# A Survey of Space Object Sensing and Space Situational Awareness Technologies

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## Abstract

Space Object Sensing and Space Situational Awareness (SSA) are essential for maintaining the safety and security of space operations amidst increasing orbital congestion. This survey explores advanced methodologies and technologies that enhance SSA capabilities, focusing on multi-source orbit determination, data fusion, and feature extraction algorithms. The integration of innovative techniques such as decentralized deep learning, Model-Based Reinforcement Learning, and interferometric sensing significantly improves the accuracy and reliability of space object tracking. Collaborative efforts, particularly within European initiatives, underscore the importance of data-sharing in enhancing SSA frameworks. CubeSats in Low Earth Orbit (LEO) and advancements in space-based surveillance technologies further augment SSA capabilities, providing real-time data and enhancing autonomous operations. The effective albedo metric and neural networks for light curve analysis are pivotal in characterizing Resident Space Objects (RSOs), improving orbit predictions and collision avoidance strategies. This survey highlights the critical need for integrating these advanced methodologies to address challenges in an increasingly congested space environment, ensuring the safety and sustainability of space operations.


## 1 Introduction

### 1.1 Significance of Space Object Sensing and SSA

Space Object Sensing and Space Situational Awareness (SSA) are crucial for ensuring the safety and security of space operations amid increasing orbital congestion from operational spacecraft and space debris. Reliable tracking systems for Resident Space Objects (RSOs) are vital for maintaining secure operations [1]. The rise in Anthropogenic Space Objects (ASOs) necessitates robust SSA systems to promote long-term space safety and sustainable utilization [2].

The significant threat posed by space debris, comprised of human-made objects in orbit, underscores the need for precise detection and tracking systems to mitigate collision risks with active satellites [3]. In Low Earth Orbit (LEO), the proliferation of debris presents substantial risks to operational satellites and future missions, with radar systems serving as the primary means for tracking and cataloging these objects [4]. Enhanced tracking methods for RSOs are essential for effective collision avoidance in distributed satellite systems [5]. Additionally, incorporating infrared technologies for detecting dim targets significantly bolsters SSA capabilities [6].

Robotic telescopes, such as those in the TBT project, enhance SSA by tracking Near-Earth Objects (NEOs) and satellites, contributing to global safety and security efforts [7]. Timely data provision regarding the space environment and potential threats, especially concerning NEOs, supports independent European space utilization [8].

Moreover, systems like automatic flare detection are essential for real-time solar activity monitoring, critical for maintaining operational safety [9]. The challenge of orbital debris fosters inter-agency and international collaboration toward debris prevention, mitigation, and enhanced SSA [10].

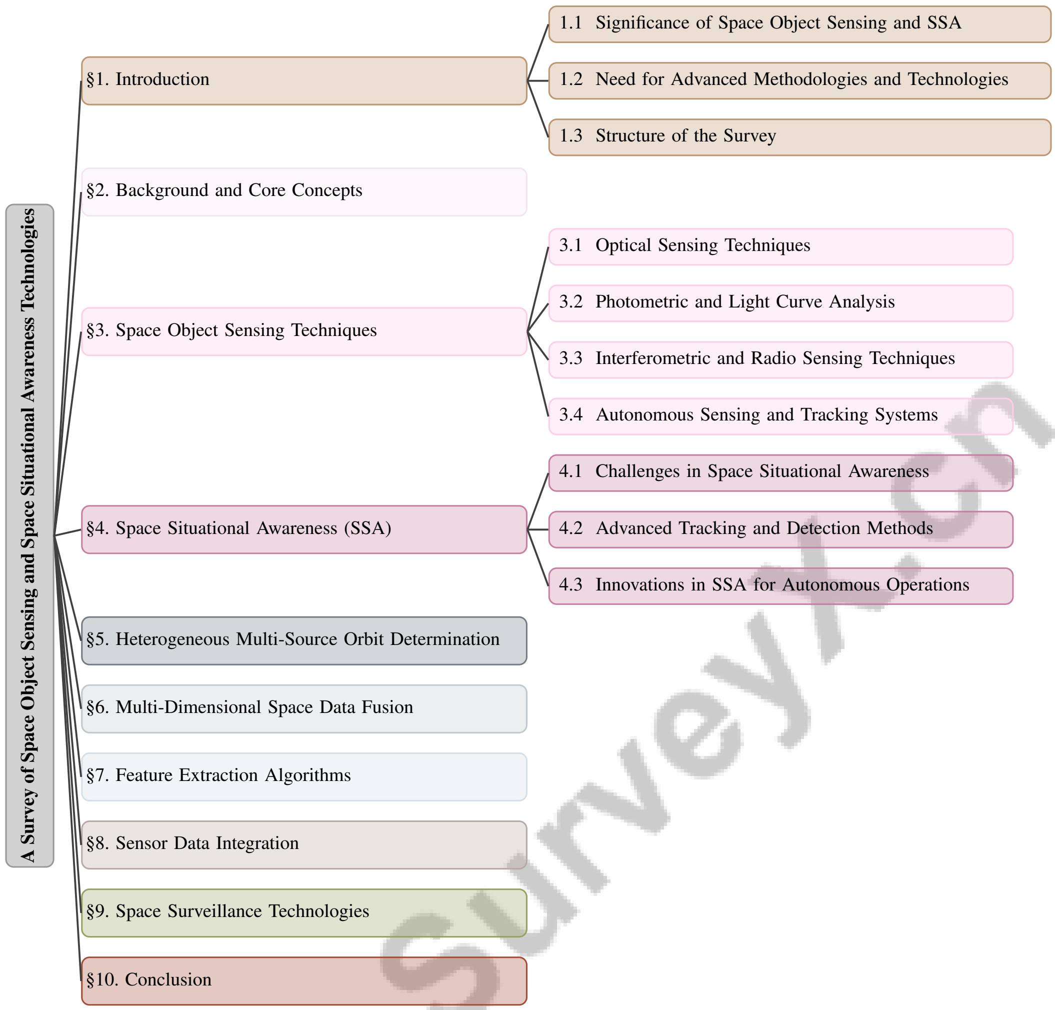


Figure 1: chapter structure



Integrating advanced sensing technologies and SSA methodologies is pivotal for safeguarding space operations and ensuring the security of current and future endeavors. As these systems evolve, they hold the potential to surpass conventional methods, advancing navigation technologies for high precision in deep space applications [11].

## 1.2 Need for Advanced Methodologies and Technologies

The increasingly congested space environment necessitates the development of advanced methodologies and technologies to enhance SSA capabilities. Traditional tracking methods have proven inadequate, as illustrated by the collision between Kosmos-2251 and Iridium-33, highlighting the urgent need for improved tracking techniques [3]. Conventional orbit prediction models often fail to accurately account for non-conservative forces, such as atmospheric drag, necessitating more precise and computationally efficient approaches [12].

Innovative methodologies like the Double Deep Q Network (DDQN) provide effective solutions for sensor management within SSA systems, facilitating improved monitoring and response strategies [13]. The limitations of previous methods in meteor detection emphasize the need for advancements in on-orbit surveillance capabilities, particularly through smart camera systems [14]. Additionally, developing a Space Situational Awareness Domain Ontology (SSAO) aims to enhance data-sharing and create robust SSA frameworks [15].

The L-DIT methodology offers a novel approach to quantifying the sustainability of ASOs without sensitive data, addressing the pressing need for advanced SSA methodologies [2]. As space traffic complexity increases, higher automation levels are essential for effective Space Traffic Management (STM), necessitating the development of autonomous decision-making systems [16]. Furthermore, optimizing trajectory planning tools for mobile observers is critical for enhancing navigation and tracking performance [17].

Integrating decentralized, trustless mechanisms, such as blockchain technology, exemplifies the necessity for innovative technologies in enhancing SSA capabilities [1]. The combination of robotic telescope capabilities and automated scheduling, as demonstrated by the TBT project, illustrates the potential for transformative advancements in SSA methodologies [7]. Collectively, these innovations highlight the urgent need for new technologies and methodologies to ensure the safety and sustainability of space operations in a complex orbital environment. This survey explores the challenge of developing efficient frameworks to enhance SSA technologies in a rapidly evolving context [18]. The exploration of space-based alternatives to existing ground-based tracking methods, which face accuracy and weather dependence limitations, further emphasizes the necessity for innovative technologies [5]. Additionally, the increasing demand for bandwidth in modern sensing and information technologies has accelerated the development of free-space optical communications for space applications [11].

### 1.3 Structure of the Survey

This survey provides a comprehensive examination of the current state and advancements in Space Object Sensing and SSA technologies. It begins with an introduction that underscores the significance of SSA in maintaining safety and security in space operations, emphasizing the need for advanced methodologies and technologies. The survey explores the background and fundamental concepts of SSA, highlighting significant contributions and collaborative innovations from European organizations, including the European Space Agency's development of a comprehensive SSA system that encompasses monitoring space weather, tracking NEOs, and surveilling manmade space debris. It also discusses the importance of improving data-sharing through computational ontologies and implementing advanced optical sensor networks for effective cataloging and tracking of space debris in LEO, underscoring collaborative efforts from institutions like Carlo Gavazzi Space SpA and the Istituto Nazionale di Astrofisica [15, 4, 8].

Subsequent sections analyze various techniques and technologies used in space object sensing, including optical sensing techniques, photometric and light curve analysis, and the application of interferometric and radio sensing methods. The role of autonomous sensing and tracking systems in enhancing SSA capabilities is also discussed, demonstrating the integration of advanced technologies.

The survey evaluates SSA's role in safeguarding space operations by identifying challenges and investigating cutting-edge tracking and detection methodologies. It highlights SSA's importance in providing timely and quality data regarding space threats, enhancing global cooperation in data-sharing, and ensuring tracking data reliability through advanced technologies such as blockchain and deep learning. This approach aims to improve safety and security in space while bolstering planetary defense against NEOs and facilitating sustainable outer space use [15, 1, 8]. Innovations enhancing autonomous operations in SSA are highlighted, showcasing technological advancements shaping the future of space surveillance.

Further sections discuss methodologies for heterogeneous multi-source orbit determination, focusing on challenges and solutions related to multi-source data integration. Advanced algorithms developed to address these challenges emphasize the importance of integrating diverse data sources for accurate orbit determination.

The paper conducts a comprehensive analysis of multi-dimensional space data fusion techniques, emphasizing advanced algorithms that significantly enhance data fusion processes. It explores practical applications of multi-dimensional features, such as infrared intensity, temperature, and micromotion period, in improving SSA systems. Innovative methods like improved Dempster–Shafer theory for target recognition and a topological sweep technique for multi-target detection demonstrate effectiveness in accurately identifying and tracking geostationary space objects amidst challenging conditions. The development of a space situational awareness ontology aims to facilitate data sharing and integration among various SSA stakeholders, ultimately contributing to enhanced global safety and security in space operations [15, 6, 19]. Feature extraction algorithms are examined, focusing on effective albedo metrics and the use of neural networks for light curve analysis.

Sensor data integration is another critical area explored, with discussions on comprehensive techniques and collaborative efforts required for effective data integration across organizations. The review of space surveillance technologies encompasses a detailed exploration of CubeSats operating in LEO, highlighting breakthroughs in space-based surveillance systems. It emphasizes the potential of CubeSats, such as the proposed SWIMSat, which utilizes advanced smart camera technology to autonomously detect and track both illuminated and unilluminated objects, including NEOs. Additionally, innovative techniques like the topological sweep method for optical detection of man-made objects in Geostationary Orbit (GEO) address the challenges of identifying small, dim targets against a backdrop of bright stars. These advancements collectively enhance SSA capabilities by enabling more efficient and accurate tracking of various space objects [14, 19].

The survey concludes by summarizing key points discussed, emphasizing the critical role of integrating advanced technologies and methodologies in SSA to enhance data-sharing, improve global safety and security, and ensure the sustainability of space operations. This integration is essential for fostering collaboration among SSA actors, supporting planetary defense initiatives, and facilitating timely monitoring of space weather, NEOs, and manmade space debris, thereby safeguarding the future of space exploration and utilization [8, 15].The following sections are organized as shown in Figure 1.

## 2 Background and Core Concepts

### 2.1 European Contributions to SSA

European organizations have played a pivotal role in advancing Space Situational Awareness (SSA) technologies, particularly in Space Weather monitoring, Near-Earth Object (NEO) surveys, and Space Surveillance and Tracking (SST) of anthropogenic objects [8]. These advancements are crucial for maintaining the safety and security of space operations amid rising orbital congestion and associated hazards.

The European Space Agency (ESA) leads efforts to enhance space debris and NEO detection through its comprehensive SSA framework. Key initiatives include deploying optical sensor networks for debris cataloging, utilizing CubeSats with smart cameras for tracking both illuminated and unilluminated objects, and fostering standardized data-sharing systems to bolster international collaboration in space safety [14, 4, 20, 10, 8]. ESA's SSA program is structured into three pillars: Space Weather, NEOs, and SST. These pillars address solar activity impacts, potential NEO threats, and the detection and cataloging of human-made orbital objects, respectively.

Collaboration is central to European SSA initiatives, illustrated by the Space Surveillance and Tracking (SST) Support Framework, which enhances cooperation among EU member states to improve SST capabilities. These initiatives aim to establish a comprehensive and autonomous SSA system that includes monitoring and forecasting space weather, surveying and tracking NEOs, and overseeing anthropogenic space objects. This system is intended to deliver timely and precise data on space objects and events, thereby improving global safety and sustainability, facilitating effective international data-sharing, and enhancing our understanding of the space environment for better planetary defense and safe space exploration [15, 8].

European contributions to SSA also involve developing policies and frameworks that enhance international cooperation and effective data sharing. Initiatives like the Tracking Data Message (TDM) standardize practices to improve SSA data reliability and accuracy, fostering collaboration among stakeholders and bolstering global space safety and security. Additionally, efforts to develop computational ontologies within the SSA domain aim to improve the representation, annotation, and integration of SSA data across multiple repositories, advancing our understanding of the space environment and strengthening planetary defense capabilities [15, 1, 8]. By promoting transparency and collaboration, these initiatives contribute to a more effective global SSA network, ensuring space remains a safe and secure environment for all users.

In recent years, the field of space situational awareness has witnessed significant advancements, particularly in the area of sensing techniques. To illustrate this evolution, Figure 2 provides a comprehensive overview of the hierarchical categorization of various space object sensing techniques. This figure delineates a spectrum of methodologies, including optical sensing with advanced telescopes and algorithms, photometric and light curve analysis, as well as interferometric and radio sensing methods. Furthermore, it highlights the emergence of autonomous sensing and tracking systems. Each category is meticulously divided into specific technologies and applications, thereby underscoring the integration of these advancements and their implications for enhancing our understanding of space dynamics.

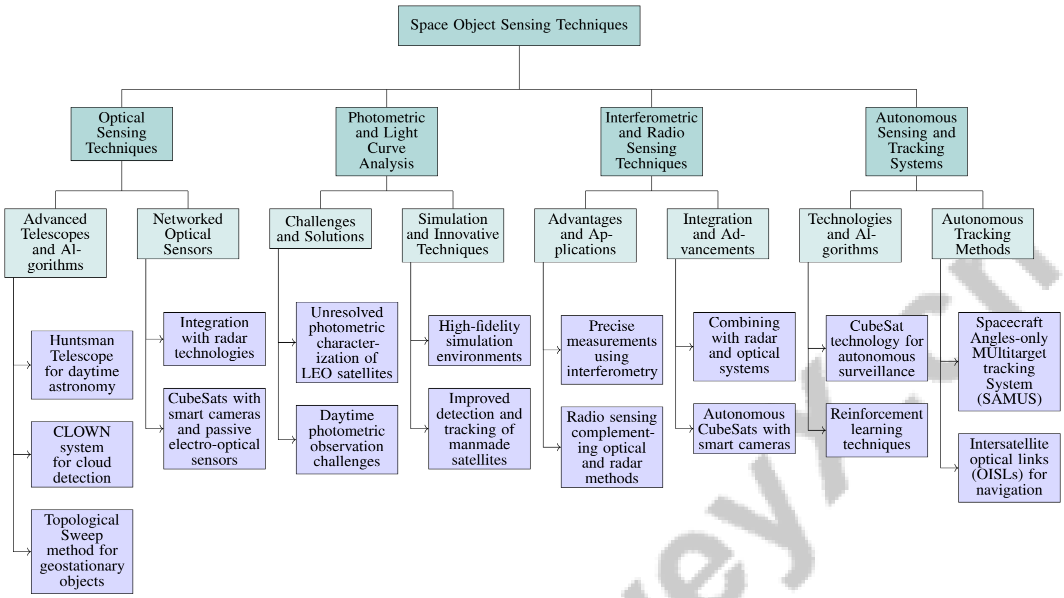


Figure 2: This figure illustrates the hierarchical categorization of space object sensing techniques, including optical sensing with advanced telescopes and algorithms, photometric and light curve analysis, interferometric and radio sensing methods, and autonomous sensing and tracking systems. Each category is further divided into specific technologies and applications, demonstrating the integration and advancements in space situational awareness.

# 3 Space Object Sensing Techniques

## 3.1 Optical Sensing Techniques

| Method Name | Technological Components | Functional Capabilities | Operational Context |
|---|---|---|---|
| TS[19] | Topological Sweep Algorithm | Detecting Geostationary Objects | Geostationary Orbit |

Table 1: Overview of the Topological Sweep method, highlighting its technological components, functional capabilities, and operational context. The method employs a Topological Sweep Algorithm to detect geostationary objects, specifically within the Geostationary Orbit as detailed in .

Optical sensing techniques are crucial for the detection and tracking of space objects, utilizing advanced telescopes and algorithms across various orbital regimes. The Huntsman Telescope facilitates optical daytime astronomy, enabling continuous monitoring of bright variable stars and LEO satellites, which is vital for maintaining situational awareness in the increasingly congested LEO environment [21]. Systems like CLOWN enhance telescope efficiency by automating cloud detection, thereby optimizing data quality [20].

Advanced algorithms, such as the Topological Sweep method, enhance optical sensor capabilities by detecting multiple geostationary objects from a series of images, thus improving tracking accuracy [19]. Table 1 provides a detailed examination of the Topological Sweep method, emphasizing its role in enhancing optical sensing techniques for space object detection and tracking. Experiments with networks of optical sensors for LEO debris tracking demonstrate their effectiveness alongside radar technologies, integrating complementary data for a comprehensive view of the space environment [4].



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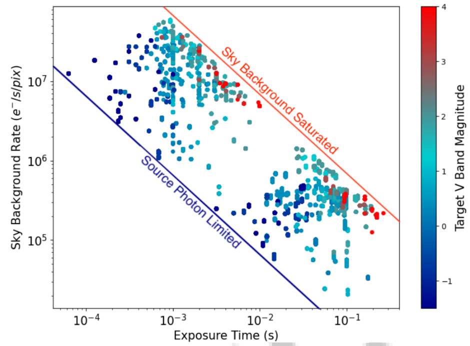
Recent advancements, including CubeSats equipped with smart cameras and passive electro-optical sensors, significantly improve detection and tracking capabilities. These technologies enable effective collision avoidance maneuvers in distributed satellite systems, enhancing sensor resolution and tracking accuracy while addressing concerns about orbital debris [14, 5]. Consequently, optical methods remain fundamental to space object sensing, contributing significantly to the safety and sustainability of space operations.

(a) Portable Observatory Shelter[22]




(b) Sky Background Rate vs. Exposure Time and Target V Band Magnitude[21]

Figure 3: Examples of Optical Sensing Techniques

As shown in Figure 4, optical sensing techniques provide critical insights into space objects. This figure illustrates the hierarchical structure of these techniques, categorizing them into advanced telescopes, algorithms and methods, and sensor networks, thereby highlighting key technologies and innovations in space object detection and tracking. Additionally, the scatter plot "Sky Background Rate vs. Exposure Time and Target V Band Magnitude" emphasizes the relationship between sky brightness and exposure times, underscoring the need for optimizing observational strategies. These examples underscore the diverse methodologies in optical sensing that enhance our understanding of celestial phenomena [22, 21].

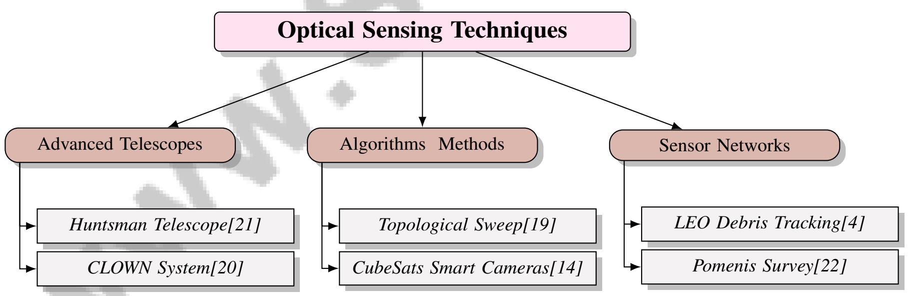



Figure 4: This figure illustrates the hierarchical structure of optical sensing techniques, categorizing them into advanced telescopes, algorithms methods, and sensor networks, highlighting key technologies and innovations in space object detection and tracking.

### 3.2 Photometric and Light Curve Analysis

Photometric and light curve analyses are vital for characterizing space objects, providing insights into their physical properties and motion. The unresolved photometric characterization of LEO satellites presents challenges due to their rapid movement, necessitating refined techniques for accurate data capture [22]. Daytime photometric observations face obstacles such as high sky brightness and atmospheric scintillation, addressed by the Huntsman Telescope project, which enhances situational awareness in crowded orbital regimes [21].

High-fidelity simulation environments generating realistic light curves advance the characterization of Resident Space Objects (RSOs), improving orbital predictions and SSA capabilities [23]. These simulations refine photometric analysis techniques, contributing to the safe management of space



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operations. Innovative photometric techniques enhance the precision and reliability of space object characterization, playing a vital role in SSA by facilitating timely monitoring, supporting effective management of potential threats like NEOs, and promoting sustainable space utilization. Improved detection and tracking of manmade satellites also foster better data-sharing among SSA stakeholders, advancing scientific understanding and ensuring the safety of future missions [15, 24, 8].

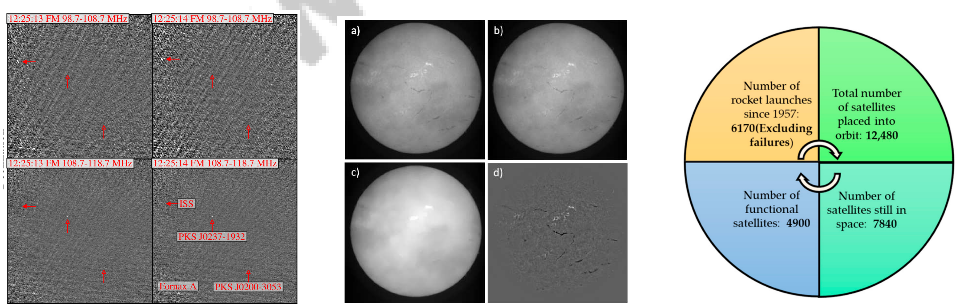
### 3.3 Interferometric and Radio Sensing Techniques

| Method Name | Sensing Techniques | Integration and Collaboration | Applications and Impact |
|---|---|---|---|
| MWA-PR[3] | Passive Radar Techniques | Radar Optical Systems | Space Situational Awareness |
| Surya[9] | Radio Sensing | Optical Systems | Space Weather |
| PSO-AN[5] | Hyperspectral Sensors | Dss Architecture | Collision Avoidance |

Table 2: Overview of various methods utilizing interferometric and radio sensing techniques for space object detection and tracking. The table details the specific sensing techniques employed, their integration with other systems, and the applications and impacts of these methods in enhancing space situational awareness and safety.

Interferometric and radio sensing techniques significantly enhance space object sensing capabilities, offering unique advantages in detecting and tracking objects not easily observable through optical methods. Interferometry allows precise measurements of object positions and velocities by analyzing electromagnetic wave interference patterns, beneficial when optical observations are compromised by atmospheric conditions or distance [3]. Radio sensing methods complement optical and radar observations, providing vital data for detecting and tracking space objects, particularly in LEO and beyond [4]. Table 2 provides a comprehensive summary of methods that integrate interferometric and radio sensing techniques to improve space object detection and tracking capabilities.

Combining interferometric and radio sensing techniques with other modalities, such as radar and optical systems, fosters a comprehensive approach to space object detection and tracking. This integration is essential for establishing a robust SSA framework that delivers precise and timely data on space objects, enhancing global data-sharing and collaboration among SSA stakeholders. Such advancements support planetary defense against NEOs, safe navigation of space operations, and sustainable management of space activities. The use of autonomous CubeSats equipped with smart cameras further improves detection and tracking of both illuminated and unilluminated space objects, ensuring the safety and security of future space endeavors [14, 15]. Leveraging interferometric and radio methods allows SSA systems to achieve higher precision and reliability, ensuring the continued security of space activities.




(a) Radio Frequency Imaging of the International Space Station (ISS) and Nearby Objects[3]

(b) Sunspots and Solar Flares[9]

(c) Satellite Launch and Orbit Status[5]

Figure 5: Examples of Interferometric and Radio Sensing Techniques

As depicted in Figure 5, the exploration of interferometric and radio sensing techniques reveals advancements in space observation. Radio frequency imaging of the ISS and nearby objects showcases the precision of radio sensing. Continuous monitoring of sunspots and solar flares is emphasized for understanding space weather. Satellite activities, detailing successful rocket launches and satellite deployments since 1957, underscore the critical role of interferometric and radio sensing techniques in advancing our understanding of both artificial and natural objects in space [3, 9, 5].



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### 3.4 Autonomous Sensing and Tracking Systems

Autonomous sensing and tracking systems are increasingly vital for enhancing space object sensing capabilities, particularly in complex and congested orbital environments. These systems utilize advanced technologies and algorithms to improve detection, tracking, and characterization of space objects, thereby strengthening SSA. This comprehensive approach encompasses monitoring space weather, conducting surveys on NEOs, and implementing surveillance of manmade objects. Advancements in CubeSat technology facilitate autonomous on-orbit surveillance, enabling coordinated observations and trajectory triangulation of both illuminated and unilluminated objects. Enhanced data-sharing and computational ontologies contribute to a better understanding of the space environment, bolstering international safety, planetary defense capabilities, and sustainable outer space exploration [15, 14, 8].

The Pomenis Survey exemplifies automation in space object sensing, employing a low-cost, mobile telescope for automated photometric observations of LEO satellites, capturing satellite brightness across various geometries, and enhancing monitoring efficiency [22]. Reinforcement learning techniques, such as the Double Deep Q Network (DDQN), optimize sensor management and tracking capabilities, allowing autonomous systems to adapt to changing conditions [13]. The integration of Model-Based Reinforcement Learning (MBRL) with Inverse Reinforcement Learning (IRL) and Long Short-Term Memory (LSTM) neural networks facilitates safe trajectory planning and collision avoidance [25].

The Spacecraft Angles-only MUltitarget tracking System (SAMUS) demonstrates autonomous tracking methods, utilizing angles-only measurements and multi-hypothesis tracking for monitoring multiple targets [26]. Additionally, integrating intersatellite optical links (OISLs) for navigation offers improved accuracy over traditional RF-based methods. Autonomous navigation algorithms, such as those using Extended Kalman Filters (EKF) with line-of-sight observations, enhance state estimation of CubeSats, enabling precise navigation in dynamic space environments.

As illustrated in Figure 6, the hierarchical categorization of concepts related to autonomous sensing and tracking systems highlights key technological advancements, algorithmic innovations, and practical applications, which collectively underscore the significance of these systems in modern space operations.

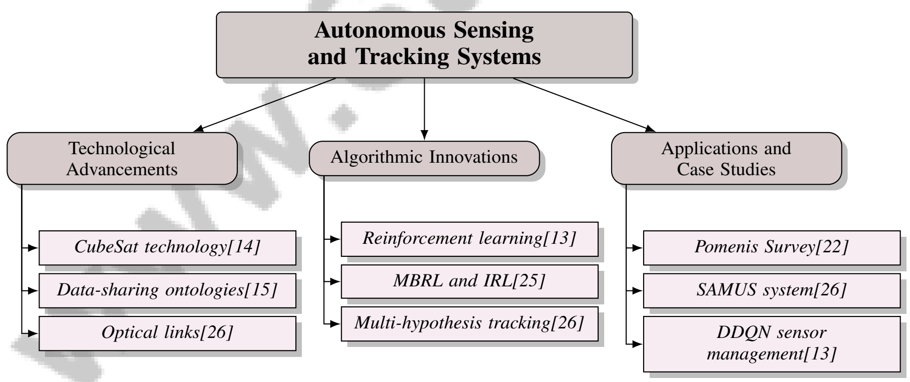


Figure 6: This figure illustrates the hierarchical categorization of concepts related to autonomous sensing and tracking systems, highlighting key technological advancements, algorithmic innovations, and practical applications.

## 4 Space Situational Awareness (SSA)

### 4.1 Challenges in Space Situational Awareness

Space Situational Awareness (SSA) faces significant hurdles that hinder effective space object monitoring and management. A key challenge is the inadequacy of current navigation methods, especially the dependency on single-satellite systems that fail to address intersatellite measurement complexities [11]. This is compounded by benchmarks that inadequately capture system complexities, leading to inaccuracies in SSA systems.

Two-Line Element (TLE) data, while extensive for satellite orbits, lacks the precision needed for accurate satellite behavior inference, resulting in orbit prediction inaccuracies and satellite lifetime assessments [24]. This issue is exacerbated by the dynamic and crowded space environment, where rapid changes in satellite status are frequent.

Tracking Near-Earth Objects (NEOs) and satellites is further complicated by their rapid movement and the photometric accuracy limitations due to high sky brightness and atmospheric conditions affecting daytime observations [21]. Ground-based radar systems often struggle with fast-moving and low-altitude debris due to weather constraints and limited surveillance capabilities.

Interoperability and data-sharing within SSA are impeded by diverse observation quality, trust issues in data transmission, and geopolitical barriers, which complicate collaborative efforts. These factors obstruct the integration of SSA data from various sources, including orbital debris databases and space object catalogs, undermining SSA capabilities essential for space safety and security [24, 1, 2, 15, 10]. The silo effect, resulting from isolated information systems with limited data sharing and disparate formats, restricts real-time predictive awareness of the space environment. This highlights the urgent need for innovative solutions and collaborative efforts to enhance data integration and interoperability across diverse platforms.

### 4.2 Advanced Tracking and Detection Methods

Recent advances in tracking and detection methods for SSA have significantly enhanced the precision and reliability of space object monitoring. Integration of sophisticated algorithms and sensor technologies has been pivotal. The Huntsman Telescope achieves photometric accuracy of 1% to 10%, comparable to nighttime observations, improving tracking capabilities for fast-moving LEO objects [21].

The TBT Cebreros telescope demonstrates exceptional tracking with average astrometric residuals under 0.5 arcseconds for asteroids and about 1 arcsecond for satellites, critical for SSA accuracy [7]. Additionally, the Distributed Deep Learning for Tracking Data Message Validation (DDL-TDM) method enhances RSO tracking data reliability [1].

High-fidelity light curve simulation environments provide realistic datasets to supplement limited observational data, facilitating neural network training for improved space object characterization [23]. Innovative methodologies, like the Surya method, use advanced image processing for real-time solar flare detection, enhancing tracking capabilities [9]. The CLOWN system optimizes observation efficiency through real-time cloud detection, optimizing telescope use during clear conditions [20].

Interferometric data from the Australia Telescope Compact Array (ATCA) improves range and DOA estimates, offering a precise alternative to traditional TLE-based methods [27]. The hybrid propagation methodology proposed by San Juan et al. extends TLE validity with minimal changes, enhancing long-term orbit prediction accuracy [28].

The Topological Sweep method shows superior accuracy and efficiency in detecting geostationary objects, confirming its potential for advanced SSA tracking [19]. The SAMUS algorithm exemplifies advancements in autonomous tracking, achieving high precision and recall in monitoring multiple targets across various orbital configurations, surpassing traditional multitarget tracking algorithms [26]. The R-FISST method, using MCMC techniques, maintains computational efficiency while accurately tracking multiple objects, showcasing its effectiveness in complex SSA scenarios [29].

These advancements underscore the necessity of integrating advanced algorithms and technologies within SSA frameworks to enhance space operations' safety and sustainability. Notably, developing a comprehensive SSA ontology aims to facilitate data-sharing and knowledge exchange among SSA stakeholders, including orbital debris databases and space object catalogs. Initiatives like the NEOPROP program focus on timely data provision and monitoring of space weather, NEOs, and manmade objects, supporting sustainable outer space utilization and enhancing planetary defense capabilities against potential threats [8, 15].

### 4.3 Innovations in SSA for Autonomous Operations

Technological innovations in SSA are crucial for enhancing autonomous operations, particularly in complex and congested orbital environments. The development of the Guidance, Navigation, and

Control (GNC) algorithm offers enhanced flexibility and reduced computational demands, facilitating autonomous collision avoidance management in satellite formations [30].

Model-Based Reinforcement Learning (MBRL) approaches improve trajectory planning and collision avoidance for distributed spacecraft, enabling autonomous systems to adapt dynamically to changing conditions and optimize operational efficiency [25]. These advancements are vital for managing extensive data generated by multiple sensors, ensuring accurate and timely decision-making in space operations.

Incorporating ontological frameworks enhances autonomous SSA operations by providing structured data-sharing mechanisms that improve interoperability and safety. The Space Situational Awareness Domain Ontology (SSAO) promotes robust data exchange, allowing diverse systems to operate cohesively and effectively [15]. This structured approach addresses data integration challenges across heterogeneous platforms, fostering a comprehensive understanding of the space environment.

Innovations in autonomous navigation and control systems, such as integrating Vision-Based Navigation (VBN) systems with docking mechanisms, enable precise navigation within compact volumes suitable for CubeSats [31]. This integration is particularly beneficial for small satellite missions requiring high autonomy and precision in maneuvering.

Emerging trends in SSA indicate a need for researchers to enhance automation and integration with other space surveillance systems to address existing limitations [18]. Future research may explore further automation enhancements, particularly in integrating SSA systems with broader space surveillance networks, ensuring comprehensive and accurate monitoring of space objects [7].

The proposed approaches offer significant advantages, including improved state estimation accuracy, reduced reliance on ground-based systems, and the capability to operate autonomously in deep space [32]. These innovations collectively emphasize the importance of leveraging advanced technologies to enhance autonomous operations in SSA, ultimately contributing to the safety and sustainability of space activities.

# 5 Heterogeneous Multi-Source Orbit Determination

## 5.1 Methodologies for Orbit Determination

Advancements in orbit determination leverage heterogeneous multi-source data to enhance the precision and reliability of tracking space objects. The CLOWN system utilizes all-sky images for star and cloud detection, improving data quality and optimizing conditions for orbit determination [20]. The Topological Sweep method efficiently handles time-indexed point sets for simultaneous multi-target tracking, crucial for integrating diverse data into coherent orbit predictions [19]. R-FISST uses Markov Chain Monte Carlo techniques for effective multi-object tracking in dense scenarios [29].

Model-Based Reinforcement Learning enhances trajectory planning in unknown environments by reconstructing dynamics through neural networks, optimizing orbit determination in complex settings [25]. SAMUS employs angles-only measurements and multi-hypothesis tracking, providing reliable orbit determination in data-limited scenarios [26]. Advanced models, benchmarked against RF navigation and Optical Inter-Satellite Link approaches, further refine orbit determination accuracy [11]. Vision-Based Navigation achieves six degrees of freedom for CubeSat docking, valuable for small satellite missions [31].

Collectively, these methodologies highlight the integration of advanced technologies and algorithms in improving Space Situational Awareness (SSA) systems, facilitating effective space object monitoring and promoting sustainable outer space exploitation. The development of computational ontologies and intelligent frameworks enhances data-sharing and integration, advancing planetary defense and ensuring safe space travel [6, 14, 8, 15].

## 5.2 Challenges in Multi-Source Data Integration

Orbit determination through multi-source data integration faces challenges due to the complexity of combining heterogeneous datasets and methodological limitations. Traditional multi-object tracking methods like Finite Set Statistics face computational intractability due to exponential hypothesis growth [29]. High computational costs of numerical methods and inadequacies of analytical methods hinder long-term predictions [12]. The reliance on multiple measurements and the inability to incorporate range-rate data complicate orbit determination [33], leading to inaccuracies, particularly with diverse data sources. The limited validity of Two-Line Elements restricts their utility for long-term predictions and collision avoidance [28].

Centralized and decentralized GNC architectures face computational demands, hindering collision avoidance in satellite formations, especially with limited onboard resources [30]. The lack of global information in distributed architectures increases collision risks during maneuvering [25]. The growing number of CubeSats makes reliance on ground-based navigation impractical, risking navigation failures [32]. Current sensor capabilities limit accuracy, necessitating improved data integration approaches [27]. Poor quality ground-truth data and inconsistencies in evaluation satellites impede standardized data integration methods [24]. Addressing these challenges requires innovative algorithms and methodologies for efficient multi-source data integration, enhancing orbit determination precision and reliability.

### 5.3 Solutions and Advanced Algorithms

Advanced solutions and algorithms are crucial for overcoming challenges in heterogeneous multi-source orbit determination. Integrating far-range and close-range navigation techniques, such as angles-only tracking and carrier-phase differential GNSS, is effective in rendezvous and proximity operations requiring precise orbit determination [34]. Innovative observing strategies, like reducing telescope requirements through preliminary orbits with minimal observations, enhance debris tracking and resource optimization [4]. The Single-Track Orbit Determination method improves estimation accuracy for LEO satellites, aiding tracking and collision avoidance [33]. SAMUS, with its high assignment precision and low computational requirements, is suitable for autonomous multi-target tracking [26].

These solutions demonstrate the potential of integrating diverse methodologies to enhance orbit determination processes. By harnessing advanced technologies, these approaches significantly improve SSA systems' accuracy and reliability. Deploying CubeSats with smart cameras and advanced vision algorithms enables autonomous detection and tracking of objects, complemented by a dense star map and optical flow algorithms for NEO tracking, enhancing SSA initiatives. Integrating multiple observation points allows precise triangulation, improving operational efficacy in safeguarding space activities [14, 8].

## 6 Multi-Dimensional Space Data Fusion

### 6.1 Advanced Algorithms for Data Fusion

Advanced algorithms are pivotal in refining Space Situational Awareness (SSA) systems, particularly for tracking Resident Space Objects (RSOs). The decentralized deep learning framework, as presented by [1], leverages distributed computing to enhance tracking accuracy and reliability. The PSO-AN method, described in [5], employs hyperspectral sensors across multiple satellites for collaborative RSO tracking, optimizing both trajectories and resource usage. Interferometric Range and Direction of Arrival (DOA) Estimation (IRDE) techniques, as discussed in [27], utilize interferometric data to refine range and DOA estimates, providing vital insights into space object dynamics.

The topological sweep method, outlined in [19], enhances data fusion by applying geometric properties to target trajectories, proving effective in scenarios where traditional methods are insufficient. Moreover, the Random Finite Set Statistics (R-FISST) approach, as demonstrated in [29], improves computational efficiency in multi-object tracking, maintaining accuracy amidst numerous objects and measurements.

These algorithms highlight the necessity for innovative data fusion techniques within SSA systems, enhancing data sharing, tracking accuracy, dim target recognition, and orbit predictions that account for non-conservative forces [6, 1, 12, 15]. By advancing the precision and reliability of space object monitoring, these methodologies contribute significantly to safe and sustainable space operations, managing the increasingly congested space environment effectively.

### 6.2 Applications of Multi-Dimensional Features

Incorporating multi-dimensional features into SSA systems significantly augments the monitoring and management of space objects through enhanced data analysis. The extraction of multi-dimensional features broadens the understanding of space object characteristics and behaviors by integrating diverse data types such as infrared intensities, temperature, and micromotion periods. This approach enhances SSA framework accuracy, facilitating better target recognition and improved monitoring capabilities for threats like near-Earth objects and space debris [19, 6, 8, 15].

A significant application is the characterization of RSOs. Algorithms, such as those in [23], enable high-fidelity light curve simulations, providing insights into RSO properties and motion, enhancing collision avoidance strategies. Multi-dimensional features also facilitate integrating optical, radar, and radio data into cohesive SSA frameworks. Techniques like decentralized deep learning [1] exemplify the potential of multi-dimensional data fusion, enhancing system performance and navigating modern space complexities effectively.

Furthermore, multi-dimensional features improve space debris detection and tracking, particularly in low Earth orbit (LEO), where object density challenges traditional methods. Innovative observing strategies, as outlined in [4], demonstrate how multi-dimensional data can optimize resource utilization and tracking efficiency, aiding effective space debris management.

Additionally, these features support the development of autonomous SSA systems, where advanced algorithms enable dynamic adaptation to changing conditions. For instance, Model-Based Reinforcement Learning (MBRL) methods [25] in trajectory planning and control allow autonomous systems to optimize operations, ensuring reliable space object monitoring.

Overall, the applications of multi-dimensional features in SSA systems underscore the importance of advanced data analysis techniques in enhancing space object tracking and management. By improving SSA frameworks' precision and reliability, these applications promote safety and sustainability in space operations, facilitating effective monitoring and management of a congested space environment. They enhance data sharing among SSA actors, expanding scientific understanding and strengthening planetary defense capabilities against near-Earth objects, ensuring long-term space travel safety [24, 8, 15].

## 7 Feature Extraction Algorithms

### 7.1 Effective Albedo Metric for Feature Extraction

The effective albedo metric is crucial in SSA systems for quantifying space objects' reflective properties through brightness and specularity, aiding in distinguishing satellite populations like Starlink and OneWeb. This metric generates distinct all-sky photometric signatures from extensive observational data, enabling SSA practitioners to identify and analyze unknown satellites and detect anomalies with high accuracy, even with minimal input [22, 8]. Albedo, defined as the fraction of incident light reflected, provides insights into surface composition and structure, essential for characterization and monitoring.

In SSA, the effective albedo metric differentiates RSOs, including satellites, debris, and natural celestial bodies. By considering range and phase angle, it allows direct comparisons among satellites, enhancing identification and categorization and improving understanding of the space environment. Validation through machine learning demonstrates its effectiveness in classifying satellites based on albedo, even with limited data [22, 8]. Analyzing reflected light reveals critical information about size, shape, and surface materials, vital for orbit predictions and collision avoidance.

Advanced algorithms leveraging high-fidelity light curve simulations enhance albedo metrics [23]. These simulations produce realistic datasets for training neural networks, improving RSO characterization accuracy. The effective albedo metric supports autonomous SSA system development, providing a robust framework adaptable to diverse conditions. Incorporating albedo metrics into autonomous systems, exemplified by Model-Based Reinforcement Learning (MBRL) methods [25], ensures reliable monitoring by dynamically adapting to changing environments.

The effective albedo metric enhances SSA feature extraction, improving space object characterization and monitoring. By integrating advanced data analysis techniques and simulations, these metrics significantly boost SSA capabilities, facilitating effective space environment management, accurate orbit predictions, and automated collision avoidance. This comprehensive approach supports planetary defense and collision prevention, ensuring the long-term viability of safe space travel amidst increasing orbital traffic [16, 24, 12, 15, 11].

### 7.2 Neural Networks for Light Curve Analysis

Neural networks have become pivotal in SSA systems for light curve analysis, effectively handling data complexities crucial for characterizing RSOs' physical properties and dynamics. Their application is enhanced by developing large, well-labeled datasets reflecting real light curves, with transfer learning improving training [23].

Neural networks excel in modeling non-linear relationships and capturing subtle patterns challenging for traditional methods. High-fidelity light curve simulations enable accurate RSO behavior recognition and prediction, essential for orbit predictions and collision avoidance. This capability allows detailed analysis of object dynamics by incorporating non-conservative forces like atmospheric drag and gravitational perturbations. Leveraging historical data and environmental variables, machine learning algorithms achieve accurate state vector forecasts with lower computational costs, enhancing SSA and facilitating autonomous decision-making in collision avoidance [16, 12].

Integrating neural networks into SSA systems fosters autonomous monitoring, adapting dynamically to changing observational conditions for continuous and reliable space object tracking. Neural networks significantly improve SSA accuracy by enhancing RSO classification and characterization, crucial for precise orbital predictions. This advancement aids in collision avoidance and space debris mitigation, promoting safety and sustainability in space operations by providing timely and reliable data on the increasing number of objects in Earth's orbit [24, 23, 22, 12, 8].

Neural networks in light curve analysis represent a significant advancement in SSA feature extraction. By leveraging advanced computational models and high-quality datasets, including precision ephemeris and Two-Line Element (TLE) data, these systems enhance space object characterization accuracy and comprehensiveness. This improvement is critical for effective monitoring and management of the increasingly congested space environment, facilitating precise orbit predictions, collision avoidance, and space debris mitigation. Innovative machine learning algorithms and high-fidelity simulations contribute to real-time tracking and classification of both illuminated and unilluminated objects, bolstering SSA efforts against challenges posed by the rising number of satellites and debris in Low Earth Orbit (LEO) [14, 24, 23, 20, 12].

## 8 Sensor Data Integration

### 8.1 Comprehensive Data Integration Techniques

Integrating data from various sensor sources is essential for advanced Space Situational Awareness (SSA) systems, enhancing understanding of the space environment and fostering collaboration among stakeholders. This integration supports monitoring of space weather, near-Earth objects, and manmade satellites, contributing to planetary defense and the safety of future missions [24, 8, 15]. By synthesizing heterogeneous data, including optical, radar, and radio observations, a unified dataset is created, improving the accuracy and reliability of space object tracking.

Decentralized deep learning frameworks enhance data integration by leveraging distributed computing resources to validate and integrate tracking data across multiple sensors [1]. This approach ensures accurate data synthesis and analysis, thereby improving space object detection and characterization reliability.

The fusion of interferometric and radio sensing with traditional optical and radar systems exemplifies multi-sensor data integration's potential, achieving higher precision in detecting and tracking space objects [27]. Algorithms like Random Finite Set Statistics (R-FISST) significantly enhance computational efficiency in multi-object tracking scenarios, maintaining accurate estimations in complex environments [29]. Additionally, advanced data fusion algorithms, such as the topological sweep method, exploit geometric properties of target trajectories, enhancing SSA capabilities in challenging conditions [19].

Comprehensive data integration techniques are vital for SSA systems' precision and reliability. By synthesizing data from diverse sensor networks and applying sophisticated algorithms, these techniques bolster space operations' safety and sustainability, addressing challenges like satellite maneuver detection, collision avoidance, and orbit prediction. Two-Line Element (TLE) data enables tracking orbital changes over decades, while advanced CubeSat systems and machine learning algorithms enhance detection and classification of both illuminated and unilluminated space objects. Space-based space surveillance (SBSS) systems offer superior tracking capabilities compared to traditional ground-based methods, significantly strengthening SSA efforts amid increasing orbital debris and satellite constellations [4, 14, 24, 12, 5].

### 8.2 Collaborative Data Integration Across Organizations

Collaborative data integration across organizations is crucial for enhancing SSA capabilities, enabling data sharing and synthesis from diverse sources to improve space object tracking and monitoring accuracy. The development of a Space Situational Awareness Domain Ontology (SSAO) exemplifies efforts to facilitate data-sharing and enhance interoperability [15]. SSAO provides a structured framework for data exchange, improving organizational collaboration and ensuring timely and accurate space object information.

The European Space Agency's (ESA) SSA program highlights collaboration's importance, with initiatives like the Space Surveillance and Tracking (SST) Support Framework enhancing SST capabilities among European Union member states, promoting an independent and reliable SSA system contributing to global space safety [8]. This collaborative approach integrates data from various national and regional sources, offering a comprehensive view of the space environment.

Inter-agency and international collaboration is critical in addressing space debris challenges. Initiatives fostering cooperation toward common goals emphasize data and resource sharing across organizations [10]. By pooling resources and expertise, organizations can devise more effective strategies for managing space debris and ensuring space operations' safety and sustainability.

Decentralized, trustless mechanisms like blockchain technology further illustrate collaborative data integration's potential in enhancing SSA capabilities [1]. These technologies facilitate secure and transparent data-sharing across organizations, reducing reliance on centralized systems and promoting a more distributed approach to SSA.

## 9 Space Surveillance Technologies

### 9.1 CubeSats in Low Earth Orbit

CubeSats have become pivotal in space surveillance within Low Earth Orbit (LEO) due to their compactness, cost-effectiveness, and versatility, supporting missions like Earth observation and Space Situational Awareness (SSA). They enhance the monitoring and tracking of space objects by utilizing commercial electronics for efficient on-orbit surveillance. For instance, SWIMSat autonomously detects and tracks illuminated objects entering Earth's atmosphere, employing advanced vision algorithms and smart camera systems. By coordinating observations, CubeSats can triangulate trajectories of both illuminated and unilluminated objects, including Near Earth Objects (NEOs), crucial for comprehensive space environment understanding and supporting the European Space Situational Awareness Preparatory Programme's objectives in providing timely, quality data on space threats [14, 8].

Equipped with advanced sensors and communication systems, CubeSats provide real-time data essential for maintaining situational awareness in congested orbital environments. This capability facilitates advanced collision avoidance strategies, enhancing space operations' safety and efficiency. Autonomous smart cameras on CubeSats enable real-time detection and tracking of both illuminated and unilluminated objects, allowing precise trajectory mapping through coordinated observations from multiple units. These innovations are vital for developing autonomous constellations dedicated to SSA, improving monitoring and mitigation of collision risks in crowded space environments [31, 14].

Autonomous docking feasibility for CubeSats in LEO addresses miniaturization and accuracy challenges in docking mechanisms, crucial for maintaining satellite constellations. Integrating guidance, navigation, and control systems ensures precise maneuvering and docking operations, facilitating effective deployment and operation of these small satellites.

CubeSats exemplify leveraging small satellite technologies to enhance SSA systems, offering a cost-effective approach to improving space surveillance networks' coverage and resolution in LEO. Utilizing advanced optical sensors and algorithms, these networks maintain a comprehensive catalog of space debris and other resident space objects (RSOs), achieving high accuracy in collision avoidance and monitoring catastrophic fragmentation events. Their autonomous capabilities facilitate continuous observation and data collection, significantly improving SSA and contributing to space operations' safety and sustainability [14, 4, 5].

### 9.2 Advancements in Space-Based Surveillance Technologies

Recent advancements in space-based surveillance technologies have markedly enhanced SSA capabilities by providing precise and reliable monitoring of space objects. The integration of Vision-Based Navigation (VBN) systems into docking mechanisms allows for accurate relative positioning and attitude determination during docking phases, benefiting autonomous docking operations with efficient and precise maneuvers [31].

VBN systems in space-based surveillance platforms enhance autonomy and precision in space operations, enabling rapid and accurate tracking of both illuminated and unilluminated objects. CubeSats equipped with smart cameras and advanced algorithms autonomously detect and report space objects, improving SSA and facilitating collision avoidance in distributed satellite systems [14, 11, 8, 5]. These systems employ advanced imaging and processing algorithms for spacecraft positions relative to targets, facilitating seamless docking and servicing missions crucial for maintaining and extending satellite constellations' operational lifetimes, enhancing space infrastructure resilience and sustainability.

The integration of advanced sensor technologies on space-based platforms, such as CubeSats with smart cameras and hyperspectral sensors, significantly improves detection and tracking capabilities for space debris and other RSOs. These systems autonomously monitor and catalog objects in LEO, achieving high detection rates and improved tracking accuracy, even for unilluminated objects. By maintaining a dense star map and employing multiple observational perspectives, these technologies facilitate precise trajectory determination and support collision avoidance maneuvers, enhancing SSA and managing orbital debris [14, 4, 5]. High-resolution cameras, radar systems, and other sensing modalities provide comprehensive space environment coverage, offering critical data for collision avoidance and space traffic management.

Recent advancements highlight the critical need for integrating space-based surveillance systems with ground-based networks, essential for developing a comprehensive SSA framework. This integration enhances data-sharing capabilities, improves RSOs' tracking accuracy, and facilitates timely responses to potential threats, ensuring safer and more sustainable outer space utilization [14, 24, 1, 15, 8]. By combining data from multiple sources, SSA systems achieve higher accuracy and reliability, ensuring the safe and sustainable management of space activities.

Developments in space-based surveillance technologies represent a significant leap in SSA capabilities, offering enhanced precision, autonomy, and integration with existing systems. Advancements in SSA are crucial for navigating the increasingly congested and complex space environment. By improving data-sharing and integrating advanced technologies like autonomous decision-making and smart surveillance systems, we enhance our ability to track both man-made objects and natural threats like NEOs. This bolsters current space operations' safety and promotes sustainable practices for future space exploration and utilization, ensuring long-term security and reliability in space activities [14, 16, 8, 15].

## 10 Conclusion

The study of Space Situational Awareness (SSA) and space object sensing technologies underscores the critical need for advanced methodologies to ensure the safety and sustainability of space operations. The introduction of comprehensive datasets enhances the analysis of satellite lifetimes and maneuver detection, providing a valuable resource for ongoing SSA research. This highlights the necessity of robust data frameworks to strengthen situational awareness capabilities. Innovations in Optical Inter-Satellite Link-based navigation demonstrate the potential for achieving precision comparable to traditional methods, offering significant benefits in autonomy and robustness for deep space missions. Such advancements are crucial for improving navigation accuracy and operational flexibility in challenging space environments. The successful application of existing technologies to support CubeSat missions illustrates their potential to bolster space surveillance capabilities and SSA frameworks. Collectively, these developments emphasize the importance of integrating innovative technologies and methodologies into SSA systems to address the challenges of a congested and complex space environment. By capitalizing on these advancements, SSA frameworks can enhance the effectiveness of monitoring and managing the space environment, ensuring the safety and sustainability of space operations.





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