Scientist reviews the key technologies for space-based situational awareness

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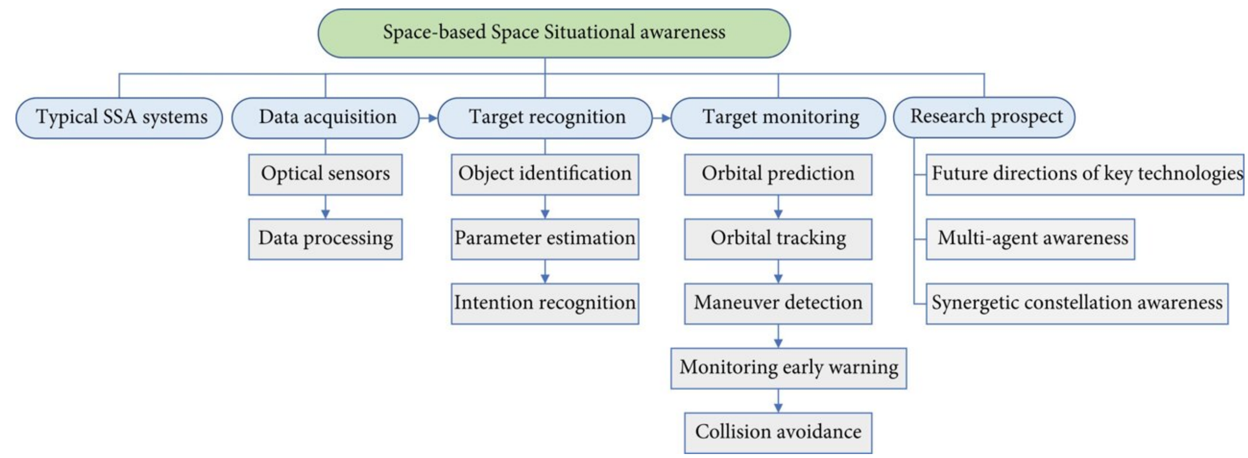


Reviewed components of space-based situational awareness. Credit: *Space: Science & Technology*

Since the launch of the first man-made earth satellite, the number of space objects has been rapidly increasing. According to the authoritative statistics from NASA, over 6,400 orbiting spacecraft still existed until early 2021. Furthermore, the total number of rocket debris above 10 cm has exceeded 16,000. The space environment has become highly congested due to the increasing space debris, seriously threatening the safety of orbiting spacecraft.

Space-based situational awareness, as a comprehensive capability of threat knowledge, analysis, and decision-making, is of significance to ensure space security and maintain normal order. Various space situational awareness systems have been designed and launched. Data acquisition, target recognition, and monitoring constituting key technologies make major contributions, and various advanced algorithms are explored as technical supports.

However, comprehensive reviews of these technologies and specific algorithms rarely emerge. This disadvantages the future development of space situational awareness. In a review paper recently published in *Space: Science & Technology*, Shuang Li from College of Astronautics, Nanjing University of Aeronautics and Astronautics, reviewed and analyzed research advancements in key technologies for space situational awareness, indicated the future directions of the key technologies, and emphasized the research prospects of multiagent and synergetic constellation technologies for future situational awareness, aiming to provide references for space-based situational awareness to realize space sustainability.

First of all, typical systems available for long-distance awareness were reviewed. The United States has greatly contributed to developing the SSA systems. Specifically, the Geosynchronous Space Situational Awareness Program (GSSAP) aims to strengthen geosynchronous situational awareness capability. This system can identify concrete features to distinguish and characterize various targets.

The Space-Based Surveillance System (SBSS) has higher capabilities of data acquisition, identification, and tracking on space debris. Besides, the Space-Based Infrared System (SBIRS) constellation contains four satellites and infrared payloads in high orbits. 24 satellites are distributed in the Space Tracking and Surveillance System (STSS), further extending the coverage of the SBIRS. The STSS has stronger capabilities of orbital tracking and maneuver detection in complicated situations.

Furthermore, the James Webb Space Telescope (JWST) integrates a telescope with near- and midinfrared cameras for ultra-far image acquisition and target monitoring.

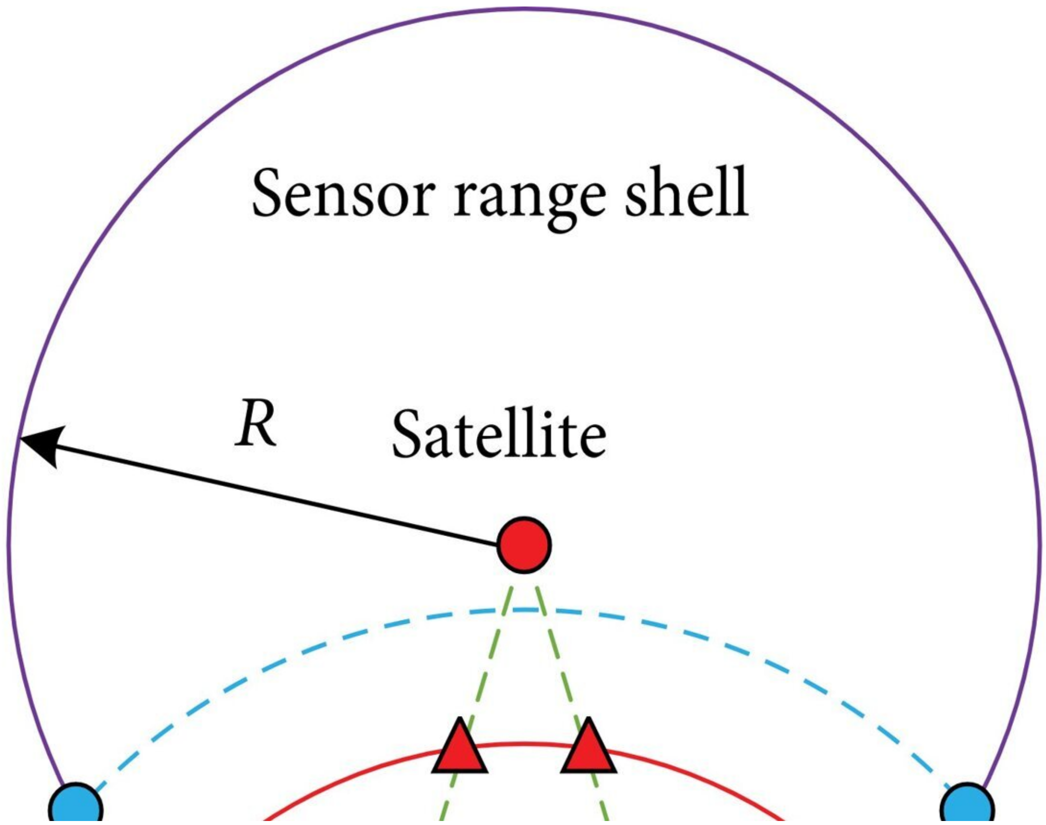
Low weight, precise, and broad observation are the significant advantages of the JWST. Following the United States, the European Union emphatically strengthens knowledge and early warning capabilities in the SSA, establishing the dual-mode detection system. Russia has advanced in debris tracking, early warning, and environmental monitoring, creating the Tree Canopy system. Overall, advanced space-based situational awareness systems constantly emerge in the United States and other countries.

Nevertheless, given the large power consumption of space-based devices and uncoordinated data processing methods, the current SSA systems are restricted by the number of detectors, detection capabilities, and location distribution, thus only concurrently possessing certain functions. In this case, the systems cannot realize accurate awareness of all space targets in real time, but only for task requirements. Therefore, the comprehensive situational awareness capability of the space-based SSA becomes a necessity.

Afterwards, the author reviewed and discussed characteristics of optical sensors and processing technologies, which plays a role of accurately acquiring the data of space targets. With the advantages of high sensitivity, rapid transmission, and strong anti-interference, optical sensors applied to the space-based situational awareness as the collectors of object data. As for the data processing, it represents the technology of processing and analyzing large spatial data, converting them into the key information of the targets. However, the increasing risky targets raise the requirements for processing massive data, and it also affects the accuracy and timeliness of situational awareness. Thus, data storage, filtering, and fusion are reviewed and discussed in order.

Then, the author presented and analyzed the technologies for target recognition. Firstly, object identification was the core section of target recognition in the space-based situational awareness. Laser radars had been dominant in object identification as sensors, while machine vision and ANN were highly explored as advanced identification algorithms. Secondly, parameter estimation, as an essential condition to acquire the accurate information of space objects, parameter estimation needs to be performed in the SSA after object identification.

Various parameter estimation technologies for space objects have been exploited so far. Photometric technologies had been more maturely developed, while optimal estimation technologies produced advanced algorithms in artificial intelligence. Thirdly, intention recognition was the process of the intention awareness and behavior inference of space objects through observed actions and effects on the situations, which were essential to improve the quality of early warning information and reduce the number of warnings, thus guaranteeing security. However, compared with the mature object identification technologies, intention recognition needs deeper research.



Geometry of dual-altitude band ATH coverage for a single satellite, shaded area. Credit: *Space: Science & Technology*

Furthermore, the author discussed the development of the target monitoring technology. In the steady period, target monitoring technologies emphasized orbital prediction, tracking, and maneuver detection, while early warning and collision avoidance dominated the risky period.

(1) Orbital prediction of space targets, as the foundation of collision warning mechanism and satellite measurement and control technology, had become a research hotspot in the SSA field. Nevertheless, the limitations of current orbital prediction methods are the low accuracy of target dynamic models, sensor measurements, and orbital determination.

For instance, atmosphere drag models generated large uncertainty for the orbital prediction in low-earth orbits. Thus, the author c the orbital prediction method based on Analytical Prediction Models and Machine Learning Algorithms.

(2) Orbital determination and tracking were both important sections of target monitoring. They had been closely connected, where orbital determination was the premise and orbital tracking was the executing purpose. Nevertheless, only the line-of-sight observation from the optical sensors to the targets is available without range information. Considering that the assumptions are all satisfied, including linear dynamics, coasting flight, single sensor, and the sensor fixed in the center of mass, the well-known angles-only orbital determination need solutions to the lack of range observability. Thus, the author discussed the developments of Angles-Only Determination Algorithms and a series of Improved Filter Tracking Algorithms.

(3) Detecting the maneuvers of space objects with retrievable historical data has become an essential mission in the SSA, especially for active objects without available operational information. Real-time detection is required to react adequately to any spacecraft anomalies and possible threats to nearby space assets. The active objects' maneuvers are detected, recording the patterns and trends in maneuver types and magnitudes. Thus, the author discussed the developments of the Sensitive Parameter Characterization Algorithms and the Joint Measurement and Processing Algorithms.

(4) Monitoring early warning technologies possessed significant advantages of wide monitoring ranges, diverse tracking means, and high warning accuracy. Therefore, early warning was promising as the mainstream direction and the future trends focus on the Space-based asteroid warning projects and the improvements of the timeliness, accuracy, and confidence.

(5) After receiving the early warning on space debris and asteroids, a vital part of the SSA was to predict and avoid satellite collisions to protect space assets. The research on collision avoidance technologies focused on collision prediction and maneuver strategies. The core of collision prediction was probability computation algorithms, while avoidance algorithms were the essence of strategy design. Thus, the author discussed the developments of the Collision Probability Computation Algorithms and the Maneuvering Avoidance Algorithms and Strategies.

Finally, the author summarized the four key conclusions and insights for the essential technologies:

(1) For the overall advance of the space-based SSA, full-dimensional and multilevel domain awareness and surveillance systems are activated. Space surveillance systems are expected to have larger coverage, higher accuracy, and shorter data updating. For system devices, the working frequency will be changed from the low to the high band. The fixed structures tend to be flexible, and a lightweight design is implemented. Furthermore, the working mechanism is evolved to the distributed and full digital array.

(2) As an essential part of the SSA, perfect target feature databases must be established to provide more prior information for accurate and rapid situational awareness. Relying on artificial intelligence and cloud computing, the development strategies of space big data should be formulated to promote new-generation information technologies. Furthermore, efficient space traffic management and commercial services are expected for higher sustainability and self-protection capability of space assets.

(3) The current intelligent algorithms for target recognition and monitoring mainly adopt small sample learning. Most models possess

slow inference after deployment and cannot meet real-time requirements. Next, the current algorithms have insufficient generalization. Therefore, designing the classifiers of different categories in homologous sample space is necessary. The learning transfers of heterogeneous data should be studied to improve the model adaptability to the target intrinsic feature changes in small samples.

(4) Multiagent and synergetic constellation awareness overcome the limitations of payload allocation. Embodied intelligence and deep, general, and evolutionary learning can be applied to multiagent systems and constellations for realistic multimodal interaction, contributing to the intelligent evolution of situational awareness systems.

More information: Beichao Wang et al, Research Advancements in Key Technologies for Space-Based Situational Awareness, *Space: Science & Technology* (2022). DOI: 10.34133/2022/9802793

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