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Where Space Technology Matters: Ensuring Space Safety in an Increasingly Reliant World

Abstract

Modern society increasingly relies on space-based infrastructure for various commercial, civil, economic, safety, and security activities. However, these essential systems face vulnerabilities from both natural and human-made space hazards, potentially disrupting or halting their operations. This study highlights the importance of space technology in protecting space infrastructure against three primary hazards: space weather, orbital debris collisions, and Near-Earth Objects (NEOs) impacts. Space weather represents a significant threat due to its fluctuating nature, which can result in spacecraft experiencing charging or increased frictional forces. To address this risk, missions like SOHO and ESA Vigil provide uninterrupted high-resolution observations of the sun, offering accurate information and early warnings of solar events. Another major concern is the growing presence of space debris which clutters the space environment and raises the risk of damage or destruction of satellites upon collision. The ClearSpace-1 mission, set for launch in 2025, will deploy a four-armed robot to capture debris remnants and perform a controlled re-entry into the Earth's atmosphere, becoming a crucial step for space cleanup. Lastly, Near-Earth Objects (NEOs), such as asteroids and comets, not only threaten Earth but also orbiting satellites. The Double Asteroid Redirection Test (DART) mission successfully altered the orbital period of a small asteroid using a kinetic impactor, showcasing the effectiveness of space observation technologies in defending critical space systems. Overall, by utilizing these cutting-edge space observation technologies, vital space infrastructure is safeguarded, and continuous delivery of space services is ensured.

Key Words: Space Technology, Satellites, Space Safety, Solar Weather, Orbital Debris, Near-Earth Objects (NEOs)

Introduction

Space systems have become indispensable in modern life, enabling critical services like telecommunications, navigation, weather forecasting and disaster management. However, society's growing reliance on these systems poses significant challenges, as they are vulnerable to both natural and human-made threats that can occur unexpectedly. Even minor disruptions or damages of the space infrastructure can have catastrophic consequences for public safety, security, economic activity, and emergency response (Krag et al., 2010). To prevent such outcomes and enhance citizen resilience, it is crucial to develop a robust situational awareness of space capable of providing comprehensive information on the population of objects orbiting Earth and the space environment (Bobrinsky & Del Monte, 2010). Thereby, potential hazards from space can be rapidly identified, their risk can be evaluated, and the relevant authorities can be informed to mitigate the threat (ESA, 2019a). This paper explores the vital role of space technology in protecting space infrastructure from hazards such as space weather, orbital debris collisions, and Near-Earth Object (NEO) impacts, by improving warning times, overcoming limitations, and laying the groundwork for future advancements.

Space weather monitoring and forecasting

Space is not a vacuum and it is consistently bombarded by the solar wind which is a stream of charged particles emitted by the Sun (ESA, 2023). In addition to this ongoing stream, the Sun can also produce more intense events such as solar flares and Coronal Mass Ejections (CMEs). Solar flares emit a range of photons including X-rays, visible and ultra-violet light, while CMEs are enormous bubbles of plasma that can contain billions of tons of fast-moving solar particles and magnetic fields (Moldwin, 2022). The impact of these events on space-borne systems can cause performance and reliability issues. For example, low earth orbit satellites can lose altitude due to increased atmospheric drag, leading to overheating, and ultimately burning up upon reentry. Other satellites in orbit can experience charging and high-energy radiation effects (Moldwin, 2022).

Anticipating potentially hazardous events and conditions on the Sun and in near-Earth space demands reliable and accurate space weather predictions. Ground-based solar observation stations play a key function in collecting essential data on solar activity, including full-disk magnetograms, H-α intensity images, and helioseismic maps. These give information on the size and position of sunspots, prominences, and plagues, which can indicate solar activity that might produce flares and CMEs (NASA, 2013). However, because Earth's magnetic field and atmosphere provide considerable protection against space weather, ground-based observations are restricted. The magnetic field deflects most charged particles from the solar wind away from Earth, while the atmosphere filters out extreme ultraviolet and X-ray wavelengths from sunlight (ESA, 2017).

Space-based solar observation is, therefore, the most reliable and consistent method for obtaining space weather information, forecasts, and warnings, as it is not influenced by Earth's atmosphere or day/night effects. It offers high spatial resolution to clearly display the Sun's outer layers and inner depths (Domingo et al., 1995). For instance, the Solar and Heliospheric Observatory (SOHO) is a joint spacecraft mission between ESA and NASA that orbits the First Lagrangian Point (L1) (Figure 1). This strategic location enables SOHO to continuously observe the Sun's structure and dynamics along the Earth-Sun line without any disruptions or interruptions (Wilkinson, 2012). Moreover, to further enhance the ability to predict solar events, ESA is now planning to deploy Vigil spacecraft at the L5 Lagrangian point (Figure 1). This vantage point gives a "side view" of the Sun, constantly streaming near real-time data on potentially dangerous solar activity before it becomes visible from Earth (ESA, 2022a). As a result, warning times are improved for operators to take effective action. By leveraging advanced space observation technologies, critical space infrastructure is protected, and the success of space services delivery is ensured.

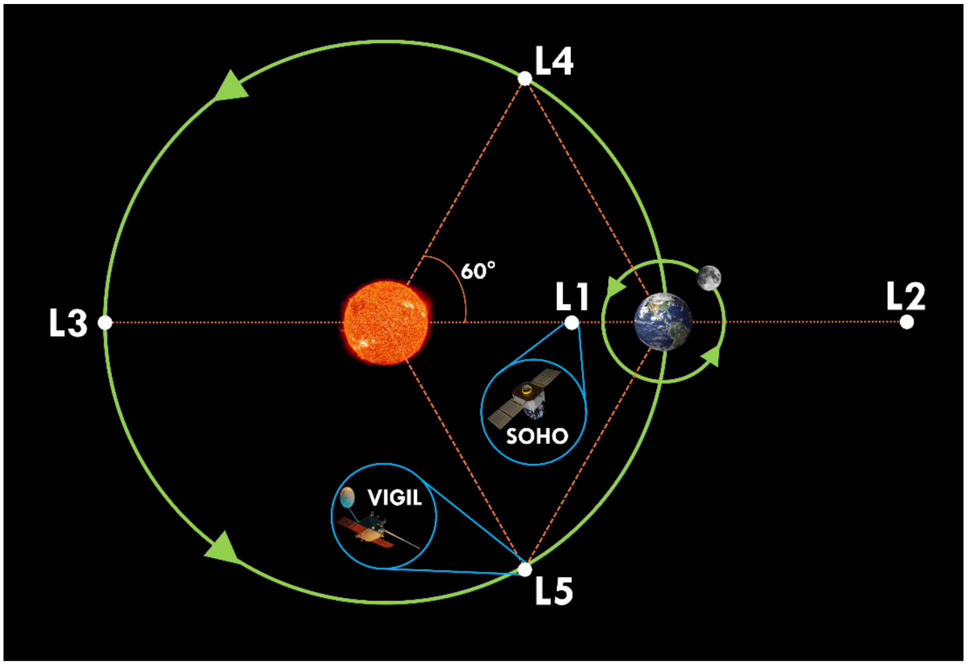

Figure 1. Not scaled diagram of the Lagrange points associated with the Sun-Earth system. Lagrange Points are positions in space where the gravitational forces of a two-body system like the Sun and the Earth balance out, granting a spacecraft to remain in position and reduce fuel consumption. Figure created based on ESA (2017).

Orbital debris: human made pollution in Space

The presence of human-made threats to spaceborne systems is also a major concern, with space debris or "space junk" being the most pressing challenge. Space debris includes inactive satellites, discarded rocket stages, and fragments from collisions or explosions (Smirnov, 2001). Over the past six decades, the amount of orbital debris has increased exponentially due to a growing number of objects launched by entities worldwide, as well as spacecraft collisions and explosions (Martin, 2021) (Figure 2). With millions of debris pieces now in low orbit (less than 2,000 km of altitude) and geostationary orbit (36,000 km above the Earth), critical satellite-dependent services face severe risks. To address this challenge, the U.S. Department of Defense collaborates with NASA to monitor, catalog, and track debris in orbit using ground-based radars and optical telescopes located worldwide, in addition to orbiting satellites (Martin, 2021). Based on the observations made, spacecraft operators can be alerted promptly about required avoidance maneuvers. However, such maneuvers often result in the satellite's instruments being turned off, leaving it unable to collect scientific measurements or provide commercial services. Additionally, precious fuel must be expended, shortening the mission's lifespan (ESA, 2021).

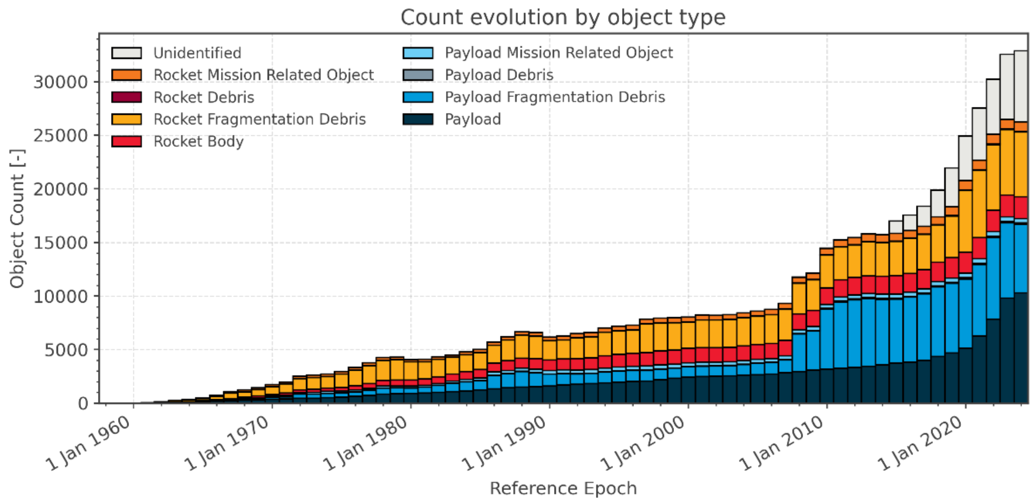

Figure 2. Evolution of number of space debris objects in orbit by class. ESA (2022b)

Hence, a more comprehensive solution to the problem of space debris, such as space cleanup with space technologies, is of top priority. Multiple studies on active debris removal have been proposed, and the search for cost-effective methods is ongoing (Martin, 2021). The Surrey Space Centre leads the RemoveDEBRIS project, which has successfully demonstrated four technologies since its launch in 2018: a net to capture debris, tracking debris in orbit, harpooning debris, and deploying a large drag sail (Forshaw et al., 2016). Although these methods were tested on simulated targets rather than real debris, they established base principles for moving towards a cleaner Earth orbital environment. In addition, the ClearSpace-1 mission by ClearSpace SA, scheduled for launch in 2025, involves using a four-armed robot (Figure 3) to latch onto debris and descend back to Earth, burning up both the machine and debris in the atmosphere (Kamal et al., 2021). The initial target for the mission is the upper stage of a Japanese rocket left over from a 2013 launch, marking the first time an existing derelict object will be removed from orbit (Biesbroek et al., 2021). The mentioned missions showcase the technological capabilities required for debris removal, which guarantee sustainable solutions for the cleanliness and safety of space.

Figure 3. ClearSpace projected model of the four-armed capture system for its robotic satellite ClearSpace-1. Source: ClearSpace SA (2022)

Position of NEOs relative to Earth and deflection advances

The final hazard to consider is the potential collision of Near-Earth Objects (NEOs), which not only represents a threat to space infrastructure, but it can also have a direct impact on the Earth. NEOs are asteroids and comets that come close to or across Earth's orbit around the Sun, and their size varies greatly. While some are small meteoroids that disintegrate harmlessly in the atmosphere, others are several kilometers wide and can cause catastrophic destruction upon impact (Daniels et al., 2023). In February 2013, an undetected house-sized asteroid exploded over Chelyabinsk, Russia, causing injuries to approximately 1,600 individuals and raising public awareness of the NEO threat, as noted by NASA (2018). Like with orbital debris, currently telescopes and radar systems with global coverage monitor and calculate the trajectory of NEOs. Nonetheless, detecting dark asteroids remains challenging. To this end, NASA is set to launch a next-generation asteroid impact monitoring system called NEO Surveyor in 2027, featuring a single telescope with a 50 cm diameter and operating in two heat-sensing infrared wavelengths (NASA, 2023a).

In the event that space agencies detect an asteroid with the potential to impact space assets or the Earth, the development of space technologies for asteroid deflection is ultimate. After centuries of observing celestial bodies, for the first time, the Double Asteroid Redirection Test (DART) successfully demonstrated the ability to alter the trajectory of a potentially hazardous asteroid. NASA launched the DART spacecraft in 2021, which collided with its target moonlet, "Dimorphos", causing a change in its orbit around the primary asteroid, "Didymos" (NASA, 2023b) (Figure 4). The upcoming Hera space mission, led by ESA and scheduled for launch in 2024, will conduct a thorough post-impact survey of the DART mission to gather specific data on the response of the asteroid composition, structure, and state to the "kinetic impact" (ESA, 2019b). The significance of Hera is enormous, as it will enable the DART experiment to become a fully functional and repeatable defense technique for ensuring the safety of Earth and space exploration.

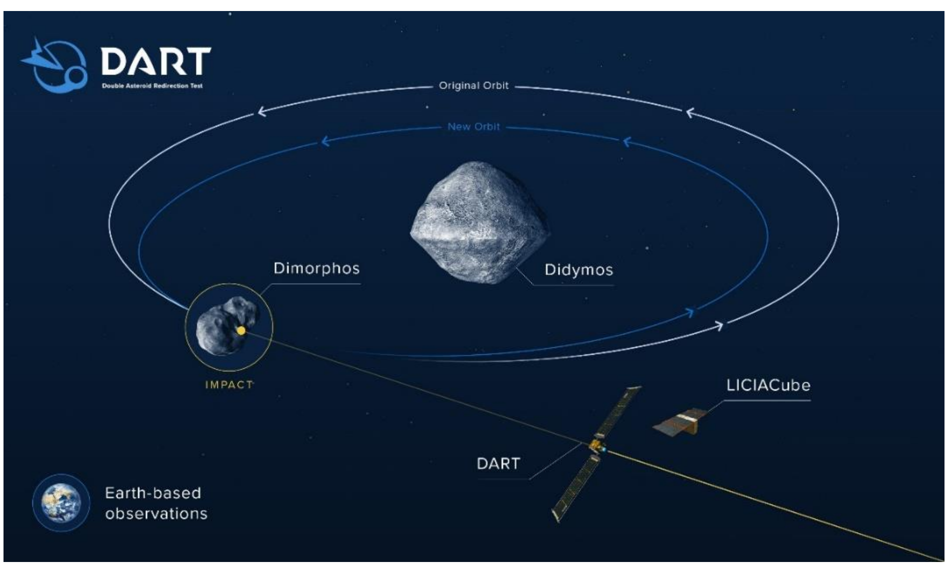

Figure 4. Schematic image of how DART's impact modified the orbit of Dimorphos moonlet about Didymos. To evaluate the impact's effectiveness, telescopes situated on Earth are utilized to measure the change in Dimorphos' orbit. Obtained from NASA (2023b)

Conclusion

In conclusion, space technology is necessary for protecting space infrastructure from various hazards, such as solar outbursts, collisions with orbital debris, and NEO impacts. Advanced observation technologies and space situational awareness allow space agencies to identify potential threats and provide early warnings to mitigate their impact. Recent technological innovations, such as Vigil, Clearspace-1, NEO Surveyor, DART, and Hera spacecrafts, hold great promise in enhancing space safety, safeguarding space assets, and guaranteeing continued services provision. However, several challenges remain, and continued investment and innovation in space technology are needed to overcome them sustainably. As reliance on space-based systems increases, prioritizing research and development in this field is decisive. Ultimately, space technology is essential for enabling humanity to continue studying both Earth and outer space.

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