptivity (dimensionless)
β = angle between Sun & orbit plane
ε = external emissivity (dimensionless)
λ = half total sunlight angle
ν = angle between SSP and z_o -axis
ρ = Earth's angular radius ~ radians
σ = Stefan-Boltzmann constant ~ W/(m$^{2\cdot}$ K^4)
θ = angle between Sun and z-axis

Introduction

Accurate spacecraft thermal analysis requires the use of complex computer programs. Consequently, several approaches have been developed to provide "quick-look" thermal data. Among these are the equivalent-sphere[1], linearization of the T^4 term[2,3] in the energy balance equation, and an equivalent massless cube[4] approach. One of the linearization approaches[3] is based on assuming the highest temperature occurs at entrance to eclipse and the lowest occurs at exit from eclipse. That spreadsheet approach yielded reasonable accuracy at altitudes below about 7000 km. However at GEO altitude, it can be in error by as much as 9ºC. This paper presents a spreadsheet approach accurate to within tenths of a degree at all altitudes for seven different shapes in both vertical and horizontal attitudes. Since the approach develops precise solar direction cosines, it is also used to assess the viability of body fixed solar panels.

Orbit Parameters

The angle β (Fig. 1) locates the sun with respect to the orbit plane, θ locates the sun with respect to the spacecraft (SC) and ν locates the SC with respect to the sub-solar point (SSP). All the angles are functions of time; however beta varies so slowly that it is considered constant for thermal and electrical power analyses. The unit sun vector in the $x_o y_o z_o$ coordinate frame is given by:

$$\mathbf{s} = -[C_\beta S_\nu \;\; S_\beta \;\; C_\beta C_\nu] \tag{1}$$

Ignoring conduction, the energy balance equation is given by[1,2] :

$$mc_p dT/dt = Q_i - \sigma\varepsilon A_t T^4 \tag{2}$$

In sun light:

$$Q_i = Q_{sun} + Q_{eq} + Q_{IR} + Q_{al} \tag{3}$$

In eclipse:

$$Q_i = Q_{eq} + Q_{IR} \tag{4}$$

Solution of Eq. (2) requires numerical integration . Runge-Kutta, Gear, Hamming, Heun and Euler Methods[5] gave similar accuracy. Euler was selected for minimum solution time using

$$T_{n+1} = T_n + \Delta T_n \tag{5}$$

where:

$$\Delta T_n = (Q_i - \sigma\varepsilon A_t T^4)_n \, \Delta t / mc_p \tag{6}$$

For circular orbits, it is convenient to replace Δt with $\Delta\nu/\omega_o$ where ν represents orbit angular position and ω_o represents orbital frequency. Spreadsheet calculation of upper and lower temperatures match simulation results within 0.2 ºC.

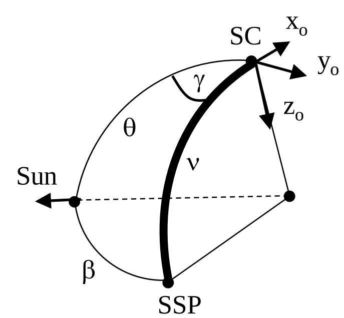

Figure 1. Orbit Geometry

The spreadsheet user interface is described in Appendix A. Appendix B shows a block diagram of the simulation and a comparison of simulation and spreadsheet temperature calculations. Spreadsheet sample calculation details are shown in Appendix C.

Conclusions

A spreadsheet which provides rapid and accurate upper average and lower orbit temperatures has been developed. The spreadsheet also shows the potential of body fixed solar panels for generation of electrical power. The spreadsheet assumes an isothermal spacecraft in a circular orbit with steady state vertical or horizontal attitude. It is not proposed as a substitute for thermal or power system analysis programs. However, it is proposed as an aid for Systems Engineers during the conceptual design phases of new programs.

References

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3. Leonard, B.S., Shape & Mass Dependent Thermal Analysis, TC Workshop ,2015
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Appendix A. Spreadsheet User Interface

The spreadsheet user interface is shown in Fig. A1. User input values (Lines 3-13) describe the orbit and S/C geometry. Upper, average and lower temperatures are shown for both horizontal and vertical attitudes for the seven shapes.

Electrical power outputs represent the difference between end of life capability[4] and the requirements (Lines 5,6 Column E). Negative values require input revisions. The necessary battery capacity[4] is also included (Lines 26,39).

The assumption of body fixed solar panels on all surfaces is overly optimistic. However, judicious selection of the cell packing factor (Line 8, Column H) can produce useful data. The average temperature (Lines 22,35) calculation is shown in Appendix C.

Accuracy is a function of the size and number of steps. A step size of one degree for 10,000 steps agreed with the simulation within 0.2 ºC

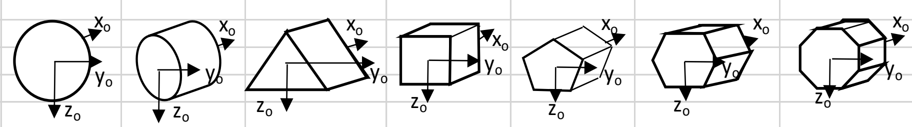
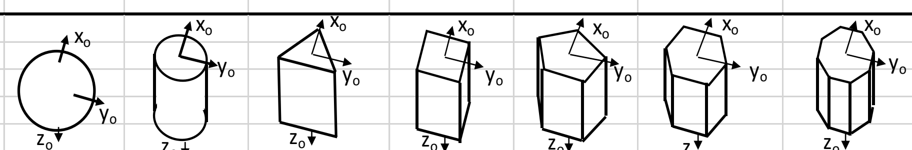
	A	B	C	D	E	F	G	H
1		THERMAL and POWER ANALYSIS						
2	**INPUT: Orbit, Thermal & Power System Data**							
3	Beta angle ~deg	0	Altitude~km		700	Solar cell efficiency		0.25
4	Solar flux ~W/m^2	1317	Planet equator radius~km		6378.14	Inherent degradation		0.85
5	Planet IR ~W/m^2	217	Sunlight equipm't pwr ~W		200	8yr Life degradation		0.961
6	Albedo coefficient	0.22	Eclipse equipm't pwr ~W		200	Xd, daylight drt. energy xfer		0.85
7	Mass~kg	130	Absorptivity		0.85	Xe, eclipse drt. energy xfer		0.65
8	Heat cap. ~W.s / kg / K	900	Emissivity		0.9	SA panels packing factor		0.9
9	Planet GM~km^3 /s^2	398600.4	Battery DOD		0.35	Battery xfer efficiency		0.9
10	**INPUT: Spacecraft Geometry**							
11	X-section Shape	Sphere	Cylinder	Triangle	Square	Pentagon	Hexagon	Octagon
12	X-section O.D. ~m	1.0	1.0	1.0	1.0	1.0	1.0	1.0
13	Length ~m		1.5	1.5	1.5	1.5	1.5	1.5
14								
15	**HORIZONTAL ATTITUDE**							
16								
17								
18								
19								
20	**Output Temperature Data**							
21	Upper Temperature ~ °C	14.0	6.3	5.7	-1.5	5.8	7.0	4.3
22	Ave. Temperature ~ °C	8.6	-3.5	-2.1	-8.7	-3.1	-2.4	-4.8
23	Lower Temperature~ °C	2.6	-14.6	-9.9	-16.5	-12.9	-12.7	-15.0
24	**Output Power Data**							
25	Peol - Preq'd ~ W	-10.0	132.5	26.9	25.6	90.0	109.1	104.0
26	Total Batt Cap ~ Whr	671.8	→					
27								
28	**VERTICAL ATTITUDE**							
29								
30								
31								
32								
33	**Output Temperature Data**							
34	Upper Temperature ~ °C	14.0	8.4	8.6	-1.0	8.3	4.5	6.2
35	Ave. Temperature ~ °C	8.6	-1.2	1.2	-8.0	-0.5	-4.0	-2.8
36	Lower Temperature ~ °C	2.6	-12.8	-7.2	-16.1	-10.8	-14.0	-13.4
37	**Output Power Data**							
38	Peol - Preq'd ~ W	-10.0	161.1	65.9	48.1	123.4	108.7	131.2
39	Total Batt Cap ~ Whr	671.8	→					

Figure A1. Spreadsheet User Interface.

Appendix B. Simulation & Spreadsheet Comparison

The simulation block diagram is shown in Fig. B1. Input 1 represents a "mode" switch to allow either horizontal or vertical attitude. Input 2 represents the orbit angle ν. A simulation output for one orbit is shown in Fig. B2. A similar spreadsheet output is shown in Fig. B3. The dashed lines between the two figures have been added for comparison purposes.

The max and min temperatures match within 0.1 K. The spreadsheet output for 13 orbits is shown Fig. B4. Although the analysis requires over a million spreadsheet cells, it responds to input changes in less than one second. A temperature "averaging block"(not shown) matched Eq. (C4) results exactly for calculation of orbit average temperatures.

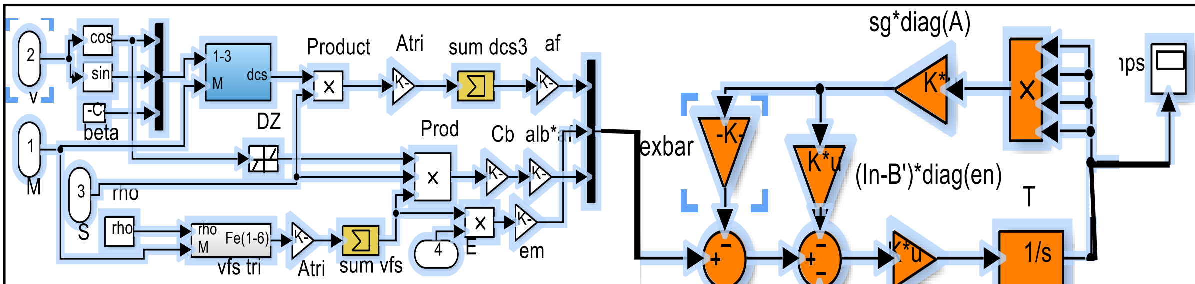


Figure B1 Simulation Block Diagram

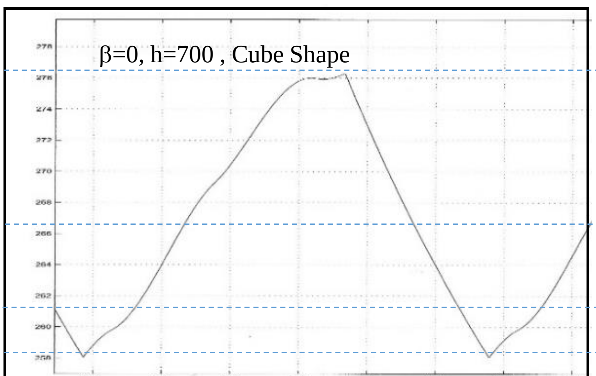


Figure B2. Simulation Output

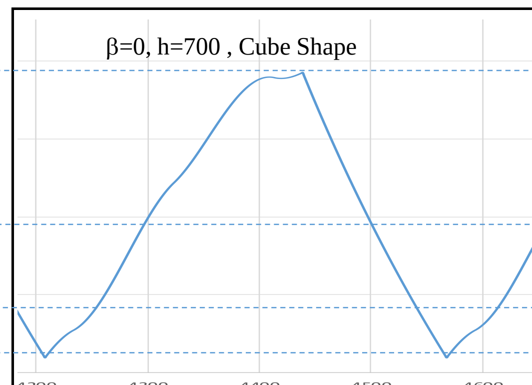


Figure B3. Spreadsheet Output

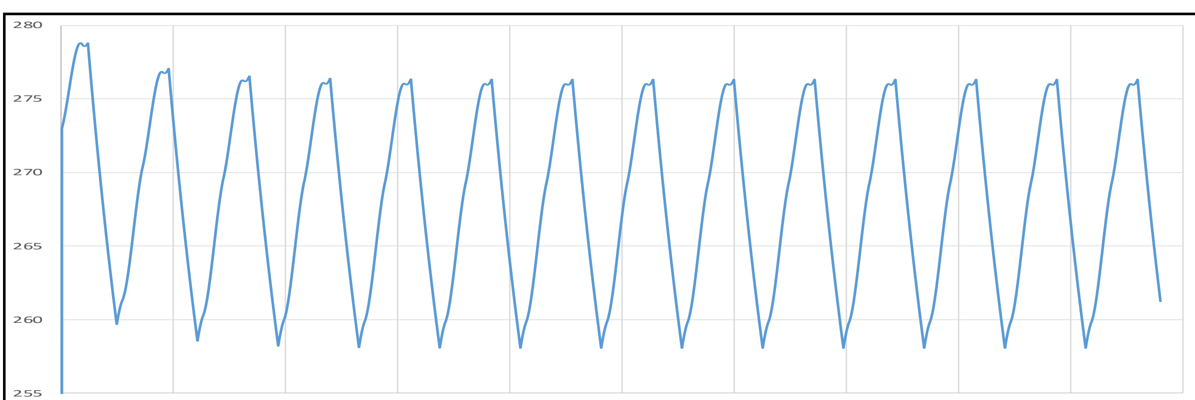


Figure B4. Spreadsheet Output (13 Orbits , Δν = 1°)

Appendix C. "Triangle" Shape Analysis Data.

Figure C1 shows the coordinate system and surface numbers for the horizontal "Triangular" configuration . Figure C2 repeats Figure 1 for reference. Table C summarizes the analysis data. The orbit average sun direction cosines (fourth column, Table C) are obtained by integrating the surface to sun direction cosines (third column, Table C) over an orbit period. Orbit average sun and IR heat loads are given by[2]

$$\mathbf{Q_s} = G\alpha\Sigma A_{\mathbf{i}}\, \overline{(\mathbf{s{\bullet}i})} \qquad \text{(C1)}$$

where:,

$\overline{(\mathbf{s{\bullet}i})}$ = ith area to sun orbit average direction cosine

$$\mathbf{Q_{IR}} = E\varepsilon\Sigma F_{ei}A_i\,; \qquad \text{(C2)}$$

F_{ei} represents the view factor from the ith surface to Earth as shown in the last column of Table C and A_i represents the ith surface area.

The orbit average albedo heat load is given by[8]

$$\mathbf{Q_a} \approx aG\alpha C_\beta \Sigma F_{ei}A_i\,/\pi \qquad \text{(C3)}$$

The orbit average temperature is given by[4]

$$\text{Orbit Ave Temp} \equiv [(\mathbf{Q_s} + \mathbf{Q_{IR}} + \mathbf{Q_a} + \mathbf{Q_{eq}})/\sigma\varepsilon A_t]^{1/4} \quad \text{(C4)}$$

Eq. (C4), used in Lines 22, 25 of Appendix A, matches simulation results exactly. The spreadsheet "average" command can only approximate Eq. (C4). The upper and lower temperatures are found using the "max" and "min" spreadsheet commands over the temperature list given by Euler's method[5], namely:

$$T_{n+1} = T_n + \Delta T_n \qquad \text{(C5)}$$

where, $\Delta T_n = (Q_i - \sigma\varepsilon A_t T^4)_n\, \Delta t/mc_p$ (C6)

and, $\Delta t = \Delta\nu/\omega_o$ (C7)

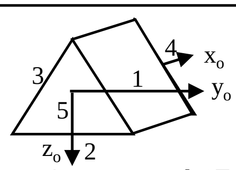


Figure C1. Horizontal "Triangle" Configuration Surface Numbers

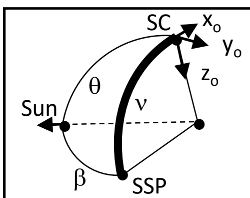


Fig. C2. Orbit Geometry

Table C. Horizontal "Triangle" Analysis Data

Surface Number	Surface Unit Vectors (**i**)	Surface to Sun Direction Cosines	Orbit Average of Sun Direction Cosines $\overline{(\mathbf{s{\bullet}i})}$	Earth View Factors $F_{ei}^{6,7}$
1	$[0 \quad C_{30} \quad -S_{30}]$	$-S_\beta C_{30}+S_{30}C_\beta C_\nu$	$[S_{\phi t1}C_\beta S_{30}-\phi_{t1}S_\beta C_{30}]/\pi$	F_{120}
2	$[0 \quad 0 \quad 1]$	$-C_\beta C_\nu$	$C_\beta(1-S_\lambda)/\pi$	S_ρ^2
3	$[0 \quad -C_{30} \quad -S_{30}]$	$C_{30}S_\beta+S_{30}C_\beta C_\nu$	$[S_{\phi t3}C_\beta S_{30}+\phi_{t3}S_\beta C_{30}]/\pi$	F_{120}
4	$[1 \quad 0 \quad 0]$	$-C_\beta S_\nu$	$C_\beta(1-C_\lambda)/2/\pi$	$(\rho-S_\rho C_\rho)/\pi$
5	$[-1 \quad 0 \quad 0]$	$C_\beta S_\nu$	$C_\beta(1-C_\lambda)/2/\pi$	$(\rho-S_\rho C_\rho)/\pi$

where:

ϕ_{t1} = IF [β<30 , acos(T_β/T_{30}) , 0] ; ϕ_{t3} = IF [T_β >$-C_\lambda T_{30}$, l , acos($-T_\beta/T_{30}$)]

F_{120}=IF[30>ρ , 0 , acos($Q/H/S_{120}$) + C_{120}/H^2*acos($-Q/T_{120}$) - Q/H^2*sqrt(1-(HC_{120})^2)]/π

λ = half sunlight angle ; $H = (h+R_e)/R_e$; Q = sqrt(H^2-1)

ρ = planet angular radius ; **s** = -[$C_\beta S_\nu$ S_β $C_\beta C_\nu$]