Orbital Debris and Collision Avoidance in Low Earth Orbit

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The increasing number of orbital debris in Low Earth Orbit (LEO) is becoming more critical to space operations. This paper explores current methods for detection and tracking, collision risk modeling, and mitigation strategies, with a focus on tools like NASA's DRAMA and emerging future technologies. Risk modeling techniques and international mitigation guidelines are also analyzed. The paper stresses the need for continued innovation and international collaboration to ensure the sustainability of Earth's orbital environment.

I. Nomenclature

DRAMA	=	Debris Risk Assessment and Mitigation Analysis
ESA	=	European Space Agency
GEO	=	Geostationary Orbit
LEO	=	Low Earth Orbit
NASA	=	National Aeronautics and Space Administration
ODQN	=	Orbital Debris Quartly News
PoC	=	Probability of Collision
SSA	=	Space Situational Awareness

II. Introduction

The critically high number of orbital debris in LEO will continue to make navigation increasingly difficult. Orbital debris can be non-functional satellites, spent rocket stages, and fragments from disintegration events. Debris has increased steadily since the inception of items being launched into space. In the past, the 2007 Fengyun-1C ASAT test and the 2009 Iridium-Cosmos collision greatly increased the amount of debris in LEO [1]. Looking towards the future, space explorations companies like SpaceX and Blue Origin (Amazon) are planning to put over 15,000 satellites into orbit – and that is just two of the larger companies. As of June 8th, there are over 550,000 satellites to be launched [2]. To explain the key challenges of this subfield, this report will cover detection and tracking systems, collision risk modeling, and operational mitigation strategies, highlighting major developments in reducing the danger of collision with orbital debris.

III. Detection and Tracking Systems

Identifying and tracking each satellite is necessary to help with collision avoidance. The United States Space Force Delta 2 performs SSA for the US Department of Defense and other agencies. They detect, track, identify, and catalog all artificial objects in space [3]. A public version of this catalog is on Space-Track.org, where you can find real-time orbital debris data, view how close objects are to collision, track reentry, and provide a database of history and current events [4]. A visual representation of satellites and their positions is on LeoLabs: LEO Visualization [5]. Platforms like this aim to prevent collisions, identify/track debris, and provide information for the public in a way they can understand. It can go a long way in helping to make and change policies for this issue. Another way to keep updated in this field is to subscribe to ODQN - a publication by the NASA Orbital Debris Program Office that publishes the latest research, statistics, projects, and notable news in the field [6]. Figure 1 below shows a recent ODQN article that illustrates the drastic increase in orbital debris over the past decade.

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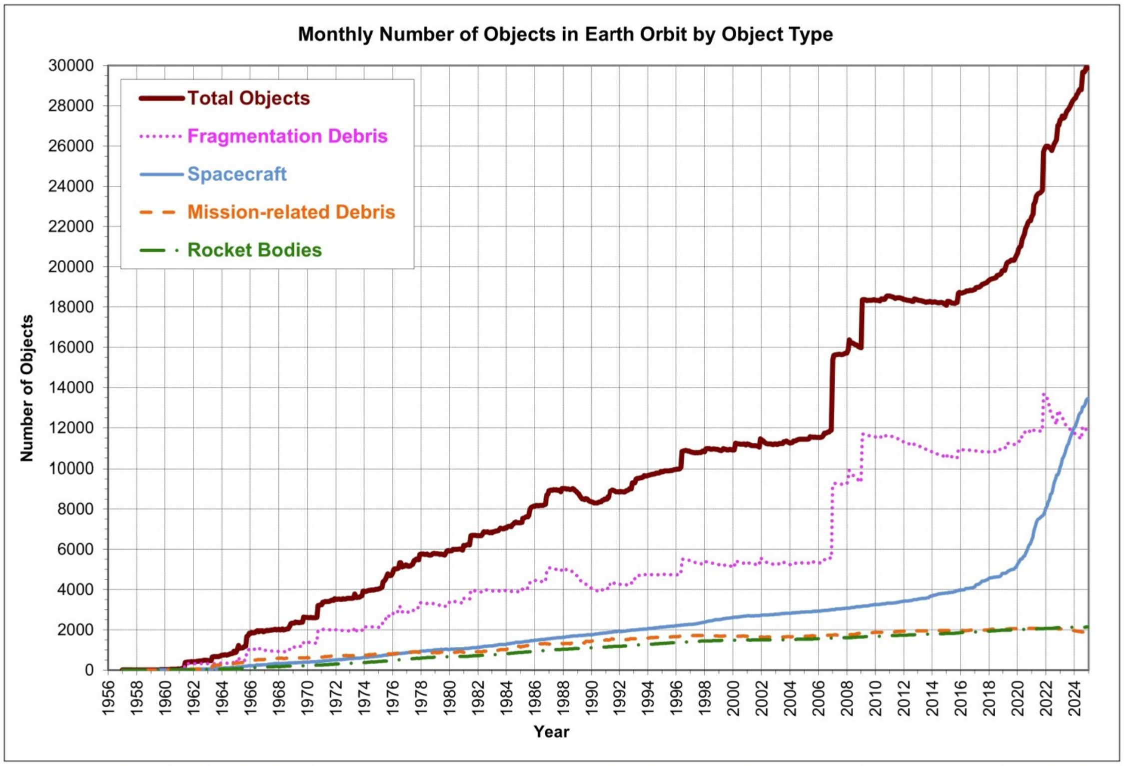

Monthly Number of Cataloged Objects in Earth Orbit by Object Type as of 9 January 2025. This chart displays a summary of all objects in Earth orbit officially cataloged by the U.S. Space Surveillance Network. "Fragmentation debris" includes satellite breakup debris and anomalous event debris, while "mission-related debris" includes all objects dispensed, separated, or released as part of the planned mission.

Fig. 1 The February 2025 issue shows a Monthly Number of Objects in Earth Orbit by Object Type [6].

IV. Collision Risk Modeling

Tools like those previously mentioned can be used to create a collision risk assessment to identify and track debris. NASA's DRAMA is a "tool for the compliance analysis of a space mission with space debris mitigation standards". DRAMA can be used for*:

- Debris and meteoroid impact flux levels (at user-defined size regimes)
- Collision avoidance maneuver frequencies for a given spacecraft and a project-specific accepted risk level
- Re-orbit and de-orbit fuel requirements for a given initial orbit and disposal scenario
- Geometric cross-section computations
- Re-entry survival predictions for a given object of user-defined components
- The associated risk on ground for at the resulting impact ground swath

For our current needs, we can minimize this tool to use an object's position, velocity, and uncertainty, to create a PoC [7]. We can take this information to assess the likeliness of collisions in LEO versus GEO. "The Consideration of Collision "Consequence" in Satellite Conjunction Assessment and Risk Analysis" investigates a method to estimate resultant debris from supposed collisions. As shown below in Table 1, they concluded that the risk assessment can be summarized where X is equal to the PoC value at which remediation is recommended [8].

*All bullet points are directly from [7]

	LEO/HEO Orbits	GEO Orbits
Catastrophic Collision	X	X
Non-Catastrophic Collision	X + (0.5 – 1) OoM	X

Fig. 2 Table 1: Summary of Risk Assessment of Colliding Bodies [8].

V. Mitigation Strategies

The risk associated with debris collision creates the problem of maneuvering spacecraft or satellites to avoid potential catastrophes. As described by E. Denenberg and P. Gurfil, there are three techniques that can be utilized to find the perfect strategy for any situation. The differences between these approaches include fuel efficiency, number of maneuvers, time, and maneuver size. The study concludes that to be most efficient, all three presented options must be explored on a case-to-case basis [9]. Scientists are also using ground-based lasers combined with telescopes to prevent debris collisions. Over a short amount of time, a laser directed through a fast-slewing telescope produces sufficient photon pressure that moves debris from one orbit to another. They calculate that "a delta-v of 1 cm/s, applied in the anti-velocity direction results in a displacement of 2.5 km/day for a debris object in LEO". This is a cost-efficient solution for a potentially expensive issue [10]. Another mitigating strategy is autonomous avoidance. Chen et. Al dives into executing a model that creates a framework for each maneuver when necessary. The two-stage autonomous mission planning framework is used to help spacecraft to avoid collisions without interrupting normal operations. This strategy applies linear programming to ensure resource and time constraints are met continuously. Simulations are tested and verified, making this a sensible strategy for orbital collision avoidance [11]. Of the mitigation strategies mentioned above, I find that the ground-based laser is the most intriguing. Using a laser on Earth to affect the way a satellite moves is efficient, smart, and is an out-of-the box approach. I also think that exploring other ideas like this will create passion and interest in this field.

VI. Next Steps

To mitigate collisions the ESA created a "Space Debris Mitigation Guidelines" which sets precedent for this issue. The guidelines include deorbiting defunct satellites, reducing in-orbit fragmentation, limiting mission-related debris, and active debris removal. All of which provide a sustainable framework for private and government space operations to conduct responsible exploration. There are not, however, any global treaties to ensure these measures are followed [12] There does not seem to be many gaps in this subfield of research as techniques and strategies are used in everyday life by functional satellites. The sheer amount of interest and research in this field creates opportunities for future breakthroughs and experiments.

VII. Conclusion

In summary, Earth's orbital plane is increasing in capacity as a massive amount of satellites are set to launch in the near future. To maintain space exploration, continual innovation in AI-guided collision avoidance, ground-based photon lasers, and case specific strategies are necessary. As Earth inhabitants continue to explore space, advancements in detection, tracking, mitigation, avoidance, and eventually removal must also evolve. These technological innovations are crucial to assist the space community to ensure the long term safety of Low Earth Orbit.

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