A Survey of Initial Orbit Determination Track Association and Space Situational Awareness

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Abstract

This survey paper provides a comprehensive analysis of the processes and methodologies integral to Space Situational Awareness (SSA), focusing on Initial Orbit Determination (IOD), track association, catalog maintenance, and the management of orbital debris. The significance of SSA is underscored by its role in preventing collisions and enhancing the safety of space operations. The paper discusses the challenges posed by orbital debris, emphasizing the need for accurate tracking systems and robust data management strategies. It highlights the advancements in IOD methodologies, such as the application of algebraic geometry and machine learning, which enhance the precision of orbit estimations. Track association processes are explored, with a focus on advanced computational techniques that improve the accuracy of space object monitoring. The importance of maintaining comprehensive and accurate space object catalogs is emphasized, with strategies for effective data management and catalog maintenance outlined. The paper also examines international efforts and policies aimed at mitigating the risks associated with orbital debris, highlighting the role of collaborative initiatives and technological advancements in enhancing SSA capabilities. The integration of astrometry and photometry is discussed, showcasing their contributions to improving the accuracy of space object tracking and characterization. The survey concludes by identifying future research opportunities and the potential for integrating advanced technologies to further enhance SSA processes, ensuring the sustainability of space operations in the face of increasing complexity.

1 Introduction

1.1 Significance of Space Situational Awareness

Space situational awareness (SSA) is a critical component in ensuring the safety and sustainability of space operations. It involves a comprehensive understanding of the space environment, including the accurate tracking and prediction of both natural and artificial objects' trajectories. SSA is essential for preventing collisions, managing space traffic, and mitigating the risks posed by orbital debris. The significance of SSA is further highlighted by its role in accurately measuring and cataloging celestial populations, which is vital for maintaining operational safety in space [1].

The advent of large-scale astronomical surveys, such as the Large Synoptic Survey Telescope (LSST), which produces vast amounts of image and catalog data, underscores the necessity for robust SSA systems to effectively manage these extensive datasets [2]. Advanced astrometric catalogs, like Gaia EDR3, serve as benchmarks for completeness, accuracy, and precision, facilitating the optimal use of these catalogs and enhancing our understanding of space objects [3]. The HSOY benchmark further improves the usability of Gaia DR1 data, which is crucial for enhancing astrometric studies and supporting safe space operations [4].

The growing interest in nanosatellite missions and CubeSat platforms necessitates global coverage with minimal data latency [5]. This trend drives the development of enhanced SSA capabilities to

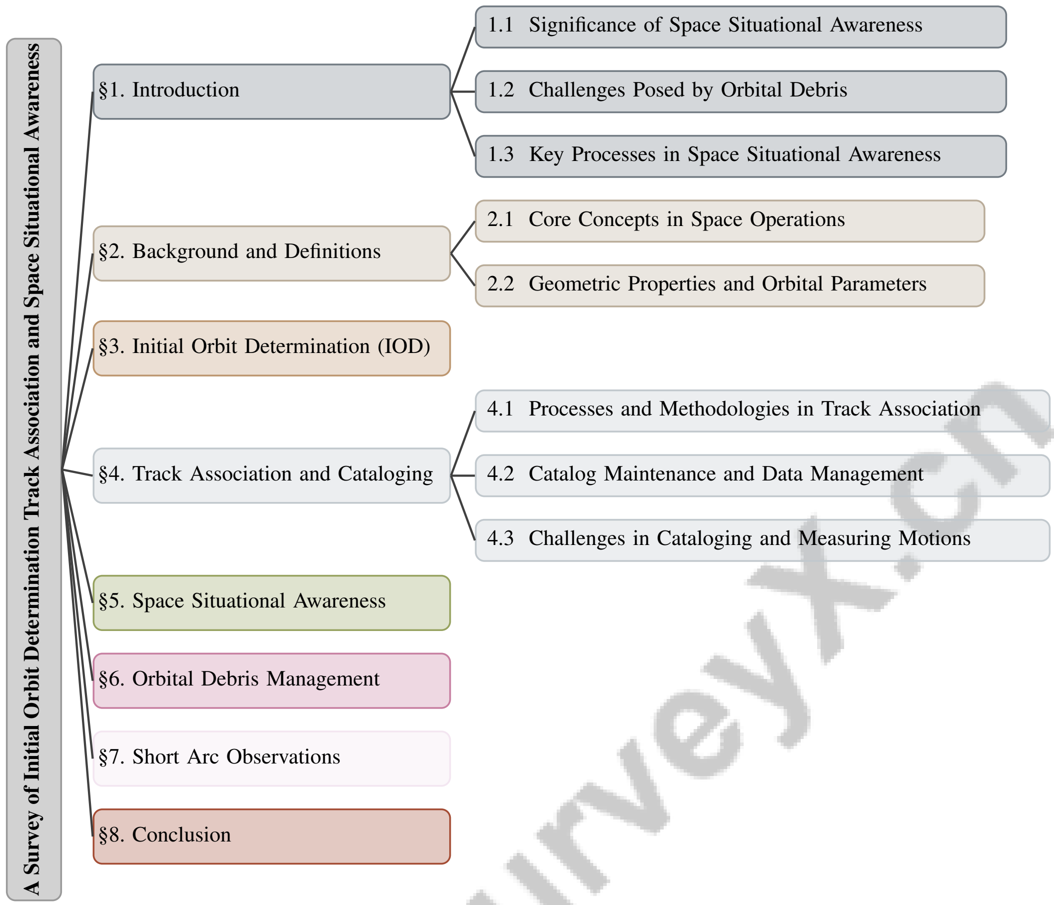


Figure 1: chapter structure

ensure that these small satellites can be effectively tracked and managed within the broader space environment. The SPHEREx mission's unique capabilities in detecting, categorizing, and cataloging solar system objects play a significant role in planetary defense against Potentially Hazardous Objects (PHOs), thereby contributing to SSA [6].

Rapid and automatic observation of moving objects, both natural and artificial, is vital for human space security, emphasizing the need for SSA in monitoring these objects to prevent potential threats [7]. Effective data management is also crucial in maintaining safe and sustainable space operations, especially when processing large-scale astronomical data [8]. The URAT1 catalog, with its precise astrometric data, serves as a reliable reference for future astronomical research, highlighting its potential impact on SSA applications [9]. Furthermore, the benchmark significantly enhances the completeness and accuracy of asteroid catalogs, enabling detailed studies of asteroid families and their properties [10].

1.2 Challenges Posed by Orbital Debris

The proliferation of orbital debris presents a formidable challenge to space situational awareness and the overall safety of space operations. One of the primary risks associated with orbital debris is the potential for collisions with operational satellites, which can lead to the generation of additional debris, thereby exacerbating the problem. The complexities involved in multitarget tracking, especially when aiming to reduce dimensionality for efficient communication while maintaining track quality, highlight the difficulties inherent in managing orbital debris [11].

Existing benchmarks often fall short in accurately simulating the intricate dynamics of inter-satellite communication and constellation management, which are critical for effective debris monitoring and mitigation [5]. Ground-based observations face challenges due to atmospheric interference and limited observational arcs, complicating the reliable tracking and orbit determination of near-Earth objects (NEOs) and other debris [12].

The limitations in accuracy and completeness of current catalogs, especially for high proper motion stars, pose additional challenges for maintaining an accurate and comprehensive space object catalog [1]. Furthermore, issues such as spurious solutions and parallax zero point errors in benchmarks like Gaia necessitate robust validation processes to ensure data quality [3]. The dense stellar backgrounds and variability in the speed and direction of multiple moving objects further complicate the detection and tracking of debris [7].

The challenges are compounded by the peta-scale data volumes and real-time requirements of modern space operations, which existing benchmarks are often inadequate to address [2]. The high rate of false detections in source catalogs, such as the HSC-SSP, further complicates the identification of genuine astronomical sources, impacting the reliability of debris tracking [13]. Accurate spectral categorization of NEOs is essential for assessing impact threats and developing effective mitigation strategies, yet remains a significant challenge [6].

The main challenge in existing methods is the propagation of errors from the line-of-sight (LOS) extraction process, making them susceptible to inaccuracies caused by bright stars and low signal-to-noise ratios [14]. The lack of proper motion data in the Gaia DR1 release further complicates astrometric studies on the majority of stars, limiting the ability to monitor and assess the space environment effectively [4]. Additionally, existing asteroid catalogs suffer from low completeness and inaccuracies in orbital elements, which hinder the reliable identification of asteroids [10].

Finally, the processing and distribution of vast quantities of data generated annually require significant computational resources and efficient data management systems, underscoring the ongoing need for advancements in this area [8]. The cumulative effect of these challenges underscores the critical need for continued research and development in orbital debris management to ensure the sustainability of space operations.

1.3 Key Processes in Space Situational Awareness

The core processes of space situational awareness (SSA) encompass Initial Orbit Determination (IOD), track association, and cataloging, each playing a pivotal role in ensuring the safe and efficient management of space operations. IOD is fundamental in identifying and predicting the trajectories of space objects. It involves the use of various methodologies to derive an object's orbit from limited observational data, which is critical for timely and accurate tracking [14]. The challenges associated with IOD include the propagation of errors from the line-of-sight extraction process, which can be exacerbated by factors such as bright stars and low signal-to-noise ratios [14].

Track association involves correlating observational data with existing tracks to ensure continuity and accuracy in monitoring space objects. This process is vital for maintaining a coherent record of an object's movement through space, which aids in collision avoidance and risk assessment. The complexities of multitarget tracking, especially in reducing dimensionality for efficient communication, underscore the importance of robust track association methodologies [11].

Cataloging is the systematic recording of space objects, which serves as a comprehensive database for reference and analysis. Accurate catalog maintenance is crucial for SSA, as it provides the baseline data required for orbit determination and track association. The limitations in current catalogs, particularly in terms of accuracy and completeness, present ongoing challenges in maintaining an up-to-date and reliable space object catalog [1]. The integration of advanced astrometric catalogs, such as Gaia, enhances the precision and reliability of these records, facilitating improved space situational awareness [3].

The integration of advanced data processing techniques and automated detection algorithms, as exemplified by initiatives like the Legacy Survey of Space and Time (LSST) at the Vera C. Rubin Observatory and extensive asteroid observations from the Sloan Digital Sky Survey, collectively establish a robust framework for Space Situational Awareness (SSA). This framework facilitates comprehensive monitoring and management of the space environment by enabling the systematic collection, analysis, and cataloging of vast amounts of astronomical data, including the identification of billions of celestial objects and their physical properties, thereby enhancing our understanding of both the Solar System and the broader cosmos. [8, 15]. The continuous development and refinement of these methodologies are essential to address the challenges posed by the increasing complexity of space operations and the growing threat of orbital debris.The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Core Concepts in Space Operations

Effective space operations hinge on key concepts essential for comprehensive space situational awareness (SSA), particularly in orbit determination and catalog correlation amidst increasing non-cooperative satellite activity. Advanced methodologies, such as the OPOD algorithm, utilize surveillance radar data to enhance orbit estimation accuracy [16]. The integration of extensive observational datasets, like those from the Sloan Digital Sky Survey, deepens our understanding of the orbital and compositional characteristics of solar system objects [15]. Initiatives like the SPHEREx mission are poised to advance the tracking and characterization of potentially hazardous objects (PHOs), bolstering planetary defense [6].

Initial Orbit Determination (IOD) is foundational, involving trajectory estimation with limited data, crucial for precise space object tracking. Track association complements IOD by correlating data with existing tracks, maintaining coherent object movement understanding. Astrometry, the precise measurement of celestial bodies' positions and movements, is vital for understanding the solar system's formation and evolution, particularly through accurate measurement of fast-moving main-belt asteroids [17]. The URAT1 catalog enhances astrometric precision for stars in the northern hemisphere, addressing challenges for those fainter than the UCAC limit [9].

Characterizing PHOs is critical in space operations due to their potential impact threat. The SPHEREx mission aids planetary defense by detecting and categorizing PHOs [6]. Proper motion catalogs, such as those from the SDSS and URHIP, are crucial for accurately measuring and cataloging stars' proper motions, aiding in identifying astrometric binaries and stars with high proper motions. The Gaia catalog provides a benchmark for validating data in terms of completeness, accuracy, and precision, particularly in astrometric and photometric solutions [3].

Linking detections from surveys like the LSST into accurate orbital paths despite false detections and noise is challenging in near-Earth object (NEO) studies [18]. The Astorb database at Lowell Observatory addresses orbit fitting for numerous asteroid observations, offering reliable ephemeris predictions [19]. The SDSS archive plays a crucial role in identifying and cataloging previously undetected Solar System objects [15]. The NOAO Source Catalog (NSC) aims to provide a comprehensive, publicly accessible astronomical database, addressing poorly cataloged data [20]. Correlating SDSS observations with existing asteroid databases enhances asteroid identification and cataloging accuracy [10].

These foundational concepts are essential for effective space environment monitoring and management, facilitating the detection, characterization, and cataloging of solar system objects and PHOs. This capability is crucial for the safety and sustainability of space operations, particularly as projects like NASA's SPHEREx and the LSST aim to enhance celestial body understanding, mitigate PHO risks, and contribute to astronomical research and planetary defense initiatives [8, 6].

2.2 Geometric Properties and Orbital Parameters

Tracking and predicting space objects necessitate an understanding of their geometric properties and orbital parameters, crucial for effective space situational awareness (SSA) and safe space operation coordination. Non-cooperative satellites performing unpredictable maneuvers underscore the need for advanced methodologies like the OPOD algorithm for accurate state estimation. Improvements in asteroid astrometry through systematic error corrections in star catalogs enhance ephemeris prediction reliability, supporting space activity management [15, 21, 16].

Orbital parameters, including semi-major axis, eccentricity, inclination, right ascension of the ascending node, argument of periapsis, and true anomaly, define an object's orbit. Accurate determination of these parameters is vital for predicting future positions and assessing collision risks. Precise measurements are often hindered by observational limitations like atmospheric refraction and CCD geometric distortion. Recent advancements, such as the Gaia catalog release, have significantly improved astrometric precision to tens of milli-arcseconds for ground-based telescopes. Correction schemes for systematic errors in star catalogs, as shown in asteroid astrometry, enhance ephemeris predictions and reduce regional systematic errors. Utilizing close approach events refines positional accuracy, achieving precisions better than 4 milli-arcseconds, and even 1 milli-arcsecond in optimal cases [21, 17, 22].

Geometric properties, including size, shape, and albedo, influence an object's visibility and detectability. Characterizing these properties is vital for improving tracking and cataloging accuracy. The SPHEREx mission enhances PHO detection and characterization by providing detailed spectral data, aiding understanding of surface properties and composition [6].

Astrometric catalogs, such as Gaia and URAT1, provide reference data for geometric and orbital characterization of space objects, offering high-precision positional data that serve as benchmarks for validating and improving orbital models. Integrating comprehensive catalogs into advanced tracking systems enhances monitoring reliability and accuracy by correcting systematic errors, improving detection precision through multi-object detection methods, and enabling efficient NEO orbit linking, facilitating better space surveillance and situational awareness [18, 7, 21, 16].

Challenges in accurately determining geometric properties and orbital parameters are exacerbated by factors like atmospheric interference, limited observational arcs, and dense stellar backgrounds. These challenges are pronounced in initial orbit determination (IOD) processes, where traditional methods often underutilize available data due to reliance on line-of-sight vectors. Newer approaches, such as direct IOD (D-IOD), aim to mitigate these issues by fitting orbital parameters directly from observed streak images without intermediate steps that may introduce errors [1, 22, 14]. These challenges necessitate developing advanced methodologies and technologies to improve space object tracking and prediction precision.

Enhancing methodologies for accurately measuring geometric properties and orbital parameters is crucial for improving SSA capabilities, especially with the increasing challenges posed by non-cooperative satellites performing unpredictable maneuvers. Recent advancements, such as the OPOD algorithm, utilize single surveillance radar data and incorporate J2 dynamics to refine orbit determination processes, while innovative geometric solutions leverage line-of-sight measurements to establish orbital characteristics without prior time knowledge. These developments are vital for ensuring long-term space operation safety and sustainability [22, 16].

3 Initial Orbit Determination (IOD)

Category	Feature	Method
Technological and Methodological Advancements	Optimization Techniques Geometric Methods	TTA-FDRE[11], D-IOD[14] HOIOD[23]

Table 1: This table summarizes recent technological and methodological advancements in Initial Orbit Determination (IOD). It categorizes the advancements into optimization techniques and geometric methods, highlighting specific methods such as TTA-FDRE, D-IOD, and HOIOD, which contribute to enhanced orbit estimation precision and reliability.

Initial Orbit Determination (IOD) is foundational for space situational awareness, crucial for accurately estimating the orbits of space objects from limited data. This section explores the methodologies and technologies that have significantly advanced the precision and efficiency of IOD, thereby enhancing tracking and prediction capabilities. Table 1 provides a comprehensive overview of the recent technological and methodological advancements in Initial Orbit Determination (IOD), categorizing them into optimization techniques and geometric methods. Additionally, Table 2 offers a detailed comparison of various methodologies for Initial Orbit Determination (IOD), emphasizing their optimization techniques, data handling approaches, and measurement accuracy. As illustrated in **??**, the hierarchical structure of IOD highlights key methodologies, technologies, and advancements. The categories depicted include mathematical and computational techniques, data management and machine learning, and innovative approaches, which together enhance precision, reliability, and space situational awareness.

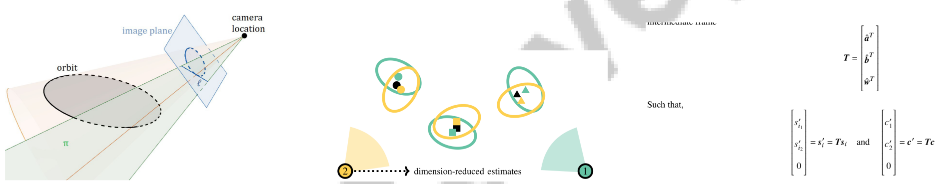
3.1 Methodologies and Technologies in IOD

Recent innovations in IOD have transformed orbit estimation processes by employing advanced mathematical and computational techniques. The reformulation of the IOD problem using algebraic geometry allows for solutions through multivariate polynomials, eliminating the need for initial guesses and overcoming traditional iterative method limitations [22]. The Direct Initial Orbit Determination (D-IOD) method further refines this process by fitting orbital parameters directly to observed streak images, enhancing accuracy by minimizing discrepancies between generated and observed images [14].

Hybrid data management systems, such as those in LSST, integrate file storage and database management to efficiently handle large-scale astronomical data, facilitating the processing required for IOD [2]. Advanced filtering and differential algebra techniques, including Lambert's problem and least-squares fitting, are employed in the OPOD methodology to improve orbit determination accuracy by incorporating comprehensive measurement data [23, 16].

Machine learning models, trained on datasets like SDSS, enhance IOD by distinguishing real from bogus detections, as seen in the Real-Bogus System (RBS), and by categorizing solar system objects based on spectral characteristics, exemplified by the SPHEREx mission [6]. Advanced data association techniques, such as 'Track-To-Track Association for Fusion of Dimension-Reduced Estimates,' optimize track association in complex environments, improving reliability [11].

Innovative approaches, including advanced trilateration techniques using MIMO radars and new detection methods leveraging neural networks, enhance measurement accuracy and efficiency. These methodologies are crucial for managing the dynamic and complex landscape of space activities [7, 24, 14, 16].



(a) Orbit and Camera Location in Image Plane[22]

(b) Dimensional Reduction in Data Visualization[11]

(c) Intermediate Frame[23]

Figure 2: Examples of Methodologies and Technologies in IOD

As depicted in Figure 2, IOD combines geometry, data science, and mathematics to enhance orbital dynamics understanding. The examples illustrate geometric approaches, dimensional reduction for data handling, and mathematical transformations, highlighting the multifaceted nature of IOD [22, 11, 23].

3.2 Technological and Methodological Advancements

Recent advancements in IOD methodologies have significantly improved orbit estimation precision and reliability. The Direct IOD method, using non-linear least-squares to minimize intensity differences in streak images, enhances accuracy by eliminating line-of-sight extraction errors [14]. The HSOY catalog's improved proper motions offer unprecedented precision in astrometric data, enhancing orbit determination [4].

Geometric properties of conics and heading measurements related to orbital hodographs provide innovative approaches to deriving orbital parameters, streamlining the IOD process [23]. Advanced data association techniques utilizing LRFS theory improve multitarget tracking reliability, optimizing dimension-reduction strategies [11].

In asteroid detection, advanced thermal infrared methodologies improve size and albedo measurement precision, surpassing conventional visible light observations. These techniques, employing large-format detector arrays and sophisticated processing, enhance detection accuracy and efficiency in complex backgrounds [7, 12]. Integration of astrometric data from HST and Gaia DR2 creates robust uncertainty models for precise stellar occultation predictions, improving spacecraft guidance.

These IOD advancements, including the direct IOD approach and advanced radar measurements, enhance space situational awareness and sustainable space environment management. By leveraging rich datasets and sophisticated algorithms, these methods ensure precise tracking of satellites and debris, supporting safer and more efficient space operations [16, 14, 24, 23, 22].

Feature	Direct Initial Orbit Determination (D-IOD)	Hybrid Data Management Systems	OPOD Methodology
Optimization Technique	Non-linear Least-squares	File-database Integration	Differential Algebra
Data Handling	Streak Images	Large-scale Astronomical	Comprehensive Measurement
Measurement Accuracy	High Precision	Efficient Processing	Improved Accuracy

Table 2: This table presents a comparative analysis of three distinct methodologies for Initial Orbit Determination (IOD): Direct Initial Orbit Determination (D-IOD), Hybrid Data Management Systems, and OPOD Methodology. It highlights key features such as optimization techniques, data handling capabilities, and measurement accuracy, providing insights into their respective strengths and applications in enhancing orbit estimation precision.

4 Track Association and Cataloging

In space situational awareness, the effective association of observational data with known tracks is crucial for accurate space object tracking and enhancing the reliability of information used in space operations. This section explores the processes and methodologies in track association, highlighting both traditional and innovative approaches that have emerged recently, contributing to improved accuracy and efficiency in space monitoring.

4.1 Processes and Methodologies in Track Association

Track association is vital for correlating observational data with established tracks, maintaining precise space object trajectory representations. Techniques such as track-to-track fusion and measurement transformations enhance data exchange efficiency among sensors, especially under communication constraints. Advances in algorithms, including belief propagation and lossless measurement transformations, have improved multitarget tracking scalability and performance, enabling real-time applications on resource-limited devices. Innovative methodologies like single-track orbit determination address orbit determination complexities and catalog correlation, particularly for non-cooperative satellites, emphasizing track association's role in reliable, timely space operations [25, 26, 11, 16].

Astrometric positions, proper motions, and photometric data from datasets like the USNO-B catalog, cross-referenced with surveys such as the SDSS, enhance proper motion measurement accuracy, crucial for multitarget tracking systems. This ensures optimal track association, minimizes communication bandwidth, and preserves association quality [25, 11, 26, 27].

Advanced methodologies, such as Forsling et al.'s dimension-reduction strategies, optimize communicated estimates, enhancing track association quality by simplifying data complexity [11]. Liu et al.'s communication-efficient multisensor track association technique employs linear transformations of track measurements, achieving efficient association without performance loss [26].

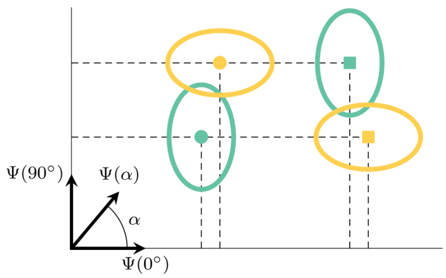
In complex multi-object tracking scenarios, associating sensor measurements with existing tracks is challenging. Altendorfer's benchmark provides a comprehensive derivation of the association log-likelihood, ensuring reliable track association [27]. The DeepDA method enhances track association by utilizing a pairwise distance matrix of input measurements to calculate association probabilities, improving multi-target tracking reliability [28].

Machine learning-based approaches are increasingly integral to modern track association. Wang et al.'s method involves extracting object features, labeling them, and training a neural network for detection, showcasing artificial intelligence's potential to improve track association accuracy [7]. Lin et al. emphasize the importance of collecting training data from stationary sources and flagged data for associating observational data with existing tracks in machine learning frameworks [13].

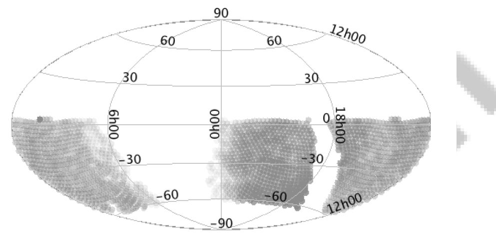
Database performance is critical in track association, especially in managing vast astronomical data. Becla et al.'s benchmark offers a structured approach to assessing database performance, ensuring efficient and reliable observational data association with existing tracks [2]. The LSST methodologies for managing astronomical data exemplify the processes of associating observational data with known tracks [8].

Ferreira's method generalizes trilateration by allowing an arbitrary number of measurements, improving track association accuracy without relying on reference trajectory propagation [24].

The methodologies highlighted emphasize the intricate and critical nature of track association in space situational awareness. These approaches ensure precise monitoring and management of space objects, addressing challenges posed by non-cooperative satellites and unpredictable maneuvers. By integrating advanced techniques like dimension-reduced track estimates and innovative orbit determination algorithms, these methodologies enhance tracking systems' reliability and effectiveness in modern space operations [11, 16].



(a) Angular Distribution of Points in a Plane[11]



(b) The image depicts a polar plot with a shaded area representing a specific region on a celestial sphere.[18]

Figure 3: Examples of Processes and Methodologies in Track Association

As demonstrated in Figure 3, track association and cataloging rely on methodologies crucial for accurate data interpretation and analysis. The "Angular Distribution of Points in a Plane" visualization showcases angular distributions using different colors and shapes, essential for understanding spatial relationships. The polar plot illustrates celestial observations using polar coordinates, emphasizing visual tools' role in track association, facilitating complex data interpretation, and enhancing spatial and celestial dataset analysis [11, 18].

4.2 Catalog Maintenance and Data Management

Effective catalog maintenance and data management are critical for space situational awareness (SSA), ensuring space object catalogs remain accurate and comprehensive. Managing astronomical catalogs involves sophisticated strategies to address space environments' expansive and evolving nature. Advanced data collection and processing techniques, like those in NASA's SPHEREx mission for cataloging solar system objects and the Vera C. Rubin Observatory's Legacy Survey for capturing celestial imagery, enhance object detection and classification, improving risk mitigation for potentially hazardous objects [8, 6, 4, 15].

Liu et al.'s linear transformations to sensor measurements facilitate efficient track association while maintaining performance, optimizing space object data management [26]. This is particularly beneficial when integrating multiple sensor inputs into a cohesive cataloging system, enhancing data management reliability.

Altendorfer's comprehensive derivation of association log-likelihoods evaluates association distances in catalog maintenance, ensuring data management systems accurately simulate tracking scenarios, supporting robust catalog updates [27].

The SDSS dataset, with over 1.5 million entries of Solar System objects and approximately 95

Efficient data management systems, like those used in the LSST, handle the peta-scale data volumes from modern surveys, ensuring rapid data processing and analysis, continuously updating catalogs with the latest observational information [2].

4.3 Challenges in Cataloging and Measuring Motions

Cataloging and measuring space object motions present challenges due to the complex, dynamic space environment. Obtaining precise astrometric measurements of faint objects, like the Kuiper Belt object MU69, is difficult due to its faintness and crowded star field location, affecting orbit fitting and uncertainty assessments [29].

Traditional orbit determination methods often require detailed models of observed bodies, which may be unavailable or inaccurate. The Hybrid Orbit Initial Orbit Determination (HOIOD) method enables orbit determination without needing a model, beneficial when traditional methods fail, such as with highly variable or poorly understood objects [23].

Dense stellar backgrounds and variable speed and direction of multiple moving objects complicate space debris detection and tracking. The growing complexity and diversity of space objects, including non-cooperative satellites and challenges from varying brightness and motion modes, necessitate advanced methodologies and technologies to enhance tracking accuracy and trajectory predictions. Recent advancements in detection algorithms, orbit determination, and high-resolution imaging systems leverage sophisticated data processing infrastructures [16, 8, 29, 14, 7]. Challenges are compounded by processing and analyzing vast data quantities from modern surveys, requiring significant computational resources and efficient data management systems.

Addressing space object catalog accuracy and reliability challenges is essential for improving space situational awareness and sustainable space operations management. The upcoming NASA SPHEREx mission's comprehensive near-infrared survey (2025-2027) aims to catalog solar system objects, enhancing Potentially Hazardous Objects (PHOs) tracking and risk mitigation. The SDSS catalog of over 1.5 million solar system object observations, with high completeness and purity rates, contributes to understanding these bodies' origins and evolution. Additionally, correcting systematic errors in star catalogs significantly improves asteroid astrometry accuracy, leading to better trajectory predictions and catalog reliability [21, 6, 15].

5 Space Situational Awareness

In the domain of space situational awareness (SSA), the precise tracking and characterization of celestial objects are crucial for ensuring the safety and sustainability of space operations. The increasing complexity of the space environment, marked by the proliferation of satellites and debris, presents significant challenges that necessitate a multifaceted approach, integrating various methodologies and technologies. The following subsection examines the critical roles of astrometry and photometry, foundational elements in enhancing SSA capabilities. These techniques provide accurate measurements of celestial objects' positions, motions, and brightness, facilitating a deeper understanding of the space environment and contributing to effective risk management.

5.1 Astrometry and Photometry in Space Situational Awareness

Astrometry and photometry are vital for enhancing space situational awareness (SSA), offering precise measurements of celestial objects' positions, motions, and brightness. By integrating deep learning for classification and statistical analysis, as demonstrated by Wang et al., these techniques significantly enhance accuracy and reduce false alarms in moving object detection, thereby bolstering SSA systems' reliability [7]. The URAT1 catalog exemplifies the importance of astrometric accuracy, providing a dense reference star catalog that improves upon previous benchmarks and aids in tracking space objects, crucial for trajectory predictions and collision avoidance [9]. Metrics like Proper Motion Precision and Astrometric Accuracy in the HSOY catalog further illustrate improvements in data quality essential for maintaining accurate space object catalogs [4].

Lin et al.'s RBS system showcases machine learning's role in refining astrometric and photometric measurements, achieving a true positive rate of approximately 99

Photometric data, including multi-color information for asteroids and their orbital parameters, as provided by datasets like the SDSS, allow detailed analysis of asteroid properties, crucial for assessing impact threats and developing mitigation strategies [10]. Metrics such as latency and throughput reflect the real-time processing needs necessary for SSA, ensuring systems effectively support space object identification and tracking [2]. The synergy between astrometry and photometry facilitates correcting systematic errors in observations, improving ephemeris predictions, and enabling automated detection and classification of space objects, contributing to comprehensive astronomical catalogs and reliable orbit linking [18, 21, 17, 8].

5.2 Characterization of Potentially Hazardous Objects (PHOs)

Characterizing Potentially Hazardous Objects (PHOs) is crucial for space situational awareness due to their potential impact threats to Earth. Developing advanced techniques for identifying and characterizing PHOs is essential for improving planetary defense measures and mitigating associated risks. A novel approach involves a correction scheme incorporating both position and proper motion errors, offering a comprehensive solution that enhances PHO tracking and characterization accuracy [21]. The GOMX-4 benchmark highlights advanced nanosatellite systems' capabilities, emphasizing inter-satellite communication and orbit control's significance in future missions, crucial for monitoring and managing PHOs [5].

The SPHEREx mission is set to transform Near-Earth Objects (NEOs) detection, tracking, and characterization by providing detailed spectral data, enhancing our ability to categorize these objects and improve our understanding of their physical properties and impact risks, advancing planetary defense initiatives [6]. Integrating advanced correction schemes, nanosatellite capabilities, and spectral analysis techniques represents a comprehensive approach to PHO characterization, essential for enhancing SSA by enabling detection, characterization, and cataloging of solar system objects, including potentially hazardous ones. This is achieved through technologies like the SPHEREx mission, which will provide critical spectroscopic data, and the Legacy Survey of Space and Time, aiming to create a comprehensive astronomical catalog. Advanced orbit determination methodologies address challenges posed by non-cooperative satellites, contributing to space activities' safety and sustainability [15, 8, 6, 16].

5.3 Applications and Implications for Space Situational Awareness

Advancements in space situational awareness (SSA) have significant practical applications and implications for managing space operations and mitigating potential risks. Enhanced SSA is critical in multi-object tracking, where sophisticated methodologies like the association log-likelihood distance provide more reliable measurement-to-track association, outperforming traditional methods such as the Mahalanobis distance, thereby improving tracking systems' accuracy and reliability [27]. In Near-Earth Object (NEO) detection, the Moving Object Processing System (MOPS) efficiently links NEOs amidst significant false detections, highlighting the potential for effective automated asteroid detection crucial for planetary defense [18].

Robust data infrastructure is vital for SSA, as Hernandez et al. emphasize. Efficiently managing and processing large datasets enhances SSA capabilities and manages risks associated with vast astronomical data [8]. This infrastructure supports continuous monitoring and assessment of space environments, ensuring safe and sustainable space operations. Comprehensive and pure catalogs of Solar System objects, as demonstrated by Sergeyev et al., advance planetary science by enhancing our understanding of the Solar System's evolution and providing valuable data for SSA applications, aiding in accurate space object tracking and characterization [15].

Forsling et al.'s proposed method offers superior performance in balancing dimensionality reduction and association quality in track-to-track fusion, pivotal for maintaining track association processes' integrity, essential for effective SSA [11]. SSA advancements enhance multi-object tracking and Near-Earth Object (NEO) detection precision, facilitating effective planetary science research. They contribute to sustainable space environment management by addressing challenges like orbit determination and catalog correlation, especially with increasing non-cooperative satellites. Innovative methodologies like the OPOD algorithm improve orbit estimation using single surveillance radar data, while extensive Solar System object catalogs from large-scale surveys like the Sloan Digital Sky Survey aid in understanding small celestial bodies' composition and dynamical pathways. These developments underscore enhanced SSA's critical role in ensuring space operations' safety and sustainability [15, 16].

6 Orbital Debris Management

The escalating issue of orbital debris necessitates a comprehensive approach to mitigate risks associated with space operations. Effective management strategies are informed by advanced measurement-to-track association techniques, enhancing data communication and addressing the complexities of multitarget tracking and characterization of potentially hazardous objects [25, 11, 6]. These strategies are critical for the safety and sustainability of current and future space endeavors. This section explores risk mitigation strategies, emphasizing the development of systems for effective orbital debris tracking and management.

6.1 Strategies for Risk Mitigation

Mitigating risks from orbital debris is crucial for safe and sustainable space operations. Enhancing space object catalogs' completeness and accuracy is foundational for effective debris tracking. The URAT1 catalog exemplifies this by offering precise astrometric data, which, when integrated with Gaia releases, improves catalog accuracy and debris monitoring [9]. Automated asteroid detection advancements, as shown by NEO linking algorithms, provide insights for developing effective detection systems to identify potentially hazardous objects and mitigate collision risks [18]. Optimizing communication protocols and expanding benchmarks to encompass additional payloads and scenarios can enhance nanosatellite systems' capabilities in debris management [5].

Survey architectures, such as the Earth-Sun L1 survey, play a pivotal role in NEA detection, offering improved detection rates and efficiency, which is vital for future survey missions aimed at enhancing debris detection capabilities [12]. Despite advancements in cataloging, issues like spurious entries in the SDSS proper motion catalog highlight the need for ongoing risk mitigation strategies [1]. Gaia's benchmark validation processes improve data quality and reliability, essential for managing orbital debris risks [3]. Establishing frameworks for evaluating database systems, as proposed by Becla et al., is crucial for managing the vast data associated with debris tracking and ensuring efficient risk mitigation [2].

Understanding PHOs' composition and characteristics is integral to planetary defense. Accurate spectral categorization, as emphasized by the SPHEREx mission, aids in assessing impact threats and developing mitigation strategies [6]. The NOAO Source Catalog (NSC) enhances researchers' ability to conduct astronomical studies, contributing to risk mitigation by expanding our understanding of the space environment [20]. Future research should refine asteroid identification methods and explore color segregation among asteroid families, offering new insights into these objects' characteristics and behaviors [10]. Collectively, these strategies reduce orbital debris risks, ensuring the long-term sustainability of space activities.

6.2 International Efforts and Policies

International collaboration is pivotal in addressing orbital debris challenges and ensuring sustainable space use. Organizations like the United Nations Office for Outer Space Affairs (UNOOSA) and the Inter-Agency Space Debris Coordination Committee (IADC) facilitate international dialogue and cooperation on debris mitigation strategies. They establish consensus-based guidelines to reduce new debris creation, enhancing current space activities' safety and sustainability and supporting long-term space exploration viability [8, 6, 15].

Implementing debris mitigation measures, such as post-mission disposal and satellite passivation, focuses on reducing collision risks and additional debris generation by enhancing NEO tracking and characterization capabilities. This proactive approach safeguards the orbital environment for future generations, facilitating scientific exploration and protecting Earth from potentially hazardous objects [18, 6, 16, 15]. The adoption of guidelines, like the IADC Space Debris Mitigation Guidelines and the United Nations Guidelines for the Long-term Sustainability of Outer Space Activities, reflects nations' growing commitment to responsible space operations and debris management.

Technological advancements and collaborative research initiatives enhance international debris management efforts. Active debris removal (ADR) technologies and space situational awareness (SSA) capabilities are developed through joint research projects and partnerships among space agencies and industry stakeholders. These initiatives improve debris detection, tracking, and removal, safeguarding operational satellites and ensuring human spaceflight safety. Advanced methodologies, such as single track orbit determination and high-fidelity detection models, enhance SSA and manage risks posed by non-cooperative satellites and NEOs. Innovative algorithms and data analysis facilitate accurate orbital predictions and reduce false detections, contributing to a safer space environment [18, 15, 16].

International policies emphasize transparency and data sharing among space-faring nations. Establishing data exchange frameworks and promoting open access to space object catalogs improve debris tracking systems' accuracy and reliability. These initiatives enhance decision-making speed and efficacy of global debris management strategies by utilizing advanced data processing techniques and large-scale astronomical surveys, such as the Legacy Survey of Space and Time (LSST) and the SPHEREx mission. These efforts collectively allow real-time detection, classification, and cataloging of celestial objects, including potentially hazardous ones, facilitating better tracking and risk mitigation [2, 8, 6].

7 Short Arc Observations

The detection and tracking of Near-Earth Objects (NEOs) have become increasingly crucial due to the potential risks they pose to Earth. This section explores advancements in detection methodologies and technologies that significantly enhance our ability to identify and characterize NEOs. We focus on improved detection capabilities facilitated by innovative survey architectures, advanced thermal infrared technology, and machine learning techniques that refine detection processes.

7.1 Improved Detection Capabilities for Near-Earth Objects (NEOs)

Significant advancements in NEO detection and tracking have been driven by developments in methodologies and technologies. Enhanced survey architectures, such as the Earth-Sun L1 survey, are pivotal in improving detection rates and efficiency, underscoring the importance of strategic survey design [12]. The integration of thermal infrared technology has refined NEO size and albedo measurements, crucial for realistic simulations in NEO linking, reducing uncertainties in NEO characterization [18].

Machine learning techniques have further advanced NEO detection capabilities. Models trained on extensive datasets, like those from the Sloan Digital Sky Survey (SDSS), enable accurate identification of moving objects and improve tracking completeness and accuracy [13]. The SPHEREx mission enhances detection and characterization by providing detailed spectral data, crucial for understanding NEO properties and supporting planetary defense [6].

Continuous improvements in detection methodologies and technologies are vital for enhancing NEO tracking systems. The NASA SPHEREx mission, with its near-infrared capabilities, aims to detect and catalog numerous solar system objects, improving our understanding of Potentially Hazardous Objects (PHOs) and aiding risk mitigation. Simulations with the Large Synoptic Survey Telescope (LSST) demonstrate high efficiency in linking NEOs into orbits, achieving over 93

7.2 Benchmarking and Validation of Astronomical Catalogs

Benchmark	Size	Domain	Task Format	Metric
SDSS-USNOB[1]	345,000	Astrometry	Star Cataloging	μ
astorb[19]	1,200,000	Astrophysics	Orbital Fitting And Ephemeris Prediction	Ephemeris error, RMS of orbit fit
NEOCam[12]	12,700	Astrophysics	Asteroid Detection	Detection Rate, Linking Success Rate
Asso-LL[27]	1,000,000	Multi-Object Tracking	Measurement-to-Track Association	Correct Assignment Rate
UrHip[30]	67,340	Astrometry	Proper Motion Measurement	Proper Motion Accuracy, Binarity Detection
LSST-BM[2]	7,000,000	Astronomy	Data Management	Latency, Throughput
SDSS-AST[10]	2,641	Astrophysics	Asteroid Identification	Completeness, Magnitude Offset

Table 3: Table summarizing representative benchmarks used in the validation and assessment of astronomical catalogs, highlighting their respective sizes, domains, task formats, and evaluation metrics. This comprehensive overview facilitates the understanding of the diverse applications and measurement criteria employed in astrometric and astrophysical data analysis.

Benchmarking and validation of astronomical catalogs are crucial for ensuring the accuracy and reliability of space object tracking, a cornerstone of effective space situational awareness (SSA). Benchmarking involves evaluating catalogs against established standards, identifying discrepancies, and enhancing data quality. Correcting systematic errors in star positions and proper motions improves astrometric observations and orbit determination algorithms, reducing regional systematic errors and refining data reliability [1, 21]. Validation involves verifying catalog data accuracy through comparison with independent datasets. Table 3 provides a detailed overview of various benchmarks utilized in the benchmarking and validation of astronomical catalogs, showcasing the diversity in size, domain, task format, and evaluation metrics.

The Gaia Early Data Release 3 (EDR3) catalog serves as a benchmark for completeness and precision in astrometric and photometric solutions, providing high-precision positional data crucial for validating other catalogs [3]. The URAT1 catalog offers a dense reference star catalog, enhancing astrometric data precision in space object tracking [9].

Validation is further supported by integrating data from multiple sources, such as combining Hubble Space Telescope (HST) and Gaia DR2 data, creating a robust uncertainty model. This integration enhances stellar occultation predictions, aiding spacecraft guidance and orbit determination. Advanced orbit fitting techniques and uncertainty analysis, as demonstrated in the flyby of Kuiper Belt Object (486958) 2014 MU69 by NASA's New Horizons, refine positional uncertainties and support long-term orbit stability [18, 21, 29]. Cross-referencing data from various catalogs enhances validation processes.

Benchmarking and validation are also critical for addressing false detections and statistical noise in astronomical surveys. The SDSS proper motion catalog allows benchmarking of proper motion measurement accuracy, vital for maintaining accurate space object catalogs [1]. The NOAO Source Catalog (NSC) offers improved photometric precision and astrometric accuracy, essential for tracking and characterizing space objects [20].

8 Conclusion

8.1 Future Directions and Research Opportunities

The advancement of space situational awareness (SSA) is set to progress significantly, driven by research and development efforts focused on enhancing the accuracy and dependability of space object tracking. A key area for future exploration is the optimization of Initial Orbit Determination (IOD) methodologies. This involves improving the computational efficiency of Direct Initial Orbit Determination (D-IOD) and incorporating advanced image processing models to bolster IOD's resilience to observational noise and broaden its applicability. In the domain of track association, there is considerable potential in extending optimization strategies to accommodate multiple dimensions and agents with diverse track sets, thereby increasing the robustness and efficiency of track association methodologies in complex settings. Additionally, further investigation into non-linear dynamic systems and set-type track association methods could lead to the development of more sophisticated tracking systems.

Enhancing astronomical catalogs is another critical research focus. Efforts should aim to refine extraction techniques and expand catalogs to include more comprehensive data on Solar System objects, thus advancing our understanding of asteroid families and their characteristics. Improving the dataset and methods used in catalogs like HSOY could enhance the accuracy of proper motion measurements, which is essential for ongoing SSA studies. Future research could also concentrate on refining the photometric calibration and real-time updates of catalogs such as the NOAO Source Catalog (NSC), offering opportunities to improve SSA capabilities through enhanced data accuracy and timeliness. Utilizing SPHEREx data to delve deeper into the spectral characteristics of Near-Earth Objects (NEOs), enhance orbital predictions, and improve impact scenario models remains a vital research area. Moreover, developing scalable data processing systems is crucial as data volumes continue to grow, with advancements in database technologies indicating potential progress in SSA, ensuring these systems can effectively support space object identification and tracking.

8.2 Integration of Advanced Technologies

Incorporating advanced technologies into SSA processes offers significant potential for enhancing the accuracy, efficiency, and reliability of space object tracking and management. Key technological advancements include the application of machine learning and artificial intelligence, which have shown substantial improvements in space object detection and classification. For example, deep learning models significantly reduce false positive rates and enhance the precision of moving object detection, which is crucial for maintaining accurate space object catalogs and improving SSA systems' overall effectiveness. The development of sophisticated data management frameworks, as employed in large-scale astronomical surveys, facilitates efficient handling of extensive datasets. By integrating file storage for images with database management for metadata, these frameworks enable rapid data processing and analysis, ensuring SSA processes remain current and responsive to dynamic space environments. Advanced astrometric catalogs, such as Gaia EDR3, provide high-precision positional data that serve as benchmarks for validating and enhancing space object tracking systems' accuracy. Incorporating these catalogs into SSA processes improves orbit determination and track association methodologies' reliability, contributing to more accurate space object trajectory predictions. Additionally, integrating advanced correction schemes for position and proper motion errors enhances SSA processes' precision, supporting planetary defense initiatives and mitigating potential impact risks. By leveraging machine learning, sophisticated data management frameworks, and high-precision astrometric catalogs, SSA systems can better manage the challenges posed by the dynamic and expansive nature of space environments, ensuring the long-term sustainability of space activities.

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