

IN-ORBIT LIFETIME OF SATELLITES

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Abstract

The space environment comprises several factors such as rarefied atmosphere and radiation from the Sun which, due to their computational complexity and unpredictability, can influence the prediction of the duration for which a satellite can remain in-orbit and functional. Increasing interest by academic institutions and commercial companies in satellite technologies has made the importance of modelling and understanding the lifetime of a satellite of great significance. In this paper, currently known factors of the space environment are reviewed in relation to their effects on satellite lifetime and functioning, along with current technologies to dampen their effects. Simulations on aerodynamic drag are also carried out on General Mission Analysis Tool (GMAT). In addition, the growing field of Very Low Earth Orbit (VLEO) satellites is also explored along with its set of unique characteristics and implications on satellite models.

Introduction

Satellites have been increasing in popularity over the past few years. An increasing number of institutions are beginning to dive into the capabilities presented by satellites due to the decreasing cost of launching satellites and their global coverage. There is also a growing interest in smaller satellites such as CubeSats which tend to be about 10cm sized cube-shaped satellites or slightly larger microsatellites with mass of between 50-250kg. The region in space where these satellites orbit in tends to be a rather eventful location due to its various phenomena. For Earth-orbiting satellites, there is a variety of chemical and physical interactions between the satellite and the various components of the atmosphere. Such interactions often lead to atmospheric drag and reactions with atomic oxygen present. Radiation in the form of high energy particles from the Sun or other cosmic bodies also constantly bombards this environment. Satellites in orbit also regularly go through substantial changes in temperature along with degassing effects due to the vacuum nature of space. Increasingly over the years, many areas in space (e.g. Low Earth Orbit (LEO) region) are beginning to be more congested due to a rapidly worsening issue of space debris. Thus, it is of ever-increasing importance to find out how long a satellite may last in its desired orbit. Satellite orbits can often be characterised and modelled via computational models due to the complexity of perturbations needed and frequent precessions which the satellite may undergo. There exist 6 primary Keplerian elements which can best describe an orbit. These elements are as follows: eccentricity, semi-major axis, inclination, longitude of the ascending node, argument of periapsis and true anomaly. Satellites often also comprise various subsystems which ensure the continued functioning of itself. These subsystems usually are as follows: structure, communications, attitude determination and control systems (ADCS), power and survival. Most missions today tend to function for at least 5 years to obtain various forms of data and draw trends over the years. The beginning of satellite missions often takes place by listing out a set of mission objectives and then going over a set of requirements and constraints. It is after this step that a set of possible cost-effective models are produced. However, due to the generally unpredictable nature of space and complexity of modelling the environment, there is still a lack of accurate models which can reasonably estimate the functioning period and in-orbit lifetime of any hypothetical model. The complexity of this environment only worsens when we consider areas of space much closer to the atmosphere. One such field of growing interest is the Very Low Earth Orbit (VLEO) region. This region has its own set of challenges and complexities along with opportunities for alternative satellite designs.

Methods

A General Mission Analysis Toolkit (GMAT) simulation was used to gain data on the rate of orbital decay for satellites in Very Low Earth Orbit (VLEO) due to atmospheric drag. For simulation purposes, satellite mass would be assumed to be 500kg and the drag coefficient will be assumed to be 0.47 in line with the spherical satellite model assumption made by the GMAT. Drag area is assumed to be 15m². Solar radiation effects are neglected. A satellite will be placed in a LEO orbit with semimajor axis of 6578.2km (initial altitude of 200km) while all other Keplerian elements (e.g. eccentricity and inclination) would be set to 0. The simulation will run till the satellite's altitude goes below the Karman line (100km).

The MSISE90 model would be used as an atmosphere model assuming a nominal solar cycle, with near-term predictions being made with reference to CSSI model and long-term predictions made by the Schatten model. The JGM-2 model is used as a gravity model and no model is used for tidal forces. A propagator is run until the satellite reaches 100km in altitude at which point it would stop. Data from that would be used to plot a graph of initial satellite altitude against time in orbit and graphs of the variation in altitude over time as a general reference of change in altitude over time. The satellite is assumed to have been launched on 3rd January 2023, at noon.

Subsequently, the satellite would be launched from higher altitudes with increments of 50km till the initial altitude of satellite is 550km. Time taken for the satellite to deorbit would be recorded from which, a best fit graph will be produced for circular orbit satellites with respect to their orbital radius to predict the changes in satellite altitude over time and to predict the lifetime of the satellite in orbit.

Results

1. Change in altitude for a satellite starting at 200km altitude

The change in altitude for a satellite starting at 200km is plotted in the following graph:

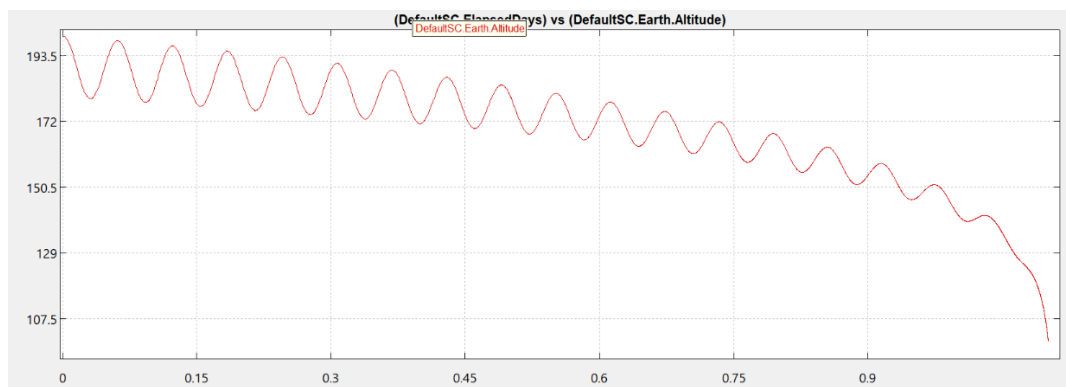


Figure 1: Graph of Satellite altitude against days elapsed for a satellite starting at 200km altitude (generated by GMAT)

As can be seen, the satellite de-orbited and began re-entry into the atmosphere within a day of being put in its orbit. This is expected to be the case as the atmospheric density in below 200km altitude is very high and would cause great drag which would lower the altitude of the satellite further and bring it to an atmosphere with higher density, causing greater drag and a continual cycle leading to the gradual lowering and eventual de-orbit of the satellite.

2. Relationship between in-orbit lifetime and initial altitude of a satellite

Similar simulations were carried out as before with similar results, a decreasing altitude with a sinusoidal variation within.

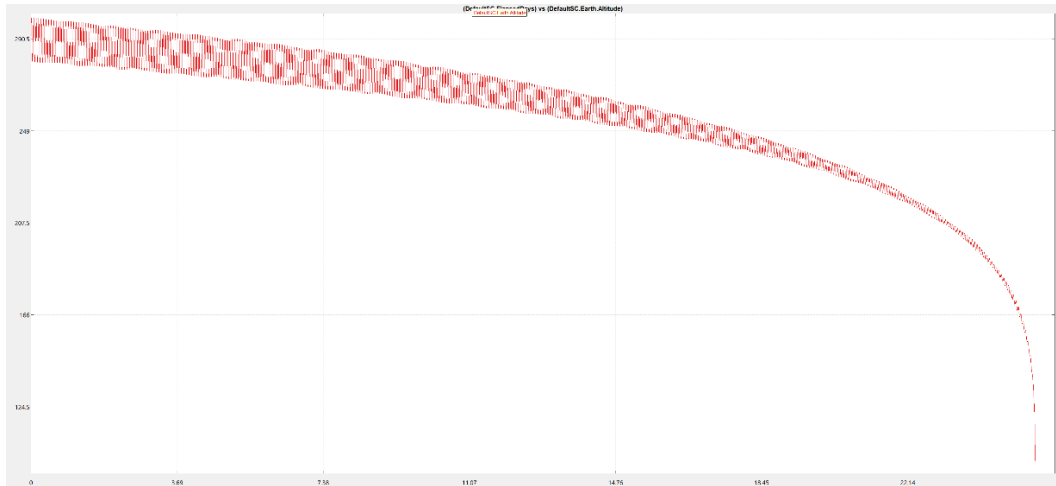


Figure 2: Graph of Satellite altitude against days elapsed for a satellite starting at 300km altitude (generated by GMAT)

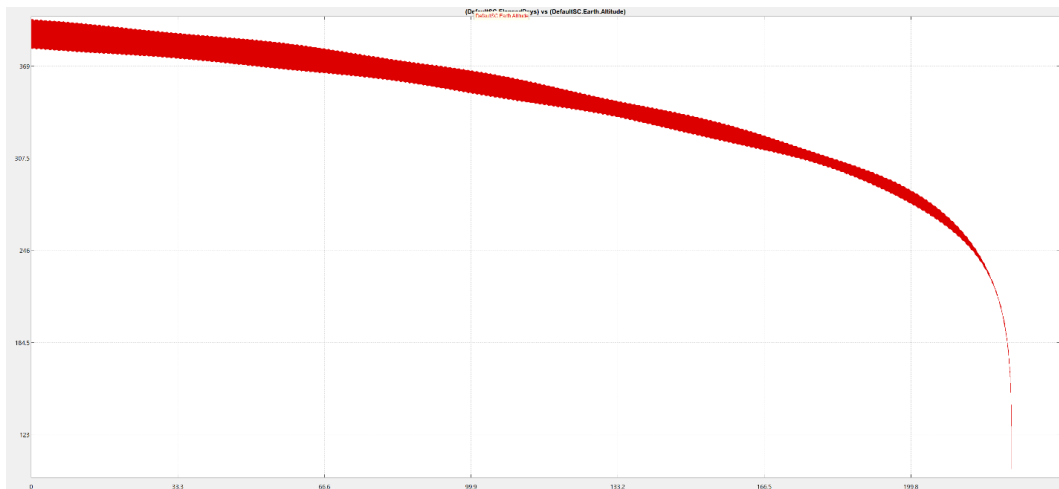


Figure 3: Graph of Satellite altitude against days elapsed for a satellite starting at 400km altitude (generated by GMAT)

The time taken for the satellite to de-orbit was then found using a data table generated by GMAT comprising of days elapsed and the altitude of the satellite. The days elapsed till the satellite reached 100km in altitude was then put in a table with the initial satellite altitude as follows:

Initial altitude (km)	In-orbit lifetime (days)
200	1.10102
250	6.386021
300	25.35058
350	78.64104
400	222.6014
450	416.5526
500	464.2146
550	1181.447

Table 1: table of initial satellite altitude and in-orbit lifetime before satellite reaches 100km altitude

Using this data, we can see that higher altitudes result in a longer in-orbit lifetime. However, this relationship is not linear. Microsoft Excel was then used to plot a scatter plot and a trend line as follows:

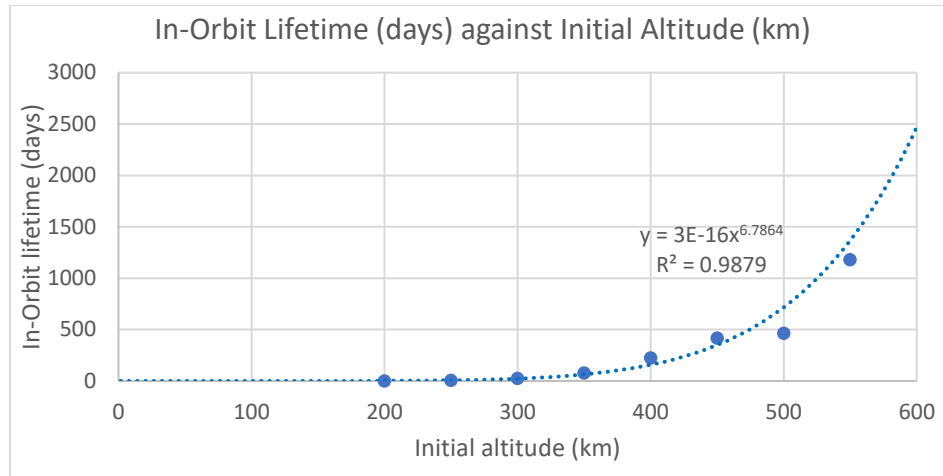


Figure 3: graph of In-Orbit Lifetime of satellite against initial altitude of satellite

The result was a trendline of $y = (3 \times 10^{-16})x^{6.7864}$ (where y is the in-orbit lifetime of the satellite and x is the initial altitude) with an R^2 value of 0.9642. This graph can correctly show that at higher altitudes, the in-orbit lifetime of a satellite increases in a manner like this equation above, should the satellite be in VLEO.

Discussion

1. Atmospheric drag and atomic oxygen

Increasing altitudes has been correlated with decreasing atmospheric densities. This leads to reduced drag in higher altitudes as atmospheric density is linearly proportional to drag experienced by the satellite. As a result, satellites in LEO would experience this as a more profound effect than would satellites in higher orbits like in Medium Earth Orbit (MEO) or Geostationary orbits (GEO). Prolonged drag would gradually lead to a reduction in orbital speed of the satellite which in turn would cause a lowering of orbital altitude and eccentricity of the satellite. If left unchecked for a long time, it may lead to satellite de-orbiting. Additionally, drag would cause certain areas of the satellite to heat up beyond their maximum operating temperature which could lead to subsystem failure or parts of the satellite being exposed to greater erosion and reaction with atomic oxygen in the atmosphere.

From simulations above, we can deduce a better estimate for the in-orbit lifetime of satellites, with similar geometries or mass, in VLEO from its initial altitude with the equation $y = (3 \times 10^{-16})x^{6.7864}$. For satellites in higher altitudes, their orbits tend to be much stabler and decay much slower due to the substantially lower atmospheric densities.



Figure 4: Graph of Satellite altitude against days elapsed for a satellite starting at 1000km altitude (generated by GMAT)

Such satellites usually have lifetimes of about 7-10 years. For satellites in orbits such as MEO or GEO, design and technological changes need to be made with other effects like radiation rather than atmospheric drag.

2. Atomic Oxygen

The atmosphere consists of various elements. However, with increasing altitudes, it would also be subjected to a greater dose of ionizing radiation from space. An effect of this is the decomposition of oxygen into atomic oxygen. This leads to the effect of a generally higher density of atomic oxygen in the upper atmosphere.

Atomic oxygen is a highly reactive substance which can increase the rate of corrosion of the surface of a satellite drastically. Though the ambient flux of Atomic Oxygen (AO) is relatively low in LEO, the high orbital speed of satellites in this region causes a higher incident flux and collision energy of about 4.5 keV which is sufficient for many reactions involving atomic oxygen to occur. Some of these reactions are addition, abstraction, elimination, replacement, and insertion reactions. Depending on the morphology of the surface and its optical, mechanical, and thermal properties, AO may either be specularly reflected off the surface in its original or charged state, may react with the atomic nitrogen on the satellite surface to produce excited nitrous oxide which produces a glow as it leaves its excited state. It may also react with the surface to produce non-adherent oxides if the surface is made of silver, polymers, carbon, and osmium which leads to a net corrosion. AO may also react with oxidative metals to produce adherent oxides which can cause growth of the satellite surface. Some results of these are degradation of optical imaging equipment due to mass loss and changes in surface morphology and AO interactions seemed to detune wavelength band width of the filters used. Space power generation is also affected because of losses in composite thickness and the reflectivity of materials used in solar arrays were also affected.

There have been some attempts to possibly alleviate such effects. Some proposed methods are coating surfaces with oxidative metals which would grow in thickness while in space. Alternative techniques involve not using materials which are shown to react with AO and to re-orient these surfaces to prevent direct AO exposure. Application of a thin coating on surfaces is the most common method used to prevent AO degradation. This usually prevents the surface from reacting with AO or in other cases, causes alternative reactions to prevent AO diffusion through the surface. Examples of these coatings are silicon dioxides and aluminium.

3. Radiation

a. Single event upset (SEU)

For a satellite in space, radiation is one of the most prominent effects. Radiation primarily originates from Solar events like solar flares or Solar Proton Events (SPEs) or from Cosmic rays. These events tend to inject highly energetic particles like protons and electrons into the space surrounding Earth. The continual rotation of the Earth's inner core continually generates a magnetic field, also known as a magnetosphere. These energetic particles being charged often get trapped within the magnetosphere. Eventually they form up in regions of higher energetic particle density known as the Van Allen's Belts. Flux of charged particles far exceeds normal flux seen in other regions. As such, for an Earth orbiting satellite, there are 3 main radiation sources, the radiation trapped in Earth's magnetosphere, the radiation from major solar events, and the radiation from cosmic rays. The charged and energetic nature of these particles tends to cause a range of effects on satellites. When a highly energetic particle collides with a microelectronic circuit, it may ionize atoms along its path and create electron hole pairs. Electric fields in the device then sweep these electron holes, also called free charges, into the source or drain point of the device, a temporary current change may take place, resulting in a signal generated and a state change in the device [10]. This is known as a Single Event Upset (SEU) and is usually harmless. However, if the free charges interact with a parasitic transistor instead, they may become integrated into the circuit and cause a positive feedback loop which can increase power consumption till the device burns out or gets reset. This is generally more serious as it can lead to subsystem or satellite's not working.

b. Total Ionization Dose (TID) and Displacement Damage Dose (DDD)

Other effects may also occur such as Total Ionization Dose (TID) whereby insulating layers can be ionized by these energetic particles and eventually build-up positive charges [9]. This usually ends up shifting the threshold of field effect transistors and causing some leakage current to occur even when certain devices are switched off. It is often seen in satellites in Low Earth Orbit (LEO) due to the presence of the South Atlantic Anomaly (SAA) and can be exacerbated by SPEs or Solar Energetic Particle Events (SEPEs). However, electron enhancement is the leading cause for TID in satellites of higher orbits such as Medium Earth Orbit (MEO) or Geostationary Orbit (GEO).

Magnetospheric shielding against protons would only worsen the effects of the radiation due to an increased flux of energetic electrons in these regions. Displacement Damage Dose (DDD) is another such effect which can occur due to radiation whereby incident radiation from an energetic particle can displace atoms in a lattice [9]. This usually affects Bipolar junction transistors but can also reduce the lifetime of minority carriers often found in solar arrays. This would usually lead to a drop in the power which the solar array can produce and is often worse affected by energetic protons than electrons. Furthermore, it has been found that most of these protons originate as trapped protons from the magnetosphere. However, in higher altitudes, DDD is worse affected by electron enhancement events than it is by SPEs. It has been found that if a 1 in 150-year solar storm hits the solar arrays of a GEO satellite, there can be a 7.6% drop in power generation [9].

c. Charging (surface and internal)

Radiation in space can also cause various kinds of charging to the satellite. Surface charging is often seen in satellites as electrons from the space environment are accumulated on surface elements which then raises the potential of the surface element and currents would travel into and out of the surface element. These electrons usually arise after being heated about 20 earth radii behind the earth in its magnetotail and get driven to the Earth due to an inductive electric field generated by the snapping of the geomagnetic field to its normal dipolar configuration from a stressed configuration. This charging continues till it hits a potential value known as the surface's floating potential. At this point, no currents would flow in or out of the surface element. The floating potential varies depending on the electrical properties of the surface element or the temperature of the surrounding plasma in space. Charging to substantially higher values would be achieved by the secondary emission properties of the surface and the flux of energetic electrons with energies greater than 30keV. Should the surface element be connected to the main satellite, this charge on the surface element would slowly leak out. However, if its isolated, the charges may remain there for a long time. During a solar storm, the potential of the surface element can jump much more and eventually result in an electrostatic discharge if the potential exceeds the satellite's breakdown voltage. This is one of the leading causes of mission failure. The first spacecraft mission believed to be lost by a surface-charging anomaly was DSCS-II (9431) on June 2, 1973. Satellites in lower altitudes would not be subject to this effect significantly due to lower electron flux in areas lower in the atmosphere. For satellites in LEO or polar orbits, surface-charging occurs as the satellites pass through auroral arcs [10].

Internal charging can also occur when energetic electrons with energies greater than 300keV pass through the satellites and deposit their charges inside it. This usually occurs when there is a generally high energetic electron flux and is often seen along field lines with L values between 3 and 7 and usually results in phantom commands, electronic noise or soft errors. More serious consequences may also emerge at times. Internal charging is generally lower during solar maximums but increases in the falling phase of a solar cycle. Lastly, the upper atmosphere often heats and expands due to auroral currents, solar X-rays or ultraviolet radiation and precipitation of radiation belts and plasma sheet particles into the atmosphere and can increase the density of the atmosphere, at altitudes where most space stations are found, by 100 times. The primary effect of this is that the satellite may decay faster, and ephemeris errors may occur due to differences in expected and actual satellite positioning. So far there have been some attempts to try and mitigate these effects, such as designing the satellite to withstand the worst estimated solar event during its lifetime and covering solar arrays in a thin glass layer which while does protect the arrays from effects like DDD and from protons with energies up to 10 MeV, cannot protect the arrays in cases like a SPE where the flux of protons above 10MeV increases drastically. For example, the GOES 7 satellite's solar array current was reduced by nearly 10% because of two large solar proton events in 1989. Increasing shielding aluminium thickness has also shown to reduce the effects of TID significantly as electrons causing it are not energetic enough to penetrate it. However, other parts of the satellite need to be radiation hardened such as circuital components to prevent SEEs. The orbit of the satellite must also be chosen such that it can receive the least possible radiation over its lifetime. This can be done by preferring orbits which can keep the altitude of the satellite low as higher altitudes risk exposing the satellite to solar winds and cosmic rays. The orbit should also be chosen to avoid areas such as the Van Allen's belts, especially so around the SAA which tends to drop down to altitudes of 200km. Circuital elements can also be designed in different ways to resist radiation better. This is known as radiation hardening by design [10].

4. Space debris and clutter

Space debris is another growing problem. The issue of space clutter has been growing greatly over the years especially due to the increased production of smaller satellites and CubeSats by various institutions. One of the main techniques to avoid worsening the issue of space debris has been to put official limits on privately-owned satellites in terms of

their in-orbit lifetime. Other methods include greater space situational awareness (SSA) systems and using Reaction Control System (RCS) to correct orbits to avoid space debris.

5. Temperature fluctuation

Space also presents a great deal of temperature fluctuation. For satellites behind the Earth, away from the Sun, temperatures can drop to 173K while for satellites facing the Sun, the temperature can rise to 393K. Most functioning equipment on a satellite usually have a range of temperatures between which they can properly function, and maintenance of this range is crucial to the success of the satellite mission. If the satellite hits temperatures beyond what the satellite components can tolerate, the subsystem may be permanently damaged or the mission itself may fail. Some common methods to maintain this range includes the use of radiators for losing heat, electrically powered heaters, heat pipes and choosing different materials which are more thermally radiative.

6. Outgassing and vacuum

Up in higher altitude orbits such as MEO, space conditions tend to vary significantly more. Atmospheric density drops more and there is a more profound vacuum effect. Various materials have been shown to have a weaker structural integrity in a vacuum than when in an atmosphere. Part of this effect is due to their structures being affiliated with various gases which while on Earth provided them with great structural strength, were lost in space due to outgassing. A simple solution most employed is the use of materials which are resistant to outgassing or undergo the process the least.

7. VLEO

Recently, in light of a new paradigm shift in space technologies, the LEO region of space has been getting increasingly used up by satellites and space junk. This only goes on to contribute to space clutter and a growing possibility of the Kessler syndrome occurring. This has brought new focus to an even lower region of space. The VLEO region of space typically defined as consisting of orbits lower than 450km in altitude, has shown new potential for satellite companies and missions for the purposes of Earth observation.

VLEO is a new place with very few accurate models which can describe the space environment in the area. This is due to some key differences in the location not found in many other regions. The atmosphere is more rarefied with various kinds of reflections and gas-surface interactions affecting how the satellite gets lift and drag forces. The atmospheric density in the area tends to be much higher than in LEO there is a much greater atomic oxygen concentration which reacts much more with the satellite's surfaces. However, there is also a much greater protection at this altitude from radiation due to it being much better shielded by the Earth's magnetosphere. Power required to send signals to the ground is also much lesser due to increased proximity to the surface. Congestion and risk of collision with space junk is also much lower due to greater atmospheric drag causing space junk to clear up and de-orbit faster than at higher altitudes. Lower altitude also means that rockets can send more payload to orbit at once and greatly reduces cost of sending a satellite to space. All this means a slew of newer technologies and satellite designing would be needed to sustain missions in VLEO. But VLEO also has its potential in the domain of Earth imaging satellites. In specific, Electro Optic (EO) satellites and Synthetic Aperture Radar (SAR) satellites have some of the greatest utility for being placed in VLEO.

a. Opportunities

The low altitude nature of VLEO provides an excellent opportunity for EO satellites to use smaller aperture cameras or smaller equipment. This is due to the low altitude of VLEO providing better resolution due to increased proximity to the surface [1]. Cost of launch also decreases for smaller VLEO EO satellites because the same rocket can be used to launch multiple EO satellites. Alternatively, using the same sized equipment for VLEO EO satellites as most other current EO satellites, we can get a better resolution of the Earth's surface.

VLEO SAR satellites also benefit due to their increased swath size as signals can be sent at a greater angle to the surface without being dispersed too much before it reaches the satellite. These satellites would also have a lower power requirement as reduced altitude results in greater proximity to ground stations which leads to reduced signal attenuation through the atmosphere.

b. Unique challenges

However, while there is much lesser radiation and greater proximity to the surface, the atmospheric density also increases much more. Thus, atmospheric drag is much greater for satellites in VLEO, leading to generally shorter in-orbit lifetimes. Usually, without orbital extension, most VLEO satellites would remain in orbit for several months to about a couple of years. The flow of air in this region is also different from that seen in lower altitudes as it is more rarefied and needs to be considered as particle flows. For most satellites in this region, this time is generally suitable and allows for satellites to be phased out quickly to be replaced by satellites with better technology. However, for longer lasting missions, more measures may need to be taken to ensure greater in-orbit lifetime. Satellites for such missions may take on more aerodynamic structures. Some satellites are also proposed to make use of greater atmospheric density in VLEO to provide lift and keep satellite in orbit for a longer time. The greater atmospheric density of VLEO also comes with increased AO densities which also leads to increased corrosion and reactions with the surface. Thicker coats of materials inert to AO may be needed. There is still a lack of materials which do not degrade under such a great density of AO. Additionally, since this area has only recently been probed, there is still a lack of complete models for the interactions and atmospheric properties of this area.

c. Technology to counter orbital decay

Some literature also proposes the use of alternative forms of propulsion. One example of this is the atmosphere breathing electric propulsion (ABEP) system. This system takes in rarefied gases found in the atmosphere of VLEO and uses it as propellant. The thruster of the system then ionizes the gases and expels these gases out at high speeds to produce thrust. Power for ionizing the gases and expulsion can be done via electricity and can be linked to the power subsystem of the satellite [2]. The design of this propulsion system must be varied according to altitude of orbit and can operate well between altitudes of 120km to 250km. However, literature has shown that exhaust plumes made by electrically propelled systems in conjunction with surface charging of the satellite can also add more drag on the satellite in the form of electrostatic attraction [2].

Conclusion

Space is an area full of various interactions. Radiation is shown to be a common effect with various effects on satellites such as reductions in power generation, SEUs, surface and internal charging. Simulation data has shown the gradual decrease in satellite altitudes over time due to aerodynamic drag and proposed a model for the estimation of orbital decay of a satellite in VLEO. Atomic oxygen has been shown to be a very reactive component of the space environment which has various effects on the surfaces of satellites. Some technologies and current techniques have also been explored and reviewed such as the use of radiation hardening and using various kinds of electric heaters to increase internal satellite temperature.

The growing interest in the region of VLEO has also been explored along with its numerous advantages in relation to EO satellites and SAR satellites. VLEO satellites could be a much cheaper alternative to current higher altitude satellites due to greater ride share feasibility and smaller components being required to achieve similar resolutions. However, the low altitude nature of this region presents greater atmospheric density compared to space in higher altitudes. Thus, various forms of passive and active orbital extension methods have been proposed and reviewed. The issue of greater AO continues to be an issue for VLEO satellites and new developments need to be made to curb the impact of this area in space.

Novel research in terms of quantifying the probabilistic impacts of radiation and rapid thermal fluctuations on satellite subsystem lifetime and functioning are still required to gain better understanding of the space environment. More data on atmospheric conditions in the altitude of VLEO satellites are needed to form a better model of the conditions and properties in this area. It would also help future satellite development for such altitudes much easier and feasible. Lastly, the electrodynamic drag experienced by satellites employing electric propulsion needs to be better modelled so that the feasibility and utility of such engines can be better identified.

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