Facilitating the development of LEO mega constellations
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The rapid development of Low Earth Orbit (LEO) mega constellations has significantly contributed to several aspects of human scientific progress, such as communication, navigation, and remote sensing. However, unrestrained deployment of constellations has also strained orbital resources and increased spacecraft congestion in LEO, which seriously affects the safety of in-orbit operations of many space assets.

For the long-term and sustainable development of space activities in LEO regions, space environment stability must be maintained using more rational surveillance and governance mechanisms. In a review paper recently published in *Space: Science & Technology*, Jingrui Zhang from School of Aerospace Engineering, Beijing Institute of Technology, analyzed the research gap and facilitated the development of LEO mega constellations.

First of all, the author reviewed the current developments of typical LEO mega constellations, including Starlink, OneWeb, Iridium Next, Globalstar, and Flock. Taking SpaceX's Starlink as an example, it aims to build a LEO constellation containing 42,000 satellites to achieve global coverage, high-speed, large-capacity, and low-latency space-based global communication system. Starlink has shown excellent performance in related fields, such as international aviation and ocean transportation. Moreover, Starlink can be constructed as a powerful command and communication network and has already been an important symbol of the weaponization of outer space in the United States.

Then, the author analyzed the impact of LEO mega constellations in terms of astronomical observation, spacecraft safety in orbit, and space environment evolution. From the perspective of space science, such impacts were particularly prominent in astronomical observations, in-orbit spacecraft safety, and the evolution of the space environment. In terms of astronomical observation, the new LEO mega constellations which would mainly be deployed at 350-1100 km, would significantly affect the normal operation of ground-based astronomical observation equipment. For ground-based optical telescopes, when a satellite passed through its field of view, it caused different degrees of damage to the observational data depending on the satellite brightness.

Besides, the excessive number of satellites and poor management capabilities of LEO mega constellations posed a serious threat to the safety of spacecraft in orbit. Especially for large, manned spacecraft of high value, this not only increased the risk of significant economic losses but also threatened astronaut safety. In addition to posing a threat to the safety of individual spacecraft in orbit, LEO mega constellations increased the uncertainty of space environment evolution. The number of uncontrollable targets had significantly increased with LEO mega constellations, which led to a sharp increase in the density of LEO space objects, posing significant challenges to space debris mitigation and space traffic management. The rapid
growth of LEO mega constellations may lead to the eventual collapse of the space environment.

Afterwards, the author divided the process of mitigating or suppressing the negative impact into two major aspects: surveillance and governance of space objects. Space target surveillance was to ensure the safety operation of spacecraft using space surveillance infrastructures and space situational awareness technologies.

Many institutions and scholars had made several research efforts and formed an applied field of space situational awareness (SSA) with a complete architecture. An observation system mainly included two deployment locations, ground-based and space-based, and two detection methods, optical and radar. Currently, the best space observation system in terms of global performance is the SSN, from the United States, followed by the Russian Space Surveillance System (SSS) and the European Union Space Surveillance and Tracking System (EUSST).

Owing to the development of LEO mega constellation, SSA was facing new challenges in terms of multi-sensor management and data fusion. To maximize the capabilities of SSA, an efficient allocation of multi-sensors was required, with an effective fusion of multi-sensor data. The multi-sensor management method can be understood in terms of sensor scheduling or the dispatch of observation tasks, which referred to the allocation of appropriate observation instructions at appropriate times, so that the entire sensor network can work together to achieve task requirements.

With the increasing number of ground-based and space-based observation sensors coming online, effective multi-sensor management methods became an urgent demand by the space community. In addition to typical optimization methods, efficient and optimal task allocation methods based on deep reinforcement learning algorithms and related methods were proposed to achieve good performance in high-dimensional and large-scale scenarios.

Multisource information fusion was a multilevel and multifaceted process of information processing that detects, correlates, and combines data from multiple sensors and information sources to obtain an accurate estimate of the target status and identity, as well as a complete assessment of environmental posture and threats.

However, multi-sensor information fusion experienced limitations, such as low autonomy and poor timeliness. Toward governance of space objects, there were two main governance methods. The first category, post-mission disposal (PMD), was to reduce the generation of new space objects by onboard deorbiting strategies. The second category, active debris removal (ADR), mainly aimed to speed up the deorbit of out-of-service space objects, and the ultimate goal was to crashing targets into the atmosphere through active human activity. PMD can significantly reduce birth rates and increased the rate of space failure targets.

However, this cannot curb the growth trend. ADR can dispose of existing failure targets and fundamentally curbed the tendency for space junk growth. However, there was an urgent need to improve removal efficiency. Therefore, the integrated use of both PMD and the active removal of space objects was a prerequisite for ensuring the sustainability of the space environment.

Finally, the future development and potential research directions of LEO mega constellations were prospected. Comprehensive applications of LEO mega constellations are still in the stage of preliminary exploration due to some unique characteristics, such as limited frequency-orbit resources, global impact, and complex constraints.

Thus, there are four main trends for the future development:

1. The bellwether firms would rapidly reserve frequency-orbit resources in batches.
2. Unprecedented damage from LEO mega constellations might be caused to the space environment.
3. The surveillance systems may evolve from ground-based to space-based.
4. The governance methods may evolve from single-objective targets to multi-objective,
low-cost, and high-efficiency targets.

According to the summarized tendency above, four potential research directions are of great interest:

1. A more equitable coordination framework for LEO frequency-orbit resource allocation should be established.
2. A reasonable and unified technical standard for space traffic management should be proposed to further improve the ex-ante negotiation mechanisms, crisis control mechanisms during accidents, and ex-post accident disposal mechanisms.
3. Critical technologies for timely surveillance, developments in the autonomy rapidity and effectiveness of multi-sensor information fusion are urgently required.
4. Key methods for efficient governance are worth being further developed. The deorbiting of defunct space objects should be accelerated by developing standardized, modular, efficient, and engineered means of governance.