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Article

Orbit Maintenance and End-of-Life Disposal Strategy for Micro-satellites Operating in Very Low Earth Orbit

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Abstract: The increasing deployment of small satellites in Low Earth Orbit (LEO) has intensified concerns regarding orbital sustainability, collision risk, and space debris accumulation. Satellites operating in Very Low Earth Orbit (VLEO), around 400 km altitude, experience significant atmospheric drag, leading to rapid orbital decay and frequent orbit maintenance requirements. This paper examines orbit maintenance strategies for a representative 200 kg satellite operating within this altitude regime. The analysis includes the primary environmental perturbations affecting orbital lifetime, station-keeping maneuver requirements, expected maneuver frequency, propellant consumption estimates, orbital decay behavior, and planned end-of-life reentry approaches. Results indicate that atmospheric drag dominates station-keeping requirements and can necessitate annual velocity corrections ranging from 20 to 80 m/s depending on solar activity. Furthermore, the naturally short orbital lifetime of satellites below 400 km offers a sustainable pathway for debris mitigation through controlled or semi-controlled atmospheric reentry.
Keywords: Atmospheric Drag, Low Earth Orbit, Orbital Decay, Orbit Maintenance, Reentry, Satellite Operations, Station Keeping, Space Debris Mitigation

1. INTRODUCTION

The rapid growth of commercial and governmental satellite constellations has increased the population of spacecraft operating in Low Earth Orbit (LEO). Orbits between 350 km and 400 km are attractive due to reduced communication latency, improved imaging resolution, and lower launch energy requirements. However, these benefits are accompanied by increased atmospheric drag, resulting in significant orbital decay.

In this paper, the analysis is carried out considering a representative ISRO microsatellite-class mission operating in the 350–400 km altitude range. A spacecraft mass of approximately 200 kg with a hydrazine monopropellant propulsion system is assumed, reflecting the characteristics of typical ISRO Earth observation and technology demonstration microsatellite missions. Orbit maintenance is modeled using periodic low-ΔV maneuvers representative of ISRO operational practices, and the corresponding propellant requirements, orbital decay characteristics, and end-of-life disposal strategy are evaluated.

In addition to operational considerations, international guidelines increasingly emphasize responsible disposal practices. Satellites operating below 400 km naturally reenter within relatively short timescales, making this altitude range particularly favorable for sustainable space operations.

2. ORBITAL ENVIRONMENT

Very Low Earth Orbit (VLEO), typically defined as the altitude range between 250 km and 450 km, offers several advantages for Earth observation, remote sensing, and low-latency communication missions. The reduced orbital altitude enables higher imaging resolution, lower communication latency, and smaller launch requirements. However, these benefits come at the expense of significantly increased atmospheric drag compared to higher Low Earth Orbit (LEO) missions.

A representative 200 kg satellite operating in a circular orbit between 350 km and 400 km travels at an orbital velocity of approximately 7.67–7.72 km/s. Although the atmospheric density at these altitudes is several orders of magnitude lower than at sea level, collisions with residual atmospheric particles continuously remove orbital energy. This aerodynamic drag gradually decreases the semi-major axis, leading to orbital decay unless periodic station-keeping maneuvers are performed.

The magnitude of drag depends primarily on atmospheric density, spacecraft velocity, cross-sectional area, drag coefficient, and spacecraft mass. Atmospheric density is highly variable and is strongly influenced by solar activity, making accurate orbit prediction and maintenance a challenging task for VLEO missions.

Parameter	Value
Satellite Mass	200 kg
Orbit Altitude	350–400 km
Orbit Type	Circular LEO
Orbital Velocity	7.67–7.72 km/s
Cross-sectional Area	1–2 m^2
Drag Coefficient	2.1–2.4
Mission Duration	3–5 years

Table 1Representative Satellite Parameters

The values listed in Table 1 represent a typical microsatellite or small Earth observation spacecraft and are used throughout this study to estimate atmospheric drag, station-keeping requirements, propellant consumption, and orbital lifetime.

3. EXTERNAL FACTORS AFFECTING ORBIT MAINTENANCE

3.1 Atmospheric Drag

Atmospheric drag is the dominant non-conservative perturbing force acting on satellites operating below approximately 500 km altitude, particularly in the Very Low Earth Orbit (VLEO) regime (350–450 km).

Unlike gravitational perturbations, atmospheric drag is a dissipative force that permanently removes mechanical energy from the orbit. Consequently, the satellite experiences a gradual reduction in semi-major axis and orbital altitude, eventually leading to orbital decay and atmospheric re-entry if no orbit maintenance strategy is employed. The severity of drag increases significantly as altitude decreases because atmospheric density increases approximately exponentially with decreasing altitude.

The aerodynamic drag acceleration is expressed as

$$a_d = F_D / m$$

where the drag force is

$$F_D = 0.5 * \rho C_D A (v_{rel})^2$$

Combining these expressions yields

$$a_d = 0.5 * \rho C_D A(v_{rel})^2 / m$$

Where a_d is drag acceleration in m/s², ρ is atmospheric density in kg/m³, C_D is drag coefficient, A is effective cross-sectional area in m², m is spacecraft mass in kg and v_{rel} is velocity relative to the atmosphere in m/s.

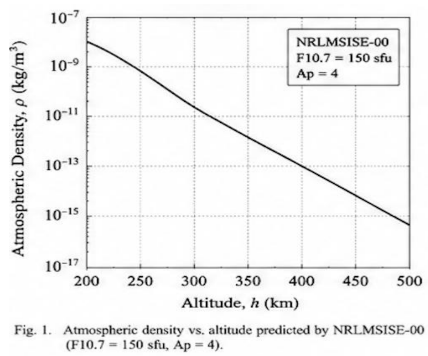

Figure 1 Atmospheric density vs. altitude predicted by NRLMSISE-00 (F10.7 = 150 sfu, Ap = 4)

Atmospheric density can vary by more than an order of magnitude due to solar activity, resulting in large fluctuations in orbital decay rates.

3.2 Solar Activity

Solar activity is one of the most significant factors influencing atmospheric density in the thermosphere and, consequently, the aerodynamic drag experienced by satellites in Low Earth Orbit (LEO) and Very Low Earth Orbit (VLEO). The Sun continuously emits electromagnetic radiation across a broad spectrum, including ultraviolet (UV), extreme ultraviolet (EUV), and X-ray wavelengths, as well as streams of charged particles known as the solar wind. Variations in this solar output alter the thermal structure of the upper atmosphere, leading to substantial changes in atmospheric density and satellite drag.

During periods of high solar activity, the thermosphere can expand by several tens of kilometers. Consequently, satellites operating at altitudes between 300 km and 500 km encounter significantly denser atmospheric conditions than during solar minimum. At an altitude of approximately 400 km, atmospheric density may increase by a factor of 3–10, while during extreme solar storms, temporary increases exceeding an order of magnitude have been observed. Since atmospheric drag is directly proportional to atmospheric density,

$F_D \propto \rho$,

any increase in density results in a corresponding increase in drag force, leading to faster orbital decay, higher propellant consumption for station-keeping, and reduced satellite lifetime.

Solar activity follows an approximately 11-year solar cycle, characterized by alternating periods of solar minimum and solar maximum. Several indices are commonly used to quantify solar activity in orbital prediction models:

i. F10.7 Solar Flux Index: Measures solar radio emission at a wavelength of 10.7 cm (2800 MHz) and serves as a widely accepted proxy for EUV radiation. Higher F10.7 values generally correspond to increased thermospheric density.

ii. Ap Index: Represents the daily average level of global geomagnetic activity and indicates disturbances in Earth's magnetic field caused by interactions with the solar wind.

iii. Kp Index: A quasi-logarithmic index describing geomagnetic activity over 3-hour intervals. Elevated Kp values are often associated with geomagnetic storms that enhance atmospheric density.

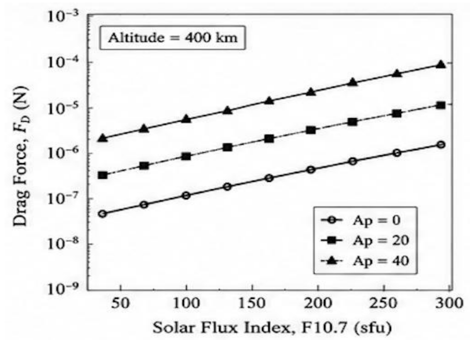

Fig. 3. Drag force at 400 km altitude as a function of solar flux index (F10.7) for different geomagnetic activity levels (Ap).

Figure 2 Drag force at 400 km altitude as a function of F10.7 for different Ap

3.3 Earth's Oblateness (J_2 Effect)

The Earth is not a perfect sphere but an oblate spheroid, with a slightly larger equatorial radius than its polar radius due to its rotation. This equatorial bulge causes deviations from a purely spherical gravitational field, resulting in gravitational perturbations that are commonly represented by the second zonal harmonic coefficient, J_2. The J_2 perturbation is the largest and most significant non-central gravitational effect acting on satellites in Low Earth Orbit (LEO).

Unlike atmospheric drag, the J_2 effect is a conservative perturbation that does not cause a loss of orbital energy or a reduction in orbital altitude. Instead, it produces gradual, long-term changes in the orientation of the satellite's orbit while leaving the semi-major axis nearly constant. These secular perturbations become increasingly important for missions requiring precise orbit maintenance and ground-track repeatability.

The primary effects of the J_2 perturbation include:

i. Nodal regression: A gradual precession of the orbital plane, causing the right ascension of the ascending node (RAAN) to shift over time.

ii. Argument of perigee rotation: A slow rotation of the orbit's line of apsides, changing the orientation of the perigee within the orbital plane.

iii. Ground track drift: Progressive displacement of the satellite's ground track due to changes in orbital geometry, which can affect revisit times and coverage patterns.

3.4 Solar Radiation Pressure

Solar photons impart momentum to spacecraft surfaces. For a compact 200 kg satellite, the resulting perturbation is generally minor compared with atmospheric drag but can influence long-duration orbital evolution.

3.5 Space Weather Events

Geomagnetic storms can temporarily increase atmospheric density by several hundred percent, accelerating orbital decay and increasing station-keeping demand.

4. ORBITAL DECAY CHARACTERISTICS

Atmospheric drag continuously removes orbital energy from satellites operating in Low Earth Orbit (LEO). In the absence of orbit maintenance maneuvers, the orbital altitude decreases gradually over time, with the rate of decay increasing rapidly as the spacecraft descends into denser regions of the thermosphere. Since atmospheric density varies approximately exponentially with decreasing altitude, orbital decay is inherently nonlinear, becoming progressively faster at lower altitudes.

For a representative ISRO-class microsatellite (mass approximately 200 kg) without orbit maintenance, the expected natural orbital lifetime under average solar conditions is summarized in Table 2.

Initial Altitude	Approximate Lifetime	Relative Decay Rate
400 km	1–2 years	Low
375 km	8–15 months	Moderate
350 km	4–10 months	High
325 km	2–5 months	Very High
300 km	1–3 months	Severe

Table 2. Typical natural orbital lifetime without maneuvers

The decay process can be divided into four distinct phases:

i) Stable Operational Phase (350–400 km): Atmospheric drag produces a slow and nearly linear reduction in altitude. Satellites equipped with onboard propulsion, such as ISRO microsatellites, compensate for these losses through periodic station-keeping maneuvers, maintaining the spacecraft within its designated operational orbit.

ii) Accelerated Decay Phase (300–350 km): As the spacecraft descends, atmospheric density increases rapidly, causing a noticeable increase in drag acceleration. Without corrective maneuvers, orbital altitude begins to decrease at an accelerating rate, reducing the remaining orbital lifetime.

iii) Rapid Descent Phase (200–300 km): Below approximately 300 km, atmospheric drag dominates orbital motion. The spacecraft experiences substantial losses in orbital energy over successive revolutions, leading to rapid altitude reduction and significantly shorter orbital periods.

iv) Atmospheric Re-entry (< 200 km): Once the spacecraft descends below approximately 200 km, aerodynamic heating and structural loads increase dramatically. Most spacecraft structures undergo fragmentation and complete burn-up during re-entry, although a limited number of high-melting-point components, such as titanium or stainless-steel elements, may survive to reach the Earth's surface. For operational ISRO microsatellite missions, natural orbital decay is generally not allowed to progress unchecked.

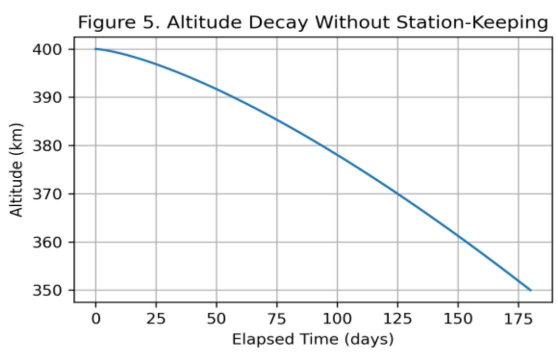

Figure 3 Altitude decay without station-keeping

Instead, periodic orbit maintenance maneuvers are performed to counteract atmospheric drag, maintain the required mission altitude and thus extend mission life.

5. ORBITAL MAINTENANCE MANEUVERS

For the ISRO mission considered for the paper, an operational concept employing four scheduled maintenance maneuvers per week is adopted.

Atmospheric drag continuously reduces the orbital energy of satellites operating in Very Low Earth Orbit (VLEO), resulting in a gradual decrease in orbital altitude. To maintain the desired operational orbit, periodic orbit maintenance maneuvers are performed using the onboard propulsion system. Unlike large impulsive orbit-raising maneuvers, VLEO missions generally employ frequent, low-magnitude corrections that compensate for the accumulated drag while minimizing disturbances to spacecraft operations.

Parameter	Typical Value
Nominal operating altitude	400 km
Orbit maintenance strategy	Frequent low-thrust corrections
Number of maneuvers	4 per week
Burn duration for each	30–40 s
Altitude variation	Typically, less than ±1 km

Table 3 Typical orbit maintenance strategy summary

For the proposed mission, an orbit maintenance strategy similar to current ISRO operational practices is considered. Rather than allowing the satellite altitude to decay by several kilometers before performing a major reboost, the spacecraft executes four scheduled maintenance maneuvers per week, each with a thrust duration of approximately 30–40 seconds. These short-duration burns compensate for atmospheric drag before significant orbital decay occurs, thereby maintaining the spacecraft within a narrow operational altitude band.

A representative maintenance profile is illustrated below: This strategy provides several operational advantages:

i. Maintains nearly constant orbital altitude and ground-track repeatability.

ii. Reduces peak thrust requirements by distributing the total correction over multiple burns.

iii. Minimizes mission interruptions associated with large orbit-raising maneuvers.

iv. Improves orbit determination accuracy and simplifies mission planning.

v. Provides flexibility to adapt maneuver timing during periods of enhanced solar activity.

The required maneuver frequency is governed primarily by atmospheric density, which varies with altitude and space weather conditions. Assuming a nominal operational profile of four maneuvers per week, the annual orbit maintenance requirements become approximately:

Parameter	Representative Value
Maneuvers per week	4
Maneuvers per year	≈ 208
Burn duration	30–40 s each
Total engine operating time	1.7–2.3 hours/year
Annual station-keeping ΔV	25–40 m/s (for 400 km)

Table 4 Typical annual orbit maneuver plan

At lower operating altitudes, such as 350 km, atmospheric drag increases substantially, leading to greater propulsion demands. Under similar operational conditions, the annual station-keeping requirement may increase to approximately 50–80 m/s, depending on solar activity and spacecraft ballistic coefficient. Consequently, propulsion system sizing and onboard propellant allocation must account for both nominal drag conditions and worst-case space weather scenarios to ensure the desired mission lifetime.

6. PROPELLANT CONSUMPTION ESTIMATES

The monthly propellant requirement for orbit maintenance depends on the total station-keeping ΔV, spacecraft mass, propulsion system specific impulse, and atmospheric drag. Assuming a 200 kg satellite equipped with a hydrazine monopropellant thruster (Isp = 225 s) and following the proposed orbit maintenance strategy of four short maneuvers per week, the propellant consumption can be estimated using the rocket equation. For the relatively small ΔV values considered here, the required propellant mass increases almost linearly with annual ΔV.

The relationship between orbital decay, required velocity correction, propellant consumption, and thruster operating time can be established using the vis-viva equation, the Tsiolkovsky rocket equation, and the mass flow rate equation.

For a circular orbit, the vis-viva equation is

$$v = (\mu/a)^{0.5},$$

where v is the orbital velocity, a is the orbital radius (semi-major axis), and μ is the Earth's gravitational parameter. Differentiating the equation yields the relationship between a small change in orbital altitude and the corresponding velocity change,

$$dv = -(v/2a)da.$$

The required velocity correction is converted into propellant consumption using the Tsiolkovsky rocket equation,

$$\Delta v = I_{sp} g_0 ln(m_0/m_f)$$

which, for small orbit maintenance maneuvers, can be approximated as

$$dm \approx mdv/(I_{sp} g_0),$$

where m is the spacecraft mass, I_{sp} is the specific impulse, and g_0 is the standard gravitational acceleration.

The propellant mass consumed is related to the thruster operating time through the mass flow rate equation,

$$\dot{m} = dm/dt = F/(I_{sp} g_0),$$

where F is the thrust produced by the propulsion system. Rearranging,

$$dt = -dm I_{sp} g_0/F.$$

Combining the three equations provides a direct analytical relationship between orbital altitude loss and the required thruster operating time,

$$dt = -mvda/(2aF).$$

These estimates exclude contingency reserves and disposal maneuvers.

Parameter	400 km	375 km	350 km
Monthly ΔV (m/s)	2.1-3.3	2.9-4.6	4.2-6.7
Hydrazine consumption (kg)	0.19-0.3	0.27-0.41	0.38-0.6

Table 5 Monthly Orbit Maintenance Requirements (Hydrazine)

7. PLANNED RE-ENTRY AND SUSTAINABLE SPACE DEBRIS MANAGEMENT

At the end of its operational life, as per IADC guidelines, the satellite is often planned to undergo a controlled orbit-lowering sequence to ensure timely atmospheric re-entry and minimize the creation of long-lived space debris. A small reserve of onboard hydrazine propellant is allocated for end-of-life de-orbit maneuvers, reducing the orbital altitude and allowing atmospheric drag to accelerate the natural decay process.

For ISRO microsatellite missions in Low Earth Orbit, re-entry is often planned as a part of mission design to ensure atmospheric reentry over pre-determined impact zone. And this is compliance with international space debris mitigation guidelines. During re-entry, most spacecraft components are expected to disintegrate due to intense aerodynamic heating, thereby minimizing the risk of debris reaching the Earth's surface.

Incorporating planned re-entry into mission operations promotes the sustainable use of the LEO environment by reducing collision risks, limiting orbital debris accumulation, and ensuring responsible disposal of spacecraft at the end of their mission life.

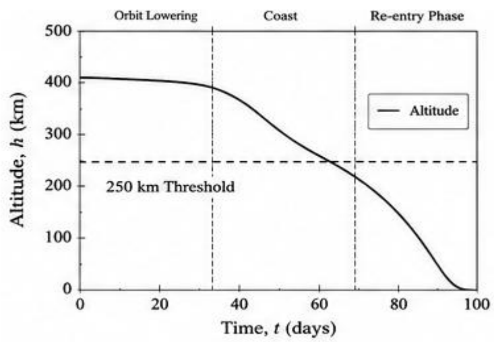

Fig. 8. Controlled de-orbit sequence: orbit lowering, coast phase, and atmospheric re-entry.

Figure 4 Controlled de-orbit sequence: orbit lowering, coast phase, and atmospheric re-entry decay

7.1 Controlled De-orbit Strategy

At the end of the operational mission, the spacecraft may perform a planned de-orbit sequence using the remaining onboard hydrazine propellant so that the final impact point is over a targeted zone. A final retrograde maneuver lowers the perigee altitude, increasing atmospheric drag and accelerating orbital decay. For typical LEO microsatellite missions, a disposal maneuver of approximately 20–40 m/s is generally sufficient to substantially reduce the remaining orbital lifetime and enable timely atmospheric re-entry.

A controlled de-orbit strategy offers several operational advantages:

– Predictable and timely end-of-mission disposal.

– Reduced probability of on-orbit conjunctions.

– Improved safety through controlled mission termination.

For a typical 200 kg ISRO microsatellite operating at an altitude of 400 km, the remaining onboard hydrazine is reserved at the end of the mission to execute a retrograde de-orbit maneuver. A disposal ΔV of approximately 20–40 m/s is generally sufficient to lower the perigee from 250 km orbit into denser atmospheric layers, substantially accelerating orbital decay. Depending on the final orbital altitude and prevailing solar activity, this maneuver can reduce the post-mission orbital lifetime from several months to only a few weeks.

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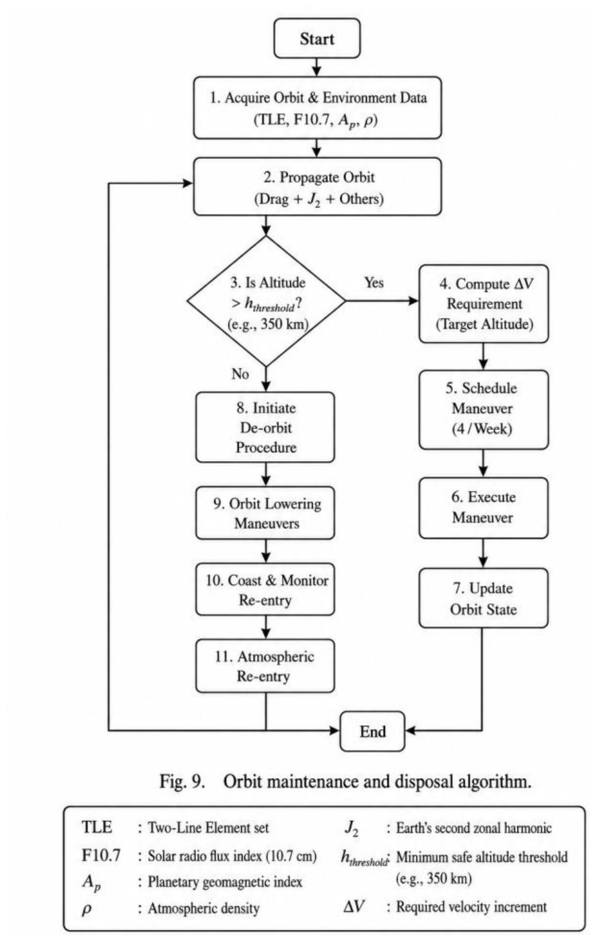

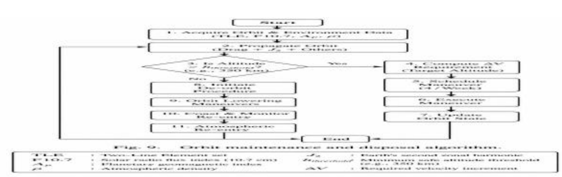

Figure 5 Orbit maintenance and disposal algorithm

7.2 Passive Disposal

In the event that propulsion is unavailable at the end of the mission, satellites operating below 400 km naturally undergo orbital decay due to atmospheric drag. The continuously increasing drag force gradually reduces orbital altitude until atmospheric re-entry occurs without further intervention. This passive disposal capability is a key sustainability advantage of Very Low Earth Orbit (VLEO) missions, as it minimizes the persistence of non-functional spacecraft in orbit and reduces the long-term accumulation of space debris.

As constellation deployments continue to expand, integrating end-of-life disposal planning into mission design is becoming a fundamental requirement.

8. CONCLUSION

Orbit maintenance for 200 kg satellites operating around 400 km altitude is dominated by atmospheric drag compensation. Depending on altitude and solar activity, annual station-keeping requirements typically range from 20 to 80 m/s, requiring either periodic reboost maneuvers or continuous low-thrust compensation. Electric propulsion systems provide substantial reductions in propellant mass compared with conventional chemical systems.

The relatively short natural orbital lifetimes in this altitude regime make VLEO operations inherently favorable from a debris mitigation perspective. Planned deorbit maneuvers and natural atmospheric decay enable responsible spacecraft disposal, supporting long-term sustainability of the near-Earth space environment. Future satellite missions should continue integrating propulsion, orbit maintenance, and end-of-life disposal strategies as a unified mission design framework to ensure safe and sustainable use of LEO.

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