

Enhancing Space Safety: A Review of CubeSat Constellations for Tracking Orbital Debris

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Abstract

Space debris includes any human-made object in orbit or idle. Debris reentering the atmosphere or orbiting the Earth are examples of these things. Debris can include satellites or launch vehicles, dysfunctional spacecraft, remains from rockets and airplanes from crashes or explosions, debris from spacecraft and vehicles that were purposefully expelled during separation or operation, etc. The danger of collisions rises as the number of items in the path increases. Over time, satellite utilization has been increasing steadily. They are used in many different fields and disciplines, including space science, Earth observation, meteorology, climate research, telecommunication, navigation, and human space travel. The number of satellites is growing along with human requirements, which is creating a very serious risk known as space debris. Due to the congested low earth orbit caused by this, it is imperative that space debris be detected. A number of crewed and uncrewed spacecraft have suffered damage or been destroyed due to space junk. Certain space industry participants carry out the measurement, mitigation, and possible removal of debris. To prevent any potential harm, we have examined and studied several publications in this paper that discuss how the constellation of CubeSats will assist us in monitoring space debris. We have also looked into the data fusion analysis, different sensor technologies, constellation designs, and orbital concerns along with an overview of several applicable space debris cleaning strategies.

Keywords: CubeSats, debris, microsensors, satellite, space safety, earth observation

INTRODUCTION

Space debris has always been a threat when operating spacecraft in orbits around the Earth, but the large growth in launch exertion have greatly increased the number of objects, both loads and space debris in route or orbit. Any human-made object that is idle or in orbit is considered space trash. These objects may include debris orbiting the Earth or reentering the atmosphere. Debris may be inoperable

spacecraft, satellites or launch vehicles, leftovers from aircraft and rockets due to explosions or collisions, and debris from spacecraft and vehicles intentionally released during separation or operation, etc. With the increase of objects in orbit follows an increased threat of collisions.

As space debris mitigation is still being enforced too sluggishly, there is a rising probability of collisions in low earth orbit (LEO), as shown by observations done in European Space Agency's (ESA's) Annual Space Environment Report [1].

On August 24, 2023, the International Space Station (ISS) performed its last landing to prevent collisions with debris. In response to the approaching

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debris, the service module of the Russian space station Zvezda fired its engines for approximately 21.5 seconds. This action caused the ISS to shift its orbit downward by approximately 1640 feet (500 m), shifting it from the orbital debris plane. Fortunately, this change does not affect the continued operation of the station [2]. Determining an avoidance strategy is important to reduce the risk of accidents. Collision avoidance operations have become routine and necessary for operational satellites.

According to Kessler syndrome, space debris poses a threat that can be caused by collisions with one another. If we do not stop it, this might set off a series of events that will leave the Earth's orbit completely uninhabitable and serve as a death trap for upcoming missions. Additionally, Dr. Kessler envisioned the creation of a “debris belt,” which would prevent space missions if they came to reality. Therefore, space trash needs to be monitored to prevent collisions with future and existing space components. Hence, CubeSats are a practical solution for this task.

There are many ways to track debris, including optical inspection, radar tracking, infrared detection, radio frequency detection, and laser ranging. CubeSats were chosen for tracking space debris due to their efficiency, flexibility, and rapid deployment capabilities. These small satellites can form constellations that improve service and reduce return visit time. CubeSats offer a flexible platform for testing new technologies thanks to their sophisticated microsensors. Their combined capabilities enable the execution of distribution and general services. Their mission goes beyond observation, as CubeSats can also be considered for the removal of space debris, demonstrating their great potential in addressing space.

BACKGROUND

Space debris initially appeared when the Soviet Union launched Sputnik 1 in 1958, the first space mission ever. Following Sputnik's launch, NORAD (North American Aerospace Defense Command) started keeping track of and building a database of all known rockets, satellites, protective casings, and other space objects. Many of the other items in orbit that the NORAD monitors who fed the database were aware of the product of in-orbit explosions. Space debris was created throughout the 1970s and 1980s when numerous space missions were undertaken by different nations. In 1978, NASA (National Aeronautics and Space Administration) scientist Donald J. Kessler gave us the first explanation of Kessler syndrome. He said in this that as the LEO becomes clogged with debris, collisions between objects would occur that will produce a disproportionately huge amount of debris because of a continuous chain reaction, rendering that particular orbit unusable. China tested an anti-satellite operation in 2007 and destroyed a malfunctioning satellite in the process, producing a lot of debris. There are currently 8377 operational satellites in different earth orbits. There are known to be around 25,000 objects bigger than 10 cm. There are roughly 500,000 particles with a diameter of 1 to 10 cm in the estimated population. More than 100 million particles bigger than 1 mm are present. Moreover, 9000 metric tonnes of material were in orbit around the Earth as of January 2022. Numerous space firms, including SpaceX, One Web, and others, intend to launch a constellation of satellites for providing worldwide internet coverage, the primary issue of which continues to be space debris and its rapid development.

Numerous initiatives are being taken to reduce space debris, such as developing satellites that deorbit once their mission is completed or using lasers to divert space debris from their course. The current scenario of space debris is shown in Figure 1.

CUBESATS IN SPACE DEBRIS MONITORING

CubeSats are tiny satellites that are constructed in accordance with the CubeSat design and usually weigh between one and fifty kilograms. The standard was created by the California Institute of Technology (Caltech) in 1999 and has been revised more than 10 times since then, most recently in 2015. It defines a “unit”, which is a cube with sides of 100 mm.

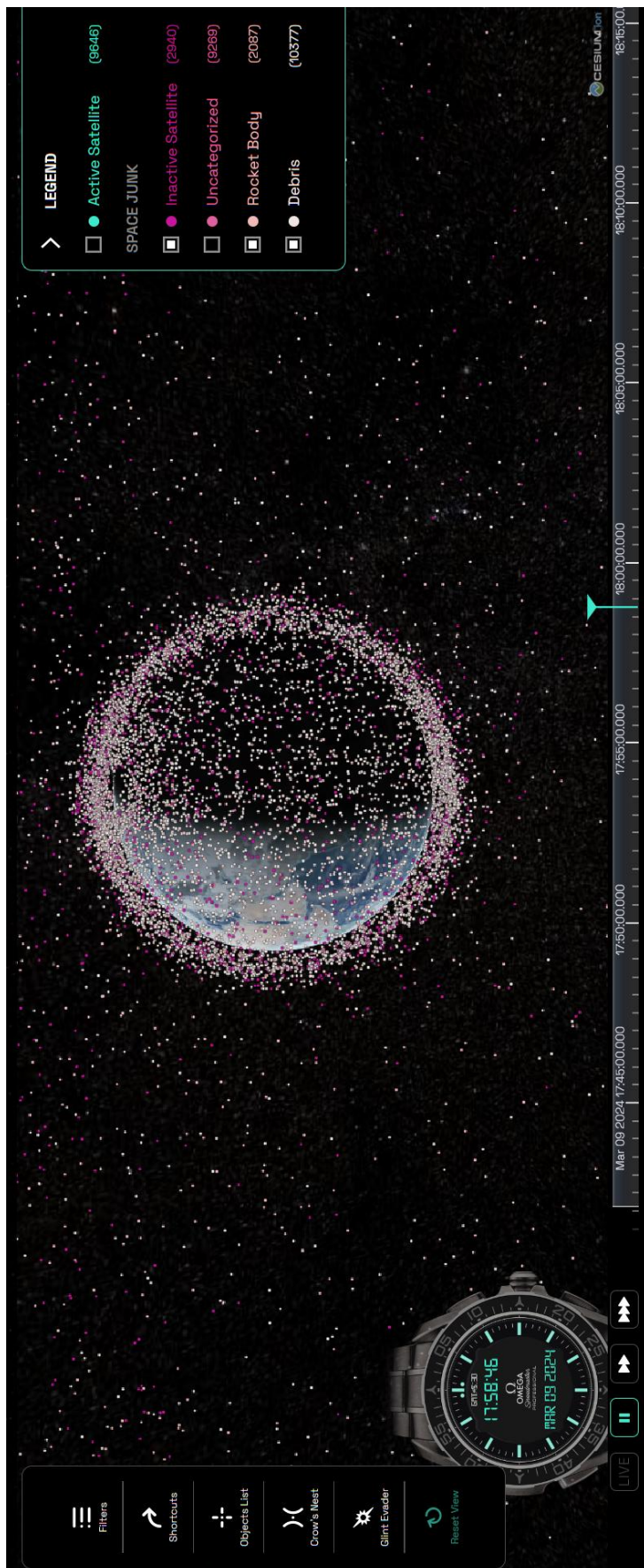


Figure 1. Image showing the current scenario of space debris.

The sizes used so far are 1U and 3U. As of August 2016, approximately 99% of CubeSats are built in the 1U to 3U range, and there has been a marked increase in sizes. Only a few 6U, only one 12U, and 27U CubeSats are currently unproduced, but many 6U CubeSats and several 12U CubeSats are planned to be released only in 2017. Due to their limited size, CubeSats are characterized by their flexibility and rapid development in terms of commercial off-the-shelf (COTS) parts; this makes them useful and usable to many audiences, including universities and even schools. Its subsystems are generally as independent as possible and are specifically designed to comply with CubeSat standards. This makes them easy to integrate, interchangeable in many cases, and simplifies the design process. The state-of-the-art technology available for use in CubeSats continues to advance rapidly, marking the beginning of the transition from an educational platform to low-cost commercial development [3].

Powered by their increased capacity and efficiency, CubeSats provide a revolutionary platform for space missions, especially to waste sites that are critical tracking and monitoring areas in space. The modular and standardized nature of CubeSats allows the creation of constellations and marks a significant departure from the traditional approach that usually involves large satellites. This scalability becomes a significant advantage by enabling multiple CubeSats to cover large areas of space, improving observation and tracking capabilities. By comparison, traditional satellite missions are often constrained by the high costs associated with complex design, construction, and launch processes, limiting the frequency and scope of deployment. CubeSat constellations represent a flexible and efficient system that facilitates rapid development, which is vital for quickly responding to urgent problems such as tracking the movement of wasteland or debris. CubeSats are cost-effective as an initial investment, including operating costs and providing independent space probes. Funding cuts leave organizations with fewer resources to access space, support innovation, and foster collaboration for space awareness. CubeSats are a catalyst for the development of technology that can be combined with small sensors and devices to help track and track space debris. This flexibility and accessibility not only expand participation in space exploration but also improves our understanding of complex environments. As demand for more surveillance capabilities grows, CubeSats are beginning to explore the evolution of geospace. Their effectiveness and efficiency have not only revolutionized the way space debris is tracked and monitored but have also made CubeSats an important part of increasing our understanding of dynamic space and environmental issues.

SENSOR TECHNOLOGIES

Various sensors can be utilized to monitor space debris. Some of which are still under testing, and some have proven to be efficient in monitoring. They are as follows.

Star Sensors

A star tracker/sensor is a device that uses the inertial coordinate system to identify stars and calculate a spacecraft's attitude. Along with dim stars, it can also detect small targets in space, such as space debris, due to the development of highly precise star sensors. The CubeSat's star sensors function as follows, according to the research article we looked at. We first identify the star map of the entire sky using the star sensor, and then we calculate the spacecraft's attitude based on that information. Following that, we look for the star on the local sky map, and using the Kalman filter, we identify the space junk from there and get an approximate idea of its exact location. After calculating the intended location, we place it [4]. Information processing flow of dim and small targets based on star sensor observations is shown in Figure 2.

Optical Imaging

Cameras, telescopes, and image processing software make up the optical system. This method involves using a telescope to locate and collect space junk first, followed by a high-resolution camera to provide a clear, bright image of the debris that includes its shape, size, and location. Following this, the picture is examined using image processing software, which uses a sophisticated algorithm to identify the object. Imaging sensors built inside cameras and telescopes take in visual signals from their surroundings and translate them into electrical signals [5].

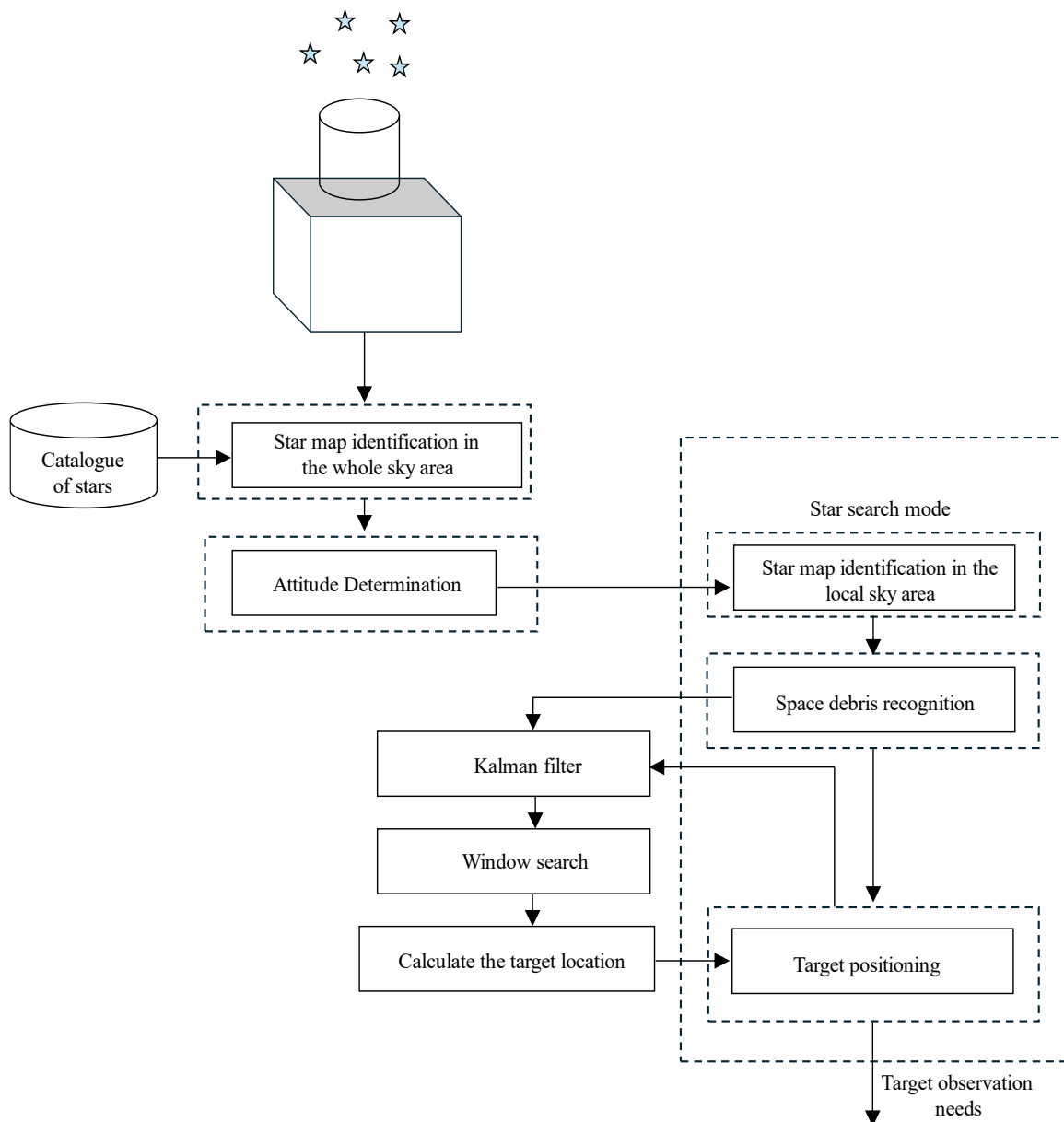


Figure 2. Information processing flow of dim and small targets based on star sensor observations.

Passive Bistatic Radar

Passive bistatic radar, or PBR for short, is a type of radar system in which the passive component is a signal from a distinct operational satellite and the bistatic element is the transmitter and receiver separated at two different locations. A radar receiver and an onboard antenna make up the CubeSat. The bistatic angle is 180° , as can be seen in the Figure 3 from the research paper we studied on this topic. If an object passes between the line connecting CubeSat and an operational satellite (i.e., an illuminating opportunity), a signal will be transmitted and detected. We can determine an object's size and shape by detecting variations in the radar signal [6]. The concept of a CubeSat based PBR system is shown in Figure 3.

Light Detection and Ranging (LIDAR)

Light detection and ranging (LIDAR) functions by applying laser pulses to the items and measuring how long it takes for the pulses to reflect off of them. Because a LIDAR utilizes its own light, it has the benefit of being used both during the day and at night. We must not forget to create a miniature LIDAR if we plan to use one for a CubeSat. This is how LIDAR operates: A LIDAR laser beam is released, and

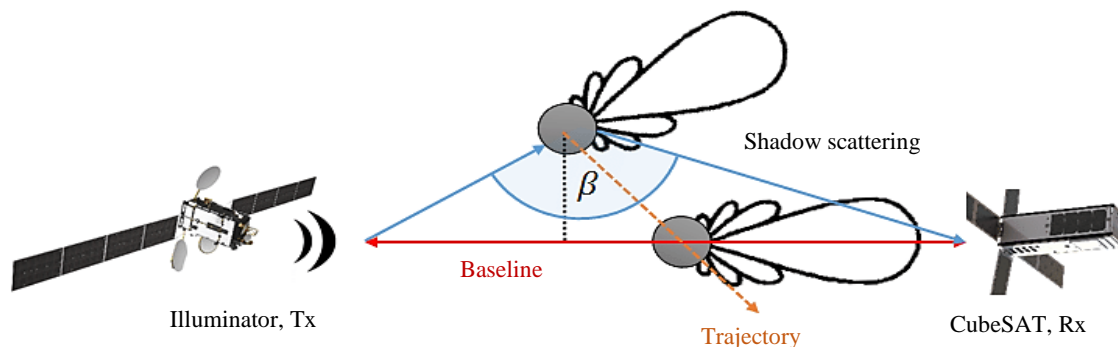


Figure 3. The concept of a CubeSat based passive bistatic radar (PBR) system [6].

if it strikes a space debris particle, the same laser pulse will reflect back, measuring the time it takes to do so. This information may be analyzed using sophisticated algorithms by the on-board computers or the data can be sent to the ground stations.

CONSTELLATION DESIGN

When designing a CubeSat constellation for space debris monitoring, many important factors must be considered. To properly identify and characterize space debris, the CubeSats must first be outfitted with the required payload, such as visible cameras and detecting chains. The possibility for space debris to fall to Earth's surface as well as its re-entry into the atmosphere should be detectable and monitored by the CubeSats. To identify faint meteors and provide adequate coverage of the Earth's surface, the CubeSats also need to be built to function in a LEO. When the CubeSat is prepared, it is crucial to consider the orbital requirements, such as a sun-synchronous orbit, which maximizes the launch dates available. Moreover, the CubeSat constellation ought to be built with effective data transmission back to Earth. It can be essential to create plans for gathering, processing, and transmitting data. In terms of technology, even with the restricted power resources on the CubeSat platform, the constellation of CubeSats should be able to identify space debris on its own.

Developing integrated image processing capabilities for the CubeSats and streamlining the processing chain to balance embedded parameters like processor compute power and power consumption with detection quality could be part of this. Some can serve as primary observers with specialized sensors, while others act as communication nodes or incorporate propulsion for collision avoidance. Efficient power management, redundancy, and ground operations ensure reliability and longevity. This integrated approach enables the CubeSat constellation to contribute effectively to space debris monitoring and enhance space situational awareness.

Some of the configurations for constellation arrangements of CubeSats are:

- *Sun-synchronous orbit (SSO):* A dispersed network of CubeSats in sun-synchronous orbit would offer thorough coverage of the planet's surface in terms of constellation layout. It is important to place the CubeSats so that their fields of vision overlap so that one can continuously monitor and detect space debris. This configuration would improve the constellation's capacity to record a variety of occurrences and phenomena, including meteor showers and space debris re-entering the atmosphere [7].
- *Hexagonal constellation:* The hexagonal constellation arrangement of CubeSats for space exploration aims to find a geometrically efficient and a configuration that balances coverage and resource use. In a hexagonal constellation, CubeSats are at the center of the connection between the hexagons, providing stable observations. This configuration minimizes duplication and allows different CubeSats to monitor space efficiently. The hexagonal structure is suitable for continuous monitoring and timely data collection and helps improve the detection ability of waste location. The geometric rules of the hexagonal star facilitate the coordination of CubeSats, facilitating satellite communications and data fusion.

- *Walker delta configuration:* The Walker Delta configuration is a proposed orbital arrangement for CubeSats, characterized by an inverted pattern along the edge of several orbital planes. This design allows for the deployment of CubeSats, reducing variability and allowing revisits to specific locations to improve space utilization. Its scalability and adaptability make it a good choice, but the challenges of maintaining the relative position and integration of multiple satellites need to be addressed in terms of continuous operation.
- *Polar constellation:* Characterized by the deployment of CubeSats in polar orbits, the Polar Constellation proposes an approach to tracking space debris by focusing on a wide range of high latitudes. In this configuration, CubeSats orbit the Earth along a line running through the Earth's poles, providing a broad view of the polar and equatorial regions in each orbit. The special significance provided by polar orbits enhances the observation of space debris orbits, especially in the orbital convergence zone, and collisions may be more likely. Because the Earth's surface is uniformly and vertically illuminated in polar orbits, optical sensors on CubeSats can operate in good lighting conditions, increasing visibility.

ORBIT CONSIDERATIONS

In this portion of our review paper, we explore the numerous orbits that can be utilized for the deployment of the CubeSat constellation, as well as their pros and disadvantages, while also taking into account the six orbital elements that are critical to the deployment.

Types of Orbits

High Earth Orbit

A satellite enters a “sweet spot” when its orbit coincides with the rotation of the Earth when it reaches 42,164 km from the center of the planet, or roughly 36,000 km from the surface. The satellite appears to stay fixed over one longitude because it circles at the same speed as the Earth, yet it may move from north to south. This specific high Earth orbit (HEO) is referred to as geosynchronous.

A satellite will have a geostationary orbit that remains stationary in relation to the ground if it is in a circular geosynchronous orbit directly over the equator (eccentricity and inclination equal to zero). It always passes straight over the same location on the Earth's surface.

Medium Earth Orbit

Because they are closer to the Earth, satellites in medium Earth orbit move more quickly. The semi-synchronous orbit and the Molniya orbit are two prominent medium Earth orbits (MEOs). Located 26,560 km from the Earth's core (around 20,200 km above the surface), the semi-synchronous orbit is a low eccentricity, near-circular orbit. The orbit of a spacecraft at this altitude takes 12 hours. Under the moving satellite, the Earth rotates. The satellite crosses the same two locations on the equator every 24 hours. This orbit is predictable and stable. The Molniya orbit is the second most popular medium Earth orbit. The Russians created the Molniya orbit, which is perfect for researching high latitudes. Satellites in geostationary orbit perform poorly for far northern or southern sites, which are always on the edge of a geostationary satellite's vision, despite the fact that these satellites are useful for providing a steady perspective because they are parked over the equator. One useful alternative is the Molniya orbit. During its 12-hour orbit, a Molniya satellite spends around two-thirds of that time in one hemisphere. Similar to a semi-synchronous orbit, a satellite in the Molniya orbit travels the same path every 24 hours [8, 9].

Low Earth Orbit

As the name suggests, a low Earth orbit (LEO) is one that is near the surface of the Earth. Although it can be as low as 160 km above Earth, which is low compared to other orbits but still rather high over the Earth's surface, it is often less than 1000 km above the planet. Location of LEO, MEO, and HEO is shown in Figure 4. LEO satellites are not obligated to follow a predetermined route around the Earth; their plane can be inclined, in contrast to GEO (geosynchronous equatorial orbit) satellites, which must continuously circle close to the equator. This indicates that there are a lot of possible routes for satellites to take when in LEO, which is one of the reasons it is so desired.

Low, medium and high earth orbits

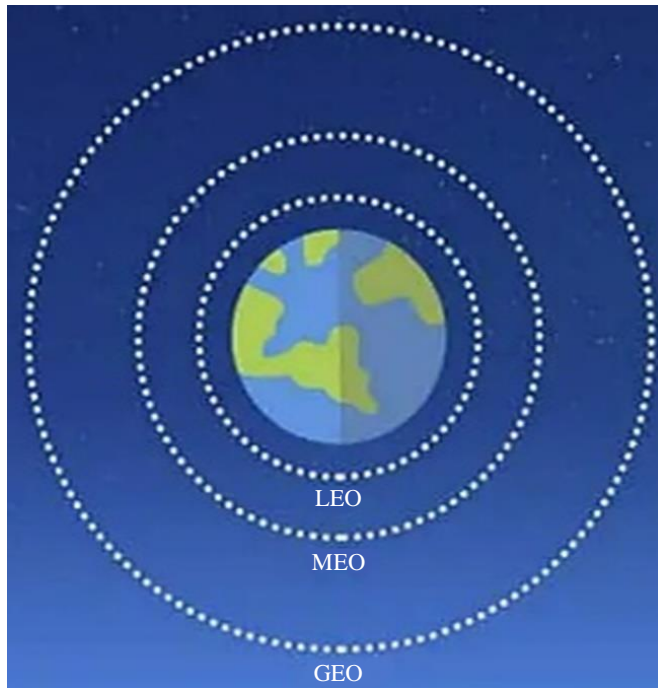


Figure 4. Location of low Earth orbit, medium Earth orbit, and high Earth orbit (geosynchronous equatorial orbit) [10].

Orbital Parameters

Setting standard parameters to determine orbits is essential to comprehending the motion of astronomical objects. The six orbital elements, or parameters, can really be used to define any orbit:

1. *Semi-major axis:* The size of the satellite's orbit is determined by the length of the semi-major axis (a). The primary axis is half of it. This extends from the center to the ellipse's edge via a focus.
2. *Eccentricity:* The satellite's orbital form is fixed by the value of eccentricity (e).
3. *Mean anomaly:* The term “perigee” refers to the point on a satellite that is closest to the Earth. The average value of the satellite's angular location with respect to the perigee is provided by the mean anomaly (M).
4. *Inclination:* Inclination (i) is the angle formed by the orbital plane and the equatorial plane of the earth.
5. *Argument of perigee:* Two spots are cut off the equatorial plane by satellite orbit. The initial location where the satellite transitions from the northern to the southern hemispheres is known as the descending node. The second location, known as the ascending node, is where the satellite transitions from the southern to the northern hemispheres. The angle between ascending node and perigee is known as the argument of perigee (ω).
6. *Right ascension of ascending node:* When a satellite moves from the southern to the northern hemisphere, it crosses the equatorial plane at the ascending node, as we know.

The angle between the ascending node and the line of Aries in the equatorial plane facing east is known as the right ascension of the ascending node (Ω). Aries is also called vernal and equinox. Six orbital elements are shown in Figure 5.

Advantages and Disadvantages of the CubeSat Constellation

CubeSat constellations deployed for space debris monitoring can be placed in various orbits depending on mission requirements, objectives, and constraints. Different orbits offer distinct advantages in terms of coverage, revisit times, and data accuracy. Here are some orbits suitable for CubeSat constellations in space debris monitoring.

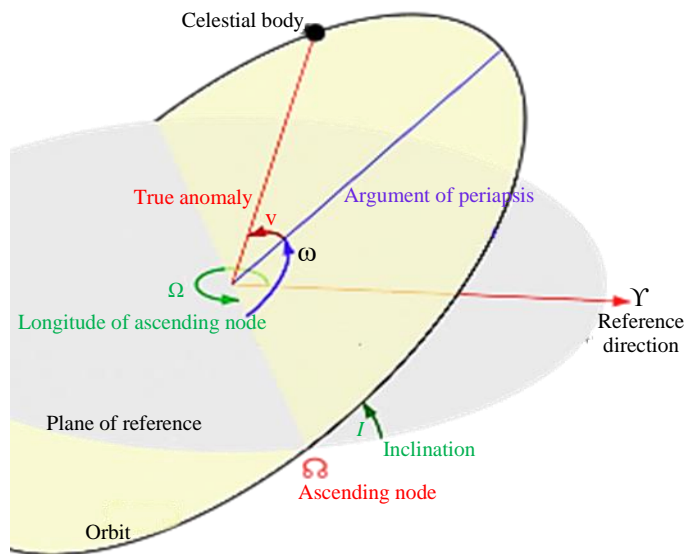


Figure 5. Six orbital elements [4].

Low Earth Orbit

Altitude

Usually 200 to 2000 km above the surface of the Earth.

Advantages

- *High revisit times:* CubeSats in LEO orbits can offer frequent revisits to specific regions of interest due to their relatively fast orbital periods.
- *Lower latency:* Closer proximity to Earth results in shorter communication delays, enabling real-time or near-real-time data transmission.
- *Improved resolution:* Closer proximity to the Earth allows for higher-resolution imaging and tracking of space debris.

Challenges

- *Atmospheric drag:* CubeSats in LEO orbits experience atmospheric drag, necessitating periodic orbit maintenance or reboost maneuvers.
- *Limited coverage:* While offering high revisit times to specific areas, LEO CubeSats may have limited global coverage compared to satellites in higher orbits [9].

Sun-Synchronous Orbit

Altitude

Typically, around 600 to 800 km above the Earth's surface.

Advantages

- *Repeatable ground track:* Sun-synchronous orbits (SSOs) enable CubeSats to pass over the same geographic locations at the same local solar time, facilitating consistent lighting conditions for imaging and observation.
- *Global coverage:* Over time, CubeSats in SSOs can provide thorough coverage of the entire planet.
- *Reduced atmospheric drag:* Higher altitude orbits compared to LEOs results in less atmospheric drag, prolonging mission lifetimes.

Challenges

- *Limited revisit times:* While offering global coverage, CubeSats in SSOs may have longer revisit times compared to those in LEO orbits.

- *Payload limitations:* SSOs impose constraints on the payload capacity and instrument capabilities of CubeSats due to the limited available power and volume.

Polar Orbit

Altitude

Can vary but typically between 500 and 800 km above the Earth's surface.

Advantages

- *Comprehensive coverage:* Polar orbits enable CubeSats to cover the entire Earth's surface, including high-latitude regions that may be missed by equatorial orbits [8].
- *Reduced interference:* Polar orbits minimize interference from Earth's magnetic field, allowing for more accurate measurement of space debris trajectories.
- *Stable lighting conditions:* CubeSats in polar orbits experience consistent lighting conditions, facilitating reliable imaging and observation.

Challenges

- *Lower revisit times:* CubeSats in polar orbits may have longer revisit times compared to those in LEO orbits due to the larger ground track swath.

CASE STUDIES

Following are case studies that explore the utilization of CubeSats for space debris monitoring and provide a concise yet insightful view into the dynamic field of satellite technology. These instances showcase the innovative approaches and advancements achieved in the pursuit of effective space debris monitoring solutions. By delving into these projects, we uncover the practical applications of CubeSats, gaining valuable lessons that contribute to the ongoing evolution of space exploration strategies.

STRATHcube

STRATHcube is a CubeSat used for space exploration using passive bistatic radar technology. It explores the concept of a CubeSat-based passive bistatic radar (a radar system launched from a broadcast, communications, or radio navigation transmitter) associated with radar receivers and

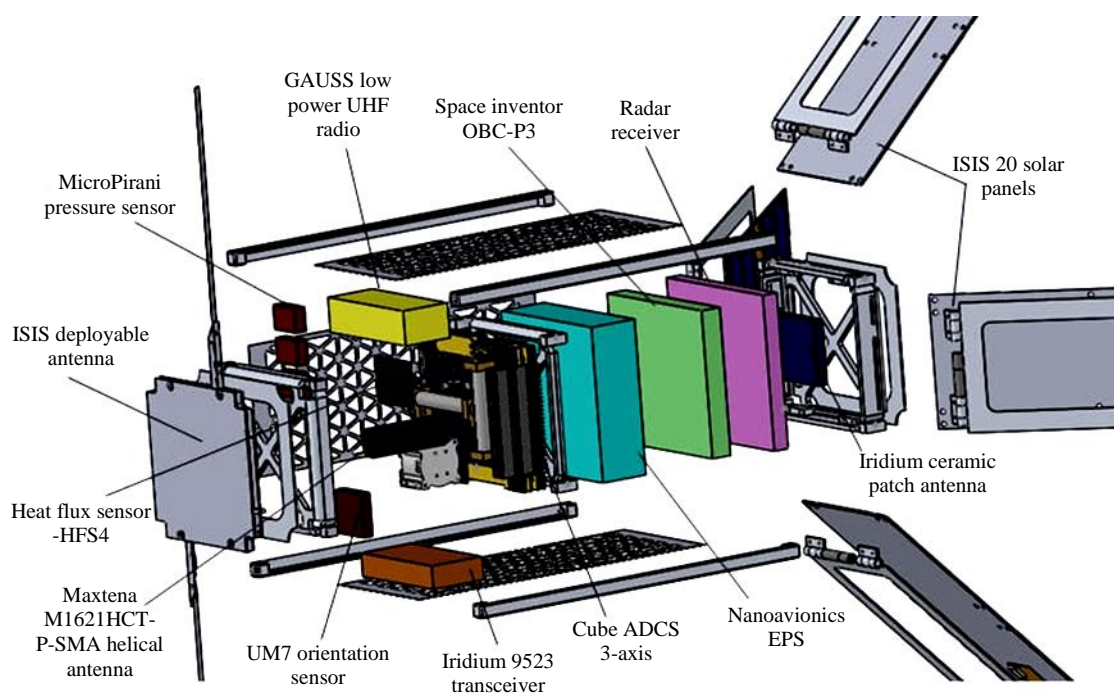


Figure 6. Exploded configuration of the STRATHcube CubeSat [11].

antennas on low-altitude CubeSats to capture signals from operating satellite radio signals. It covers the selection of illuminators of the time, such as the Iridium constellation, and the trade-off of different design options, eventually leading to the selection of the Pulse LARSEN patch antenna for the STRATHcube brand scheme. The paper demonstrates the potential for space-based passive bistatic radars to provide communities with a cheaper and more versatile way to monitor the ground, helping to improve the condition of the field and reduce waste. This article also discusses the challenges of developing experiments on the CubeSat platform and describes the integration of PBR technology for space exploration in CubeSats as payment for STRATHcube purposes. It shows the results of the preliminary design and lessons learned during development, including the selection of the Pulse LARSEN patch antenna as the antenna for the PBR payload. In addition, progress is made in demonstrating the effectiveness of passive bistatic radar technology in space, providing effective and easy-to-use results in detecting and tracking space debris [10]. Exploded configuration of the STRATHcube CubeSat is shown in Figure 6.

MOVE-III

MOVE-III is a CubeSat project which is a student-led mission by the Technical University of Munich aimed at acquiring in-situ measurements of sub-millimeter space debris and meteoroids in the LEO. The mission's scientific objectives include validating space debris models, characterizing the space environment, and providing data to support further studies related to space debris and meteoroids. Three Debris Density Retrieval and Analysis (DEDRA) plasma ionization sensors are intended to be carried by the CubeSat, which uses the MOVE-BEYOND platform. It has a detailed system architecture, subsystems, and interactions, as well as the expected space debris and meteoroid flux.

In their paper, the authors also showcase the mission timeline, risk assessment, data processing chain, and debris mitigation plan to ensure compliance with international guidelines for orbital lifetime and disposal. Also, they have outlined the expected data products, including impact direction readings, particle mass and velocity measurements, and the potential contributions to space debris model validation and environment characterization studies. The MOVE-III mission is expected to launch in 2024 at an altitude between 500 and 600 km, with simulations indicating the collection of up to 150 impacts within one year of operations. The CubeSat is designed to comply with international guidelines for LEO orbits and disposal, with a remaining lifetime of about 20 years at altitudes below 600 km [11, 12]. Render of MOVE-III after deployment (A) and in space is shown in Figure 7.

Meteorix

The Meteorix mission is a university-led CubeSat space project whose goal is to identify and study space debris and meteors. The project is a demonstration for the identification and description of meteors and space debris from space, and it has confirmed the feasibility phase. The mission's scientific

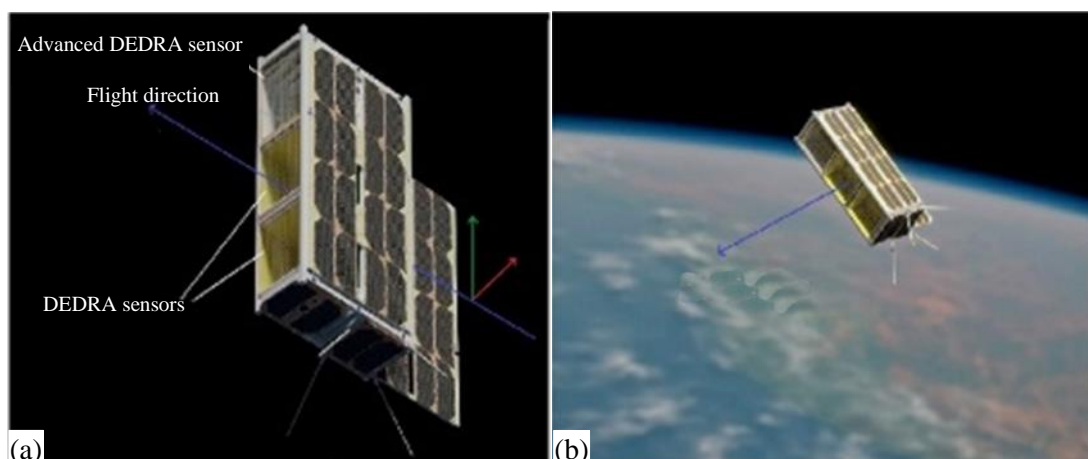


Figure 7. Render of MOVE-III after deployment (a) and in space (b) [11].

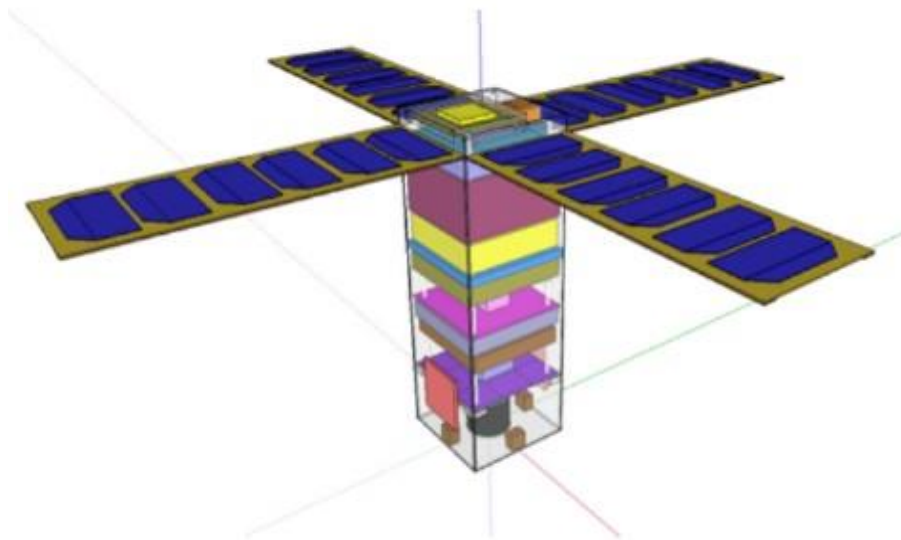


Figure 8. Design of the Meteorix 3U CubeSat [12].

requirements include determining the flux density of meteors and space debris, studying ablation, fragmentation, and rotation processes, and detecting other faint luminous atmospheric phenomena. Due to the CubeSat platform's limited power resources, the technological objective, which is focused on the autonomous detection of meteors on board, presents a considerable obstacle. Lessons learned from the mission include the development of an embedded image processing chain onboard a CubeSat, the adaptation of a 3D PLUS sensor for meteor detection, and the utilization of a visible camera to measure meteors and space debris. Advancements achieved through the Meteorix mission include the demonstration of the feasibility of an embedded image processing chain onboard a CubeSat, the validation of the mission's scientific and technological objectives, and the potential for future developments in space debris monitoring and meteor science [12, 13]. Design of the Meteorix 3U CubeSat is shown in Figure 8.

DATA FUSION AND ANALYSIS

Integrating data from multiple CubeSats in a constellation is essential for enhancing accuracy in space debris tracking and characterization. Data fusion techniques play a crucial role in this process by combining information from multiple sources to generate more comprehensive and accurate representations of the space debris environment. Here is how data fusion enhances accuracy.

Multi-Sensor Fusion

CubeSats in a constellation may be equipped with various sensors, such as optical cameras, radar systems, and infrared detectors, each providing unique data about space debris. Data fusion combines observations from different sensors to create a more complete picture of the debris population, improving detection and tracking capabilities.

Redundancy and Reliability

By integrating data from multiple CubeSats, redundancy is increased, and the reliability of observations is enhanced. In cases where individual CubeSats may experience technical issues or limitations, data fusion ensures that accurate information can still be obtained from other satellites in the constellation.

Improved Spatial Coverage

CubeSat constellations offer the advantage of increased spatial coverage compared to single-satellite missions. By integrating data from multiple CubeSats with overlapping fields of view, a more extensive area of space can be monitored, allowing for the detection and tracking of debris across a broader range of orbital altitudes and inclinations.

Enhanced Tracking Accuracy

Data fusion techniques incorporate information about the dynamics of space debris, including position, velocity, and orbital parameters, to improve tracking accuracy. By combining observations from multiple CubeSats over time, more precise trajectories can be calculated, enabling better predictions of future positions and potential collision risks.

Real-Time Updates

CubeSat constellations equipped with data fusion capabilities can provide real-time updates on the location and movement of space debris. Rapid dissemination of accurate information allows satellite operators and space agencies to make timely decisions regarding collision avoidance maneuvers and mission planning.

Adaptive Algorithms

Data fusion algorithms can adaptively integrate information from multiple CubeSats based on factors such as sensor reliability, observation quality, and environmental conditions. Adaptive algorithms ensure that the most reliable and relevant data is used to generate accurate assessments of the space debris environment.

In summary, data fusion techniques enable CubeSat constellations to integrate observations from multiple sources, improve spatial coverage, enhance tracking accuracy, and provide timely updates on the status of space debris. By leveraging the collective capabilities of multiple satellites, data fusion enhances situational awareness and supports effective decision-making for space operations and safety.

SPACE DEBRIS REMOVAL STRATEGIES

Various space removal strategies have been studied over the past few years. Some of them have been implemented whereas some are still under study. According to the research paper we studied we have found that the space debris removal methods have been divided into two categories:

1. Space environment-based methods
2. Non-space environment methods

Space Environment-Based Method

Space environment-based methods include drag augmentation methods and electrodynamic tether method.

Drag Augmentation Method

The main purpose of increasing drag is to increase the area/mass ratio of parts to increase drag. There are three ways to do this: air-filled reinforcement, fiber-based reinforcement, and foam-based reinforcement. Satellites use foam-based foam development in the waste area, collecting the foam and increasing its area and drag. Like foam-based construction, fiber-based construction sprays fibers into the waste area. The inflation method uses a magnetic material that attaches to the waste area. Due to increased competition, debris is entering the Earth's atmosphere faster than it should, causing the sky to explode from orbit. Drag increasing has potential, but also has disadvantages such as difficulty in delivery, survival of the rope in place, and the need for cycle estimation to ensure availability and safe return of garbage. Example – ESA cleanSat Program [4]. The inflated ball method for drag augmentation of the debris is shown in Figure 9.

Electrodynamic Tether

The geomagnetic field is utilized in the electrodynamic tether technique to reenter the atmosphere with the debris. It has two field electrode arrays and a long, clean semiconducting gadget. When a lengthy conductive tether is extended from the spaceship and travels through the earth's magnetic field, electromagnetic induction causes it to produce an electric current. At the ends of the tethers is a plasma contractor that permits current to flow on both sides. In addition, one electrode captures electrons while



Figure 9. Inflated ball method for drag augmentation of the debris [4].

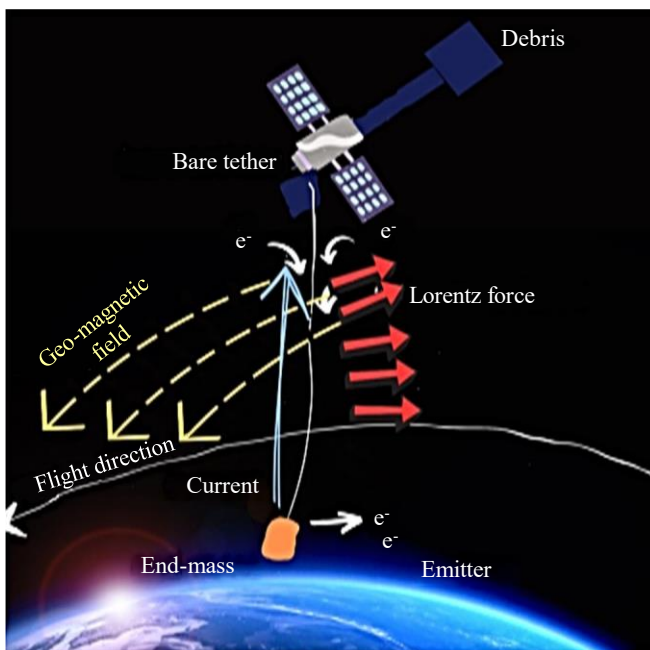


Figure 10. Electrodynamic tether [4].

the other radiates them to generate current. Since aluminum is conductive and lightweight, it is the most widely used material for tethers. An electrodynamic tether system can be used to target certain debris items in the context of space debris clearance. It is possible to use electrodynamic forces to reduce the debris' orbit and accelerate its fall into Earth's atmosphere by attaching a conductive tether to it [4]. An electrodynamic tether is shown in Figure 10.

Non-Space Environment–Based Method

Non-space environment–based method also has two categories:

1. Contact-based removal method
2. Contactless removal method

Contact-Based Removal Method

SlingSat Method

The University of Texas created the “SlingSat Space Sweeper” to remove space junk. In this procedure, when a satellite captures a space debris, it imparts momentum and matches its speed before ejecting the debris at a precise angle, forcing it to hit the earth's atmosphere and burn up, and the process



Figure 11. SlingSat developed by the University of Texas [4].

repeats again. It is essentially a catch-and-throw technique. SlingSat developed by University of Texas is shown in Figure 11. The goal is to remove as much space trash as possible. The satellite is spin stabilized and consists of two arms, the length of which determines the spin velocity. This method's fuel efficiency is its most noteworthy feature [4].

Adhesive Method

The adhesive approach employs a sticky substance to grab and remove debris from the object. It is a simple procedure in which the debris adheres to the adhesive material and is recovered and drawn back towards Earth, where it will burn up as soon as it enters the atmosphere. It is typically used to collect a tiny variety of detritus. This procedure should be utilized cautiously to avoid the release of undesired elements.

Contactless Removal Method

Laser Satellite

A laser satellite technology could be a viable solution to the space debris problem. There are two types of lasers proposed in this scenario. One of them is a ground-based laser, while the other is a space-based laser. Space-based lasers are more appropriate. In this procedure, a pulsed laser is directed at the debris, changing its velocity and causing it to wander from its intended path. Functioning of laser satellite to deviate space debris is shown in Figure 12. This can cause debris to divert into the earth's atmosphere. A high-intensity laser is not desirable because it will generate more space junk. This procedure is sometimes not favored owing to military reasons [4].

Ion Beam Shepherd

In this procedure, an ion thruster is utilized. This thruster ejects a stream of charged particles onto space junk, which, depending on their polarity, can repel or attract the spacecraft by manipulating the electric field. This uses two propulsion modules. An ion beam shepherd is shown in Figure 13. One ejects

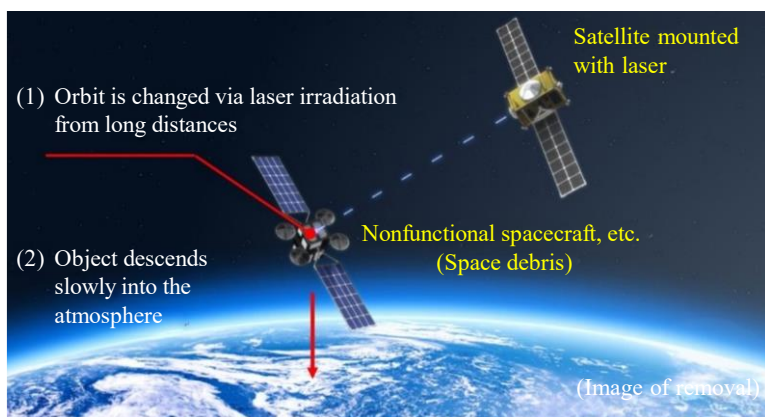


Figure 12. Functioning of laser satellite to deviate space debris.

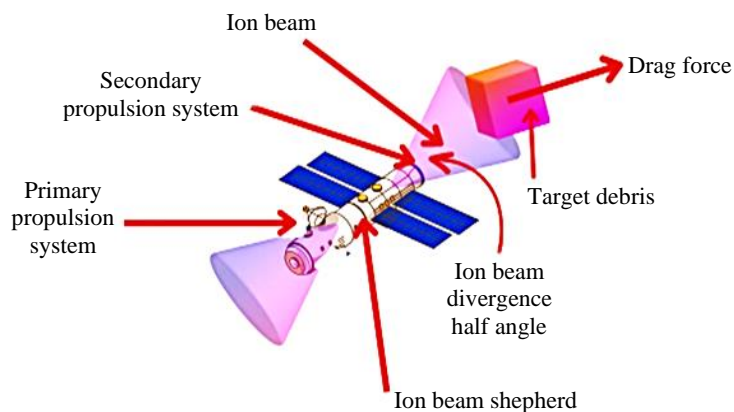


Figure 13. Ion beam shepherd [4].

a powerful beam of ions onto space junk, while the other does the same but in the opposite direction, resulting in improved satellite stabilization. This approach has the benefit of lowering the possibility of debris and spacecraft damage [4].

Self-Eating Satellites

Self-eating satellites are a fascinating theoretical topic. During this process, the satellite will be designed in such a way that at the end of the mission, it will disassemble itself, resulting in less debris. While the concept sounds enticing, it is important to note that no self-eating satellites have ever been developed or launched into space. The concept is still purely conceptual and speculative [4].

CHALLENGES AND FUTURE DIRECTIONS

The deployment of CubeSat constellations for space debris monitoring is hampered by a number of issues. To begin with, the size and capabilities of onboard sensors are constrained by the small payload capacity of CubeSats, which reduces the extent and accuracy of data collecting. The limitations of power and energy make mission planning much more difficult, particularly when the mission is long term. Data transmission between CubeSats and ground stations is hampered by communication limits, including those related to bandwidth and line-of-sight. Sophisticated collision avoidance techniques are required due to orbital dynamics and the possibility of collisions with other satellites or debris, which means that CubeSat paths must be continuously monitored and adjusted. The increasing quantity of CubeSats in orbit also prompts worries about possible collisions and space traffic control [7, 14].

Developments in miniaturized sensor technologies, such as lightweight and powerful equipment, can increase payload capacity and help overcome the difficulties in deploying CubeSat constellations for space debris monitoring. Power limitations can be lessened by using more advanced solar panel technology, energy-efficient parts, and innovative power management techniques. In the face of communication constraints, research on relay satellites and sophisticated communication protocols may improve data transfer. Orbital dynamics problems can be solved by combining sophisticated propulsion systems with autonomous collision avoidance algorithms. It is essential to work together with international organizations to create automatic collision prevention technologies and standardize space traffic management procedures. By reducing dependency on ground-based resources, studying onboard data processing techniques can maximize CubeSat efficiency in space debris monitoring.

CONCLUSION

In conclusion, this research paper has delved into the pivotal role of CubeSats in revolutionizing space missions, with a particular focus on their advantages in monitoring and tracking space debris. The inherent scalability and cost-effectiveness of CubeSat constellations have emerged as transformative features, enabling a paradigm shift from traditional, singular satellite approaches. The modular and standardized design of CubeSats allows for the deployment of multiple satellites, forming constellations

that enhance coverage and monitoring capabilities, particularly in tracking the dynamic movements of space debris. The cost-effectiveness of CubeSats extends beyond their initial affordability, encompassing operational expenses and democratizing access to space exploration. This financial accessibility not only empowers entities with limited resources to actively participate in space missions but also encourages collaborative endeavors, fostering innovation and advancing space situational awareness. CubeSats have become catalysts for technological advancements, integrating cutting-edge miniaturized sensors that contribute to precise monitoring and tracking of space debris. In addition, CubeSats showcase adaptability by offering the flexibility to be deployed in various orbits, adjusting positions for optimized observations. Their collaborative swarming capabilities facilitate distributed tasks, covering larger volumes of space and enhancing the efficiency of monitoring efforts. The research highlights CubeSats' integral role in addressing the challenges associated with space debris, not only through observation but also as potential tools for active removal strategies.

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