SESA3041 and SESA6079

Problem sheet 2: Space Debris Guidelines and Standards

1. A 3000 kg remote-sensing spacecraft has a cross-sectional area of 15 m^2 and is in a circular, sun-synchronous orbit at 800 km altitude when it reaches the end of its mission, with 40 kg of propellant remaining (one-quarter of the total propellant mass at launch). The satellite has 8×15 N hydrazine thrusters (I_{SP} = 180 s) for orbit control. The remaining orbital lifetime is estimated to be 150 years. According to international space debris mitigation guidelines, the long-term presence of the satellite in the Low Earth Orbit (LEO) region should be limited to 25 years. Ideally, large spacecraft should be de-orbited in a controlled fashion to remove the risk for people and property on the ground.

   Using the data and equations to provide your evidence, explain the consequences of the spacecraft design on the compliance with the space debris mitigation guidelines. In your answer you should address the following points:

   a. Why the satellite is unable to achieve a controlled de-orbit (this would be achieved by lowering its perigee to an altitude of 100 km)
   b. Why the satellite cannot be transferred to a decay orbit with a remaining lifetime of 25 years (this would be achieved by lowering its perigee to an altitude of 450 km)

   [8 marks]

   DATA:
   - Gravitational constant for the Earth: μ_E = 3.986×10^5 km^3/sec^2
   - Acceleration due to gravity: g_0 = 9.81 m/sec^2
   - Earth's radius R_E = 6.378×10^3 km

   EQUATIONS:
   - Energy equation: $\frac{V^2}{2} - \frac{\mu}{r} = -\frac{\mu}{2a}$
   - Perigee distance: $r_p = a(1-e)$
   - Apogee distance: $r_a = a(1+e)$
   - Exhaust velocity : $V_{ex} = g_0 I_{SP}$
   - Propellant mass : $M_e = M_0(1 - \exp[-\Delta V/V_{ex}])$

2. Explain what international space debris mitigation guidelines exist and their impact on spacecraft systems design.
   [9 marks]

3. The United Nations (UN) Space Debris Mitigation Guidelines propose that the long-term presence of spacecraft in the low Earth orbit (LEO) and geostationary Earth orbit (GEO) protected regions should be limited after the end of their mission.

   For spacecraft in LEO, guidelines suggest that the remaining orbital lifetime, after the end of mission, should be less than 25 years. Typically, this is achieved by lowering the perigee of the orbit such that atmospheric drag results in the re-entry of the spacecraft in the desired timeframe.

   For spacecraft in GEO, guidelines suggest that the two following conditions should be fulfilled:

   - A minimum increase in perigee altitude of 235 km + (1000×C_R×A/m), where C_R is the solar radiation pressure coefficient and A/m is the cross-sectional area to dry mass ratio (m^2kg^{-1}), and
   - An eccentricity less than or equal to 0.003

(i) Use the information above and the data below (including the figures) to compare and contrast the challenges and benefits of compliance for the European Space Agency's Sentinel 1A spacecraft in LEO and Inmarsat's Alphasat in GEO. Provide evidence to support your answer by including:
[20 marks]

a. A calculation of the delta-V and mass of propellant required for each spacecraft to comply with the space debris mitigation guidelines,
b. A calculation of the delta-V and mass of propellant required for the controlled de-orbit of each spacecraft. You may assume that a controlled de-orbit will occur if the orbit perigee is lowered to an altitude of 75 km, and
c. A brief description of the congestion occurring in the orbits occupied by each spacecraft.

(ii) If the Sentinel 1A spacecraft were to fail before it was able to perform its post-mission disposal manoeuvre, what might be done to reduce the risk of a collision occurring in the future? Give three examples of methods/concepts that might be used to achieve this.
[5 marks]

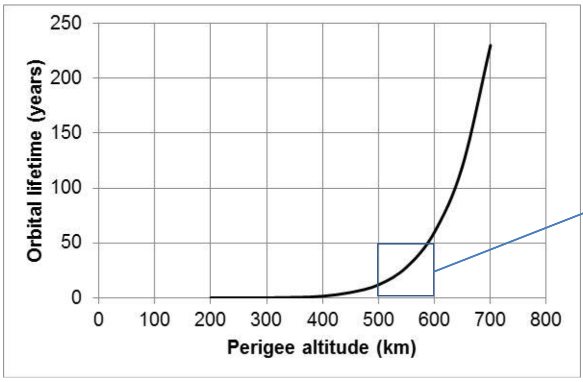
DATA:

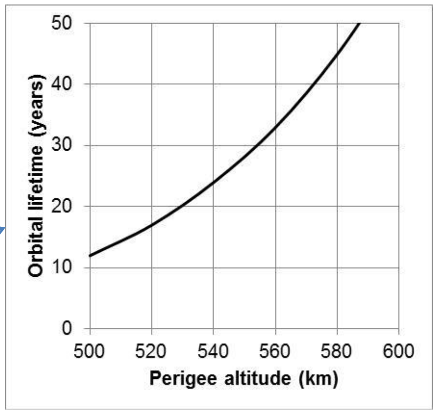
- Earth's radius: R_E = 6378 km
- Earth's gravitational constant: $\mu_E = 3.986\times10^5$ km^3/sec^2
- Acceleration due to gravity: g_0 = 9.81 m/sec^2
- Sentinel 1A:
  - Launch: 3 April 2014
  - Lifespan: 7 years (consumables: 12 years)
  - Semi-major axis: a = 7072 km
  - Eccentricity: e = 0.00015
  - Inclination: $i = 98.18°$
  - Dry mass: m = 2170 kg
  - Propellant mass: m_e = 130 kg
  - Average cross-sectional area: 20.8 m^2
  - Orbit control: 6 thrusters (each: 1 N, I_{SP} = 213 sec)
  - Remaining orbital lifetime (without orbit control): see Figure Q.1 (a) and Figure Q.1. (b)
- Alphasat:
  - Launch: 25 July 2013
  - Lifespan: 15 years
  - Semi-major axis: a = 42164 km
  - Eccentricity: e = 0.00036
  - Inclination: $i = 0.14°$
  - Dry mass: m = 3480 kg
  - Propellant mass: m_e = 3170 kg
  - Average cross-sectional area: 92.5 m^2
  - Solar radiation pressure coefficient: 1.2
  - Orbit raising: 500 N European Apogee Motor (I_{SP} = 325 sec)

EQUATIONS:

- Energy equation: $\frac{V^2}{2} - \frac{\mu}{r} = -\frac{\mu}{2a}$
- Perigee distance: $r_p = a(1-e)$
- Apogee distance: $r_a = a(1+e)$

- Propellant mass : $m_e = m_0(1 - \exp[-\Delta V/V_{ex}])$
- Exhaust velocity : $V_{ex} = g_0 I_{SP}$





4. A communications satellite in geostationary Earth orbit requires sufficient propellant for disposal. Calculate:

   a. The ΔV required to re-orbit the satellite to a circular, equatorial graveyard orbit at an altitude of 250 km above the geostationary orbit at the end of the satellite's operational life;
   [8 marks]

   b. The fraction of the satellite's mass needed as propellant for the transfer to the disposal orbit: $M_f = 1 - e^{-\Delta V / g_0 I_{sp}}$

   where g_0 = 9.81 ms^{-2} and I_{sp} = 180 s for a chemical propulsion system
   [2 marks]

You may take the radius of the Earth to be 6378 km. The energy equation is $\frac{V^2}{2} - \frac{\mu}{r} = -\frac{\mu}{2a}$ with μ = 398600 km^3/s^2, r is the orbit radius and a is the orbit semi-major axis. Perigee radius: $r_p = a(1-e)$ and apogee radius: $r_a = a(1+e)$ where e is the orbit eccentricity and $a = \frac{1}{2}(r_p + r_a)$.

5. How is the GEO Protected Region defined?
   [4 marks]

6. A Geostationary communications satellite in a circular orbit with semi-major axis a = 42165 km, eccentricity e =0.005, and with a mass m = 4000 kg, a cross-sectional area A = 16 square metres, and a solar radiation pressure coefficient C_R =1.2 must be transferred to a graveyard orbit after the end of its mission, according to the IADC Space Debris Mitigation Guidelines. The two following conditions should be fulfilled:

   - A minimum increase in perigee altitude of 235 km + (1000×C_R×A/m); and
   - An eccentricity less than or equal to 0.003

   Calculate suitable values for the perigee radius and apogee radius of the graveyard orbit, where the perigee radius $r_p = a(1-e)$ and apogee radius $r_a = a(1+e)$.
   [5 marks]