THERMAL NODAL ANALYSIS OF SATELLITES AT LOWER ALTITUDES

INTERNSHIP REPORT

submitted by

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Nellipudi Poojitha Reddy: *Thermal Nodal Analysis of Satellites at Lower Altitudes*

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ABSTRACT

Satellites are exposed to the harsh environment in space, that vary its temperature widely as the satellite orbits around a planet. A thermal control system for a satellite at lower altitudes must be designed to regulate the fluctuations in the temperature. In the current work, a thermal analytical model for an isothermal, single-noded satellite revolving in a Low altitude Planet Orbit has been developed from the fundamental principles. The primary aim of this project is to solve the temperature of the satellite as a function of its orbital position using MATLAB code. Parameters like absorptivity and IR emissivity of the satellite effect the thermal condition of the satellite. Thus, the variation in the temperature of the satellite w.r.t various parameters is observed using MATLAB code to study its thermal effects. The temperature of the satellite, solved using the MATLAB code, returns the temperature, which obtain a reasonable approximation for the satellites at lower altitudes.

Keywords: Thermal Control System, Thermal Analytical Model, MATLAB

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LIST OF SYMBOLS

GREEK SYMBOLS

α	Absorptivity
β	Angle between the orbital plane and the solar direction
ϵ	Emissivity
η	Efficiency of solar cells
ϕ	Angular position of the satellite along its orbit
ϕ_{es}	Angular position of the satellite along its orbit when eclipse ends
ϕ_{ee}	Angular position of the satellite along its orbit when eclipse starts
ψ	Phase lag
ρ	Reflectivity
σ	Stefan-Boltzmann constant

ROMAN SYMBOLS

A	Area
c	Thermal Capacity of the satellite
$F_{1,2}$	View Factor from surface 1 to surface 2
F_a	Albedo function
F_e	Eclipse function
F_{pg}	Packaging Factor of solar cells
H	Altitude of the satellite from the surface of the planet
m	Mass of the satellite
q	Heat transfer rate
q_{int}	Rate of internal heat dissipated by the satellite
R	Radius
R_{sp}	Distance between the Sun and Planet
T	Temperature
t	Time
T_a	Amplitude Temperature of the satellite
T_m	Mean Temperature of the satellite
t_o	Orbital time period

Roman Symbols

$1, 2, 3$	Local reference frame components
i, j	Computational indices
p	Planet
s	Sun
sat	Satellite
sur	Surroundings

1 INTRODUCTION

Thermal Control Systems play a vital role in maintaining the temperature of the instruments in a satellite within a specified acceptable range. On-board thermal environment of a satellite is determined by the external radiation and internal heat dissipation.

Active thermal control system requires continuous power supply. Therefore thermal control has been more passive. Paints or reflective coatings act as passive thermal systems. Temperature of the satellite placed in an orbit depends on various parameters. Subtle change in these parameters alters the temperature of the satellite significantly. Hence, the primary aim of the project is to investigate various thermal effects on a satellite placed in an orbit w.r.t. various parameters and develop a thermal analytical model to obtain its temperature.

1)Active Thermal Control System
2)Passive Thermal Control System

1.1 MOTIVATION BEHIND THE WORK

Satellites are operated for all sorts of purposes. Satellites like the Hubble Space Telescope, the International Space Station, and the other space stations help scientists explore space in new and exciting ways. Communication satellites help us communicate with people all over the world. Weather satellites help us observe the Earth from space to predict weather patterns.

The increasing trends in space industry motivate to develop innovative solutions for complex problems. Simulating the outer-space weather conditions and performing the experiments to obtain the temperature of the satellite would be cumbersome. Therefore, developing a thermal model for the satellite and calculating the temperature of the satellite analytically by solving equations would be rather easier. This project focuses on the development of a thermal model to find the temperature of the satellite as a function of its orbital position.

An analytical thermal model is developed to estimate the thermal behaviour of a satellite.

1.2 OBJECTIVES

The primary objectives of the project are mentioned below:

1. To study the theory behind the thermal analysis of a satellite at lower altitudes

2. To develop a thermal analytical model for a satellite at lower altitudes

3. To obtain the temperature of the satellite as a function of its orbital position for the developed analytical model using MATLAB programming language

4. To study and observe the variation in the temperature of the satellite w.r.t. various parameters using MATLAB programming language

1.3 OUTLINE

This report provides an overview of thermal nodal analysis of a single-noded satellite at lower altitudes. Chapter 2 provides the theoretical background to interpret the thermal analysis of a satellite at lower altitudes. Furthermore, a thermal analytical model is developed with required assumptions. Chapter 3 describes an approach to obtain the temperature of a satellite as a function of its orbital position. Furthermore, a flow chart is depicted to obtain its temperature using MATLAB programming language. In chapter 4, results are validated. In Appendix A, data related to planets is tabulated and the MATLAB codes used to obtain the temperature of the satellite are attached.

2 THEORETICAL BACKGROUND

Model Description Consider a three body system, the sun, Planet and the Satellite. Assume interactions due to the other planets, and bodies with the satellite is negligible. Furthermore, assume the satellite is spherical and isothermal.

2.1 HEAT SOURCES

1)Solar Radiation
2)Albedo radiation
3)Planetary radiation
4)Satellite infrared radiation
5)Internal heat dissipation

Radiation is the sole mode of heat transfer, as it doesn't require any medium to propagate. The primary sources of radiation are solar radiation, albedo and planetary radiation. Satellite also emits radiation to the surroundings. Apart from the external radiations, heat is dissipated internally by the electrical components in the satellite which increase the temperature of the satellite.

2.1.1 *Solar Radiation*

Solar energy impinging on a satellite can be approximated by a parallel beam irradiance. The sun is assumed to be a black body. Solar radiation absorbed by the satellite is given by

$$\boxed{q_s = (\sigma T_s^4 * 4\pi R_s^2) * \frac{R_{sat}^2}{4R_{sp}^2} * \alpha_{sat}} \tag{2.1}$$

2.1.2 *Albedo Radiation*

Albedo is the part of the solar radiation that reaches the planet and is reflected back to space. It depends on the reflectivity of the planet. Albedo radiation absorbed by the satellite is given by

$$\boxed{q_a = (\sigma T_s^4 * 4\pi R_s^2 * F_{s,p} * \rho_p) * F_{p,sat} * \alpha_{sat}} \tag{2.2}$$

2.1.3 *Planetary Infrared Radiation*

In infrared region, $\alpha = \epsilon$

Unlike Solar radiation, Planetary emission cannot be considered as black body radiation. In infrared region, $\alpha = \epsilon$. Planetary infrared radiation absorbed by the satellite is given by

$$\boxed{q_p = (\sigma \epsilon_p T_p^4 * 4\pi R_p^2) * F_{p,sat} * \alpha_{sat}} \tag{2.3}$$

2.1.4 *Satellite Infrared Radiation*

Satellite looses heat to the surroundings and the expression is given by

$$\boxed{q_{sat} = (\sigma \epsilon_{sat} T_{sat}^4 * 4\pi R_{sat}^2) * F_{sat,sur}} \tag{2.4}$$

We get 2.4 by neglecting the temperature of the vacuum. Since, we assumed a spherical satellite, energy emitted by the satellite completely radiates to the surroundings, therefore $F_{sat,sur} = 1$

2.1.5 *Internal heat dissipation*

Electrical components in the satellite dissipate energy, transforming electrical energy into thermal energy. Assume, the total heat dissipated by the electrical components in the satellite is equal to q_{int}.

2.2 VIEW FACTORS

The view factor $F_{1,2}$ is the fraction of energy exiting an isothermal, opaque, and diffuse surface 1, that directly impinges on surface 2. View factors depend only on geometry.

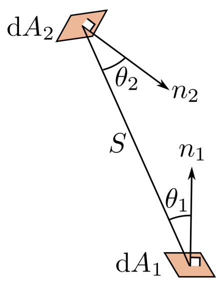


Figure 2.1: Geometry for view factor definition

The view factor between finite surfaces A_1 and A_2 for the geometry mentioned in figure 2.1 is given by

$$\boxed{F_{1,2} = \frac{1}{A_1} \int_{A_1} \left(\int_{A_2} \frac{\cos\theta_1 \cos\theta_2}{\pi S^2} dA_2 \right) dA_1} \tag{2.5}$$

View factors for different configurations can be solved using 2.5

Reciprocity relation for view factors is given by

$$\boxed{F_{1,2} A_1 = F_{2,1} A_2} \tag{2.6}$$

2.2.1 *View factors for the Satellite and the Sun interaction*

Since, the satellite is much smaller than the sun, the view factors for the Satellite and the Sun interactions are given by

$$\boxed{F_{sat,s} = \frac{1}{2}\left(1 - \sqrt{\left(1 - \frac{R_s^2}{(R_{sp} - R_p - H)^2}\right)}\right)} \tag{2.7}$$

From reciprocity relation 2.6,

$$\boxed{F_{s,sat} = F_{sat,s} \frac{A_{sat}}{A_s}} \tag{2.8}$$

2.2.2 *View factors for the Planet and the Sun interaction*

Since, the planet is much smaller than the sun, the view factors for the Planet and the Sun interactions are given by

$$\boxed{F_{p,s} = \frac{1}{2}\left(1 - \sqrt{\left(1 - \frac{R_s^2}{R_{sp}^2}\right)}\right)} \tag{2.9}$$

From reciprocity relation 2.6,

$$\boxed{F_{s,p} = F_{p,s} \frac{A_p}{A_s}} \tag{2.10}$$

2.2.3 *View factors for the Planet and the Satellite interaction*

Since, the satellite(considering small satellite) is much smaller than the planet, the view factors for the Planet and the Satellite interactions are given by

$$\boxed{F_{sat,p} = \frac{1}{2}\left(1 - \sqrt{\left(1 - \frac{R_p^2}{(H+R_p)^2}\right)}\right)} \tag{2.11}$$

From reciprocity relation 2.6,

$$\boxed{F_{p,sat} = F_{sat,p}\frac{A_{sat}}{A_p}} \tag{2.12}$$

2.3 FACTORS EFFECTING THE RADIATION ABSORBED BY THE SATELLITE

2.3.1 *Effect of Solar cells on Solar radiation*

Solar cells convert the solar radiation into electrical energy. During this process, some of the energy is dissipated by solar panels in the form of electromagnetic radiation which reduces the incident solar radiation on the satellite.
When the satellite is completely enclosed by solar cells, replace α_{sat} with $\alpha_{sat} - \eta F_{pg}$.

2.3.2 *Effect of eclipse on Solar radiation*

A satellite may spend a fraction of its time in eclipse, depending on the orbit. Assume there are no partial eclipses. In that case, during eclipse, solar radiation incident on the satellite is equal to zero. Therefore, Net Solar radiation absorbed by the satellite = $q_s F_e$.

Eclipse function F_e is given by

$$\boxed{F_e = \begin{cases} 0 & \text{if } \phi_{es} < \phi < \phi_{ee} \\ 1 & \text{otherwise} \end{cases}} \tag{2.13}$$

$$\text{where, } \phi_{es} = \pi - \arccos\left(\frac{\sqrt{h^2-1}}{h\cos\beta}\right)$$
$$\phi_{ee} = \pi + \arccos\left(\frac{\sqrt{h^2-1}}{h\cos\beta}\right)$$
$$h = \frac{H + R_{sat}}{R_{sat}}$$

2.3.3 *Effect of eclipse on Albedo radiation*

Assume there are no partial eclipses. In that case, during eclipse, albedo radiation incident on the satellite is equal to zero. Therefore, Net Albedo radiation absorbed by the satellite = $q_a F_a$

Albedo function F_a is given by

$$\boxed{F_a = F'_e\left(\frac{1+\cos\phi}{2}\right)^2\left(1-(\frac{\phi}{\phi_{es}})^2\right)\cos\beta} \tag{2.14}$$

$$\text{where, } F'_e = \begin{cases} 1 & \text{if } -\phi_{es} < \phi < \phi_{es} \\ 0 & \text{otherwise} \end{cases}$$

2.4 THERMAL BALANCE

Heat Balance equation is given by

Heat stored = Heat in - Heat out

Energy is stored in a satellite due to variation of its temperature with time and is given by $mc\,(\,dT/dt)$.

$$\boxed{mc\,(dT_{sat}/dt) = q_s F_e + q_a F_a + q_p - q_{sat} + q_{int}} \tag{2.15}$$

2.5 ANALYTICAL ONE-NODE SINUSOIDAL SOLUTION

The fundamental goal of thermal analysis is finding the temperature distribution for a body discretized into multiple nodes. Satellite is divided into multiple nodes. Nodes are the sensitive parts of a satellite, required to be maintained within the working temperature range. Temperature of each node can be found by solving the energy balance equation for the respective nodes.

In this project, satellite is assumed to be isothermal(single node). Since, 2.15 is a non-linear equation, assumptions must be taken to approximate the temperature of the satellite.

2.5.1 *Assumptions*

1. The solar and albedo radiations absorbed by the satellite are high during the sunshine and negligible during the eclipse. Therefore, the albedo and eclipse functions can be approximated to a sinusoidal function of its orbital position as given below

$$\boxed{F_a = F_e = \frac{1+\cos\phi}{2}} \tag{2.16}$$

2. The temperature of the satellite at lower altitudes doesn't vary exceedingly. Therefore, the temperature of the satellite can be approximated to a sinusoidal function of its orbital position as given below

$$\boxed{T_{sat} = T_m + T_a \cos(\phi - \psi)} \tag{2.17}$$

2.5.2 *Analytical Solution*

Substituting 2.16 and 2.17 in 2.15, and linearizing the non-linear(T_{sat}^4) term by expanding, we get

$$\begin{aligned} mc\frac{2\pi}{t_o}[-T_a \sin(\phi-\psi)] &= (\sigma T_s^4 * 4\pi R_s^2) * \frac{R_{sat}^2}{4R_{sp}^2} * \alpha_{sat} * \left(\frac{1+\cos\phi}{2}\right) \\ &+ (\sigma T_s^4 * 4\pi R_s^2 * F_{s,p} * \rho_p) * F_{p,sat} * \alpha_{sat} * \left(\frac{1+\cos\phi}{2}\right) \\ &- (\sigma\epsilon_{sat} * [T_m^4 + 4T_m^3 T_a \cos(\phi-\psi)] * 4\pi R_{sat}^2) * F_{sat,sur} \\ &+ (\sigma\epsilon_p T_p^4 * 4\pi R_p^2) * F_{p,sat} * \alpha_{sat} + q_{int} \end{aligned} \tag{2.18}$$

Expanding the combined trigonometric functions, and cancelling the coefficients in $\sin\phi$, in $\cos\phi$, and the independent terms in 2.18, we get T_m, T_a and ψ, with independent terms yielding the mean temperature, T_m, the $\sin\phi$ terms yielding the phase lag, ϕ, and the $\cos\phi$ terms yielding the temperature oscillation amplitude, T_a.

3 APPROACH TO THE SOLUTION

The modelling approach in Satellite Thermal Control can be discretized into multiple nodes. The satellite is broken down into finite sub-divisions called nodes, which are the sensitive parts of a satellite, required to be maintained within the working temperature range. Resolution increases with increasing nodes. But, with increasing nodes, number of equations to be solved analytically increases, which makes the process cumbersome. Therefore, number of nodes must be chosen wisely based on the accuracy and precision required.

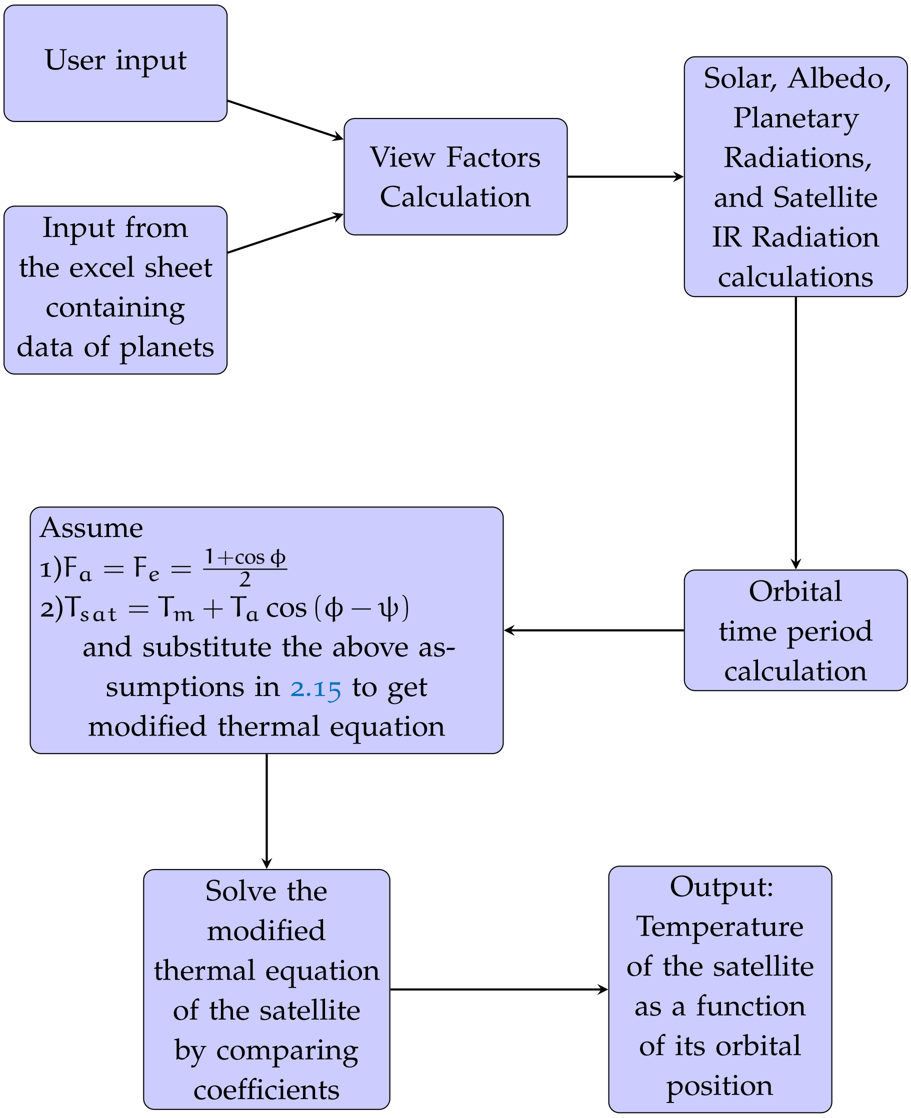
Considering an isothermal spherical mass dissipating heat, exposed to the sunshine, under the influence of a single planet, and completely enclosed by solar cells, would be the simplest thermal model to assume for a satellite. Since, the satellite is isothermal, it can be considered as a single node problem. Solving 2.18 would obtain the approximate temperature of the satellite as a function of its orbital position.

3.1 FLOW CHART

The calculations for solving the temperature function are done using MATLAB programming language. The code returns the average temperature of the satellite as a function of its orbital position for a simple thermal model, with total number of nodes being equal to one. MATLAB code for solving the temperature of the satellite is attached in the appendix A.2. Flow Chart for the solving the thermal equation using MATLAB code is as follows:

In flow chart 3.1, inputs like geometry and thermo-optical properties of the planet and the satellite are taken along with the rate of internal heat dissipated by the satellite from the user, whereas the planets data is loaded from the excel sheet. Both the inputs are used to calculate all the possible view factors. View factors calculated, are used to calculate the radiation absorbed and emitted by the satellite. Assumptions must be followed inorder to linearize 2.15. Substituting the assumptions in 2.15, we get a modified thermal equation. It is solved by comparing the co-efficents of independent and sinusoidal terms respectively to obtain the temperature of the satellite as a function of its orbital position as its output.

Figure 3.1: Flow chart to find the temperature of the satellite using MATLAB code



4 RESULTS

Satellites are exposed to the harsh environment in space, which fluctuate its temperature widely as the satellite orbits around the planet. Rapid fluctuations in temperature can damage any kind of equipment present in the satellite. But, with an appropriate choice of solar absorptance(α) and Infrared emissivity(ϵ) of the satellite, the range of temperature of the satellite can be brought to the operating temperature of the equipment. In this chapter, we study about the various parameters effecting the temperature of the satellite.

4.1 Parametric study of the temperature of the satellite

Temperature of the satellite, revolving around the planet in an orbit, depends on various parameters. Parametric study of the temperature of the satellite represent the study of change in its temperature by varying its parameters.

4.1.1 *Temperature of the satellite as a function of its orbital position*

At lower altitudes, the temperature of a satellite is assumed to be a sinusoidal function of its orbital position. Therefore, plot of the temperature of the satellite v/s orbital position will result in a sinusoidal curve.

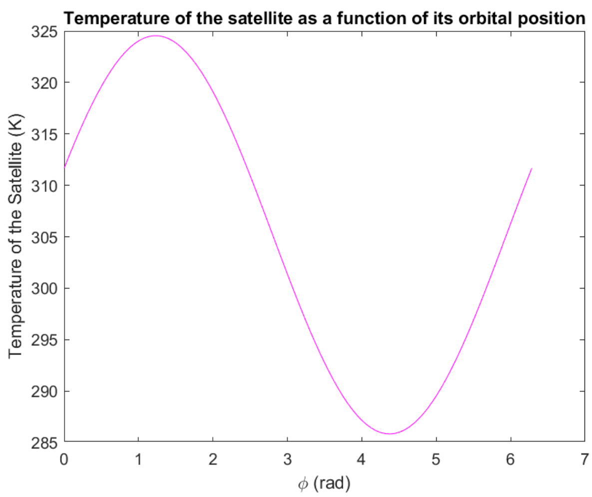


Figure 4.1: Temperature of the satellite as a function of its orbital position($T_{sat}(\phi)$)

Figure 4.1 is obtained by substituting $\alpha_{sat} = 1, \epsilon_{sat} = 1, H = 300km$ and $q_{int} = 100W$ in 2.18

4.1.2 *Variation of the temperature of the satellite with its solar absorptance(α) and IR emissivity(ϵ)*

1. **For constant α/ϵ ratio of the satellite** : Following are the plots for different ratios.

   a) For $\alpha_{sat}/\epsilon_{sat} = 1$

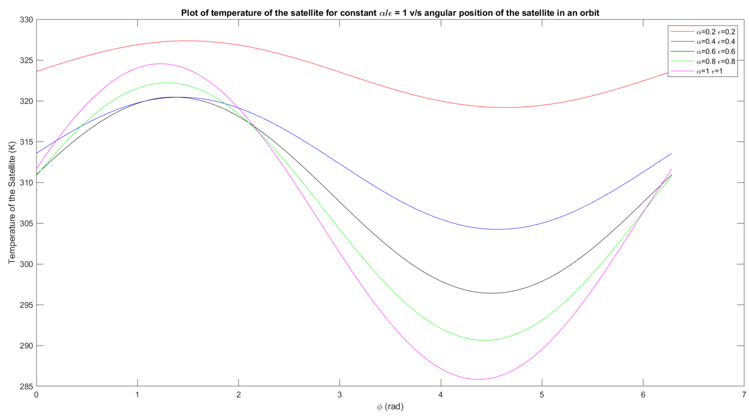


Figure 4.2: Temperature of the satellite as a function of its orbital position for $\alpha/\epsilon = 1$

   b) For $\alpha_{sat}/\epsilon_{sat} = 0.5$

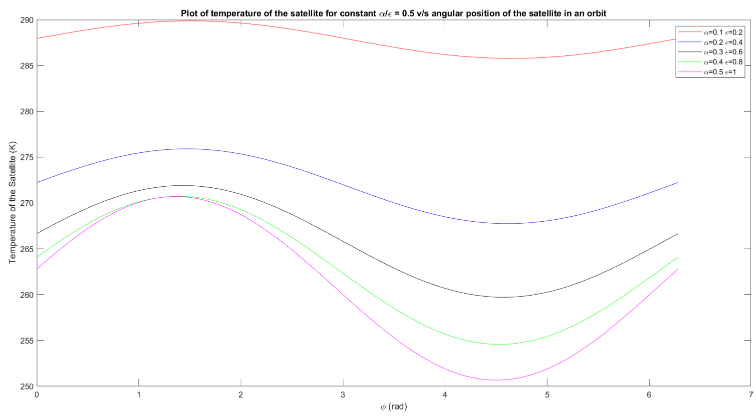


Figure 4.3: Temperature of the satellite as a function of its orbital position for $\alpha/\epsilon = 0.5$

c) For $\alpha_{sat}/\epsilon_{sat} = 2$

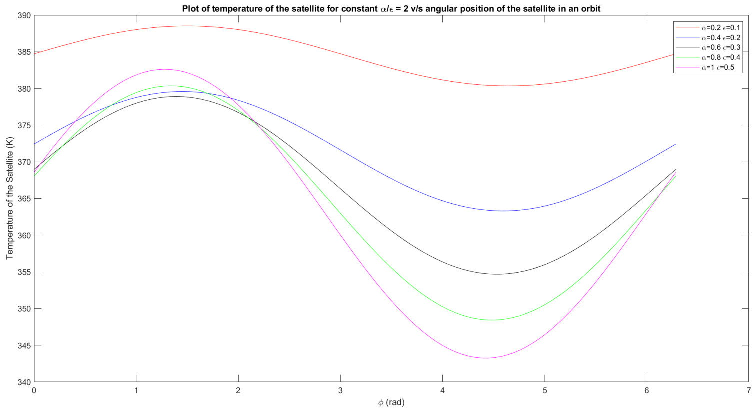


Figure 4.4: Temperature of the satellite as a function of its orbital position for $\alpha/\epsilon = 2$

From figures 4.2, 4.3, and 4.4, one can observe that, with increasing α or ϵ values, the amplitude temperature of the satellite increases, whereas the mean temperature of the satellite decreases.

2. **For constant solar absorptance(α) of the satellite with varying ϵ values** : Following is the plot for $\alpha_{sat} = 0.5$ and different ϵ values

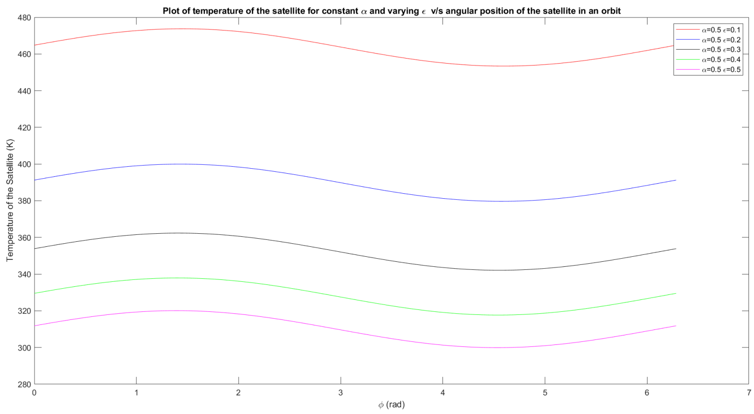


Figure 4.5: Temperature of the satellite as a function of its orbital position for $\alpha = 0.5$

From 4.5, one can observe that, for constant α values, and with increasing ϵ values, both the amplitude and mean temperatures of the satellite decreases.

3. **For constant IR emissivity(ϵ) of the satellite with varying α values** : Following is the plot for $\epsilon_{sat} = 0.5$ and different α values

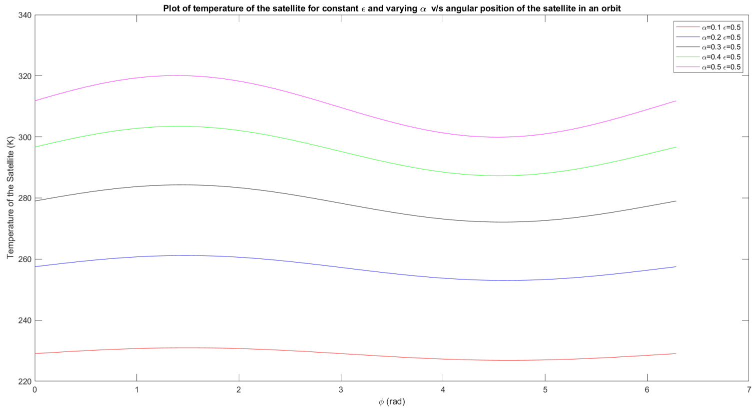


Figure 4.6: Temperature of the satellite as a function of its orbital position for $\epsilon = 0.5$

From 4.6, one can observe that, for constant ϵ values, and with increasing α values, both the amplitude and mean temperatures of the satellite increases.

4. **For various coatings** : Following is the plot for different coatings used on the satellite.

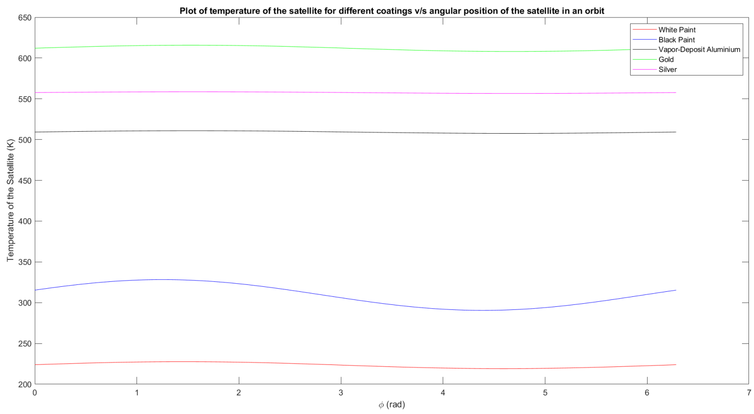


Figure 4.7: Temperature of the satellite as a function of its orbital position for different coatings

From 4.7, one can observe that the black paint is the best coating to maintain the temperature of the satellite within the operating temperature range of the equipments.

4.1.3 *Variation of the temperature of the satellite with the altitude*

Variation of the temperature of the satellite with the altitude is plotted below

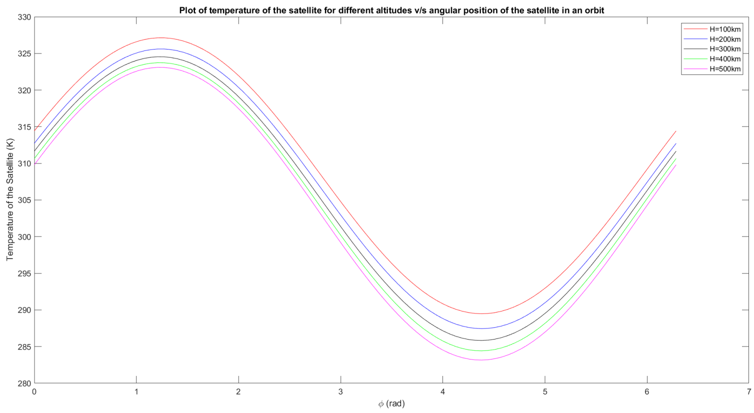


Figure 4.8: Temperature of the satellite as a function of its orbital position for different altitudes

From figure 4.8, one can observe that, with increasing altitude of the satellite, the amplitude temperature of the satellite increases, whereas the mean temperature of the satellite decreases.

4.1.4 *Variation of the temperature of the satellite with the internal heat dissipation*

Variation of the temperature of the satellite with the internal heat dissipation is plotted below

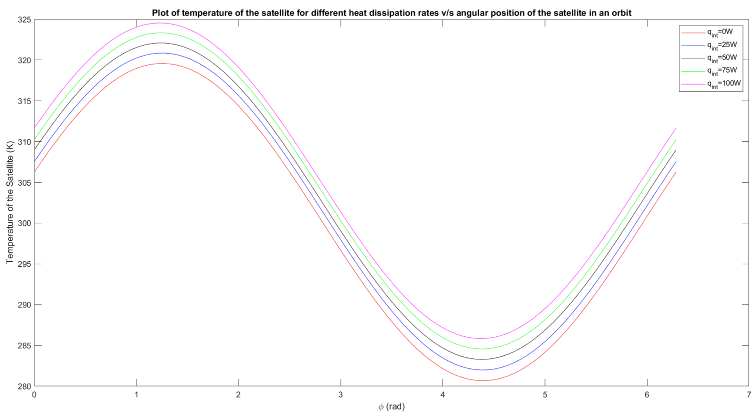


Figure 4.9: Temperature of the satellite as a function of its orbital position for different internal heat dissipation rates

From figure 4.9, one can observe that, with increasing rate of internal heat dissipation by the satellite, the mean temperature of the satellite increases, whereas the amplitude temperature of the satellite decreases.

5 CONCLUSION

A satellite must be thermally analysed to ascertain the proper operation of the satellite. Considering only the sun-planet and satellite interactions, thermal nodal analysis is performed on an isothermal, spherical satellite. Thermal equation is solved with appropriate assumptions to obtain the temperature of the single-noded satellite as a function of its orbital position at lower altitudes using MATLAB programming language. Variations in the temperature of the satellite is analysed w.r.t. various parameters using MATLAB.

The following conclusions can be depicted from the report.

1. With increasing α or ϵ values, the amplitude temperature of the satellite increases, whereas the mean temperature of the satellite decreases.

2. For constant α values, and with increasing ϵ values, both the amplitude and mean temperature of the satellite decreases.

3. For constant ϵ values, and with increasing α values, both the amplitude and mean temperature of the satellite increases.

4. With increasing altitude of the satellite, the amplitude temperature of the satellite increases, whereas the mean temperature of the satellite decreases.

5. With increasing rate of internal heat dissipation by the satellite, the mean temperature of the satellite increases, whereas the amplitude temperature of the satellite decreases.

The above results are depicted using MATLAB programming language.

5.1 FUTURE WORK

In this project, satellite is assumed to be an isothermal, spherical body. In further development, satellite can have different temperatures for different subsystems which make the system explicit. Hence, it is suggested to perform multi-nodal analysis for better results. Furthermore, satellite is assumed to be spherical which can be replaced with some other geometry in future. Assumption of temperature of the satellite as a sinusoidal function of its orbital position is valid only for satellites at lower altitudes, Therefore, the thermal equation becomes much more complicated for higher altitudes.

A APPENDIX

Matlab Programming language is used to find out the temperature of the satellite as a function of its orbital position by solving the thermal balance equation 2.18.

A.1 PLANET DATA

Data of the planets in the solar system is tabulated below:

PLANET NAME	DISTANCE FROM SUN (m)	MASS (Kg)	TEMPERATURE (K)	RADIUS (m)
MERCURY	5.79E+10	3.30E+23	440.15	2.44E+06
VENUS	1.08E+11	4.87E+24	737.15	6.05E+06
EARTH	1.50E+11	5.97E+24	288.15	6.38E+06
MARS	2.28E+11	6.42E+23	208.15	3.40E+06
JUPITER	7.79E+11	1.90E+27	163.15	7.15E+07
SATURN	1.43E+12	5.68E+26	133.15	6.03E+07
URANUS	2.87E+12	8.68E+25	78.15	2.56E+07
NEPTUNE	4.50E+12	1.02E+26	73.15	2.48E+07

A.2 TEMPERATURE OF THE SATELLITE AS A FUNCTION OF ITS ORBITAL POSITION USING MATLAB CODE

The below code returns the temperature of the satellite, for simple thermal models, revolving around any planet in an orbit. Planet data is loaded from an excel sheet shown in A.1

```
%% Temperature of the satellite w.r.t angular position of the satellite in an orbit
%%
% Input from user

n = input(['Please enter' ,...
    '\n1 for Mercury' ,...
    '\n2 for Venus' ,...
    '\n3 for Earth' ,...
    '\n4 for Mars' ,...
    '\n5 for Jupiter' ,...
    '\n6 for Saturn' ,...
```

```
    '\n7 for Uranus' ,...
    '\n8 for Neptune\n']);

abs_p = input('Please enter absorptivity of the planet\n');

emi_p = input('Please enter emissivity of the planet\n');

ref_p = input('Please enter reflectivity of the planet\n');

abs_sat1 = input('Please enter absorptivity of the satellite\n');

emi_sat = input('Please enter emissivity of the satellite\n');

mass_sat = input('Please enter mass of the satellite in "kg"\n');

tc_sat = input('Please enter thermal capacity of the satellite "J
    /(kg.K)"\n');

r_sat = input('Please enter radius of the satellite in "m"\n');

H = input('Please enter altitude of the satellite in "m"\n');

q_int = input('Please enter internal heat dissipated by the
    satellite in "W"\n');

eff = input('Please enter efficiency of the solar cells\n');

if eff~=0
    pf = input('Please enter packaging factor of the solar cells\
        n');
end
%%
% Input data from excel sheet

X = xlsread('planets_data.xlsx');

distance = (X(:,1))';

mass = (X(:,2))';

temperature = (X(:,4))';

radius = (X(:,5))';

temp_p = temperature(n);

mass_p = mass(n);

r_sp = distance(n);    %distance between sun and planet
```

```
r_p = radius(n);

temp_s = 5778;

r_s = 6.9551e8;

if eff~=0
   abs_sat = (abs_sat1 - eff * pf);
else
    abs_sat = abs_sat1;
end

sigma = 5.67e-8;       %All are in SI units
%%
% View Factors Calculation

vf_sat_s = 0.5 * (1-sqrt(1-((r_s^2)/(r_sp-r_p-H)^2)));

vf_s_sat = (vf_sat_s * (r_sat^2))/(r_s^2);

vf_sat_p = 0.5 * (1-sqrt(1-((r_p^2)/(H+r_p)^2)));

vf_p_sat = (vf_sat_p * (r_sat^2))/(r_p^2);

vf_sat_surr = 1;

vf_p_s = 0.5 * (1-sqrt(1-((r_s^2)/(r_sp^2))));

vf_s_p = (vf_p_s * (r_p^2))/(r_s^2);
%%
% Planetary emission,  solar and albedo radiations

q_s = (sigma * power(temp_s,4) * 4 * pi * power(r_s,2) * power(
    r_sat,2) * abs_sat) / (4 * power(r_sp,2)); %solar radiation

q_a = (sigma * power(temp_s,4) * 4 * pi * power(r_s,2) * vf_s_p *
     ref_p * vf_p_sat * abs_sat);            %albedo radiation

q_p = (sigma * emi_p * power(temp_p,4) * 4 * pi * power(r_p,2) *
    vf_p_sat * abs_sat );                    %planetary emission

q_sat0 = (sigma * emi_sat * 4 * pi * power(r_sat,2) * vf_sat_surr
     );                                      %(IR radiation
    emitted by satellite)/(T^4)
%%
% Orbital time period of satellite

t_o = 2 * pi * sqrt(power(r_p+H,3)/((6.67e-11)*mass_p));
%%
```

```
% Albedo and eclipse functions in terms of satellite angular position

sympref('FloatingPointOutput',true);             %Function used to convert symbolic display to decimal points

syms f_a f_e temp_mean_sat temp_amp_sat psi phi

f_e = (1 + cos(phi));                            %cosine modulation over the average may be a suitable first approximation for albedo and eclipse functions

f_a = f_e;
%%
% The temperature variations of the satellite can be approximated to a sinusoidal
% function of its orbital position

temp_sat = temp_mean_sat + temp_amp_sat * expand(cos(phi-psi));
%%
% Solving thermal balance equation for the satellite

eq1 = -expand((mass_sat * tc_sat * 2 * pi * temp_amp_sat * expand(sin(phi-psi)))/t_o) ;       %Rate of energy stored in the body due to the thermal capacity of the satellite
eq2 = expand(q_s*f_e + q_a*f_a + q_p - expand(q_sat0*power(temp_mean_sat,3)*(temp_mean_sat+4*temp_amp_sat*expand(cos(phi-psi))))) + q_int ; %Net heat interactions on the satellite
%%
% Co-efficients of sin(phi) and cos(phi) are stored in co-efficient matrix along
% with the independent terms

c1 = coeffs(eq1, [sin(phi) cos(phi)]);
c2 = coeffs(eq2, [sin(phi) cos(phi)]);
c0 = [0 c1(1) c1(2)];
%%
% Equating co-efficient matrix gives phase lag(psi) and Amplitude and mean temperatures
% of the satellite

[temp_mean_sat, temp_amp_sat, psi] = solve(c0==c2, [temp_mean_sat, temp_amp_sat, psi]);

fprintf('Temperature of the satellite as a function of orbital position is given by %.2f + %.2fcos(phi-%.2f)\n', abs(temp_mean_sat(1)), abs(temp_amp_sat(1)), abs(psi(1)));
```

A.3 PARAMETRIC STUDY OF THE TEMPERATURE OF THE SATELLITE USING MATLAB CODE

Parametric study of the temperature of the satellite is done using MATLAB programming language.

A.3.1 *Study of the variation in the temperature of the satellite with α and ϵ using MATLAB code*

Values of the variables, defined as constants can be edited in the code to vary the temperature function only in terms of α and ϵ of the satellite. The following code helps in studying the variation of the temperature of the satellite with α and ϵ.

```
function steady_temp(abs_sat1, emi_sat)


% defining constants
% all are in SI units
n = 3;
abs_p = 0.4;
emi_p = 0.6;
ref_p = 0.3;
mass_sat = 50;
tc_sat = 1000;
r_sat = 0.5;
H = 300000;
q_int = 100;
eff = 0;

if eff~=0
    pf = 0.3;
end


% Input data from excel sheet
X = xlsread('planets_data.xlsx');
distance = (X(:,1))';
mass = (X(:,2))';
temperature = (X(:,4))';
radius = (X(:,5))';


% Assigning corresponding data from excel sheet to new variables
temp_p = temperature(n);
mass_p = mass(n);
r_sp = distance(n);    %distance between sun and planet
r_p = radius(n);

```

```
%Defining constants
%All are in SI units
temp_s = 5778;
r_s = 6.9551e8;
sigma = 5.67e-8;
abs_sat = 0;

if eff~=0
      abs_sat = (abs_sat1 - eff * pf);
else
      abs_sat = abs_sat1;
end


%View factor calculations
vf_sat_s = 0.5 * (1-sqrt(1-((r_s^2)/(r_sp-r_p-H)^2)));
vf_s_sat = (vf_sat_s * (r_sat^2))/(r_s^2);
vf_sat_p = 0.5 * (1-sqrt(1-((r_p^2)/(H+r_p)^2)));
vf_p_sat = (vf_sat_p * (r_sat^2))/(r_p^2);
vf_sat_surr = 1;
vf_p_s = 0.5 * (1-sqrt(1-((r_s^2)/(r_sp^2))));
vf_s_p = (vf_p_s * (r_p^2))/(r_s^2);


%Planetary emission, solar and albedo radiations
q_s = (sigma * power(temp_s,4) * 4 * pi * power(r_s,2) * power(
    r_sat,2) * abs_sat) / (4 * power(r_sp,2)); %solar radiation
q_a = (sigma * power(temp_s,4) * 4 * pi * power(r_s,2) * vf_s_p *
     ref_p * vf_p_sat * abs_sat);            %albedo radiation
q_p = (sigma * emi_p * power(temp_p,4) * 4 * pi * power(r_p,2) *
    vf_p_sat * abs_sat );                    %planetary emission
q_sat0 = (sigma * emi_sat * 4 * pi * power(r_sat,2) * vf_sat_surr
     );                                      %(IR radiation
    emitted by satellite)/(T^4)


% Orbital time period of satellite calculation
t_o = 2 * pi * sqrt(power(r_p+H,3)/((6.67e-11)*mass_p));


% Albedo and eclipse functions in terms of satellite angular
    position
sympref('FloatingPointOutput',true); %Function used to convert
    symbolic display to decimal points
syms f_a f_e temp_mean_sat temp_amp_sat si phi
f_e = (1 + cos(phi));   %cosine modulation over the average may
    be a suitable first approximation for albedo and eclipse
    functions
f_a = f_e;
```

```
% Temperature of satellite is assumed as approximate sinusoidal function for single node satellite
temp_sat = temp_mean_sat + temp_amp_sat * expand(cos(phi-si));

% Solving thermal balance equation for the satellite
eq1 = -expand((mass_sat * tc_sat * 2 * pi * temp_amp_sat * expand(sin(phi-si)))/t_o) ;       %Rate of energy stored in the body due to the thermal capacity of the satellite
eq2 = expand(q_s*f_e + q_a*f_a + q_p - expand(q_sat0*power(temp_mean_sat,3)*(temp_mean_sat+4*temp_amp_sat*expand(cos(phi-si))))) + q_int ; %Net heat interactions on the satellite

% Co-efficients of sin(?) and cos(?) are stored in co-efficient matrix along with the independent terms
c1 = coeffs(eq1, [sin(phi) cos(phi)]);
c2 = coeffs(eq2, [sin(phi) cos(phi)]);
c0 = [0 c1(1) c1(2)];

% Equating co-efficient matrix gives phase lag(?) and Amplitude and mean temperatures of the satellite
[temp_mean_sat, temp_amp_sat, si] = solve(c0==c2, [temp_mean_sat, temp_amp_sat, si]);

%Printing output in a file
fileID = fopen('steadytemp.txt','a+');
fprintf(fileID,'Temperature of the satellite as a function of orbital position for absorptivity = %0.3f and emissivity = %0.3f is given by %.2f + %.2fcos(  -%.2f)\n', abs_sat1, emi_sat, abs(temp_mean_sat(1)), abs(temp_amp_sat(1)), abs(si(1)));
fclose(fileID);

end
```

A.3.2 *Study of the variation in the temperature of the satellite with the altitude of the satellite using MATLAB code*

Values of the variables, defined as constants can be edited in the code to vary the temperature function only in terms of the altitude of the satellite. The following code helps in studying the variation of the temperature of the satellite with the altitude.

```
function steady_temp_alt(H)


% defining constants
n = 3;
abs_p = 0.4;
emi_p = 0.6;
ref_p = 0.3;
abs_sat1 = 1;
emi_sat = 1;
mass_sat = 50;
tc_sat = 1000;
r_sat = 0.5;
q_int = 100;
eff = 0;

if eff~=0
    pf = 0.3;
end


% Input data from excel sheet
X = xlsread('planets_data.xlsx');
distance = (X(:,1))';
mass = (X(:,2))';
temperature = (X(:,4))';
radius = (X(:,5))';


% Assigning corresponding data from excel sheet to new variables
temp_p = temperature(n);
mass_p = mass(n);
r_sp = distance(n);    %distance between sun and planet
r_p = radius(n);


%Defining constants
%All are in SI units
temp_s = 5778;
r_s = 6.9551e8;
sigma = 5.67e-8;
abs_sat = 0;

if eff~=0
      abs_sat = (abs_sat1 - eff * pf);
else
      abs_sat = abs_sat1;
end
```

```
%View factor calculations
vf_sat_s = 0.5 * (1-sqrt(1-((r_s^2)/(r_sp-r_p-H)^2)));
vf_s_sat = (vf_sat_s * (r_sat^2))/(r_s^2);
vf_sat_p = 0.5 * (1-sqrt(1-((r_p^2)/(H+r_p)^2)));
vf_p_sat = (vf_sat_p * (r_sat^2))/(r_p^2);
vf_sat_surr = 1;
vf_p_s = 0.5 * (1-sqrt(1-((r_s^2)/(r_sp^2))));
vf_s_p = (vf_p_s * (r_p^2))/(r_s^2);


%Planetary emission, solar and albedo radiations
q_s = (sigma * power(temp_s,4) * 4 * pi * power(r_s,2) * power(r_sat,2) * abs_sat) / (4 * power(r_sp,2)); %solar radiation
q_a = (sigma * power(temp_s,4) * 4 * pi * power(r_s,2) * vf_s_p * ref_p * vf_p_sat * abs_sat);           %albedo radiation
q_p = (sigma * emi_p * power(temp_p,4) * 4 * pi * power(r_p,2) * vf_p_sat * abs_sat );                     %planetary emission
q_sat0 = (sigma * emi_sat * 4 * pi * power(r_sat,2) * vf_sat_surr );                                     %(IR radiation emitted by satellite)/(T^4)


% Orbital time period of satellite calculation
t_o = 2 * pi * sqrt(power(r_p+H,3)/((6.67e-11)*mass_p));


% Albedo and eclipse functions in terms of satellite angular position
sympref('FloatingPointOutput',true); %Function used to convert symbolic display to decimal points
syms f_a f_e temp_mean_sat temp_amp_sat si phi
f_e = (1 + cos(phi));   %cosine modulation over the average may be a suitable first approximation for albedo and eclipse functions
f_a = f_e;


% Temperature of satellite is assumed as approximate sinusoidal function for single node satellite
temp_sat = temp_mean_sat + temp_amp_sat * expand(cos(phi-si));


% Solving thermal balance equation for the satellite
eq1 = -expand((mass_sat * tc_sat * 2 * pi * temp_amp_sat * expand(sin(phi-si)))/t_o) ;       %Rate of energy stored in the body due to the thermal capacity of the satellite
eq2 = expand(q_s*f_e + q_a*f_a + q_p - expand(q_sat0*power(temp_mean_sat,3)*(temp_mean_sat+4*temp_amp_sat*expand(cos(phi-si))))) + q_int ; %Net heat interactions on the satellite
```

```

% Co-efficients of sin(?) and cos(?) are stored in co-efficient
    matrix along with the independent terms
c1 = coeffs(eq1, [sin(phi) cos(phi)]);
c2 = coeffs(eq2, [sin(phi) cos(phi)]);
c0 = [0 c1(1) c1(2)];


% Equating co-efficient matrix gives phase lag(?) and Amplitude
    and mean temperatures of the satellite
[temp_mean_sat, temp_amp_sat, si] = solve(c0==c2, [temp_mean_sat,
     temp_amp_sat, si]);


%Printing output in a file
fileID = fopen('steadytemp_alt.txt','a+');
fprintf(fileID,'Temperature of the satellite as a function of
    orbital position at an altitude = %ikm is given by %.2f + %.2
    fcos(  -%.2f)\n', H/1000, abs(temp_mean_sat(1)), abs(
    temp_amp_sat(1)), abs(si(1)));
fclose(fileID);

end
```

A.3.3 *Study of the variation in the temperature of the satellite with internal heat dissipated by the satellite using MATLAB code*

Values of the variables, defined as constants can be edited in the code, to vary the temperature function only in terms of the internal heat dissipated by the satellite. The following code helps in studying the variation of the temperature of the satellite with the rate of internal heat dissipated.

```
function steady_temp_int(q_int)


% defining constants
n = 3;
abs_p = 0.4;
emi_p = 0.6;
ref_p = 0.3;
abs_sat1 = 1;
emi_sat = 1;
mass_sat = 50;
tc_sat = 1000;
r_sat = 0.5;
H = 300000;
eff = 0;
```

```
if eff~=0
    pf = 0.3;
end


% Input data from excel sheet
X = xlsread('planets_data.xlsx');
distance = (X(:,1))';
mass = (X(:,2))';
temperature = (X(:,4))';
radius = (X(:,5))';


% Assigning corresponding data from excel sheet to new variables
temp_p = temperature(n);
mass_p = mass(n);
r_sp = distance(n);     %distance between sun and planet
r_p = radius(n);


%Defining constants
%All are in SI units
temp_s = 5778;
r_s = 6.9551e8;
sigma = 5.67e-8;
abs_sat = 0;

if eff~=0
      abs_sat = (abs_sat1 - eff * pf);
else
      abs_sat = abs_sat1;
end


%View factor calculations
vf_sat_s = 0.5 * (1-sqrt(1-((r_s^2)/(r_sp-r_p-H)^2)));
vf_s_sat = (vf_sat_s * (r_sat^2))/(r_s^2);
vf_sat_p = 0.5 * (1-sqrt(1-((r_p^2)/(H+r_p)^2)));
vf_p_sat = (vf_sat_p * (r_sat^2))/(r_p^2);
vf_sat_surr = 1;
vf_p_s = 0.5 * (1-sqrt(1-((r_s^2)/(r_sp^2))));
vf_s_p = (vf_p_s * (r_p^2))/(r_s^2);


%Planetary emission, solar and albedo radiations
q_s = (sigma * power(temp_s,4) * 4 * pi * power(r_s,2) * power(
    r_sat,2) * abs_sat) / (4 * power(r_sp,2)); %solar radiation
q_a = (sigma * power(temp_s,4) * 4 * pi * power(r_s,2) * vf_s_p *
     ref_p * vf_p_sat * abs_sat);            %albedo radiation
```

```
q_p = (sigma * emi_p * power(temp_p,4) * 4 * pi * power(r_p,2) * vf_p_sat * abs_sat );                    %planetary emission
q_sat0 = (sigma * emi_sat * 4 * pi * power(r_sat,2) * vf_sat_surr );                                       %(IR radiation emitted by satellite)/(T^4)


% Orbital time period of satellite calculation
t_o = 2 * pi * sqrt(power(r_p+H,3)/((6.67e-11)*mass_p));


% Albedo and eclipse functions in terms of satellite angular position
sympref('FloatingPointOutput',true); %Function used to convert symbolic display to decimal points
syms f_a f_e temp_mean_sat temp_amp_sat si phi
f_e = (1 + cos(phi));   %cosine modulation over the average may be a suitable first approximation for albedo and eclipse functions
f_a = f_e;


% Temperature of satellite is assumed as approximate sinusoidal function for single node satellite
temp_sat = temp_mean_sat + temp_amp_sat * expand(cos(phi-si));


% Solving thermal balance equation for the satellite
eq1 = -expand((mass_sat * tc_sat * 2 * pi * temp_amp_sat * expand(sin(phi-si)))/t_o) ;       %Rate of energy stored in the body due to the thermal capacity of the satellite
eq2 = expand(q_s*f_e + q_a*f_a + q_p - expand(q_sat0*power(temp_mean_sat,3)*(temp_mean_sat+4*temp_amp_sat*expand(cos(phi-si))))) + q_int ; %Net heat interactions on the satellite


% Co-efficients of sin(?) and cos(?) are stored in co-efficient matrix along with the independent terms
c1 = coeffs(eq1, [sin(phi) cos(phi)]);
c2 = coeffs(eq2, [sin(phi) cos(phi)]);
c0 = [0 c1(1) c1(2)];


% Equating co-efficient matrix gives phase lag(?) and Amplitude and mean temperatures of the satellite
[temp_mean_sat, temp_amp_sat, si] = solve(c0==c2, [temp_mean_sat, temp_amp_sat, si]);


%Printing output in a file
```

```
fileID = fopen('steadytemp_int.txt','a+');
fprintf(fileID,'Temperature of the satellite dissipating heat at
    the rate of %iW as a function of orbital position is given by
     %.2f + %.2fcos(  -%.2f)\n', q_int, abs(temp_mean_sat(1)),
    abs(temp_amp_sat(1)), abs(si(1)));
fclose(fileID);

end
```

BIBLIOGRAPHY

[1] Aboobakar and Sofia de Fátima Caeiro. "Dynamic and Thermal Models for ECOSat-III" (2016).

[2] Martinez I. *Radiation View Factors*. URL: http://webserver.dmt.upm.es/~isidoro/tc3/Radiation%20View%20factors.pdf. (Accessed: 05.07.2019).

[3] Martinez I. *Spacecraft Thermal Modelling and Testing*. URL: http://webserver.dmt.upm.es/~isidoro/tc3/Spacecraft%20Thermal%20Modelling%20and%20Testing.pdf. (Accessed: 05.07.2019).

[4] Robert Lyle, Perikles Stabekis, and Robert Stroud. *Spacecraft Thermal Control*. Vol. 8105. National Aeronautics and Space Administration, 1973.