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SPACE

Beyond the High Ground

A Taxonomy for Earth-Moon System Operations

Adam P. Wilmer
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Situational and space domain awareness in the space domain can no longer be confined to that which is found in geosynchronous orbit. International activities—commercial and military—and threats to the planet itself exist and are increasing across the entire Earth-Moon system. This reality requires a new taxonomy to accurately classify space domain awareness missions and better apply resources to and development of the same. This work presents such a taxonomy for the classification of space domain awareness regions.

The 2010s witnessed a renewed international interest in space operations extending outside near-Earth space. Invigorated Chinese, Russian, and US lunar mission initiatives; planned commercial lunar projects; and coalescing international efforts to reach Mars encompass the cislunar environment (the spherical volume of space extending from super-synchronous orbit to the Moon's orbit) and beyond. Based on these development initiatives, space beyond geosynchronous orbit will likely become competitive and congested in the coming decades.

Attaining space-situational and wider space domain awareness (SDA) will thus require a field of view not limited to the traditional bounds of geosynchronous orbit. This new reality demands a novel way of classifying SDA missions that encompass the entire Earth-Moon system, including the spatial expanses in the outside vicinity of Earth's gravitational sphere of influence (SOI).

This article presents new taxonomy for the classification of space domain awareness regions. The new taxonomy will enable a spatial division of the national SDA mission portfolio, with specific regions corresponding to compounding distances from Earth and multiple SDA mission subsets including space traffic management, space control, lunar and Earth-Moon Lagrange point surveillance, space weather observation, and planetary defense.

Background

The US Space Force has declared that space domain awareness "encompasses the effective identification, characterization, and understanding of any factor associated with the space domain that could affect space operations and thereby impact the security,

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safety, economy, or environment of our Nation."[1] The space domain is becoming increasingly congested, contested, and competitive as peer, near-peer, and emerging space powers expand their presence in space. Consequently, SDA will remain a critical mission for securing and advancing the space operations of the United States, its Allies, and partners in the coming decades.[2]

Until the 2010s, SDA missions were nominally restricted to the near-Earth space orbital regime bounded by geosynchronous and super-synchronous orbits due to the volume of space traffic within this region. But the late 2010s and early 2020s marked a shift in the space operations paradigm, with renewed international interest in pursuing missions extending into the cislunar environment, to the Moon, and beyond the gravitational influence of the Earth-Moon system.

Domestically, this shift is represented by reinvigorated initiatives to return to the Moon via the National Aeronautics and Space Administration's (NASA) Artemis program and planned commercial space projects. Recent international cislunar activity includes plans to develop a joint Chinese-Russian base at the lunar south pole in the 2036–45 timeframe, China's Chang'e-5 lunar sample-return mission in 2020, Israel's attempted lunar surface mission in 2019, and China's Chang'e-4 far-side lunar mission in 2018.[3] Of note, China's Queqiao communications relay satellite, which is accompanied by the Chang'e-4 mission, is the first vehicle to orbit the Earth-Moon Lagrange point located on the far side of the Moon.[4] International missions in cislunar space will likely increase throughout the 2020s, with a corresponding increase in the number of spacecraft operating in this region, as scientific exploration expands, space system technology evolves, and the lunar economy emerges and develops.

Undoubtedly, the largest DoD SDA mission will be to protect space lines of commerce. Nations and private companies alike are exponentially building space-based infrastructure to ensure communication, surveillance, and transportation. In doing so, near-Earth space is becoming congested with thousands of active spacecraft, and 23,000 debris fragments

1. US Space Force (USSF), *Spacepower: Doctrine for Space Forces*, Space Capstone Publication (Peterson Space Force Base [SFB], CO: USSF, June 2020), 38, https://www.spaceforce.mil/.

2. Robert M. Gates and James R. Clapper, *National Security Space Strategy: Unclassified Summary* (Washington DC: Department of Defense and Office of the Director of National Intelligence, January 2011), 1, https://www.hsdl.org/.

3. Eva Dou, "China and Russia to Open Moon Base, Expanding Space Cooperation," *Washington Post*, March 10, 2021, https://www.washingtonpost.com/; Adam Mann, "China's Chang'e-5 Lunar Mission: Sampling the Lunar Surface," Space.com, December 2020, https://www.space.com/; and Maria Temming, "Israel's First Moon Mission Lost Moments before Landing," ScienceNews, April 11, 2019, https://www.sciencenews.org/.

4. Leonard David, "U.S. Military Eyes Strategic Value of Earth-Moon Space," Space.com, August 29, 2019, https://www.space.com/.

larger than a softball and half a million debris fragments larger than a marble resulting from historical mishaps and breakups.[5]

This congestion, combined with the growing connection of space access to national security and economic growth, has prompted many nations to realize the benefit and prestige of extending space operations into cislunar space. Cislunar space and the outer reaches of the Earth-Moon system are becoming the new high ground for space operations. The SDA mission and focus must expand accordingly to handle this growth of congestion and competition to ensure continued US space dominance.

A key component of a broadened SDA mission is a new multiregion taxonomy that will enable a spatial division of the national SDA mission portfolio. This taxonomy includes five constituent regions, which, in total, extend from the planetary surface and low-Earth orbit to out beyond Earth's gravitational sphere of influence. The article emphasizes the spatial volume outside of geosynchronous orbit, as four of the five regions exist in cislunar and higher orbital regimes. Critically, these five regions host different SDA missions based on potential orbits.

Space Domain Awareness: Structure and Missions

In the wake of World War II, the United States acknowledged the growing importance of the air domain in national security operations by establishing the US Air Force—a service dedicated to attaining and projecting airpower. Similarly, the US Space Force has emerged as an independent service due to the need to attain and maintain national power and superiority in space—a domain now irrevocably linked to US sovereignty and economic power.

Until the 2010s, the US military was hesitant to refer to space as a war-fighting domain. But the patent realization of space as a congested, contested, and competitive domain has prompted an evolution in how space is viewed and framed from a national security perspective.[6]

For almost 50 years following the start of the first Space Age in the mid-twentieth century, space represented a supporting function to wider terrestrial conflict—either on land, at sea, or in the air. Yet as early as 1982, space was described as the "ultimate high ground."[7] Indeed, space operations enabled the introduction of game-changing technologies through persistent overhead surveillance, communication beyond the line of

5. Mark Garcia, "Space Debris and Human Spacecraft," National Aeronautics and Space Administration (NASA) (website), last updated May 27, 2021, https://www.nasa.gov/.

6. Sandra Erwin, "Air Force: SSA is No More; It's 'Space Domain Awareness,'" Spacenews, November 14, 2019, https://spacenews.com/.

7. Benjamin S. Lambeth, *Mastering the Ultimate High Ground: Next Steps in the Military Uses of Space* (Santa Monica, CA: RAND Corporation, 2003), 27, https://www.rand.org/.

sight, and precision navigation and timing that would spur a revolution in US military strategy and operational art in the later twentieth and early twenty-first centuries.[8]

Against a backdrop of expanding space access and utilization during the first half century of the Space Age, a new mission emerged in the 1960s: early warning and space object tracking and characterization. The protoform of what became known as space situational awareness (SSA) arose due to the need to differentiate between nonhostile resident space objects (i.e., operational satellites and debris) and ballistic missile nuclear payloads.[9]

The SSA mission grew to encompass four functions: search, detect, track, and characterization. Once a space object was characterized and its orbital position and velocity were known for predictive tracking, it was cataloged. At its heart, the SSA mission became one of space traffic management; ground- and space-based sensors constantly updated and refined the space object catalog to deconflict orbits and generate collision-avoidance warnings.[10]

While SSA remains a consistent term in civilian space flight, the general SSA mission has become a subset of a wider mission set for the Department of Defense—space domain awareness. In 2019, then-Major General John E. Shaw, the US Space Command deputy commander, discussed the formal shift from SSA to SDA within the Department of the Air Force. "The implication of space as a warfighting domain demands we shift our focus beyond the Space Situational Awareness mindset of a benign environment to achieve a more effective and comprehensive SDA."[11]

According to Space Force doctrine, SDA "leverages the unique subset of intelligence, surveillance, reconnaissance, environmental monitoring, and data sharing arrangements that provide operators and decision makers with a timely depiction of all factors and actors—including friendly, adversary, and third party—impacting domain operations."[12] Based on the requirements of securing full-domain awareness in near-Earth space and beyond, five distinct missions compose the broader endeavor to attain SDA: 1) space traffic management; 2) space control; 3) lunar and Earth-Moon Lagrange point surveillance; 4) space weather; and 5) planetary defense.

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8. Lambeth, *Ultimate High Ground*, 27.

9. Brian Weeden, Paul Cefola, and Jaganath Sankaran, "Global Space Situational Awareness Sensors" (lecture, Advanced Maui Optical and Space Surveillance Technologies Conference, Maui, HI, 2010).

10. Mark A. Baird, "Maintaining Space Situational Awareness and Taking It to the Next Level," *Air & Space Power Journal* 27, no. 3 (September-October 2013): 60.

11. Erwin, "SSA Is No More."

12. USSF, *Spacepower*, 38.

Mission Types

Space Traffic Management

Like air traffic management and—from a localized perspective—sea traffic management, the space traffic management mission promotes safe access to and operations in the space domain. Baseline operations include the SSA function of space catalog maintenance and orbit prediction to avoid collisions between resident space objects such as active and retired satellites, rocket bodies, and space debris.

The space debris population is continuously growing due to decreased launch costs, the expansion of space mission architectures, the increasing reliance on space communication, commerce, and defense, and the emergence of new space-faring nations. The low-Earth orbital regime, due to ease of access and proximity to terrestrial space users, has become increasingly congested, making space traffic management all the more critical. This congestion will only further and dramatically increase with the expansion of mega-constellations and as new private/commercial and state-affiliated players enter the space operations arena.[13]

Space Control

The United States has a vested interest in securing space superiority to ensure unrestricted access to and the use of space to fulfill national security objectives, support terrestrial military campaigns, and, ultimately, preserve national sovereignty. Space control represents a military-centric mission intended to counter the growing competitive and contested nature of space and is "a mixture of defensive and offensive measures. . . and is particularly important during periods of increased international tensions or hostilities."[14]

One subset of the space control mission will mirror actions performed in the maritime domain: the protection of US economic interests amid the growing competitive nature of the space domain. In July 2020, the commander of the Air Force Research Laboratory Space Vehicles Directorate discussed this subset mission and stated that "our mission in the Space Force will become to protect . . . the 'celestial lines of commerce,' or the space lines of commerce."[15]

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13. Jonathan C. McDowell, "The Low Earth Orbit Satellite Population and Impacts of the SpaceX Starlink Constellation," *Astrophysical Journal Letters* 892, no. 2 (2020), https://iopscience.iop.org/; and Dan Swinhoe, "China's Moves into Mega Satellite Constellations Could Add to Space Debris Problem," Data Center Dynamics, April 20, 2021, https://www.datacenterdynamics.com/.

14. Terrence Smith, "Challenges to Future U.S. Space Control," *Army Space Journal* (Summer 2002): 1, https://apps.dtic.mil/.

15. Theresa Hitchens, "DoD Needs Plans to Protect Commercial Space Industry, Says New Study," Breaking Defense, July 28, 2020, https://breakingdefense.com/.

Lunar and Earth-Moon Lagrange Point Surveillance

A subset of space traffic management and space control, the lunar and Earth-Moon Lagrange point surveillance mission focuses on the surveillance of lunar orbit, the Earth-Moon corridor comprised of the Moon and the L1 and L2 Lagrange points, and the vicinity of the unstable L3 and stable L4 and L5 Lagrange points. These regions are of particular interest to the international space community due in part to growing international and commercial interest in cislunar and lunar exploration.

In particular, the Lagrange points proffer lucrative positions within the Earth-Moon system for a variety of missions including scientific monitoring of space weather and celestial bodies and intrasystem SSA. Consequently, surveillance satellites operating at the Lagrange points could bolster orbit deconfliction and collision avoidance as a space traffic management function and could track potentially hostile space vehicles under the space control mission.

Space Weather

Space represents a challenging operating domain for both manned and unmanned space vehicles due largely to the natural environmental conditions. The dynamic space weather is primarily a function of solar activity via the generation of thermal radiation, ionizing particles, and plasma. With events such as solar flares and coronal mass ejections, the Sun imperils satellites and their constituent electronic equipment and sensitive payloads with radiation and high-energy particles that may cause temporary or even permanent damage based on the intensity of the event.[16] Tracking space weather contributes to the general SDA mission and enables operators to forecast potentially harmful or destructive natural environmental events, enhancing the safety posture of space vehicles operating within the Earth-Moon system.

Planetary Defense

Apart from tracking manmade objects, debris, and space weather, another SDA mission involves tracking objects outside of the Earth-Moon system for planetary defense. Asteroids, meteors, and comets orbiting the Sun are classified as near-Earth objects (NEOs) when their orbits bring them within 30 million miles of Earth's orbit. NEOs pose an impact risk to both the Earth and the Moon; searching for and tracking these objects enables the overall planetary defense mission.

Currently, NASA manages this mission by providing early detection, tracking, and characterization of NEOs. Additionally, NASA develops strategies and technologies for

16. K. L. Bedingfield, R. D. Leach, and M. B. Alexander, eds., NASA *Spacecraft System Failures and Anomalies Attributed to the Natural Space Environment,* NASA Reference Publication 1390 (Cape Canaveral, FL: NASA, August 1996), http://www.dept.aoe.vt.edu/; and NASA, *Spacecraft Charging*, NASA Reference Publication 1375 (Cape Canaveral, FL: NASA, 1995).

mitigating potentially hazardous objects and plays a lead role in coordinating US government planning in response to an actual impact threat.[17]

Constraints and Limitations

As peer and near-peer competitor nations edge toward pursuing space superiority, the sensors and ground stations that formed the cornerstone of US space domain awareness in previous decades are becoming restrictive in their range and resolution. Previous conceptions of space operations nominally limited to geosynchronous orbit and below are being superseded by a growing necessity to attain situational awareness of resident space objects deep within the cislunar environment.

Current US space sensing assets must be upgraded or replaced to ensure US global superiority. The International Academy of Astronautics assesses "the capacity and accuracy of current space monitoring systems is not sufficient to cover small objects or to provide for orbital avoidance service for all space assets."[18] Ground-based radar and optical systems are the primary methods for characterizing objects in space; however, weather, solar blind spots, and the equipment's terrestrial moorings all cause limitations.[19]

Furthermore, many ground-based systems have significant optical capability gaps. The Ground-Based Electro-Optical Deep Space Surveillance (GEODSS) system is only capable of tracking basketball-sized objects at a distance of 32,187 km (20,000 miles), a distance far below that of cislunar space, which is measured in the hundreds of thousands of kilometers.[20]

One primary challenge regarding tracking and orbit determination via optical sensors is the solar exclusion angle—the cone region within which an optical sensor cannot view a given object. In other words, the Sun is too close to the sensor's line of sight for the object to be resolved and distinguished against the celestial background. Cislunar-based sensors offer a solution to these issues in the Earth-Moon system by hosting a wider range of angles from which to view objects compared to ground-based or near-Earth orbital optical sensors.

Of note, Air Force Research Laboratory's Space Vehicles Directorate is beginning to push the bounds of SDA into cislunar space. Once developed and fielded, the Cislunar Highway Patrol System (CHPS) intends to search, detect, track, and characterize missions within cislunar space and the lunar exclusion zone, or a spatial region imperceptible to Earth-based sensors due to lunar albedo.[21]

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17. "Planetary Defense Coordination Office," NASA (website), last updated March 14, 2019, https://www.nasa.gov/.

18. Corinne Contant-Jorgenson, Petr Lála, and Kai-Uwe Schrogl, eds., *Cosmic Study on Space Traffic Management* (Paris: International Academy of Astronautics, 2006), 11, https://www.black-holes.eu/.

19. Baird, "Space Situational Awareness," 60.

20. Baird, 58.

21. Joseph J. Roth and Eric J. Felt, "Overcoming Technical Challenges from Low Earth Orbit to Cislunar" (lecture, Advanced Maui Optical and Space Surveillance Technologies Conference, Maui, HI, 2020).

Proposed Taxonomy

Currently, the US Space Force uses an SDA taxonomy comprising five altitude-delimited regions: very low-Earth orbit (VLEO), low-Earth orbit (LEO), medium Earth orbit (MEO), geosynchronous-Earth orbit (GEO), and XGEO.[22] While LEO, MEO, and GEO are all universally standard orbital regions, VLEO is a special LEO case corresponding to the higher-drag environment of the 250-350 km altitude range.[23]

First employed by the Air Force Research Laboratory in 2020, the term XGEO describes distances beyond the GEO belt, with XGEO denoting some multiple "X" of the GEO radial distance.[24] Although the inclusion of XGEO into the current SDA taxonomy highlights the necessary pivot to cislunar space awareness, the existing region-based model is limited and fails to capture the scope of the Earth-Moon system adequately.

The increasing spatial scope of space operations necessitates an SDA taxonomy that considers the entire Earth-Moon system rather than the near-Earth space region confined by GEO and geostationary Earth orbits (GSO). The following proposed SDA taxonomy comprises five distinct, spatially delimited regions radiating outward from Earth (fig. 1).

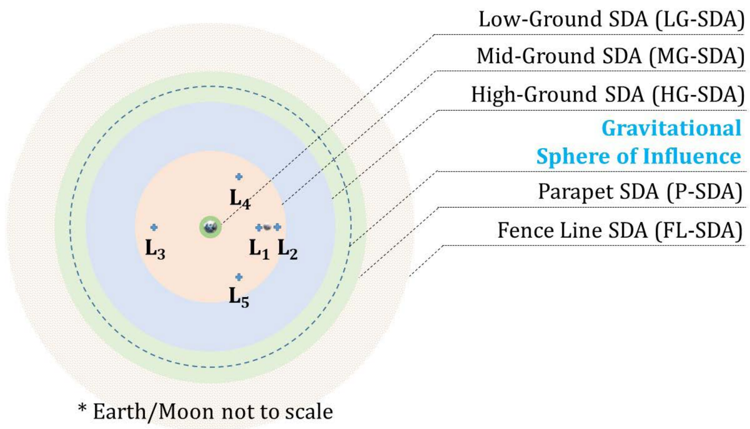

Figure 1. Proposed Earth-Moon system SDA taxonomy (not to scale)

These regions relate to different dynamical zones of operation within the Earth-Moon system. Each contains different potential SDA missions and space system requirements for access to and operations in these regions. Some regions present more challenges than

22. Roth and Felt, "Low Earth Orbit."

23. Eric Kuhu, "Satellite Constellations—2021 Industry Survey and Trends" (lecture, 35th Annual Small Satellite Conference, Logan, UT, 2021).

24. David Buehler et al., "Posturing Space Forces for Operations Beyond GEO," Space Force Journal, January 31, 2021, https://spaceforcejournal.org/.

others to maintain a specified trajectory due to the chaotic nature of the Earth-Moon system, such as near the Earth SOI, the region around the planet within which the Earth's gravitational influence exceeds the gravitational pull of other celestial bodies. Each proposed region is described below with a corresponding identification of the associated spatial distance as measured radially from the center of the Earth in terms of kilometers and the previously mentioned XGEO canonical unit. For comparison purposes, other key locations within the Earth-Moon system, such as the Moon and Lagrange points, are also given.[25]

Low-Ground Space Domain Awareness

The first three SDA regions contain a similar naming convention exploiting the notion that space is the "ultimate high ground."[26] The first region, low-ground SDA (LG-SDA), encompasses near-Earth space and includes the common orbital regimes of LEO, MEO, and GSO/GEO. Specifically, LG-SDA extends from the Von Karman Line (~100 km from the surface of the Earth), a nominal delimitation for the start of space, out to a super-synchronous orbit beyond GEO (42,464 km from the center of the Earth), an orbital regime approximately 300 km above GEO typically used for spacecraft disposal at mission end-of-life.[27]

The LG-SDA region contains most current space operations and represents the highest density of resident space objects and debris to search, detect, track, characterize, and catalog for the general ground- and space-based SDA missions. In terms of the XGEO canonical unit, the LG-SDA region extends from the planetary surface to about 1XGEO.

Mid-Ground Space Domain Awareness

Next, mid-ground SDA (MG-SDA) denotes SDA operations occurring in the region of space commonly referred to as cislunar. The MG-SDA region also contains all five Lagrange points and extends 15,000 km beyond the collinear L2 Lagrange point (~465,000 km). Therefore, MG-SDA encompasses space operations occurring from ~42,500 km to 480,000 km as measured from the Earth's center (between 1–11.4XGEO). Plans for and the development of space-based infrastructure in cislunar space are rapidly growing, thus making MG-SDA an attractive region for performing SDA in the near future.[28]

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25. All values are based on the Earth-Moon nondimensional mass parameter, $\mu=0.01215058655$.
26. Lambeth, *Ultimate High Ground*, 27.
27. Nicholas L. Johnson, "A New Look at the GEO and Near-GEO Regimes: Operations, Disposals, and Debris," *Acta Astronautica* 80 (2012): 82–88, https://ntrs.nasa.gov/.
28. James A. Vedda, "Cislunar Development: What to Build—And Why," (Arlington, VA: Aerospace Corporation, Center for Space Policy and Strategy, April 17, 2018), https://csps.aerospace.org/.

High-Ground Space Domain Awareness

High-ground SDA (HG-SDA) is associated with the translunar orbital regime of the Earth-Moon system. The HG-SDA spherical region begins at the outer boundary of the MG-SDA region (480,000 km) and extends to within 25,000 km of the outer bounds of the Earth's SOI, a demarcation occurring at approximately 925,000 km from the Earth (21.9XGEO). At the outermost bounds of the Earth SOI, the effects of solar gravity begin to supersede that of Earth's gravity. Overall, HG-SDA represents SDA operations occurring between 480,000–900,000 km (11.4–21.3XGEO).

Parapet Space Domain Awareness

Beyond the HG-SDA layer is the parapet SDA (P-SDA) region, a spherical volume containing the demarcation of the Earth-Moon gravitational sphere of influence, and extending 25,000 km on either side of said boundary. The gravitational SOI is loosely analogous to the dynamical wall or fence of the Earth-Moon system and, as a result, the P-SDA region derives its name from a parapet—the protected walkway and/or battlement located on top of a castle wall.[29]

In terms of spatial distance, P-SDA defines operations occurring between 900,000–950,000 km (21.3–22.5XGEO). Orbital trajectories residing exclusively within the P-SDA region are challenging to define and maintain due to the chaotic instabilities of the Earth-Moon gravitational system at these distances. Consequently, space systems seeking to perform a P-SDA mission will likely require orbits that traverse other regions within the Earth-Moon system to deliver the necessary transit times in and around the SOI.

Fence-Line Space Domain Awareness

The final region within the proposed taxonomy is referred to as fence-line SDA (FL-SDA). Continuing the analogy of the gravitational SOI resembling a pseudo-barrier, FL-SDA embodies the concept of performing surveillance and security operations outside a barrier that may surround a forward operating base in theater or a secure installation. Space system orbits within the FL-SDA region are still influenced by the gravity of the Earth-Moon system; however, the gravitational influences of the Sun have a greater effect on trajectories.

Tertiary bodies to the Earth-Moon system also become increasingly relevant at this distance. A given SDA mission could extend well beyond the Earth SOI, based on the needs of the mission and the corresponding design of the orbital trajectory. Therefore, an outer boundary for the FL-SDA is only estimated herein. For the purposes of this article,

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29. E. Viollet-Le-Duc and Martin MacDermott, *Military Architecture* (London: James Parker and Co., 1907), 66, 85.

the FL-SDA region starts at 950,000 km from Earth and extends to approximately 2.3 million km (22.5–55XGEO).

Mission Mechanics

Mission Mapping

The efficacy of a new SDA taxonomy depends upon missions allocated to each region and the types of trajectories that can be generated to perform these missions. Nominally, the space traffic management mission will reside in the regions closest to Earth and the Moon, specifically LG-SDA and MG-SDA, due to issues related to orbital congestion and collision avoidance between spacecraft and resident space objects (e.g., debris).

The space control mission will reside in regions where space traffic management is a priority due a similar need to monitor spacecraft trajectories. But we suggest including HG-SDA as a potential region for space control due to the vantage point that translunar space proffers for inward surveillance of the Earth, the Moon, and orbital regimes of interest in the LG-SDA and MG-SDA regions.

Overall, the space weather mission can be performed in any orbital regime within the Earth-Moon system based on specific program needs such as scientific observation or warning. The outer regions of HG-SDA, P-SDA, and FL-SDA are identified as potential areas for space weather missions due to their distance from both the Earth and the Moon, thereby proffering an outward surveillance perspective for pseudo-early warning of space weather events. While the first tier of space weather early warning and monitoring occurs at the Sun-Earth Lagrange points, such as the National Oceanic and Atmospheric Administration's Deep Space Climate Observatory (DSCOVR) at L1, the placement of monitoring spacecraft in trajectories traversing HG-SDA or other outer regions would provide a second tier for warning and solar event intensity.[30]

As previously stated, surveillance of the Moon and Earth-Moon Lagrange points is of interest due to the planned infrastructure development at or near these locations in the coming years. Specifically, the collinear L1 and L2 Lagrange points around the Moon have become a focus for mission planners because of their proximity to the Moon. For instance, the Gateway, a critical component of NASA's Artemis program that will provide "vital support for a long-term human return to the lunar surface [and] a staging point for deep space exploration," is planned to orbit near L2.[31] Therefore, the lunar and Lagrange point surveillance mission will occur in either the MG-SDA or HG-SDA region.

30. "Points of Lagrange: A Satellite a Million Miles from Home," National Environmental Satellite, Data, and Information Service, National Oceanic and Atmospheric Administration, October 26, 2015, https://www.nesdis.noaa.gov/.

31. David E. Lee, "Gateway Destination Orbit Model: A Continuous 15 Year NRHO Reference Trajectory," white paper (Houston, TX: NASA Johnson Space Center, August 20, 2019), https://ntrs.nasa.gov/.

The final mission set, planetary defense, is appropriate for the P- and FL-SDA regions. These regions give the ultimate vantage point for the outward surveillance of NEOs and other transient asteroids and meteoroids that may pass near or traverse the Earth SOI. Early warning is critical to averting and/or preparing for catastrophe arising from an NEO or similar piece of cosmic debris, and the stand-off distance of approximately 21–55 XGEO established by the P- and FL-SDA regions contribute to an early warning posture for planetary defense. In addition to surveillance, the vast spatial volumes of the P- and FL-SDA regions also enable the international space community to field defensive systems that can deflect or destroy potential threats arising from outside the Earth-Moon system.

Mission Orbits

Multibody gravitational systems are inherently chaotic: small changes to the initial position and velocity of a spacecraft can generate large changes in its overall trajectory. Despite the chaotic challenges posed by gravitational fields such as the Earth-Moon system, periodic orbits are indeed possible that permit the formation of repeating trajectories beneficial for a variety of missions sets, especially SDA. Different dynamical models can be employed to explore and generate periodic orbits, and all models can seek to simplify the gravitational field by examining the complex dynamical interactions of a limited number of bodies.

Example periodic orbits were generated using the dynamics assumed by the circular restricted three-body problem (CR3BP) that corresponds to each region comprising the proposed SDA taxonomy (fig. 2). The CR3BP is a useful trajectory model that considers only the gravitational influences of the Earth and Moon on the spacecraft and permits a preliminary mapping of orbit geometry.

Figure 2 depicts only a small subset of the many periodic orbits that may be found in the various SDA taxonomy regions; many more periodic orbits, specifically in the cislunar region, may be seen in Wilmer.[32] In fig. 2a, the dotted/dashed line identifies geosynchronous orbit in relation to the example LG-SDA orbit; in figs. 2b–2f, the dotted/dashed line identifies the Earth SOI.

The unique design of each example periodic orbit is the result of trajectory generation performed with respect to the synodic reference frame, a rotating reference frame with the Earth and Moon held on the x-axis. While the exact shape of a given orbit will change based on the perspective of the viewer (e.g., from the Earth or the Sun), the spatial volume within which a given orbit traverses remains the same. As a result, periodic orbits can be built that provide surveillance coverage to key locations within the Earth-Moon system including the Moon, Lagrange points, the Earth SOI, and outside the Earth SOI.

32. Adam P. Wilmer, "Space Domain Awareness Assessment of Cislunar Periodic Orbits for Lagrange Point Surveillance" (master's thesis, Air Force Institute of Technology, December 2021), https://scholar.afit.edu/.

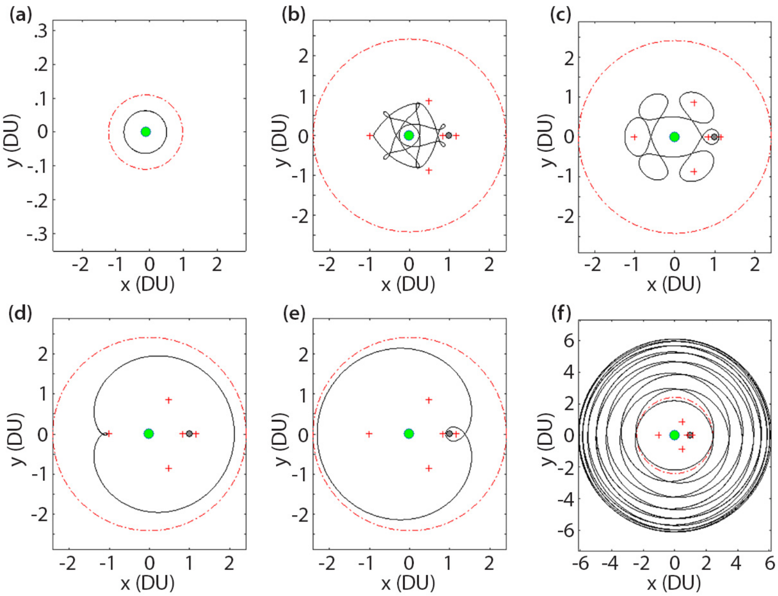

Figure 2. Example SDA orbits: (a) low-ground SDA; (b) mid-ground SDA; (c) mid-ground SDA; (d) high-ground SDA; (e) parapet SDA; and (f) fence-line SDA

Orbit Design Considerations

Within the Earth-Moon system, spacecraft can be injected into periodic orbits such as those portrayed in fig. 2 via direct launch from either the Earth or the Moon. Only a launch from the Earth is currently feasible, but the construction of lunar infrastructure could enable the launch of spacecraft into periodic orbits that pass near the Moon (e.g., figs. 2c and 2e) at relatively low propellant cost— lunar launches will require less propellant than conventional Earth-based launches due to a weaker gravitational field and the absence of virtually any atmosphere.

Regarding orbit maintenance—the expenditure of propellant to maintain a desired orbital geometry, periodic orbits in the Earth-Moon system may remain stable for weeks depending on the selected geometry, particularly depending on how closely a trajectory passes by the Earth, Moon, or the various Lagrange points. We assess that orbit maintenance will require a low amount of propellant. This low-order amount of required propellant for orbit maintenance will enhance any SDA mission's lifetime and desirability for implementation.

When designing SDA missions in any of these proposed regions, the duration of a single period will influence the number of spacecraft to perform the mission. Multiple spacecraft will likely be needed to provide a desired level of sensor coverage and revisit time in a particular region, either with a phased operation in the same periodic orbit or with the spacecraft spread over different yet similar periodic orbits. For example, the need for a constellation of SDA spacecraft will likely be important for the planetary defense mission in the FL-SDA region. Due to a single period being on the order of approximately 1–1.5 years, numerous spacecraft—potentially on the megaconstellation scale—may be needed to provide timely and persistent monitoring and defense posture for threats external to the Earth-Moon system.

Conclusion

In the early years of spaceflight, space operations primarily consisted of near-Earth missions with few spacecraft ever venturing to the Moon. As time progressed, more missions began extending beyond geosynchronous orbit. This pattern continues today, with the contemporary space domain facing increasing concerted efforts by commercial and nation-based entities worldwide to reach and operate within the cislunar environment.

This trend will likely continue, with humankind reaching outward to the new high ground. Missions will become increasingly frequent near the Moon, in the high-ground SDA region, and beyond. As such, it is important to develop policy and terminology to address the evolving SDA mission, establishing a paradigm that will come to embrace the entirety of the Earth-Moon system and its celestial environs. At the same time, with the development and growth of the US Space Force, new policies and doctrine intended to secure US space dominance will continue to emerge. As such, the space domain awareness taxonomy presented here is vital to conceptualizing space as a war-fighting domain, better describing missions such as space domain awareness that ensure the continuous protection of US space assets.