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Failure Mode and Effects Analysis (FMEA) for CubeSat Deorbit Systems: A Comparative Risk Assessment of Drag Sails, Electrodynamic Tethers, and Propulsion Modules

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Abstract

The rapid proliferation of CubeSats in low-Earth orbit (LEO) has intensified concerns about space debris, requiring reliable end-of-life disposal under both the longstanding 25-year international guideline and the newer 5-year rule now in force for FCC-licensed missions. While previous studies have compared the deorbit performance of drag sails, electrodynamic tethers, and propulsion systems, no systematic analysis has quantified their relative reliability. This study presents a comparative Failure Mode and Effects Analysis (FMEA) of the three primary CubeSat deorbit technologies, generalizing the scoring methodology into an explicit, reproducible set of anchoring rules for severity, occurrence, and detection. A functional decomposition of each system identified failure modes across critical subsystems, each scored to generate a Risk Priority Number (RPN) for quantitative comparison. Results reveal distinct risk profiles: drag sails achieve the highest performance, but concentrate risk in a single-point deployment mechanism and, newly identified in this analysis, in maintaining post-deployment orientation. Electrodynamic tethers show the highest density of serious risks, led by plasma contactor failure (RPN=315) and tether severance (RPN=300). Propulsion systems carry lower average risk due to better detectability, but the highest number of catastrophic-severity failure modes. A Pareto analysis of the underlying risk data shows that the ten highest-RPN failure modes, representing 42% of all identified modes, account for approximately 64% of cumulative risk. These findings give CubeSat developers an evidence-based framework for selecting deorbit technologies based on both performance and reliability, supporting sustainable, compliant space operations.

1. Introduction

The advent of the CubeSat standard has democratized access to space, enabling universities, small companies, and developing nations to conduct low-cost missions for education, Earth observation, and technology demonstration (Aglietti et al., 2020; Alnaqbi et al., 2024). This dramatic increase in launch rates, however, has intensified concerns about

the long-term sustainability of the low-Earth orbit (LEO) environment. With each non-deorbited satellite representing a potential source of catastrophic collisions for decades or centuries, the need for guaranteed end-of-life disposal has become a critical issue for the global space community (Bilén, 2021; Cotten et al., 2017).

To mitigate the increase of space debris, the Inter-Agency Space Debris Coordination Committee

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(IADC) and NASA-STD-8719.14C have long recommended that satellites be designed to re-enter Earth's atmosphere within 25 years of mission completion (IADC, 2021; NASA, 2021). This 25-year guideline remains the baseline referenced by many national and international mitigation standards. However, the regulatory landscape has tightened materially since this study's earlier work on this topic (Shermatova, 2026): in September 2022, the U.S. Federal Communications Commission (FCC) adopted a new rule requiring LEO satellites licensed by, or seeking market access through, the FCC to deorbit within five years of end-of-mission (FCC 22-74, Second Report and Order), effective for license applications filed after September 29, 2024. This sharply shorter compliance window raises the stakes of deorbit-system reliability: a technology whose nominal deorbit time is compliant under the legacy 25-year guideline may not meet the FCC's 5-year standard even under nominal, non-failure operation, and any failure mode that extends deorbit time becomes proportionally more consequential for FCC-licensed missions. Because both regulatory regimes are presently in force – the 25-year guideline for missions not requiring FCC market access, and the 5-year rule for those that do – this study retains the 25-year-anchored Severity scale developed in this study's earlier work (Shermatova, 2026) as the general case (Section 2.3), and provides explicit guidance for rescaling it to the 5-year standard where applicable. While larger satellites often employ propulsion for controlled deorbiting, most CubeSats lack the mass, volume, and power budgets for such conventional systems (Alnaqbi et al., 2024). Consequently, without dedicated, miniaturized deorbit technologies, many CubeSats risk becoming permanent orbital debris, violating mitigation standards and exacerbating collision risks.

Several passive and active deorbit technologies have been developed specifically for small satellites. Drag sails increase the satellite's cross-sectional area to accelerate atmospheric decay (HPS GmbH, 2024). Electrodynamic tethers (EDTs) generate a decelerating Lorentz force through interaction with Earth's magnetic field (Bilén, 2021). Miniature propulsion systems can perform targeted deorbit burns (Alnaqbi et al., 2024). Previous comparative studies, including

earlier work by this author (Shermatova, 2026), have focused on evaluating the deorbit timeline performance of these systems, consistently identifying drag sails as the most mass-efficient solution for complying with the 25-year rule from typical LEO altitudes. However, performance efficiency is only one dimension of a successful deorbit system. For a technology to be viable, it must not only be effective but also reliable. A system that promises a 2-year deorbit but has a significant probability of deployment failure is ultimately more dangerous than a slower but more robust alternative, as it creates a false sense of compliance. To date, the comparative reliability and inherent failure risks of drag sails, electrodynamic tethers, and propulsion systems have not been systematically analyzed or quantified. This represents a critical knowledge gap for CubeSat mission planners who must make informed trade-offs between performance, cost, and risk.

To address this gap, this study employs Failure Mode and Effects Analysis (FMEA), a cornerstone methodology in reliability engineering and risk management (NASA Goddard Space Flight Center, 2024; Reliability Analysis Center, 1993). FMEA provides a structured, proactive framework for identifying all potential ways a system can fail, assessing the severity, likelihood, and detectability of each failure, and prioritizing risks to guide design improvements. While standard practice in aerospace for large missions, its application to the novel, commercial-off-the-shelf (COTS) deorbit systems used on CubeSats is novel.

This paper presents a comparative FMEA for CubeSat deorbit technologies. Section 2 details the methodology, including the functional decomposition of each system, the risk-scoring rationale, and explicit general guidelines for assigning Severity, Occurrence, and Detection values so the scoring is reproducible. Section 3 presents the complete FMEA results, organized by system, using four figures: a functional block diagram, a risk-matrix bubble chart that visualizes how each technology's failure modes cluster by severity and occurrence, a grouped bar chart comparing aggregate risk metrics across the three systems, and a Pareto chart ranking the highest-priority failure modes. These figures directly support the paper's central claim that each deorbit technology

carries a distinct, quantifiable risk profile, not just a distinct deorbit timeline. Section 4 discusses what these risk profiles mean for mission design, and Section 5 concludes with recommendations for CubeSat developers.

2. Methods

2.1. System Selection and Functional Decomposition

This analysis focuses on three commercially representative deorbit systems for a standard 3U CubeSat (4.0 kg dry mass): a drag sail, an electrodynamic tether (EDT), and a cold-gas propulsion module. These systems were selected due to their prevalence in the CubeSat ecosystem and their fundamentally different operating principles, which imply distinct failure profiles.

A corresponding functional block diagram illustrating the interactions between these subsystems is provided in Figure 1.

2.2. Failure Mode and Effects Analysis (FMEA) Methodology

The FMEA was conducted following the procedural guidelines outlined in the AIAG-VDA FMEA Handbook (AIAG & VDA, 2019), a recognized standard in reliability engineering, adapted for the CubeSat context. The process consisted of five sequential steps applied to each subsystem listed in Table 1:

- 1. *System Structure Analysis*: Creation of a functional block diagram (Figure 1) to map subsystem interactions.

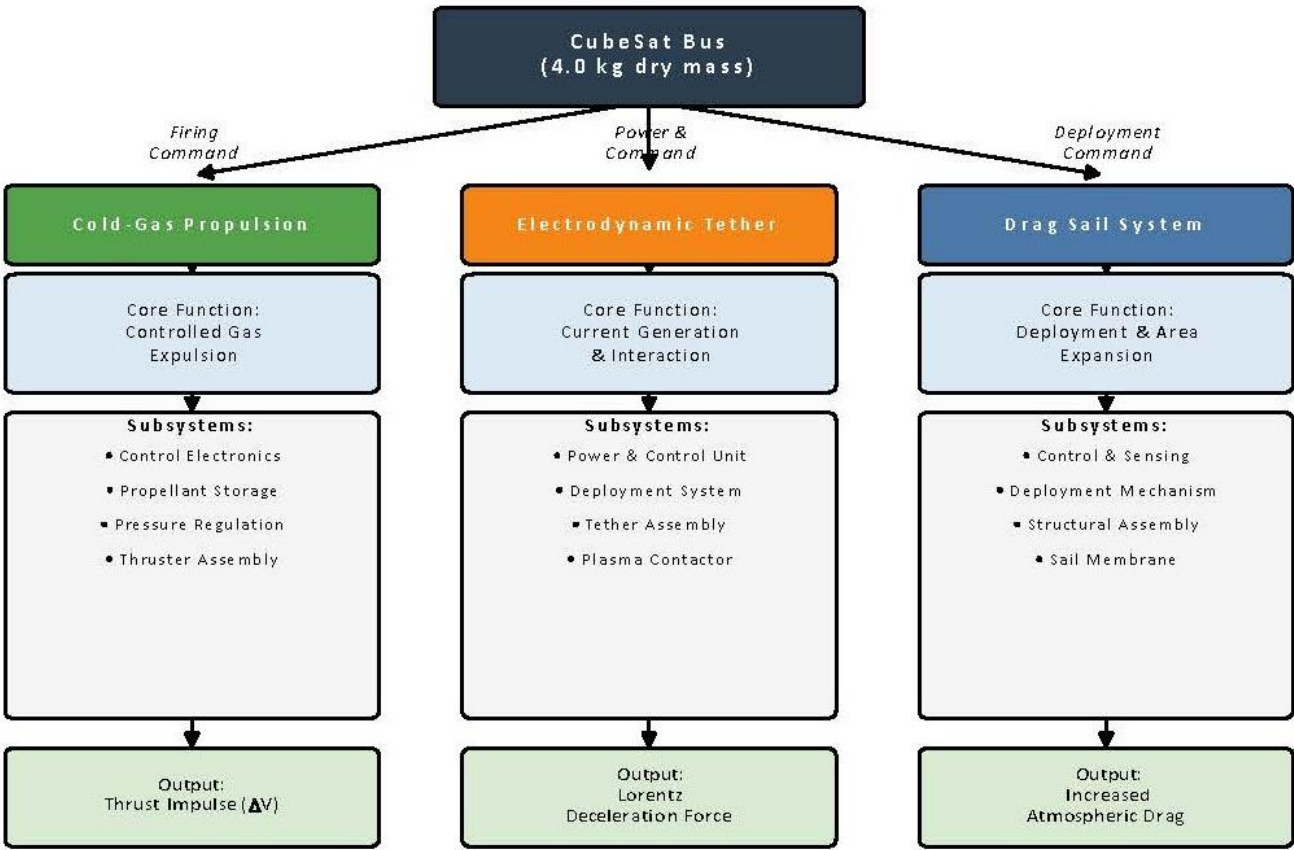


Figure 1: Functional block diagrams of the analyzed CubeSat deorbit systems. Each system receives an input command from the CubeSat bus and produces a distinct output for orbital decay. Subsystems correspond to the functional decomposition detailed in Table 1.

- 2. *Function Analysis*: Explicit definition of the primary and secondary functions of each subsystem.
- 3. *Failure Analysis*: Systematic brainstorming and documentation of all potential failure modes for each function.
- 4. *Risk Assessment*: Each identified failure mode was evaluated using three standardized risk metrics, scored on a 1–10 scale according to the criteria defined in Table 2. The Risk Priority Number (RPN) was calculated as $RPN = S \times O \times D$.
- 5. *Optimization*: High-priority failure modes were analyzed to derive specific design or operational mitigation actions.

An RPN threshold of 100 was selected as the action-priority cutoff for this study (rows meeting this threshold are marked with † in Tables 3–5). While no single universal RPN threshold exists in FMEA practice, industry convention for regulated, safety-critical industries— aerospace and medical device design in particular—commonly places the action threshold in the 75–125 range, compared with 150 or higher for less safety-critical consumer products, consistent with the threshold guidance discussed in the AIAG-VDA FMEA Handbook (AIAG & VDA, 2019). This study selected 100 as a mid-point value consistent with this regulated-industry convention. Consistent with that

Table 1: Functional Decomposition of CubeSat Deorbit Systems

Drag Sail – Increase satellite cross-sectional area to accelerate atmospheric drag decay	Deployment Mechanism : store energy, release latch, and initiate sail deployment on command (HPS GmbH, 2024). Structural Assembly : provide rigid framework (booms) and large surface area (membrane) for drag generation; passively maintain sail orientation relative to the velocity vector via aerodynamic and/or gravity-gradient stabilization (Laube et al., 2021). Control & Sensing : issue deployment command and confirm deployment status and post-deployment orientation via telemetry (e.g., switch, potentiometer).
Electrodynamic Tether (EDT) – Generate a decelerating Lorentz force via current flow in a conductive tether within Earth’s magnetic field	Deployment System : spool out the tether to its full length in a controlled manner and secure it. Tether Assembly : act as a long conductor with an end-mass for stabilization and electron collection. Plasma Contactor : establish electrical contact with the ionospheric plasma to close the current loop. Power & Control Unit : provide power to the emitter and manage tether current/voltage for optimal thrust.
Cold-Gas Propulsion – Provide impulsive ΔV through expulsion of stored propellant for a targeted deorbit maneuver	Propellant Storage : safely contain high-pressure inert gas (e.g., Butane, R236fa) until commanded for use. Thruster Assembly : regulate gas flow and accelerate it through a nozzle to generate thrust. Pressure Regulation : maintain operating pressure and manage tank pressure decay over mission life. Control Electronics : execute firing sequences, pulse valves, and monitor system health (pressure, temperature).

Table 2: FMEA Scoring Criteria (Severity, Occurrence, Detection)

Score	Severity (S) – Effect on Deorbit Mission	Occurrence (O) – Failure Fraction of Missions	Detection (D) – Ability to Detect Before Loss
10	Catastrophic. Complete deorbit failure; satellite remains as long-term debris.	> 1 in 2 (>50%)	Absolute uncertainty; no way to detect or predict.
9	Critical. Deorbit time exceeds 100 years.	1 in 3 to 1 in 2 (33–50%)	Very remote; detection only after catastrophic event or not at all.
8	Major. Deorbit time 50–100 years.	1 in 5 to 1 in 3 (20–33%)	Remote; very low probability of detection with standard telemetry.
7	Moderate–Major. Deorbit time 40–50 years.	1 in 10 to 1 in 5 (10–20%)	Low; failure may be detected indirectly with delay.
6	Moderate. Deorbit time 25–50 years (guideline violation).	1 in 20 to 1 in 10 (5–10%)	Low; failure might be inferred from secondary parameters post-event.
5	Low. Deorbit time delayed by 50–100%.	1 in 50 to 1 in 20 (2–5%)	Medium; 50/50 chance of timely detection via indirect signatures.
4	Minor–Low. Noticeable delay but mission still compliant.	1 in 100 to 1 in 50 (1–2%)	Medium–High; detectable with careful telemetry analysis.
3	Minor. Deorbit time delayed by 10–50%.	1 in 200 to 1 in 100 (0.5–1%)	Moderately high; good chance of detection via standard telemetry.
2	Very minor. Negligible impact on compliance margin.	1 in 1000 to 1 in 200 (0.1–0.5%)	High; easily detectable with telemetry.
1	Negligible. No impact on deorbit time or success.	< 1 in 1000 (<0.1%)	Very high; failure immediately apparent and unmistakable.

Handbook’s more recent shift toward severity-gated review rather than a single RPN cutoff, every failure mode with Severity ≥ 9 is additionally flagged for mandatory design review regardless of its RPN, since RPN alone can mask a low-occurrence, low-detectability but catastrophic failure mode; Table 6 reports Severity-10 counts separately for exactly this reason.

2.3. Risk Scoring Rationale and Data Sources

To ensure consistency and objectivity in scoring (Table 2), the following rationale and data sources were employed. Severity (S) was anchored directly to the mission outcome, the projected deorbit timeline, creating an objective, physics-based metric directly tied to the regulatory guideline in force. Occurrence (O) estimates were derived from a targeted review of publicly available anomaly databases (e.g., NASA’s Small Satellite Anomaly Reports), post-mission summaries for relevant CubeSat flights, and literature on component reliability in the space environment. Detection (D) scorings were based on the standard telemetry suite of a typical resource-constrained CubeSat.

2.3.1 General Scoring Guidelines

To generalize the anchoring logic beyond the two worked examples below, every Severity, Occurrence, and Detection value in Tables 3–5 was assigned according to the following priority rules:

- **Severity (S)** is anchored strictly to the resulting deorbit-timeline impact per Table 2 – never to subjective engineering judgment about a component’s perceived importance. A failure mode is scored by asking: if this failure occurs and is not otherwise mitigated, what deorbit timeline results?
- **Occurrence (O)** is anchored, in priority order, to: (1) documented in-flight anomalies for that specific component class; (2) component reliability literature for the analogous mechanism in the space environment; (3) only where neither exists, engineering judgment based on functional complexity and heritage, explicitly flagged as such.
- **Detection (D)** is anchored to the standard CubeSat telemetry suite actually available for that

subsystem (e.g., a binary deployment switch, motor current draw, tank pressure) – not to an idealized or custom instrumentation suite the mission does not carry. A failure with no corresponding telemetry signature is scored $D \geq 8$ by definition, regardless of how apparent the failure might seem in hindsight.

Two representative scoring decisions from the FMEA are provided to illustrate this methodology:

Failure Mode: Latch corrosion/seizing in the drag sail deployment mechanism. This failure would prevent sail deployment entirely. It was assigned $S=10$ (catastrophic, complete deorbit failure). Based on documented cases of mechanism seizing due to outgassing or cold welding in a limited sample of small satellite missions, $O=3$ was assigned (low, relatively few known failures). Standard telemetry (a single deployment switch) cannot distinguish between a failed latch and other causes of non-deployment, leading to

$D=8$ (remote detection). The resulting $RPN = 10 \times 3 \times 8 = 240$, classifying it as a high-priority risk.

Failure Mode: Micro-meteoroid or debris puncture of the drag sail membrane. A localized puncture reduces effective drag area, but standard rip-stop weave construction arrests tear propagation, limiting the loss to the local puncture region provided the sail is sized with adequate margin. This mitigating detail lowers Occurrence relative to an unmitigated tear ($O=2$, versus $O=3$ for a design without rip-stop construction), while Severity ($S=5$, delayed but not failed deorbit) and Detection ($D=9$, no standard telemetry monitors membrane integrity) are unaffected. The resulting $RPN = 5 \times 2 \times 9 = 90$.

2.4. Limitations of the Analysis

This FMEA constitutes a first-order, qualitative risk assessment intended for preliminary design guidance. The Occurrence and Detection scores are based

Table 3. Complete Failure Mode and Effects Analysis (FMEA) results – Drag Sail

Subsystem	Potential Failure Mode	Potential Effect(s)	S	O	D	RPN
Deployment Mechanism	Latch seizure (corrosion/cold welding) – fails to release.	Sail does not deploy – deorbit impossible.	10	3	8	240 †
Deployment Mechanism	Actuator failure (motor/spring) – mechanical fault.	Partial or no deployment – reduced or zero drag.	9	4	7	252 †
Structural Assembly	Boom fails to fully deploy/lock.	Reduced effective drag area – longer deorbit time.	7	3	5	105 †
Structural Assembly	Boom structural failure due to dynamic loads.	Sail collapses – significant area loss.	8	2	6	96
Sail Membrane	Puncture/tear from micrometeoroid or debris.	Localized puncture; rip-stop weave arrests tear propagation, limiting area loss to the local puncture region provided sail area is sized with adequate margin.	5	2	9	90
Sail Membrane	Material degradation, atomic-oxygen erosion (material-dependent).	Significant for uncoated Mylar/Kapton-class films; substantially reduced for AO-resistant materials or standard AO-protective coating. UV embrittlement is a secondary, compounding contributor (unlike solar sails, where UV is a primary driver).	4	3	8	96
Control & Sensing	Deployment command not issued (software fault).	System remains stowed – no deorbit.	10	2	3	60
Control & Sensing	False-positive deployment confirmation sensor.	Ground believes sail is deployed when it is not.	9	3	9	243 †
Structural Assembly / Control & Sensing	Failure to achieve/maintain sail orientation relative to velocity vector.	Reduced effective cross-sectional area in the ram direction; extends deorbit time even with full physical deployment.	6	4	7	168 †

† $RPN \geq 100$ (flagged for mitigation review per Section 2.2).

Failure Mode and Effects Analysis (FMEA) for CubeSat Deorbit Systems: A Comparative Risk Assessment of Drag Sails, Electrodynamic Tethers, and Propulsion Modules

Table 4: Complete Failure Mode and Effects Analysis (FMEA) results – Electrodynamic Tether (EDT)

Subsystem	Potential Failure Mode	Potential Effect(s)	S	O	D	RPN
Deployment System	Tether jams on spool during deployment.	Partial deployment – drastically reduced Lorentz force.	9	4	6	216 †
Deployment System	Deployment motor/mechanism fails.	Tether remains stowed – no electrodynamic effect.	10	3	7	210 †
Tether Assembly	Tether severed by micrometeoroid/debris.	Loss of electrical continuity – system rendered inert.	10	3	10	300 †
Tether Assembly	Tether insulation failure (arcing/short).	Loss of generated current – reduced or no thrust.	8	4	8	256 †
Plasma Contactor	Contactor fails to emit/collect electrons.	Current loop cannot close – no Lorentz force.	9	5	7	315 †
Plasma Contactor	Contactor surface contamination/erosion.	Increased impedance, reduced current, lower thrust.	7	4	8	224 †
Power & Control Unit	Anode/cathode power converter failure.	No current driven through tether.	9	3	4	108 †
Power & Control Unit	Control software fault (current regulation).	Suboptimal or zero current – reduced deorbit efficiency.	7	4	5	140 †

† RPN ≥ 100 (flagged for mitigation review per Section 2.2).

Table 5: Complete Failure Mode and Effects Analysis (FMEA) Results – Cold-Gas Propulsion

Subsystem	Potential Failure Mode	Potential Effect(s)	S	O	D	RPN
Propellant Storage	Micro-leak in tank/valve seal over mission life.	Insufficient propellant mass for required delta-V.	10	2	7	140 †
Propellant Storage	Tank rupture (corrosion/defect).	Catastrophic propellant loss, possible satellite damage.	10	1	2	20
Thruster Assembly	Solenoid valve sticks open/closed.	No thrust or uncontrolled thrust (propellant waste).	10	3	5	150 †
Thruster Assembly	Nozzle clogging (contamination).	Reduced thrust or misdirected thrust vector.	8	2	6	96
Pressure Regulation	Pressure regulator failure (stuck open/closed).	Unable to feed propellant at correct pressure.	9	2	4	72
Control Electronics	Firing sequence software fault.	Maneuver not executed or executed incorrectly.	10	2	3	60
Telemetry System	Faulty pressure/temperature sensor readings.	Incorrect system state knowledge – faulty decisions.	7	3	6	126 †

† RPN ≥ 100 (flagged for mitigation review per Section 2.2).

on engineering judgment informed by case studies, not on statistical failure rates from large, homogeneous populations, which do not yet exist for COTS CubeSat components. The analysis assumes a standard LEO environment; extreme but possible events are not modeled as primary failure initiators. The system boundary ends at the component interface; human factors in integration, testing, and operations are outside the formal scope of this design-focused FMEA.

3. Results

3.1. Failure Mode Identification and Risk Prioritization

Potential failure modes for each subsystem were identified based on documented incidents and engineering analyses. Tables 3–5 present the complete, per-system FMEA results. The debris/micrometeoroid puncture risk (Table 3) accounts for standard rip-

stop thread construction, which arrests tear propagation and limits area loss to the local puncture region provided the sail is sized with adequate margin. The UV/atomic-oxygen degradation risk is scored as material- and coating-dependent: erosion is significant for uncoated Mylar/Kapton-class films but substantially reduced for AO-resistant materials or a standard protective coating, with UV embrittlement acting as a secondary, compounding contributor rather than the primary driver it is for solar sails. A failure mode addressing the sail's post-deployment orientation is included, tracing to the orientation-stability function named in Table 1.

The drag sail's risks concentrate in the physical deployment mechanism and in the sensors and orientation control that verify and maintain its post-deployment state.

The electrodynamic tether's risks are distributed across four interdependent subsystems—deployment, tether integrity, plasma contact, and power/control—reflecting its systemic complexity.

The cold-gas propulsion system's failures are comparatively easier to detect via standard pressure/temperature telemetry, but it carries the highest count of catastrophic-severity ($S=10$) failure modes of the three technologies.

3.2. Aggregate Risk Metrics by System

Aggregate risk metrics for each deorbit technology, computed directly from Tables 3–5, are summarized in Table 6 and visualized in Figure 2.

The Electrodynamic Tether (EDT) exhibits the highest average RPN (221.1), the greatest number of high-priority failure modes (6 of 8 modes at $RPN \geq 150$ †), and the single highest RPN of any failure mode in the entire dataset (315, plasma contactor failure). The Drag Sail, while not carrying the single highest RPN, shows a substantial number of high-severity ($S=9-10$) modes and the widest spread in Occurrence across its failure modes. The Cold-Gas Propulsion system demonstrates the lowest average RPN (94.9), primarily due to superior Detection (average $D=4.71$ versus 6.89 and 6.88 for Drag Sail and EDT respectively), but retains the highest count of catastrophic-severity ($S=10$) failure modes.

3.3. Risk Profile Clustering

To visualize how each technology's failure modes cluster by risk characteristics rather than relying on RPN alone, Figure 3 plots every failure mode by Severity and Occurrence, with bubble size representing Detection.

The clustering in Figure 3 delineates distinct intrinsic risk profiles for each deorbit technology. The Drag Sail exhibits a critical single-point, sensor-, and orientation-driven profile: its highest-severity modes ($S=9-10$) span a wide range of Occurrence values, and only one of its nine failure modes falls in the combined high-severity, high-occurrence zone – but that mode (deployment mechanism failure) is catastrophic and difficult to detect. The Electrodynamic Tether demonstrates a high-density systemic complexity profile: three of its eight failure modes cluster in the high-

Table 6: Aggregate FMEA Risk Metrics by Deorbit System

Metric	Drag Sail	Electrodynamic Tether (EDT)	Cold-Gas Propulsion
Total Failure Modes Analyzed	9	8	7
Average Severity (S)	7.56	8.62	9.14
Average Occurrence (O)	2.89	3.75	2.14
Average Detection (D)	6.89	6.88	4.71
Average RPN	150.0	221.1	94.9
Failure Modes with $RPN \geq 100$	5	8	3
Failure Modes with $RPN \geq 150$	4	6	1
Failure Modes with Severity (S) = 10	2	2	4

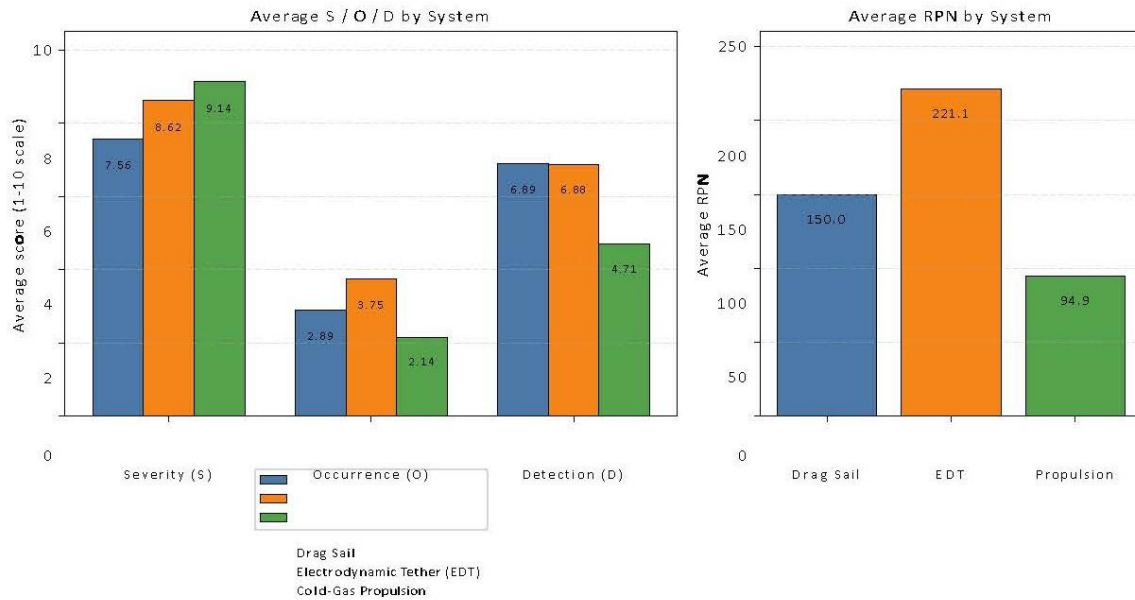


Figure 2: Aggregate risk metrics by system, visualizing Table 6. Left: average Severity, Occurrence, and Detection scores (1–10 scale) per system. Right: average Risk Priority Number (RPN) per system. The Electrodynamic Tether carries both the highest average Occurrence and the highest average RPN of the three technologies, while Cold-Gas Propulsion’s higher average Severity is offset by markedly better average Detection.

severity, high-occurrence zone, distributed across three different subsystems (deployment, tether integrity, plasma contact), indicating that reliability must be engineered across an interdependent chain of physical phenomena rather than a single weak point. The Cold-Gas Propulsion system presents an attenuated catastrophic severity profile: none of its seven failure modes fall in the high-severity, high-occurrence zone (its high-severity modes cluster at low Occurrence), consistent with its lower average RPN, but it retains the highest raw count of S=10 failure modes of the three systems.

3.4. Pareto Analysis of High-Priority Risks

A Pareto analysis was performed to identify the failure modes constituting the most significant contributors to total risk, computed directly from the data in Tables 3–5. Across all 24 identified failure modes, the ten highest by RPN – approximately 42% of all identified modes – account for approximately 64% of cumulative RPN (Figure 4). Extending the ranking further, cumulative RPN crosses the 50% mark at the 8th-ranked failure mode and the 80% mark at the 15th-ranked failure mode.

The Pareto chart (Figure 4) reveals several critical insights. The single greatest risk remains the failure of the EDT’s plasma contactor (RPN=315). EDT failure modes occupy six of the top ten positions in the ranking, consistent with the high-density clustering seen in Figure 3. The drag sail’s actuator failure (RPN=252) and false-positive deployment sensor (RPN=243) are the highest-ranked non-EDT failures, underscoring the importance of both the deployment mechanism and sensor reliability for a predominantly mechanical system. The newly identified sail-orientation failure mode (RPN=168) enters the top 10, reflecting that a physically deployed but poorly oriented sail still represents a meaningful, previously unquantified risk to schedule compliance.

4. Discussion

4.1. What the Risk Profiles Mean for Designing a Mission

The FMEA presented in this paper provides a way to evaluate deorbit technologies beyond simply comparing how quickly they work. Prior performance modeling (Shermatova, 2026) identified the drag sail

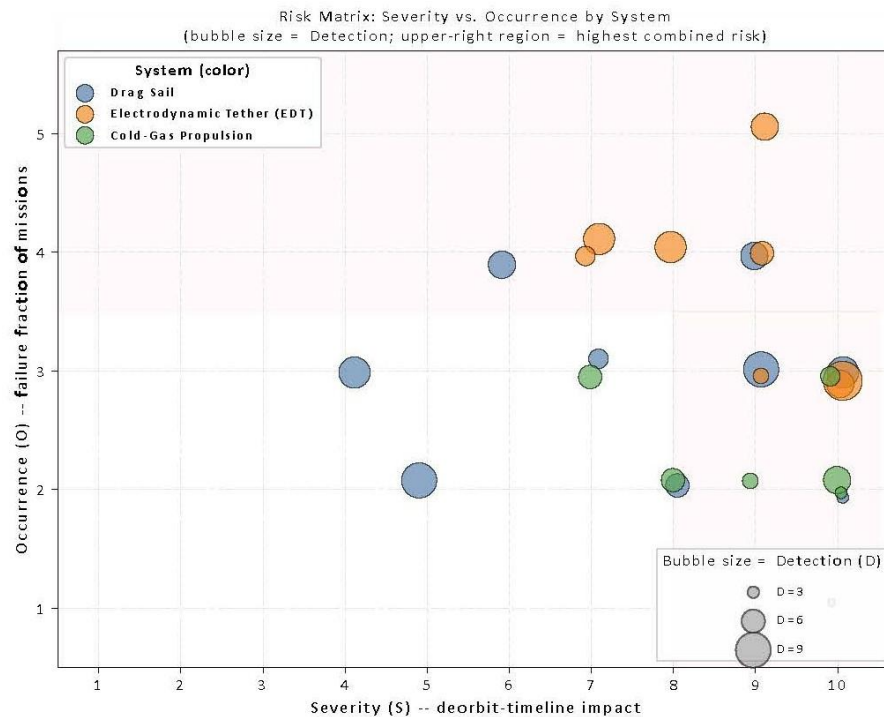


Figure 3: Risk matrix: Severity versus Occurrence for all 24 failure modes, colored by system, with bubble size proportional to Detection. The shaded region ($S \geq 8$, $O \geq 3.5$) marks the combined high-severity, high-occurrence zone. Electrodynamic Tether failure modes occupy this zone most frequently (3 of 8 modes), compared to Drag Sail (1 of 9) and Cold-Gas Propulsion (0 of 7), visually confirming the high-density systemic complexity risk profile discussed in Section 4.1.

as the fastest of the three technologies; this analysis identifies its central weakness: if the deployment mechanism fails, the mission fails outright, and even after successful deployment, failure to maintain orientation can still erode the schedule margin that a fast nominal deorbit time is meant to provide (Table 3, Figure 3). Under the FCC's tightened 5-year rule for FCC-licensed missions, this margin erosion is materially more consequential than it was under the legacy 25-year guideline, since there is little schedule slack to absorb degraded performance from any single failure mode.

The Electrodynamic Tether presents a different problem: not speed, but distributed complexity. Three of its eight failure modes cluster in the combined high-severity, high-occurrence zone of Figure 3, spanning three physically distinct subsystems (deployment, tether integrity, and plasma contact). Achieving high reliability for an EDT therefore requires engineering across an interdependent chain of

physical phenomena rather than hardening a single component.

The Cold-Gas Propulsion system tells a third story. Its failures are comparatively easy to detect via standard pressure and temperature telemetry, which is why its average RPN (94.9) is the lowest of the three technologies (Table 6). However, it also carries the highest raw count of catastrophic-severity failure modes (4 of 7 at $S=10$), meaning reliability for a propulsion-based deorbit system is not automatic; it must be deliberately engineered in through component quality and redundancy rather than assumed from good detectability alone.

The overarching lesson is a trade-off between speed and reliability, and no single technology dominates on both axes. The appropriate choice depends on a mission's altitude, budget, applicable regulatory timeline (5-year or 25-year), and tolerance for risk.

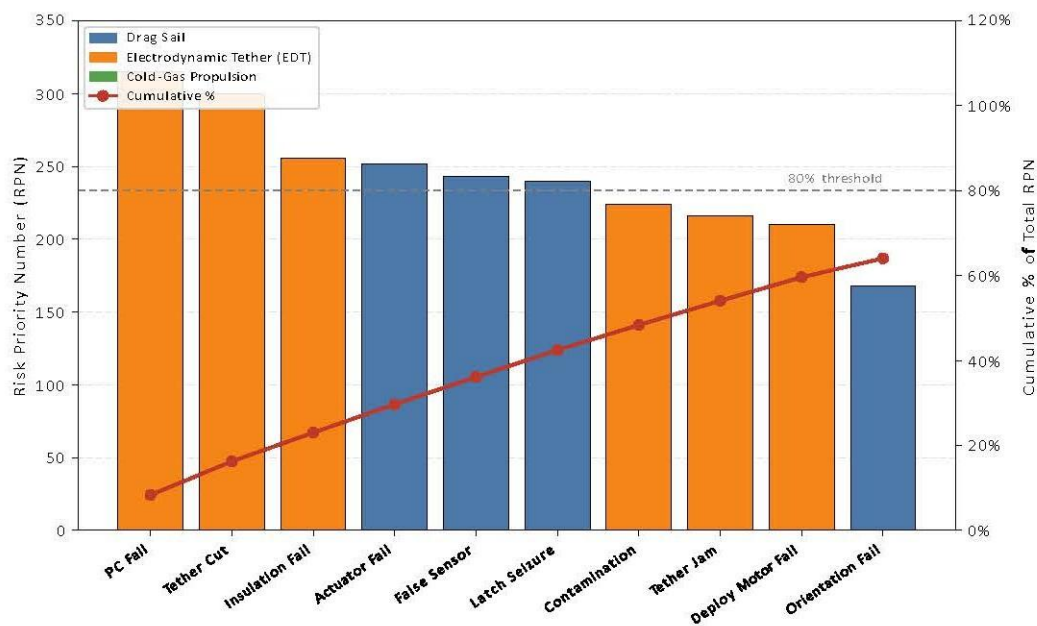


Figure 4: Pareto chart of the ten highest-risk (RPN) failure modes across all analyzed systems, with color coding by system and a cumulative-percentage curve on the secondary axis. Bars are drawn directly from Tables 3–5; percentages are computed over all 24 identified failure modes.

4.2. Connecting Reliability to Performance: A Guide for CubeSat Builders

Combining these FMEA results with prior performance modeling (Shermatova, 2026) yields a practical guide for technology selection.

Drag Sail (fast but risky): best suited for missions below 700 km where speed is the priority. Recommendation: concentrate testing and quality assurance on the deployment mechanism, and separately validate passive orientation stability (gravity-gradient or aerodynamic stabilization performance) before flight, since this analysis identifies orientation failure as a meaningful, previously unquantified contributor to schedule risk (RPN=168, Table 3).

Electrodynamic Tether (high-potential but complex): its achievable performance depends entirely on resolving reliability challenges. Recommendation: prioritize development effort on two of the highest-risk subsystems identified here—the plasma contactor (RPN=315) and the tether deployment system (RPN=216, 210)—since these offer the largest risk-reduction return per engineering effort invested (Table 4).

Cold-Gas Propulsion (useful, but not for deorbit alone): this analysis confirms it is a comparatively poor choice when its sole purpose is deorbit. Its real value emerges for missions that already require propulsion for primary mission objectives (e.g., orbit-raising or station-keeping), where it can then perform an end-of-life deorbit burn at minimal additional mass cost.

For the majority of university and small-team CubeSat missions, the practical path is a rigorously tested drag sail with both deployment reliability and post-deployment orientation stability validated prior to flight.

4.3. Limits of This Study and Directions for Future Research

This study is a first-order, qualitative risk assessment, and its limits are inherited directly from the constraints described in Section 2.4: the Occurrence and Detection scores rely on engineering judgment informed by a still-limited body of case studies, not on

statistical failure rates drawn from large, homogeneous flight populations, which do not yet exist for COTS CubeSat deorbit hardware.

Three directions for future work follow directly from this limitation. First, as CubeSat deorbit systems accumulate flight heritage, Occurrence and Detection scores should be revisited against real failure statistics rather than case-study-informed estimates. Second, hybrid architectures—for example, a drag sail paired with a small backup thruster—warrant dedicated study to determine whether they can combine the drag sail's speed with a meaningfully lower single-point-failure risk.

Third, this analysis assumes a standard LEO environment; extreme space weather (e.g., geomagnetic storms affecting atomic-oxygen flux or electrostatic discharge risk) was deliberately excluded as a primary failure initiator and represents a natural extension of this framework.

5. Conclusion

This study presents a systematic, comparative reliability analysis of the three primary deorbit technologies used by CubeSats. By applying the FMEA, it moves beyond the question of how fast a system de-orbits to the more consequential question of how likely it is to succeed. Three distinct risk profiles emerge. The drag sail is the most performant of the three technologies but carries a concentrated, high-stakes risk in its deployment mechanism and, as newly identified in this analysis, in maintaining its orientation after deployment. The electrodynamic tether holds high theoretical potential but is challenged by systemic complexity distributed across multiple interdependent subsystems. The cold-gas propulsion system's value as a deorbit solution is unlocked only when propulsion is already a core mission requirement, rather than as a standalone disposal mechanism.

Reflecting the trade-off identified throughout this analysis, the right choice among the three is a strategic decision rather than a universal answer. For the majority of educational and commercial CubeSat missions in low Earth orbit, this integrated analysis indicates that a rigorously tested, correctly oriented drag

sail offers the most practical and dependable path to regulatory compliance. This work provides CubeSat developers, particularly students and small teams, with an evidence-based framework for making design choices that treat reliability as a first-class design requirement alongside performance—supporting sustainable, compliant space operations as CubeSat launch rates continue to grow.

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