Extremely Low earth orbit Imaging and Technology Explorer (ELITE): A Very Low Earth Orbit Mission

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ABSTRACT

Extremely Low earth orbit Imaging and Technology Explorer (ELITE) is an experimental micro-satellite on a mission to demonstrate the very low earth orbit (VLEO) flight, high-resolution imaging, and atmospheric data collection. The spacecraft will be launched at an altitude of 550 km, and it will gradually manoeuvre its orbit into VLEO and perform sustained flights are different altitudes for data collection. The camera on-board uses time-dependant integration (TDI) technology to produce high-resolution images. Therefore, the objective is to orbit as low as possible while maintaining the attitude stability required for TDI imaging. Besides the primary imaging mission, the spacecraft also carries: 1) atomic oxygen (AO) fluence detector for characterising the changing AO field in the region of flight, and 2) an ionospheric probe for in-situ plasma density and drift velocities. To support the orbit manoeuvres and drag compensation, the spacecraft is equipped with a propulsion system. There are numerous challenges to overcome to sustain a flight in VLEO which do not occur in LEO. The atmospheric density increases exponentially with altitude, i.e. the drag increases exponentially as the orbit altitude is lowered. The propulsion system has to be sized with adequate margin for sustained operations in VLEO. The increased drag also applies additional stress on to the attitude control system, compromising the stability of the spacecraft.

The power generation and ground contact will also be affected as the spacecraft shall maintain minimum drag and high stability orientation instead performing sun-tracking or ground tracking. Besides the ambient environmental challenges, the spacecraft is also subjected to surges in atmospheric density due to solar storms. The storms can increase the density by 10 or 100 times which can be catastrophic for the spacecraft. This paper discusses the mission design for ELITE mission considering the estimated launch time. Analytic results are shown for altitude profile, drag analysis, and structure optimisation. The objective is to highlight the mission design process considering the limitations and considerations of sub-systems. ELITE mission is fully funded by Singapore government and developed by Nanyang Technological University.

INTRODUCTION

The satellite industry has developed interest in Very Low Earth Orbit (VLEO) missions in the past decade. The market has recognised the advantages of VLEO for applications in communications and earth observation. By orbiting in VLEO, it is possible to avoid the E/F region of the ionosphere which affects the radio frequency (RF) signals significantly [1]. Orbiting closer to the surface of the earth has an obvious advantage in imaging. However, in VLEO, there are significant challenges due to increased atmospheric density compared to low earth orbit (LEO). The density imposes drag on the satellite resulting in the reduction of orbital altitude. The other major effect is the increase in disturbance torque adding significant stress on the attitude control system. Some of the other effects include surface charging and atomic oxygen erosion of the surfaces.

Only a few satellites had flown in VLEO until recently, Starlink launched many satellites to establish a fast communication network globally. The Gravity-field and steady-state Ocean Circulation Explorer (GOCE) developed by European Space Agency (ESA) launched in 2009 was one of the first satellites to successfully orbit in VLEO and provided valuable data for earth observation studies [2]. GOCE performed active drag compensation based on highly sensitive accelerometers and maintained a steady altitude for gravity field measurements [3]–[5]. It successfully demonstrated VLEO flight at ~250 km. GOCE followed another satellite called Challenging Minisatellite Payload (CHAMP) developed by Deutsches Zentrum für Luft- und Raumfahrt (DLR) launched in 2002. It collected data on the atmosphere and gravity-field from an orbit of around 440 km. It also used an internal 3-axis accelerometer to counter the forces applied on the satellite. In 2017, Japanese Aerospace Exploration Agency (JAXA) launched Super Low Altitude Test Satellite (SLATS) which successfully demonstrated operation in VLEO. The lowest altitude it achieved was 167.4 km, at which it operated for seven days. SLATS used power ion engines to compensate for drag in VLEO while capturing high-resolution images [6].

The data collected in VLEO is still in the early stages and more *in-situ* measurements of the atmosphere can lead to significant improvements in the weather models which can be used for developing reliable operational satellites. This gap in the market has led to the development of the Extremely Low earth Imaging and Technology Explorer (ELITE) mission. This paper will discuss the mission objectives, mission and system design of the ELITE satellite in the following sections.

MISSION OBJECTIVES

The ELITE is a technology demonstration mission that aims to develop a system that can be the pathfinder for future operational earth observation missions from VLEO. ELITE is set to launch in second half of the year 2025. Therefore, the objectives of this mission are to:

1) Demonstrate a sustained VLEO flight.
2) Demonstrate the ability to maintain attitude stability for high-resolution imaging.
3) Collect atmospheric data to augment the weather models.

Besides the technical objectives, the mission also aims to develop the capability in Singapore to design and develop such systems.

SYSTEM DESIGN

The system engineering approach must consider the mission requirements and design the system accordingly while considering the cost and timeline in mind. Due to low altitudes, the drag is main the concern, therefore, the propulsion system should be sized appropriately to meet the requirements. Following that, the attitude control system should be sized to compensate for the disturbance torques and any internal torques generated.

Propulsion System

The increased drag in VLEO altitudes impose a continuous retarding force on the spacecraft motion. This causes the orbital altitude to decrease gradually. This effect is present at higher altitudes also, however, due to low drag, the retarding force is negligible for most small satellite mission lifetimes. While sizing the propulsion system, it is important to analyse the drag in the environment the satellite is supposed to orbit.

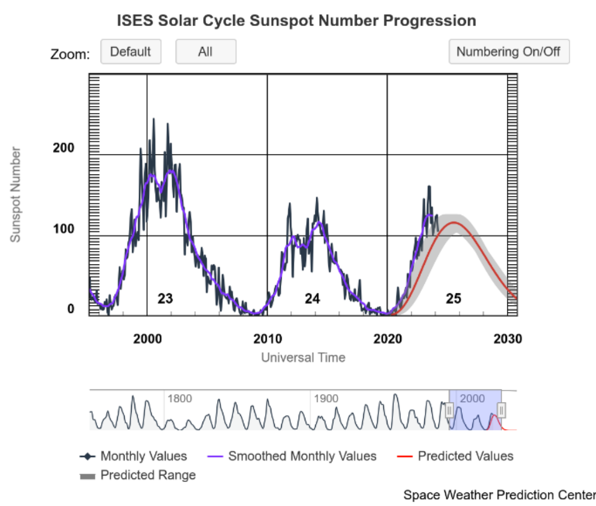

Figure 1: Sunspot number variation over the year showing the solar cycle progression.

Figure 1 shows the present and past two solar cycles with sunspot numbers. by Space Weather Prediction Center. This represents the solar cycle progression over the years showing the maximum and minimum activity of the sun. Solar cycle #25 is the current cycle in which the maximum is occurring around 2025. Entering the VLEO altitude regime during the solar maximum increases the risk significantly to the mission as the atmospheric density can increase tenfold or even higher during solar storms. However, sizing the propulsion system to compensate directly for solar storms may result in over-sizing. Therefore, the system will be sized for average environmental forces.

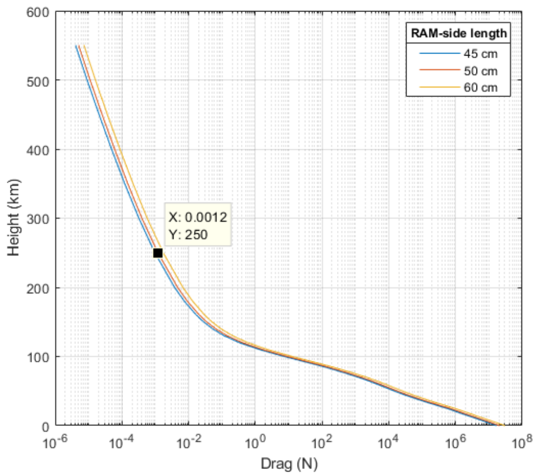

Figure 2: Drag calculated at various heights based on NRLMSIS model for three different surface areas.

From a preliminary estimation of the satellite size, the drag at 250 km for 50 cm x 50 cm area of RAM face, and density taken from predicted data for solar cycle #25 is 1.2 mN as shown in Figure 2. This calculation assumes that the surface area is constant, and the drag coefficient is 2.2. With more than 100% margin, a propulsion system with a thrust force of 3 mN was chosen. This will ensure adequate margin is maintained in the force balance and the thruster will not have to be fired constantly to maintain orbit. However, this would also mean that the 250 km will be operational limit for the satellite.

The propulsion system used in ELITE is developed by Aliena is based on Multi-Stage Ignition Compact (MUSIC) Hall thruster. The thruster is equipped with two redundant hollow cathodes. It is capable of a specific impulse of 1000 s at the given thruster force.

Attitude Control System

There are three main considerations for sizing an attitude control system: the momentum required to overcome the disturbance torques, the torque required to perform slew manoeuvre, and stability required to perform payload missions. For ELITE mission, there is not strict requirement for slew rate, therefore, the sizing will be based on the other two requirements. A preliminary analysis was conducted to derive the approximate size of the actuators required based on methods provided in [7].

The disturbance torques consists of aerodynamic force, magnetic force, gravity-gradient force, and solar-radiation pressure. All these effects act at certain location called centre of pressure (C_p). The distance of C_p from the centre of gravity (C_g) is the moment of arm for the resultant torque. We assumed the moment of arm to be 5 cm and calculated the torques based on that which are shown in Figure 3. It is seen that below 350 km, the total disturbance torque increases, mainly driven by the aerodynamic torque.

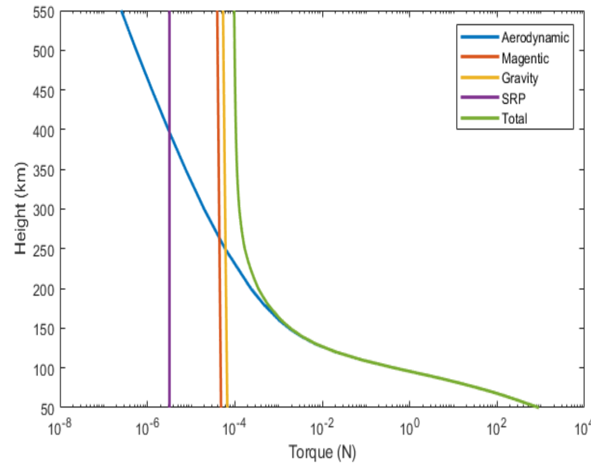

Figure 3: Disturbance torques variation with altitude calculated for a moment of arm of 5 cm.

By adding the disturbance torques to the internal torques, the reaction wheel angular momentum required can be calculated. If we assume that the maximum thrust vector misalignment is 10 cm, the required angular momentum to compensate the total disturbance torque is 398 mNms, and 9.26 mNms to compensate the external disturbance torques only.

System Specifications

The previous two sections discussed the preliminary approaches to size the orbit and attitude control systems. These two are the most significant regarding sizing a system specific for VLEO operation. Another major subsystem is the power system. To support the operations of propulsion and attitude control system constantly, the power system has to be sized to generate enough power while the satellite is operating in VLEO. To keep the drag low on the satellite for majority of the orbital flight, the solar panels cannot perform sun-tracking. This limitation increases the size of the solar panels as the satellite will only roll along with principal axis and point along the same elevation plane on which the sun vector lies. Based on this, ELITE has three deployable solar panels on each side of the principal axis and one body-mount solar panel. To increase the stability and keep the structural complexity to a minimum, the deployable panels are tilted downwards at an anhedral angle of 15°. The overall satellite physical specifications are shown in Table 1.

Table 1: Satellite specifications.

Aspect	Description
Mass	175 kg
Size	Stowed: Deployed
Propulsion	3 mN thrust, Hall-effect
Control System	4x 1.2 Nms Angular momentum 4x 90 mNm Max. torque 3x 20 Am^2 Dipole momentum
Aerodynamics	4.36 Drag coefficient 15° tilt on solar panels

AERODYNAMIC ANALYSIS

The main mission of the satellite is to demonstrate flight in VLEO. The satellite is set for launch in 2025 in a sun-synchronous orbit. The mission and system design are iterative processes to meet the overall mission requirements. In this project, the mission requirements are not stringent, therefore it is possible to amend the mission design based on the system limitations. It is important to understand the system limitations to plan the mission profile accordingly to reduce and mitigate the risks. Based on the sizes estimated of the different systems, the satellite physical size is designed. Using this design, an aerodynamic study is conducted determine the flight performance that is to be expected. As solar cycle #25 is predicted to be similar or higher than cycle #24, it is sensible to analyse the aerodynamic forces and moments based on different solar maxima. We have considered three solar maxima for our analysis: March 1989 (#22, SM1), July 2000 (#23, SM2), and April 2014 (#24, SM3). For each of those months, the drag will be calculated at 250 and 350 km.

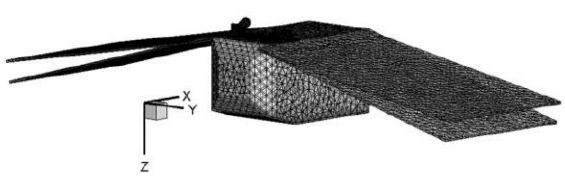

Figure 4: Mesh design of ELITE showing the solar panels tilted at 10° and 15° for TPMC simulation.

Table 2: Thermospheric density and orbital velocity at 250 and 350 km for different solar maxima.

Altitude (km)	Density based on six species (kg/m^3) ($x\ 10^{-11}$)			Velocity (m/s)
	SM1	SM2	SM3	
250	19.03	13.57	8.427	7755
350	3.768	2.104	1.217	7697
Satellite wall temperature: 300 K Gas surface interaction: DRIA Accommodation coefficient: 0.95				

Table 2 shows the thermospheric density and orbital velocity at 250 and 350 km for SM1, SM2 and SM3. The density data is obtained from NRLMSIS2.0 model based on the historical data [8]. The simulations to obtain the aerodynamic forces and moments are performed using Test Particle Monte Carlo (TPMC) based computational tool. The simulations are conducted at different solar panel tilt angles to verify the aerodynamic stability mentioned in the previous section. The model mesh with solar panel tilt angles of 10° and 15° required for TPMC simulations are shown in Figure 4.

The drag is calculated for the two satellite configurations at different pitch angles to determine the worst case. The peak pitch angles are limited to ±20° based on the operational requirements. Table 3 and Table 4 shows the variation of drag force calculated using TPMC tool for SM1-3 at 250 and 350 km for solar panel tilt angles of 10° and 15°. The drag force is seen to increase with higher solar activities and at lower altitude which is as expected. The higher solar activities also result in a higher ambient temperature that will increase the random thermal fluctuations in the incoming flow, leading to a further increase in the aerodynamic forces and moments. The drag due to variation in pitch angle varies significantly as they surface area exposed to the incoming flow increases. At 250 km, even during RAM flight (0° pitch), the drag force is higher than the maximum thrust of the propulsion system. This means that orbit maintenance at 250 km is not feasible with the current system even for SM3. It is also seen that the drag force is not much different for different solar panel tilt angle and the difference is in the order 0.1-0.2 mN. This is in-line with the drag equation as the overall surface area doesn't vary much between the two configurations.

Table 3: Drag force variation at different solar events for solar panel tilt angle of 10°.

Pitch angle (°)	Drag (mN)					
	350 km			250 km		
	SM1	SM2	SM3	SM1	SM2	SM3
-20	4.61	2.57	1.48	23.6	16.7	10.4
-6	2.29	1.26	0.72	11.5	8.09	4.98
0	1.86	1.01	0.57	9.13	6.32	3.86
6	2.23	1.23	0.7	11.2	7.87	4.84
20	4.51	2.51	1.44	23	16.4	10.2

Table 4: Drag force variation at different solar events for solar panel tilt angle of 15°.

Pitch angle (°)	Drag (mN)					
	350 km			250 km		
	SM1	SM2	SM3	SM1	SM2	SM3
-20	4.53	2.53	1.45	23.2	16.5	10.2
-6	2.27	1.25	0.71	11.4	8	4.94
0	1.86	1.01	0.57	9.14	6.34	3.88
6	2.22	1.22	0.7	11.1	7.82	4.82
20	4.44	2.47	1.42	22.7	16.1	10

To further understand the effects of solar panel tilt angle, a sensitivity study is conducted for drag and pitching moment for different tilt angles and pitch angles. The chosen solar condition for this study is SM3 since the RAM facing drag force at 250 km is close to the thrust limitation. From Figure 5, it can be derived that the maximum deviation on drag force across the two tilt angles of solar panels, namely, 10°, and 15°, is within a marginal 2.5%, which occurs at a pitch angle of 20°. In contrast, from Figure 6, it is seen that the pitching moment for solar panel with tilt of 10° is considerably higher than the other one.

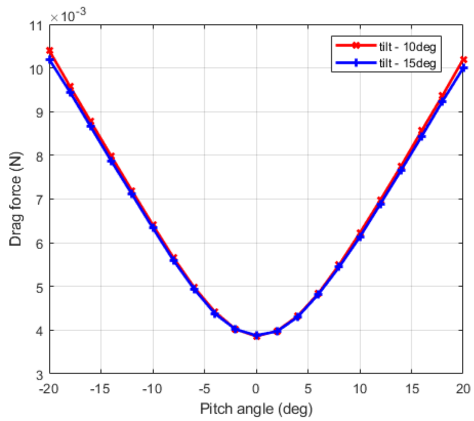

Figure 5: Drag force variation with pitch angle for solar panel tilt angles of 10° and 15°.

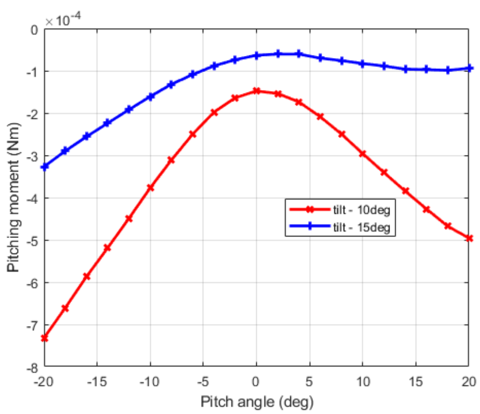

Figure 6: Pitching moment variation with pitch angle for solar panel tilt angles of 10° and 15°.

Given the significant contribution of solar panels to the drag force, the centre of pressure is likely to be located above the centre of gravity and closer to the solar panels. Therefore, increasing the tilt angle to 15° will draw the centre of pressure to be closer to centre of gravity, thereby, reducing the pitching moment. this helps to justify the solar panel tilt design for ELITE satellite. For this configuration, the pitching moment at 20° pitch angle at 350 km is -0.037 mNm and -0.14 mNm for SM1. The maximum torque of each reaction wheel in the satellite is 90 mNm, which well above the moments generated.

The drag coefficient can be evaluated from the drag force calculated using the TPMC tool. The reference surface area at 0° pitch angle is taken to be 0.3716 m^2. For a RAM flight with small variation in pitch angle, the drag coefficient varies from 4.1 to 4.5 as shown in Figure 7. Interestingly, the drag coefficient at 350 km is higher at 250 km, given its inversely proportional relationship with the atmospheric density.

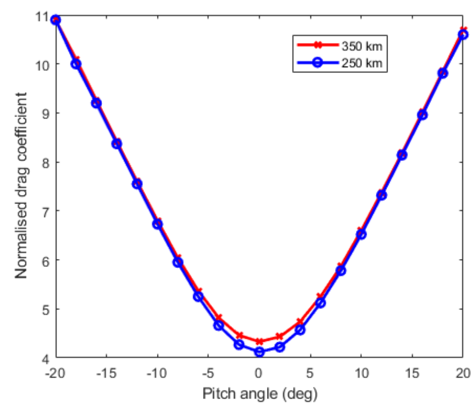

Figure 7: Normalised drag coefficient variation with pitch angle for solar panel tilt angle of 15° at 250 and 350 km.

MISSION PROFILE

Based on the system design and aerodynamic analysis, the most feasible mission profile can be simulated. ELITE mission is not planned to be launched directly into VLEO to avoid certain risks due to unknown environment. The satellite will be launched in LEO at approximately 550 km altitude. At this altitude, the satellite will conduct the early operations and verifications of all the systems. Once those tasks are completed, the satellite will gradually descent to VLEO. This will be conducted in several steps to minimise the risks caused by solar activity. The simulation parameters are shown in Table 5.

Table 5: Parameters for mission simulation.

Parameter	Value
Mass	175 kg
Surface area	0.3716 m^2
Drag coefficient	4.3
Atmosphere model	NRLMSIS2.0
Orbit inclination	98°
Initial altitude	550 km

To analyse the worst case and best case scenarios, three solar cycle events are chosen. The launch is expected to be in 2025, therefore, the predicted case of solar activity is considered to be the best case. This is the maximum of solar cycle #25. To add a margin to the best case, the cycle #23 maximum is considered, and the worst-case scenario is based on cycle #19 which is the maximum recorded solar maximum to date. For all the cases, the attitude control is assumed to maintain the drag coefficient variation within 20%.

The mission profiles are designed to perform on year of operation in VLEO. The satellite lifetime is divided into several phases. After launch, the early operations are performed at the launch altitude, followed by orbit altitude reduction phase, VLEO operation phase, and orbit decay phase. To keep the mission from being prolonged, the time taken to reach the desired VLEO altitude is six months in each case. The operational altitude in each case is calculated based on minimising the risk of deorbit. The average drag at the operational altitude shall have margin of four times or higher in case of solar storm events.

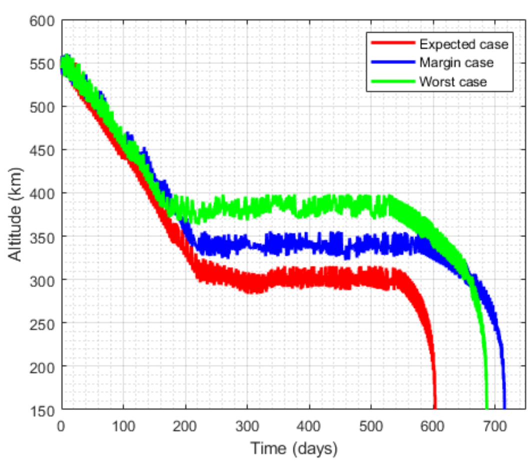

Figure 8: Altitude profile of the satellite for expected, margin and worst case scenarios.

Figure 8 shows the altitude profile of the satellite for expected, margin and worst case scenarios. The operational altitude for expected case is 300 km, 340 km for margin case, and 380 km for worst case with 90 mins of firing every three orbits. For the expected case, the lowest operational altitude is 290 km with 80 mins of firing every two orbits and highest is at 310 km with 70 mins of firing every three orbits. For the margin case, the lowest operational altitude is 330 km with 80 mins firing every two orbits and highest is at 350 km with 70 mins of firing every three orbits. For the worst case, the lowest operational altitude is 370 km with 80 mins of firing every two orbits, and highest is at 390 km with 70 mins of firing every three orbits.

Each case is designed to retain enough fuel at the end of one year of nominal operation providing the opportunity to extend the operation or perform lower altitude experiments. Table 6 shows the fuel consumption and fuel budget for each designed case. The total fuel capacity is 7 kg based on the system limitation. As indicated in Table 6, the total fuel consumption for the expected, margin, and worst-case scenarios are 4.8 kg, 4.6 kg, and 4.1 kg, respectively. The variation in fuel budget across these cases stems from poorer system parameters and adverse space weather conditions in the margin and worst cases, such as reduced thrust, increased drag density, and heightened solar activity. Consequently, the operational altitudes for the margin and worst cases are higher than in the expected case, resulting in lower fuel consumption. It is seen that the scenarios with lower drag use more fuel for orbit lowering as the orbital momentum must be overcome using the thruster. It is also seen that the operational periods are longer for margin and worst due to higher altitudes. This concludes the case study of different mission profiles that is feasible. However, it is to noted that this is just an indicator, and the actual case might differ based on the real-time solar activity data.

Table 6: Fuel budget shown for each case.

	Fuel consumption (kg) for each case		
Phase	**Expected**	**Margin**	**Worst**
Orbit lowering	2	2	1.5
VLEO operation	2.8	2.6	2.6
Total	4.8	4.6	4.1
Margin	31%	34%	41%

CONCLUSIONS

This paper introduced the ELITE mission developed in Nanyang Technological University, Singapore. The motivation, objectives and the design approach of the satellite has been discussed. The critical system design relevant to VLEO is discussed in detail along with the aerodynamic analysis which provides inputs for obtaining feasible orbital profile for the mission. With the possible orbital profile, it is possible to demonstrate the VLEO flight with high-resolution imaging which can serve as a pathfinder for future operational missions.

ACKNOWLEDGMENT

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