Aero 5 ELSS - Project - IPSA

Satellite Design Project

Authors :
M. Chris De Claverie
M. Baptiste Rubino-Moyner

Teacher :
M. Vincent Robert

Version 1.0.0, 25 décembre 2020

1 Introduction

A customer mandated your agency for the preliminary design of a 6-ton telecommunication satellite as maximum weight (after separation)

In this project, we will be trying to build the preliminary design for the customer's satellite, including (but not limited to) propellant needs, electrical generation, and thermal budgets. The theoretical calculations and simulations will be described, and customer advice will be given to ensure the best approach is taken for the different subsystems.

All numerical applications are available as open-source python code on GitHub :
https://github.com/pwnorbitals/SatelliteDesign

2 Propellant budget

2.1 Manual calculations

The launcher leaves the satellite on a 190 x 190 km orbit.

The orbit decays quickly, as atmospheric drag is still very present. We need to make a burn to rise our apoapsis to the one of our final orbit, the geostationary orbit (35 786 km).

In this objective, we first define a couple of helper functions :

$$V(a, r) = \sqrt{\mu * (\frac{2}{r} - \frac{1}{a})} \tag{1}$$

$$A(z_a, z_p) = 6371 + \frac{z_p + z_a}{2} \tag{2}$$

$$R(a) = 6371 + a \tag{3}$$

From this, we can easily compute the required velocity change to :

$$V_{init} = V(A(190, 190), R(190)) = 7794.42\ m/s \tag{4}$$

$$V_{GTO} = V(A(35786, 190), R(190)) = 10253.9\ m/s \tag{5}$$

$$\Delta V_{LEO-GTO} = V_{GTO} - V_{init} = \textbf{2459.48 m/s} \tag{6}$$

The propellant mass used in the maneuver can be calculated through the following function :

$$M(dV, I_{sp}, m_i) = mi - \frac{m_i}{e^{\frac{dV}{I_{sp} * g_0}}} \tag{7}$$

The numerical value for our case is :

$$m_{LEO-GTO} = M(\Delta V_{LEO-GEO}, 280, 6000) = \textbf{3549.33 kg} \tag{8}$$

At the GTO apoapsis, we need another burn to circularize on our final GEO orbit. The calculations for the burn are the following :

$$\Delta V_{GTO-GEO} = V(A(35786, 35786), R(35786)) - V(A(35786, 190), R(35786)) \quad (9)$$

$$\Delta V_{GTO-GEO} = \textbf{1479.08 m/s} \quad (10)$$

$$m_{GTO-GEO} = M(\Delta V_{GTO-GEO}, 300, 6000 - m_{LEO-GTO}) \quad (11)$$

$$m_{GTO-GEO} = \textbf{968.09 kg} \quad (12)$$

The station keeping in GEO needs $55\ m/s\ \Delta V$ per year, which equates to $17 * 55 = 935\ m/s$ over the satellite lifetime. This gives is the propellant masses needed, depending on the engine (chemical or electrical) :

$$m_{sc} = M(935, 290, 6000 - M_{GTO} - m_{GTO-GEO}) = \textbf{415.29 kg} \quad (13)$$

$$m_{se} = M(935, 1700, M_{GTO} - m_{GTO-GEO}) = \textbf{80.83 kg} \quad (14)$$

The following calculations are the necessary masses for deorbiting :

$$m_{dc} = M(6, 290, M_{GEO} - m_{sc}) = \textbf{415.29 kg} \quad (15)$$

$$m_{de} = M(6, 1700, M_{GEO} - m_{se}) = \textbf{80.83 kg} \quad (16)$$

This gives us the total payload mass for the mission :

$$M_{pc} = M_{GEO} - (m_{sc} + m_{dc}) = \textbf{1065.05 kg} \quad (17)$$

$$M_{pe} = M_{GEO} - (m_{se} + m_{de}) = \textbf{1401.25 kg} \quad (18)$$

$$\Delta M = M_{pe} - M_{pc} = \textbf{336.2 kg} \quad (19)$$

It is very clear that embedding an electrical engine has good advantages in terms of payload capacity. Depending on the price difference between the two engines, and considering the other tradeoffs (ground servicing, availability, integration capabilities, etc.), the customer would have to make the best-worth choice. Statically, we see a clear trend towards more electric station-keeping engines in GEO, which could be a good indication of the best choice to make for this particular mission.

2.2 Comparaison with GMAT

To compare our results with GMAT, we have to modelize the mission. It starts at 190km in a circular Low Earth Orbit with an engine and a tank. In order to define the propellant mass needed,

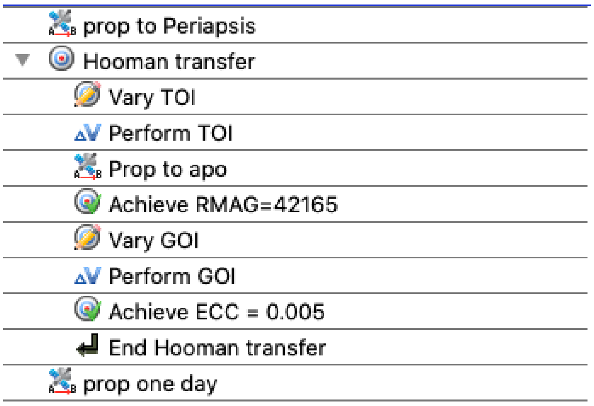

FIGURE 1 – Mission tab in GMAT

we have to set it at 0 kg and allow a negative value. By doing this, the engine will show how much propellant is needed for the mission. The mission sequence is show in figure 1. The results compare to those obtained are quite similar, an average relative difference of 0.4% is observed. It could be due to the computation accuracy of our Python algorithm, and the fact that GMAT has more accurate atmosphere and gravity models.

/	Python	GMAT	Abs. diff	Rel. diff
LEO-GTO ΔV	2459.48m/s	2456.51 m/s	2.97	0.12 %
LEO-GTO mass prop.	3549.33kg	3546.68 kg	2.65	0.08 %
GTO-GEO ΔV	1479.08 m/s	1489.93 m/s	10.85	0.73 %
GTO-GEO mass prop.	968.09 kg	974.59 kg	6.5	0.67 %

3 Electrical budget

Considering that the satellite has the following characteristics :

- Satellite power consumption in operational mode $P_{sl} = 2\text{kW}$
- Satellite power consumption in transition phases $P_{slt} = 1\text{kW}$
- Maximum duration of a transition phase $T_t = 24\text{h}$
- Power regulator efficiency $\eta_{reg} = 93\%$
- Battery efficiency $\eta_{bat} = 91\%$
- Typical eclipse duration is 5% of orbit

The average power that the solar generator must provide during the day period of the orbit, the average power that the solar generator must provide during the orbital period and the nominal power that the solar generator must provide are given by :

$$P_{gs} = \frac{P_{sl}}{\eta_{reg}}(1 + \frac{(\frac{T_e}{T_d})}{\eta_{bat}}) = \textbf{1137.45W} \tag{20}$$

$$P_{gsm} = P_{gs}\frac{T_d}{T} = \textbf{1080.58W} \tag{21}$$

$$P_{gsn} = K_a \times P_{gs} = \textbf{1364.95W} \tag{22}$$

For the battery sizing we take the same specifications as the ones in the practical works.

- DOD1 $= 0.8$
- $DOD_{init} = 0.3$
- DOD2 $= 0.7$

Now, we need to compute the battery energy for transition phase ($W_{bat,1}$) and for eclipses in operational mode ($W_{bat,2}$).

$$W_{bat,1} = \frac{Pslt \times Tt}{DOD1 - DOD_init} = \textbf{96000 Wh} \tag{23}$$

$$W_{bat,2} = \frac{Psl \times Te}{DOD2} = \textbf{1709.16 Wh} \tag{24}$$

We can conclude that our battery should provide an energy of 96kWh. With a battery density of 10kg per kWh, it will weight **960 kg**

4 Solar generator budget

We use AsGa triple junction solar cells with efficiency $\eta_{cell} = 31\%$. Relative illumination K_r and relative power K_m over the year are given in appendix.

The Asg solar cell surface needed for worst case orbit could be determined by the following equation :

$$A_{sg} = \frac{K_a \times P_{gsm}}{K_m \times C0 \times eff_{cell}} \quad (25)$$

$$A_{sg} = \mathbf{3.47\ m^2} \quad (26)$$

In order to determine the payload mass we should first compute the A_{sgp} factor and multiply it with the density coefficient, $\rho_{sgp} = 6.18\ kg/m^2$

$$\alpha = \frac{1}{0.77} \quad (27)$$

$$A_{sgp} = A_{sg} \times \alpha \quad (28)$$

$$M_{sgp} = A_{sgp} \times \rho_{sgp} \quad (29)$$

$$M_{sgp} = \mathbf{27.88\ kg} \quad (30)$$

Thanks to this result, it's possible to compute the payload mass depending on the thruster used. As shown in the tabular below, the electrical engine allows us to put more payload mass in orbit by a factor 5.4

(mass in kg)	Elec. engine	Chem. engine
LEO-GTO	3549.33	3549.33
GTO-GEO	968.09	968.09
Drag. compensation	415.29	80.8
Deorbitation	2.25	0.5
Batteries	960	960
Solar pannels	27.88	27.88
Payload mass	**77.16**	**413.4**

5 Warming budget

Considering the average volumic mass of the satellite of about $3000\ kg/m^3$, and knowing the satellite mass is $6\ T$, we can show the needed satellite volume is $V_{sat} = \frac{mass}{density} = \mathbf{2\ m^3}$

The cube containing this volume has a side length of $l_{sat} = \frac{1}{3}V_{sat} = \mathbf{1.26\ m}$, and the radius of the sphere containing that cube is $\frac{\sqrt{3}}{2}l_{sat} = \mathbf{1.09\ m}$

From this data, we can compute the total energy and temperatures of the equivalent structures at equilibrium. For this, we will be using the following constants :

— Solar flux : $G_{sc} = 1353 W/m^2$

— Earth albedo ratio : $E_a = 0.3$

First, we need to compute the albedo and terrestrial fluxes :

$$f_a = E_a \times G_{sc} = \mathbf{473.55\ W/m^2} \tag{31}$$
$$f_t = \frac{1}{4}(G_{sc} - f_a) = \mathbf{219.86\ W/m^2} \tag{32}$$

The surface and projected surface of the sphere needs to be computed :

$$S_p = \pi r^2 \tag{33}$$
$$S = 4\pi r^2 \tag{34}$$

The absorptivity and emissivity considered are detailled in the following table :

Material	Black	White	Golden
α	0.95	0.15	0.30
ϵ	0.90	0.85	0.03

Finally, the energies involved can be calculated (sun, albedo, terrestrial), and this lets us find out the temperature :

$$E_s = \alpha S_p G_{sc} \quad (35)$$

$$E_a = 0 \quad (36)$$

$$E_t = 0 \quad (37)$$

$$E = E_s + E_a + E_t \quad (38)$$

$$T = \frac{1}{4} \times \frac{E}{5.67 \times 10^{-8} \times \epsilon \times S_p} \quad (39)$$

The numerical application for our specific cases give the following results :

Material	Black	White	Golden
E_s (W)	**4807.50**	**759.08**	**1518.16**
E_a (W)	**0**	**0**	**0**
E_t (W)	**0**	**0**	**0**
E (W)	**4807.50**	**759.08**	**1518.16**
T (K)	**398.38**	**254.73**	**698.92**

The terrestrial and albedo energies have been neglected since they are typically near zero at GEO altitude.

6 Cooling budget

At equilibrium, we can find the emitted power P_e through the following calculation, which is the direct result of the power equilibrium :

$$P_e = (\eta_{ins} P_t) + P_{eq} \tag{40}$$

When considering the insulation efficiency $\eta_{ins} = 0.4$ and the internal power $P_i = 700\ W$, we find the following values for the emitted power :

Material	Black	White	Golden
P_e (W)	**2623.00**	**1003.63**	**1307.26**

The radiators need to dissipate enough power to limit the maximum temperature to $T_{max} =$ 40°C = 313.15 K. To do so, we can proceed as follows to find S_r, the radiator surface :

$$S_r = \frac{P_e}{\sigma \epsilon T_{max}^4} \tag{41}$$

Material	Black	White	Golden
S_r (m^2)	**5.35**	**2.17**	**79.92**

Finally, considering the new radiators have different characteristics ($\alpha = 0.15$, $\epsilon = 0.75$), we can find the new surface needed using the same equation as before :

Material	Black	White	Golden
$S_{r,new}$ (m^2)	**6.14**	**2.45**	**3.19**

In practice, we have to equally-sized radiators and each will be half the needed surface. The values we get are very consistent with the sizes found in previous questions.