**ME 597 Small Spacecraft Design I**

**Report 3: Star Tracker Overview**

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**Table of Contents**

[List of Figures 3](#_Toc191840924)

[Acronyms/Abbreviations 4](#_Toc191840925)

[1 Introduction 5](#_Toc191840926)

[2 Background 6](#_Toc191840927)

[3 Applications in Space Domain Awareness 8](#_Toc191840928)

[3.1 Star Tracker/GNSS Integration for Tracking RSOs 8](#_Toc191840929)

[3.2 Satellite Formations for Enhanced RSO Detection 8](#_Toc191840930)

[3.3 Dual-Use Star Tracker System for SSA 8](#_Toc191840931)

[4 Possible Future Cases 9](#_Toc191840932)

[5 Conclusion 9](#_Toc191840933)

[References 10](#_Toc191840934)

# List of Figures

[Figure 1: Rocket Lab Star Trackers 5](#_Toc191840951)

[Figure 2: General Star Tracker Algorithm (Modification and hardware implementation of star tracker algorithms) 6](#_Toc191840952)

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# Acronyms/Abbreviations

* ADCS (Attitude Determination and Control System)
* AI (Artificial Intelligence)
* APS (Active Pixel Sensors)
* CCDs (Charge-Coupled Devices)
* GNSS (Global Navigation Satellite System)
* RSO (Resident Space Object)
* SSA (Space Situational Awareness)
* SDA (Space Domain Awareness)
* STM (Space Traffic Management)
* EO (Earth Observation)
* CubeSats (Cube Satellites)
* SOA (Space Operations Awareness)

# Introduction

In the vastness of space, spacecraft must navigate without the familiar cues we rely on here on Earth, such as gravity or a visible horizon. Instead, they look to distant celestial bodies to find their way. This need for precise orientation has led to the development of advanced technologies, with star trackers playing a crucial role in spacecraft navigation. These systems help spacecraft maintain accurate alignment, ensuring that communication, power systems, and scientific instruments stay on course and aligned with mission goals. Star trackers work by capturing images of the star field and comparing them with preloaded star catalogs to determine the spacecraft’s orientation relative to a fixed reference frame, typically the stars themselves [1]

Star trackers have become indispensable in modern spacecraft design. They are a key component of the Attitude Determination and Control System (ADCS), providing highly accurate angular measurements that are critical for the spacecraft's functionality, often within a few arcseconds [2]. This level of precision is particularly important for missions that require precise orientation, such as Earth observation, planetary exploration, and deep-space exploration [3]. Compared to other attitude sensors like sun sensors or magnetometers, which are influenced by factors such as solar radiation or Earth's magnetic field, star trackers offer a reliable alternative by using the fixed, predictable nature of stars. This makes them especially valuable for missions in deep space, where other navigational cues are unavailable.



Figure 1: Rocket Lab Star Trackers

The technology behind star trackers has evolved significantly over the years. Early models relied on basic optical systems, but modern star trackers incorporate advanced sensors such as charge-coupled devices (CCDs) and active pixel sensors (APS). These sensors enable star trackers to capture images with remarkable clarity and speed. Additionally, with the integration of artificial intelligence (AI) and machine learning algorithms, star trackers can now process images faster, improving their efficiency and resilience in challenging space environments [1]. However, despite their precision, star trackers are not without challenges. Bright celestial bodies like the Sun or Earth can interfere with their functionality, and space radiation can degrade the performance of the sensitive optical components. Nevertheless, ongoing advancements in sensor technology, miniaturization, and AI have helped mitigate these issues, expanding the capabilities of star trackers for future space exploration [2].

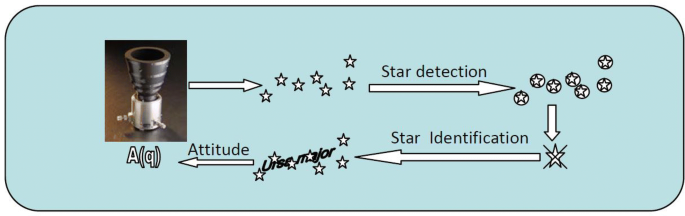


Figure 2: General Star Tracker Algorithm (Modification and hardware implementation of star tracker algorithms)

Star trackers are now standard components on most modern spacecraft, from small CubeSats to large interplanetary missions. Their miniaturization has enabled their use on smaller satellites without sacrificing accuracy, demonstrating their versatility and importance for space missions of all scales [1]. As space exploration continues to advance, star tracker technology will remain at the heart of spacecraft navigation systems, enabling more autonomous operations and deeper missions into the solar system and beyond. The continuous improvement in accuracy, durability, and efficiency of star trackers will undoubtedly play a pivotal role in the success of future space missions, supporting scientific discoveries and expanding humanity’s presence in space.

# Background

Star trackers are advanced optical devices critical for spacecraft attitude determination and control. These devices are essential for space missions where precise orientation is required, such as Earth observation, planetary exploration, and communication satellite operations. Unlike traditional terrestrial navigation methods, spacecraft in orbit cannot rely on cues such as gravity or the horizon. Instead, star trackers use the fixed positions of distant stars as reference points to determine the spacecraft's attitude. Through imaging the star field and comparing the captured images to an onboard star catalog, star trackers calculate the spacecraft’s orientation relative to a fixed reference frame, allowing it to maintain stability for tasks such as communication, power generation, and scientific measurements [3].

The operation of a star tracker involves capturing images of the night sky with sensitive optical sensors, such as charge-coupled devices (CCDs) or CMOS sensors. These sensors convert the light from stars into electrical signals, which are then processed by onboard algorithms. These algorithms match observed star patterns to preloaded star catalogs, enabling the tracker to determine the spacecraft’s precise orientation. Star trackers are integral to the spacecraft’s Attitude Determination and Control System (ADCS), offering remarkable accuracy—often to a few arcseconds [4]. This level of precision is critical for maintaining accurate pointing, particularly in missions that require detailed imaging or communication with ground stations.

While star trackers provide exceptional performance, they face several challenges. Space radiation, interference from bright objects like the Sun or Earth, and image blurring caused by spacecraft motion can degrade their accuracy. However, advancements in sensor technology, such as active pixel sensors (APS), offer improved durability and lower power consumption compared to earlier CCD-based sensors. Furthermore, the integration of machine learning and artificial intelligence into the algorithms for star identification enhances their resilience and performance in dynamic environments, allowing for faster and more reliable star identification [5, 6].

Star trackers have evolved significantly over the years, starting from the first CCD-based tracker introduced in 1976. Modern algorithms for star identification have been optimized to handle large datasets efficiently and are categorized based on their operational requirements. Some algorithms, like "lost-in-space" algorithms, operate without prior attitude knowledge, while others, such as recursive algorithms, improve identification accuracy by incorporating prior estimates [4]. For small satellites, low-cost star trackers have been developed that use feature extraction and catalog search methods to maintain high performance at a reduced cost [7]

These devices are integral not only for maintaining spacecraft stability but also for enhancing satellite autonomy. This is particularly valuable for deep-space missions, where real-time communication with ground stations may be limited. Additionally, star trackers have found applications beyond traditional attitude control, including in space debris detection and monitoring. By analyzing sequences of images, star trackers can also identify and track the movement of debris or other objects in space, helping to mitigate risks associated with space congestion [6]

As spacecraft missions grow more complex and as satellite miniaturization continues, the role of star trackers becomes ever more crucial. Advanced star trackers are no longer limited to large spacecraft but have also been adapted for small satellites like CubeSats. This miniaturization ensures that even the most compact space missions can benefit from precise attitude determination, thereby enabling a wider array of scientific, commercial, and exploration applications in space. With continuous advancements in algorithmic efficiency, sensor technology, and computational power, star trackers are poised to remain at the heart of spacecraft navigation and control systems, supporting a new generation of missions to explore our solar system and beyond.

# Applications in Space Domain Awareness

The growing accumulation of orbital debris in Low Earth Orbit presents significant risks to operational satellites and human space exploration. As space missions increase, managing space debris has become a critical priority. Researchers have explored various technologies and strategies to address this issue, including mechanical capture systems, laser-based removal methods, and inflatable drag devices. This review examines key studies and advancements in orbital debris removal, highlighting the effectiveness and feasibility of different approaches. This is by no means an extensive literature of current approaches, but a few have been selected that are deemed relevant.

## Star Tracker/GNSS Integration for Tracking RSOs

[8] introduced a framework that integrates star trackers with GNSS to enhance the tracking of RSOs. Their proposed system utilizes a constellation of satellites organized in formations, with each formation having a leader and several followers. This structure allows for efficient observation of RSOs, optimizing the observational duration and minimizing risks in Low Earth Orbit (LEO). The integration of star trackers and GNSS provides autonomous satellite systems with precise attitude determination and positional data, which is crucial for observing and tracking objects in space. Such systems improve the overall efficiency of space traffic management by enabling better surveillance of space objects, and their incorporation into satellite constellations contributes to a more robust SDA capability.

## Satellite Formations for Enhanced RSO Detection

[9] explored the use of satellite formations for enhancing RSO detection and tracking in space. By utilizing the formation of satellites equipped with star trackers and GNSS receivers, this method enables the simultaneous observation of the same RSO from different angles. This multi-static approach capitalizes on parallax effects, which help improve the accuracy of orbit determination. The integration of star trackers allows precise attitude control, while GNSS data provides critical position information. This combined approach facilitates a real-time, multi-satellite tracking network, enhancing the accuracy and reliability of RSO orbit predictions and improving Space Traffic Management (STM) efforts. The use of star trackers in satellite formations is particularly beneficial for Earth Observation (EO) missions and plays a crucial role in maintaining a safe space environment as the density of objects in orbit increases.

## Dual-Use Star Tracker System for SSA

[10] demonstrated the potential of dual-purpose star tracker systems for Space Situational Awareness (SSA) through the successful launch of a star tracker system on a stratospheric balloon platform. This system, originally designed for attitude determination, was adapted to detect and characterize RSOs. The mission, RSONAR II, collected over 95,000 images of the sky under varying conditions, providing valuable data for RSO detection and characterization algorithms. By using existing star tracker technology for both attitude determination and RSO imaging, this approach offers a cost-effective solution for SSA, making the technology more accessible for space missions without the need for additional, expensive equipment.

The integration of star trackers with GNSS and other advanced technologies has revolutionized Space Domain Awareness, enabling precise tracking, monitoring, and identification of RSOs. Whether through satellite formations, dual-use systems, or autonomous tracking capabilities, star trackers play a critical role in improving the safety and sustainability of space operations. As the number of space objects continues to increase, the need for efficient and reliable SDA systems will only grow, and the advancements in star tracker technology discussed here are key to addressing these challenges.

# Possible Future Cases

As space exploration and satellite technology continue to advance, the role of star trackers in future missions will evolve to address new challenges and opportunities. One promising direction is the use of star trackers in autonomous spacecraft operations, particularly for long-duration missions to deep space. With the increasing complexity of interplanetary missions, star trackers will likely be integrated into fully autonomous systems that require minimal human intervention. These systems will rely on the precision of star trackers for navigation, orientation, and scientific measurements, supporting missions that venture beyond the reach of traditional ground-based communication.

Another possibility is the development of advanced star trackers for small satellite constellations. As miniaturization and cost reduction continue, star trackers will become more accessible for low-cost CubeSats and nanosatellites, enabling precise attitude control. These small satellites could be deployed in formations to monitor space debris, assist in planetary exploration, or support global communication networks. In these cases, the integration of star trackers with other sensors and artificial intelligence will improve the ability to detect and track space objects in increasingly crowded orbits, contributing to safer and more efficient space operations in the future.

# Conclusion

Star trackers are essential for spacecraft navigation, providing precise attitude determination and control. Their integration with advanced sensors, machine learning, and AI enhances efficiency and resilience, enabling more autonomous spacecraft operations and expanding space exploration capabilities. As space becomes more crowded, star trackers will be pivotal in Space Domain Awareness, helping detect and track debris while ensuring the safety of space operations. With continued miniaturization, star trackers will support small satellite constellations, ensuring that precise navigation remains integral to both large and compact missions, driving safer, more efficient space activities in the future.

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