SEMESTER 1 ASSESSMENT 2021/22

TITLE: **Advanced Astronautics**

DURATION: 120 MINS

This paper contains **FOUR** questions.

Answer All **FOUR** questions on this paper.

Your answer to each question attempted should commence on a new page and be appropriately numbered.

All Questions are worth 25 marks (total 100 marks). An outline marking scheme is shown in brackets to the right of each question. Note that marks will only be awarded when appropriate working is given.

The following will be provided on request:

1. An Engineering Data Book by Calvert and Farrar
2. Graph paper

Note that the Astro Equation Booklet is provided separately

Only University approved calculators may be used.

A foreign language direct ‘Word to Word’ translation dictionary (paper version ONLY) is permitted, provided it contains no notes, additions or annotations.

Q1 The Soyuz TMA re-entry vehicle is a blunt-body re-entry capsule for a direct entry (ballistic entry) with an angle of attack of -22.3 degree. It can carry up to three astronauts and has an entry mass of about 2,950 kg. Figure Q1a shows the schematic of the Soyuz TMA re-entry vehicle. As can be seen, it is 2.24 meters long and 2.17 meters in diameter. From LEO, the Soyuz TMA re-enters at 7.6 km/s. Its drag and lift coefficients are about 1.26 and 0.0, respectively.

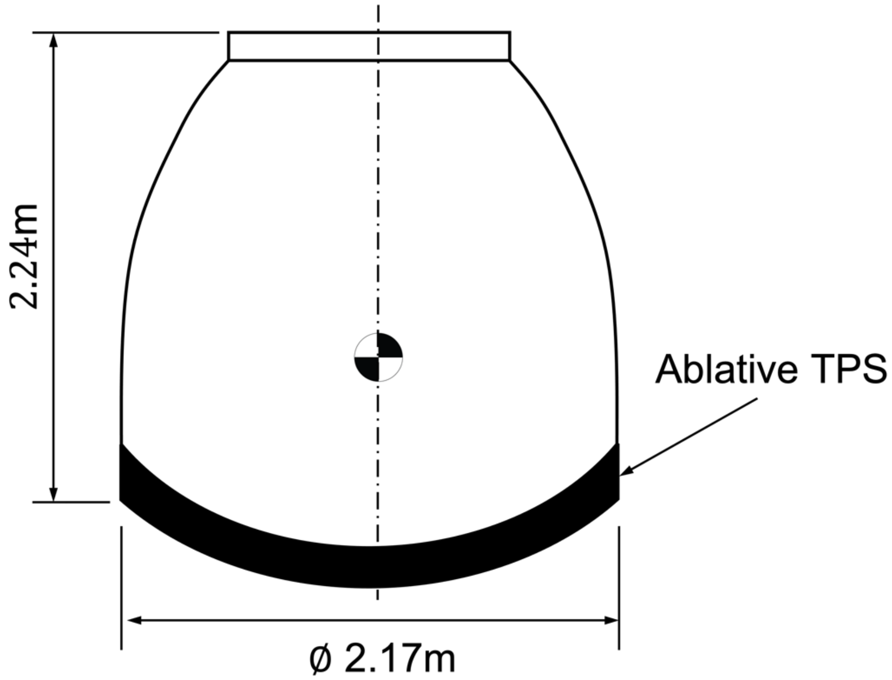

Figure Q1a. A schematic of Soyuz TMA re-entry vehicle

For the prediction of the air density during the reentry, a new isothermal exponential model can be used as:

$$\rho(h) = \rho_s \cdot e^{-\frac{h}{H_g}} \qquad \text{(Equation Q1a)}$$

where $\rho_s = 1.225\ [\mathrm{kg \cdot m^{-3}}]$ and $H_g = 8435\ [\mathrm{m}]$.

Using the given isothermal exponential model and information of the Soyuz TMA vehicle, answer the following questions

(i) Find the ballistic coefficient of the Soyuz TMA vehicle in kg/m^2.

[5 marks]

Q1. Cont…

Q1. Cont…

(ii) The cover of the parachute container is jettisoned, and the parachute system begins to deploy when its velocity reaches 150 m/s. Find the corresponding altitude in km.

[5 marks]

(iii) Calculate the altitude of the Soyuz TMA re-entry vehicle at which maximum deceleration occurs during atmospheric re-entry.

[5 marks]

(iv) Calculate the altitude of Soyuz TMA re-entry vehicle at which peak heating occurs during atmospheric re-entry.

[5 marks]

(v) The maximum deceleration that astronauts can withstand is $49 m/s^2$. Calculate the possible range of re-entry angles which is defined as the flight path angle in negative direction.

[5 marks]

[Total 25 marks]

TURN OVER

Q2. Use the given information to answer the following questions.

(i) The Orion spacecraft will use high-temperature reusable surface insulation tiles to protect the bottom of the spacecraft during the reentry. The tiles use a black borosilicate glass coating that has an emittance value of 0.8 and covers areas of the vehicle in which temperatures reach up to 1,400 K. The thermal conductivity of the tile is 0.4500 W/m·K. The tile should prevent heat transfer to the underlying orbiter aluminium skin and structure, which should be below 3,500 W/m^2 with a maximum temperature of 500 K. Assume that conduction will be the most significant means of heat transfer within the insulation tile.

Estimate the minimum thickness of the insulation tile on the Orion spacecraft. Give your answer in mm.

[5 marks]

(ii) A spacecraft requiring an average power loading of 600 W during Sun-time has a solar array which consists of two deployed single-panel wings. Each solar panel is 1.5m wide and 2.0m long and has 2,500 Advanced Triple Junction (ATJ) solar cells. ATJ solar cell efficiency used in the solar array is 28.5%, which will be constant during the mission. The packing factor of the solar array is 90%. The emissivity and absorptance of the used ATJ solar cell are 0.85 and 0.92, respectively. The back of the solar array is coated with barium sulphate, the emissivity and absorptance of which are 0.88 and 0.06, respectively. Assume the solar array is highly conductive thus the front and back of the solar array will be at same temperature.

During the mission, the spacecraft encounters large solar distance variations from 1 AU near Earth to 0.5 AU. Assume that only direct solar radiation affects the temperature of the solar array.

Q2. Cont…

Q2. Cont…

Calculate the maximum temperatures of the solar array during its operation while considering the heat loss by radiation from the back of the solar array.

[5 marks]

(iii) A spherical asteroid has a visible albedo of 0.25 and the thermal emissivity of 0.6. The average intensity of solar radiation is 1,500 W/m^2 at its orbit. Assume this asteroid has no atmosphere and its surface temperature is mainly dictated by incident solar radiation. Estimate the average temperature of its Sun-facing surface.

[5 marks]

(iv) A thin black plate of 0.5 m^2 is suspended in a vacuum chamber with a liquid nitrogen cooled wall (100 K). The plate temperature is maintained at 350 K with a heater. Assume that both sides of the plate absorb all incident radiation and a thin black plate can be modelled as a black body. Find the heater power required to maintain the plate's temperature.

[5 marks]

(v) 1U CubeSat has an internal heat dissipation of 5W and absorbs 35W from the external environments. The average temperature of this CubeSat needs to be maintained below 300 K. The surface emissivity of the CubeSat is 0.7, and a radiator having emissivity of 0.85 will be attached to the one side of the CubeSat's surface (See Figure Q2a). Find the radiator size needed to keep the average temperature of the CubeSat below 300 K.

[5 marks]

TURN OVER

Q2. Cont…

Q2. Cont…

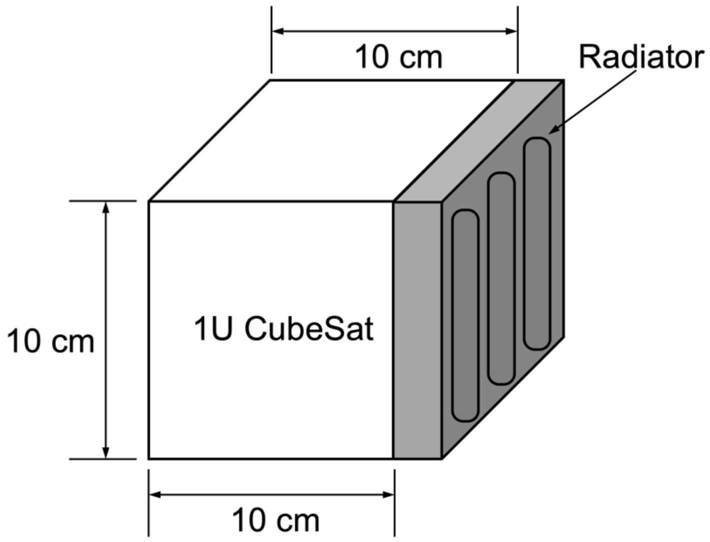

Figure Q2a. 1U CubeSat with radiator.

[Total 25 marks]

Q3. A small LEO satellite at an altitude of 750 km requires 1 kW of power for a nominal 5-year lifetime. The bus voltage is to be 28 V(±0.8V) in sunlight at EOL (End-Of-Life). Its solar array will be maintained pointing directly to the Sun during the mission. The same satellite also requires 120 W of power to charge a secondary power system. Assume there is no transmission losses and voltage drop.

The properties of the power module used in the satellite including a solar array and battery pack are listed as:

Solar Cell	
Maximum operating temperature	401 K
Minimum operating temperature	301K
EOL degradation (5 year) for both voltage and current at maximum power	90.0% of beginning- of-life (BOL) capacity for both voltage and current at maximum power
Solar intensity	1350 W/m^2 at 1 AU
Voltage at maximum power at 301K	2.2 V
Current at maximum power at 301K	400 mA
Temperature coefficient at EOL for voltage	-2.1 mV/K (Increase by 5% per year due to radiation)
Temperature coefficient at EOL for current	250 μA/K (Decrease by 3% per year due to radiation)

As a secondary power system, a Li-ion battery is used. The design data of the Li-ion battery are given as:

Average cell charge voltage	4.20 V
Average cell discharge voltage	3.55 V
Maximum DOD	70 %
Specific energy based on discharge capacity	170 Wh/kg

Q3. Cont…

TURN OVER

Q3. Cont…

The charge rate drives battery size. If the charge rate is too high, it can cause overheating of the battery. A good rule for the allowable charge rate is

$$R_{charge} = \frac{C_{charge}}{15} \text{ [A]}$$

where C_{charge} is charge capacity in Ah.

Assume the packing efficiency of the solar array is 100%. Answer the following questions.

(i) Calculate the minimum number of cells in a string to support the bus voltage at the maximum operating temperature during the entire mission period.

[5 marks]

(ii) Calculate the number of strings in a solar array to support the satellite power requirement at the maximum operating temperature during the entire mission period.

[5 marks]

(iii) Estimate the maximum power generated by the solar array during the mission.

[5 marks]

(iv) Assume we need to charge 70% of the total battery capacity while considering its DoD. Find the desired charge current of the secondary power system

[5 marks]

(v) Estimate the minimum weight of a Li-ion battery to support the required power load.

[5 marks]

[Total 25 marks]

Q4. A satellite of $120\ \mathrm{kg}$ with body-fixed inertia tensor

$$I = \begin{pmatrix} 300 & 0 & 0 \\ 0 & 150 & 0 \\ 0 & 0 & 150 \end{pmatrix} \mathrm{kg} \cdot \mathrm{m}^2$$

around its centre of mass is initially spinning around its body-fixed x-axis with angular velocity $\omega = 0.5\ \mathrm{rpm}$. Its orbital state is given by $a = 8000\ \mathrm{km},\ e = 0.05,\ i = 90°,\ \Omega = 0°,\ \omega = 0°,\ \theta = 60°$. After receiving reports of an anomaly, further telemetry analysis shows a suddenly change in the satellite's translational and rotational state.

From evaluating on-board camera recordings taken at 30 frames per second at the time of the event, it becomes apparent that a piece of space debris (to be modelled as a point mass) has impacted the satellite. The debris is estimated to be moving $10.5\ \mathrm{m}$ in the direction of the vector $(1, 1, 1)$ on the two consecutive frames just before the impact. It punches a clean hole and seems to leave physically unchanged moving $4.7\ \mathrm{m}$ in the direction of the vector $(1, 1, 0)$ on the two consecutive frames just after the collision. The linear velocity of the satellite after collision v_1 is observed to differ from the previous velocity v_0 by $\Delta v = v_1 - v_0 = (0.550, 0.540, 1.21)\ \mathrm{m/s}$ in the ECI frame.

Unless otherwise specified, all vectors are given in the inertial frame centred at the centre of mass of the satellite and aligned with the ECI frame axes at time of impact.

Use the given information to answer the following questions.

(i) Estimate the mass, or if not possible a range of possible masses, of the debris involved in this collision. Justify your answer.

[4 marks]

Q4. Cont…

TURN OVER

Q4. Cont…

(ii) Explain under what conditions an exact estimate of the mass is possible and list the practical circumstances which could prevent such estimates to be made.

[4 marks]

(iii) To avoid further contact with debris, an impulsive change of velocity is to be performed. Mission requirements specify that the spacecraft must maintain its original orbit period and inclination. Describe all compliant velocity changes $\Delta\vec{v}$ (from the initial state **before** impact) and justify your answer.
You may use a sketch to support your argument.

[4 marks]

(iv) Find the position and velocity vectors (in the ECI frame) of the satellite **before** the impact.

[5 marks]

(v) After performing an impulsive velocity change, the new velocity is $\vec{v} = (-5.863,\ 0,\ 4.2651)\ \mathrm{km/s}$. How long does it take the satellite to reach apoapsis?
You may assume a position vector of $\vec{r} = (3892, 0, 6742)\ \mathrm{km}$.

[8 marks]

[Total 25 marks]

END OF PAPER