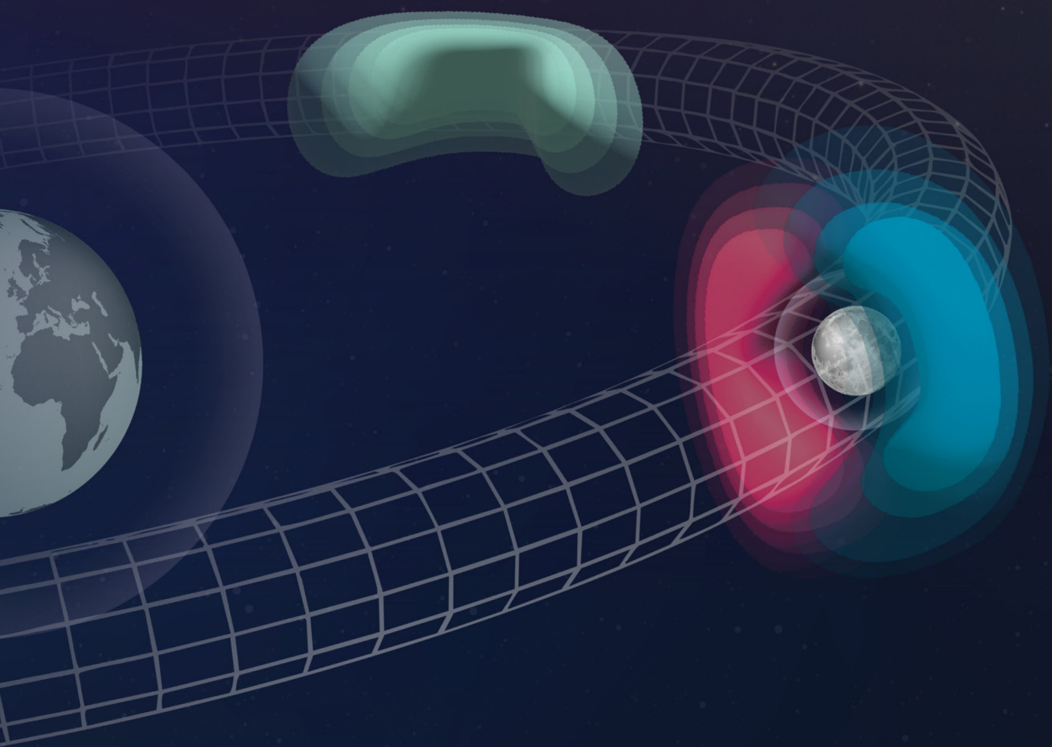
Research Report

CHARTING THE COSMOS

Operational Astrography for the New Space Era



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Published by the RAND Corporation, Santa Monica, Calif.

Library of Congress Cataloging-in-Publication Data is available for this publication.

ISBN: 978-1-9774-1548-6

Cover: Adapted from images by aryos/Getty Images and KICKINN/Getty Images.

RR-A4003-1

Summary

The vast region of outer space encompassing the Earth, the Moon, and their combined gravitational effects presents significant opportunities for humanity across the areas of science, commerce, and geopolitics. With the rapid acceleration of activities on orbit, space professionals are increasingly grappling with delineations of the domain that are highly technical, misunderstood, and variably accepted. We present an astrographic framework that is designed to be *accessible* to policymakers and space planners of all types, *durable* enough to remain useful as space activities intensify in complexity, and *generalizable* as humanity expands its footprint beyond Earth. We define four basic astrographic regions: surface environment, near-body space, celestial neighborhood, and deep space. We explain the physics or conventions on which these regions are defined and highlight three areas of opportunity to further enhance this framework: distinguishing two-body and three-body dynamics, developing multidimensional representations, and investigating additional astrographic regions and features.

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CHAPTER 1

Introduction

Since the dawn of humanity, a spirit of curiosity and adventure has driven us to explore our planet. Enduring through generations and across civilizations, this impulse has propelled humans to explore every corner of Earth. Humans developed maps to facilitate their Earthly exploration—translating our planet's physical features into symbols, colors, and form. Through millennia of iterations and refinement, humans have created maps with incredible detail and scope, developing robust sets of terms and definitions as they documented virtually every inch of Earth's surface.

The Case for an Astrographic Framework

As technology has made space exploration possible, humanity has drawn from existing mapmaking practices to navigate the cosmos and better understand the vast unknown; however, depictions of space remain an unfinished project. In the 1960s, the National Aeronautics and Space Administration (NASA) faced uncertainty in how to safely land Apollo spacecraft on the Moon's surface—despite having relatively thorough maps of the Moon's near side, documented from Earth for centuries.[1] Recent years have seen steady improvements in space mapping, such as the 2024 Geologic Atlas of the Lunar Globe that documents the Moon's surface with double the accuracy of Apollo-era maps.[2] However, despite such advancements in mapping the Earth, the Moon, and even nearby planets, the field lacks agreed-upon terms and definitions for depicting and describing the empty space between celestial bodies.[3] Furthermore, existing space depictions have tended to originate in academia and thus prioritize exactness and detail over accessibility, affecting their utility for decisionmakers and space operators.

As humans venture farther into space—be it launching tourists on cruises around the Moon or telescopes into deep space—the need grows for clear terms and definitions with which to construct distinct astrographic regions. A coherent, precise lexicon that prioritizes simplicity in pursuit of accessibility over scientific detail offers significant advantages. By using well-defined terms to describe different regions of space, policymakers and space operators may communicate more effectively, minimizing misunderstandings or misinterpretations that could arise from murky or overly technical language. Ultimately, such clarity can contribute to better decisionmaking, as policymakers balance technological advancements with the safety and risks associated with human space exploration.

[1] In 1961, author Arthur C. Clarke captured the uncertainty about how well we understood Moon topography in his classic novel, *A Fall of Moondust*. NASA increased its understanding of lunar topography through the Surveyor mission, which landed on the Moon in 1966 (Arthur C. Clarke, *A Fall of Moondust*, Harcourt, Brace & World, 1961; Rod Pyle, "Fifty Years of Moon Dust: Surveyor 1 Was a Pathfinder for Apollo," Jet Propulsion Laboratory, June 2, 2016).

[2] Ling Xin, "China's Moon Atlas Is the Most Detailed Ever Made," *Nature*, April 25, 2024.

[3] As an example, there is no unified definition of *celestial body*, although the term is employed throughout the foundational Outer Space Treaty of 1967 (Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, January 27, 1967).

Guiding Principles for Our Astrographic Framework

Rather than add to the existing library of space maps, we offer a novel *framework* for delineating the astrographic regions for any given gravitational system. In constructing the framework, we sought to follow three guiding principles: ensuring a framework that is *accessible* to policymakers and space planners of all types, *durable* over the long term, and *generalizable* across different gravitational systems.

Stakeholder accessibility: First, we aim to employ a level of technical detail that preserves our astrography's usefulness to a wide variety of stakeholders, particularly senior policymakers and mission operators. To ensure the accessibility of terms and definitions, we prioritize simplicity and clarity over technical nuances. In the same way that an airpower strategist or policymaker should not need advanced knowledge in aeronautics to understand the basic operating regions for airpower, a space policymaker or strategist should not need an astronautical engineering degree to do the same for spacepower. Accordingly, we intend our framework to be comprehensible to anyone with a basic understanding of space terms and concepts.

Durability: Second, although we cannot predict the specific details of future space operations, we nevertheless attempt to provide criteria for astrographic boundaries that will stand the test of time rather than needing to be adjusted with advances in technology.[4] Where possible, we connect our boundaries to durable physical thresholds or, at the very least, widely held conventions. Time will tell if our proposed boundaries are enduring; if nothing else, they provide a usable framework for the near term and a foundation for future refinement.

Generalizability: Finally, we aim to create a framework that is generalizable to both the Earth-Moon celestial neighborhood and other gravitational systems. Ideally, this generalizability means that proficiencies developed for operating in and around the Earth and the Moon remain applicable for operations around other systems. If our approach holds, policymakers and operators will already possess a latent familiarity with Near-Martian Space by the time such operations kick off in earnest.

[4] The historical *cannon-shot rule* once defined the extent of a state's territorial waters to be three miles from its coastline based on the maximum range of 17th-century coastal artillery weapons (Oxford Reference, "Cannon-Shot Rule," webpage, undated).

How We Organize This Report

We organize our analysis in three parts. First, we overview our approach to developing maps for celestial gravitational systems, drawing on concepts from geography and cartography, as well as from past precedent applying Earth-based mapping principles in outer space. Using the Earth-Moon celestial neighborhood as an example, we explain five concepts that serve as building blocks for our astrographic framework: minimum orbit (minorbit) spheres, mass concentrations (mascons), Lagrange zones, reference frames, and Hill spheres. This part will be of most interest to more technically oriented readers who wish to explore our underlying analysis.

Using these mapping principles and concepts, we then outline clear definitions of four regions of space—surface environment, near-body space, celestial neighborhood, and deep space—and explain how we decided on these regions and their boundaries. We include these definitions and their applications to Earth-Moon space region in Table 1.1. This part will be most useful as a quick reference for decisionmakers, planners, and operators who want a consistent astrographic framework to use today and in the future.

Finally, we articulate possible opportunities to enhance this astrographic framework: distinguishing areas with two-body versus three-body dynamics, leveraging multidimensional representations, and investigating additional astrographic regions and features. This portion will be of interest to future researchers and those interested in contributing to the astrographic framework through more-detailed research and analysis.

Quick Win: Providing a Clear Definition of the Earth-Moon Region

Though designed to be broadly applicable to any celestial body or gravitational system, our framework finds its proximate application in the region of space encompassing the Earth and the Moon known as Cislunar Space. Cislunar Space generally refers to the region of space between Earth and the Moon, but there are variations in its specific definition, which will be discussed later. Cislunar Space was an early focal point of Cold War competition, including the culmination of the U.S.-Soviet space race in the 1969 Apollo 11 Moon landing.[5] Cislunar Space now attracts investments from nations and private companies around the world, and budding commercial opportunities range from space tourism to resource extraction.[6] The region also holds immense promise for scientific discovery, enabling groundbreaking research in planetary science, radio astronomy, advanced manufacturing, and experiments that could support long-term human presence beyond Earth.[7] As interest in Cislunar Space accelerates, the clear definition and consistent depiction of this region offered in this report will be helpful to support coordination, safety, and future space development.

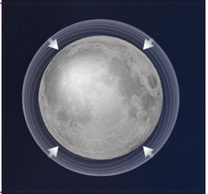
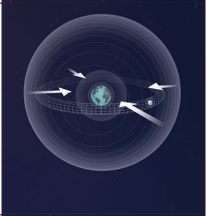
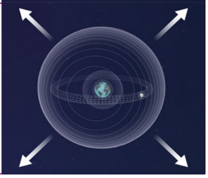
[5] David R. Williams, "The Apollo Program (1963–1972)," webpage, NASA National Space Science Data Center Coordinated Archive, last updated February 17, 2023.

[6] Brian Baker-McEvilly, Surabhi Bhadauria, David Canales, and Carolin Frueh, "A Comprehensive Review on Cislunar Expansion and Space Domain Awareness," *Progress in Aerospace Sciences*, Vol. 147, May 1, 2024.

[7] Cislunar Technology Strategy Interagency Working Group, *National Cislunar Science & Technology Strategy*, National Science and Technology Council, November 2022.

We present the following definitions of four regions of space that may be present within any gravitational system. We include example applications of these regions to Cislunar Space, the next stage of development for scientific, commercial, and geopolitical progress in outer space.

Table 1.1 | Four Astrographic Regions and Cislunar Examples

		Four Astrographic Regions Applied to Earth and the Moon		
Astrographic Region	**Generalized Definition**	**Cislunar Example**	**Cislunar Definition**	**Simplified Depiction**
Surface environment	Volume contained within a celestial body's minorbit sphere (the lowest stable orbit for the celestial body)	Terrestrial Environment	Earth's surface to 100 km above mean sea level; includes subsurface and atmospheric activities	
		Lunar Environment	The Moon's surface to 100 km above mean surface level	
Near-body space	A celestial body's immediate orbital neighborhood, from its minorbit sphere to its furthest Keplerian orbit	Near-Earth Space	100 km to 50,000 km above Earth's mean sea level; includes all demonstrated Keplerian orbital regimes	
		Near-Lunar Space	100 km to 60,000 km above the lunar surface; includes all theoretical Keplerian Lunar orbits	
Celestial neighborhood	Volume of primary gravitational influence by the constituent bodies of the gravitational system	Cislunar Space	Volume of space contained within the Earth's Hill sphere (1.5M km from Earth's center), minus Near-Earth and Near-Lunar Space	
Deep space	Remainder of space outside a given Celestial Neighborhood	Deep Space (from a Cislunar perspective)	Known universe, minus Cislunar Space	

CHAPTER 2

Approach to Mapping Space

The absence of fixed landmarks, combined with the continuous influence of forces across vast distances, makes space a distinct and challenging context for mapping. On Earth, terrain features remain largely stable, serving as durable reference points for navigation. In space, however, all elements remain in constant motion relative to different perspectives, Earth-based situational awareness of the domain may be limited, and complex forces continuously alter the trajectories of objects large and small.

In establishing well-defined regions of space, we draw on principles from established academic domains—geography and cartography—to develop terms and parameters for application to the cosmos. Effective mapping relies on clear communication, and we explain how best practices from Earth-based cartography provide a foundation for visualizing space. Previous examples applying these principles, such as for planetary surface mapping and tracking of near-Earth objects, demonstrate the value of adapting Earth-based mapping techniques to space environments. Finally, we identify five features of space to serve as building blocks toward our overall astrography.

Applying Geographical and Cartographical Principles to Space Mapping

Whereas geography pertains to "the study of the diverse environments, places, and spaces of Earth's surface and their interactions,"[8] the International Cartographic Association describes cartography as "the discipline dealing with the conception, production, dissemination, and study of maps."[9] Practitioners in these disciplines stress the importance of following certain basic principles in constructing effective maps, including legibility, contrast, and visual hierarchy.[10] Cartographic best practice involves leveraging visual variables for clear map communication; as articulated by French cartographer Jacques Bertin, such variables may include size, shape, value, color, and orientation.[11] As Cislunar activity achieves a sustained presence, integrating these practices will be critical for navigation, resource planning, and mission interoperability.[12]

Once focused only on Earth, geography and cartography have long since been adapted to support a wide variety of space missions, and past applications of these principles to space offer precedent and further guidance on constructing an effective space map. Such efforts have included detailed planetary mapping for mission planning, tracking of hazardous near-Earth objects using telescopic surveys, and engagement of the public through accessible astrophotography.

Every celestial body requires its own bespoke map projection owing to its unique shape and geodetic properties, such as its gravity field and surface topography. The U.S. Geological Survey applies traditional geodetic techniques to extraterrestrial surfaces using coordinate systems akin to Earth's latitude-longitude framework. Star charts and celestial atlases use right ascension and declination as measurements, much like Earth's own coordinate system. These resources provide durable reference points for deep space navigation, like traditional maritime navigation on Earth, as well as near-Earth missions. Contributions from such missions as the European Space Agency's Gaia astronomy satellite, which has mapped more than one billion stars with extreme precision, continue to advance celestial cartography's impact on space sciences.

Just as terrestrial maps have recorded Earth's geological history, planetary geologic maps help explore the evolution of celestial bodies. Satellite imagery and remote sensing technology, such as light detection and ranging systems, assist in creating digital elevation models for planetary exploration, which in turn help identify impact craters, tectonic features, and potential resource sites, making them essential for exploration and navigation. Given the success of such efforts in applying traditional geographical and cartographical principles to space, we aim to construct an astrographic framework that builds on this well-established foundation.

[8] Ron Johnston, "Geography," *Encyclopaedia Britannica*, last updated December 9, 2024.

[9] International Cartographic Association, "Mission," webpage, last updated February 26, 2021.

[10] Andrea Nass, Kaichang Di, Stephan Elgner, Stephan van Gasselt, Trent Hare, Henrik Hargitai, Irina Karachevtseva, E. Kersten, Nicolas Manaud, T. Roatsch, et al., "Planetary Cartography and Mapping: Where We Are Today, and Where We Are Heading For?" *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. 42, No. 3/W1, 2017.

[11] Robert Roth, "Visual Variables," in Douglas Richardson, Noel Castree, Michael F. Goodchild, Audrey Kobayashi, Weidong Liu, and Richard A. Marston, eds., *The International Encyclopedia of Geography: People, the Earth, Environment and Technology*, John Wiley & Sons, Ltd., 2017.

[12] Deborah Jean Warner, *The Sky Explored: Celestial Cartography 1500–1800*, Alan R. Liss, Inc., 1979.

Challenges of Mapping Space

Although Earth-based mapping principles provide a useful starting point, the stark physical and conceptual differences between Earth and space prevent their immediate application. Simply defining *outer space* poses a complex and unresolved challenge. At a glance, the definition seems simple: the unoccupied physical space of the universe. Yet, without distinctions of what matters and what may be neglected, this definition is hardly useful for detailed mission planning.

Instead, planners begin with their own human senses of size and time, extrapolate this understanding to the scale of the exact mission, and end by filtering out elements that do not *meaningfully* affect the mission. For most space missions, this leads to the underlying assumption of outer space as a single, continuous volume of physical space characterized by an overwhelming absence of physical matter.

However, defining outer space becomes even more challenging in edge cases, in which outer space abuts large physical objects, such as planets and moons, because these large objects affect all other objects in space far beyond their own physical boundaries. Considering that human activity is clustered on or around one such planet, such boundary cases have been the norm for space operations up to and including today. Contemporary science identifies four fundamental forces throughout the universe by which objects can affect their surroundings: gravitational, electromagnetic, and the strong and weak nuclear forces. The latter two are out of scope, but the former are eminently relevant to constructing a map of these regions.[13]

Gravity highlights the critical role that physical distance plays in space planning. The gravitational pull of large, planetary-scale bodies is so powerful that it influences the motion of satellites and spacecraft even at vast distances away; in the case of Earth, this pull can meaningfully affect the trajectory of satellites across hundreds of thousands of kilometers. Accordingly, useful space maps must distinguish between regions of gravitational influence as they relate to one or many celestial bodies in a given gravitational system.

Electromagnetic forces, on the other hand, underpin most other forces that an orbiting object may experience in outer space. This includes the repulsion experienced as drag by satellites orbiting planets with gaseous atmospheres. The local density of such atmospheres is constantly in flux at their outer boundaries, as molecules break free and disseminate into space, where they may be run into by spacecraft orbiting at low altitudes.

There is no hard mathematical boundary defining the extent of the gravitational and electromagnetic forces exerted by large celestial bodies. Rather, forces stemming from countless sources all act in concert to perturb a satellite's idealized trajectory, and mission planners and operators must determine which forces are *meaningful* based on mission timing and location. We therefore apply the concept of "fuzzy" logic to select rule-of-thumb boundaries whose foundations in physics may be more easily communicated than their exact, mathematical locations. The ability to quickly assess such distinctions underscores the importance of an accessible astrographic framework for enabling future missions in and through increasingly complex regions of space.

Finally, we recognize that visual depictions of space must strike a balance between accuracy and clarity because of the domain's scale, complexity, and dynamism. Whereas detailed Earth maps typically prioritize a rigorous adherence to proper scale so that users may accurately calculate distances between two points, the vast relative distances between space objects (as well as their constant motion) require dedicated three-dimensional visualization technology to enable rigorously accurate depictions. To support clarity for policymakers and space planners, our depictions involve simple designs, forgoing accurate scaling in favor of accessibility.

[13] NASA, "Four Forces," webpage, last updated October 22, 2024.

Concepts for Delineating Astrographic Regions

We now define the five building blocks used to construct our astrographic framework: minimum orbit (minorbit) spheres, mass concentrations (mascons), Lagrange zones, reference frames, and Hill spheres. We introduce the term *minorbit* and recommend its use as a term of art to address the concept of minimum stable orbit around any celestial body; the other terms are already in use. These concepts are used as reference points for defining the regional boundaries; as an explanatory example, we also discuss their application in Cislunar Space. However, these features can and should be applied to other celestial bodies and gravitational systems.

Minorbit Spheres

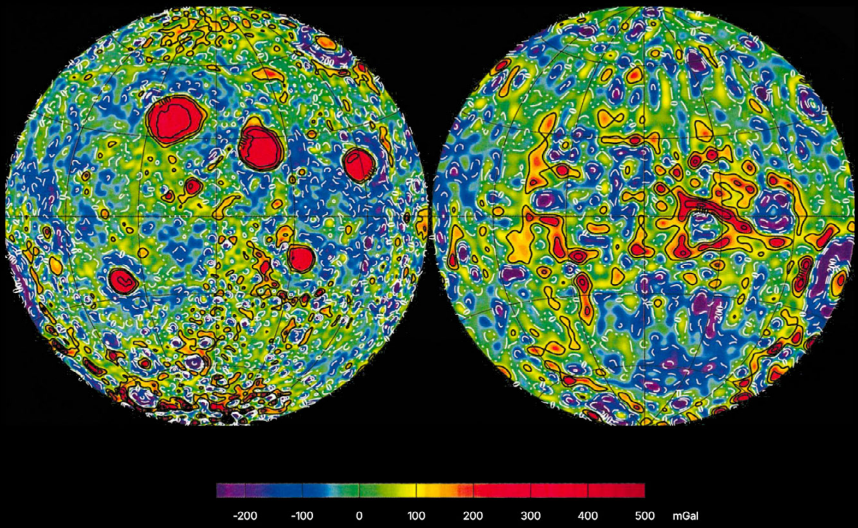
The first of these terrain features—the minimum orbit sphere, or minorbit sphere—uses a celestial body's lowest stable orbit to mark the transition between surface environment and near-body space. This boundary can be visualized as a spherical shell, centered on the body's center of gravity, whose radius coincides with the altitude of the lowest stable orbit around the body.

Such factors as a gaseous atmosphere or variations in mass distribution can push a body's minorbit sphere beyond what might be expected based solely on the body's shape. For Earth, we define the minorbit sphere as 100 km above mean sea level (MSL), a boundary known as the Kármán line. Past this altitude, the impact of aerodynamic forces on an orbiting object declines in importance relative to the object's inertia, facilitating stable natural orbits around Earth without the need for continuous propulsion to stay in orbit for a meaningful amount of time. For the Moon, we define the minorbit sphere as 100 km, not for atmospheric reasons but because of the perturbing impact of significant mascons. For Mars, the minorbit sphere is approximately 200 km based on the very thin Martian atmosphere.

Mass Concentrations

Dense pockets of mass—known as mass concentrations, or mascons—may be indiscriminately distributed across a planetary body, further influencing an object's orbit. Mascons on the Moon (Figure 2.1), likely originating from ancient asteroid impacts, result in a minorbit sphere at approximately 100 km above the Moon's mean surface—an altitude coincidentally similar to Earth's Kármán line, despite the Moon lacking an atmosphere. Mascons have the effect of creating uneven gravitational forces that de-orbit satellites at lower-than-expected altitudes; lunar orbits at inclinations of 27°, 50°, 76°, and 86° are particularly affected.

Figure 2.1 | Lunar Mass Concentrations



SOURCE: Reproduced from A. S. Konopliv, S. W. Asmar, E. Carranza, W. L. Sjogren, and D. N. Yuan, "Recent Gravity Models as a Result of the Lunar Prospector Mission," *Icarus*, Vol. 150, No. 1, March 2011, p. 9.
NOTE: mGal = milligals.

Lagrange Zones

Chaotic, nonrepeating orbits predominate throughout Cislunar Space because of the complex combined gravitational dynamics of the Earth and the Moon, disallowing the identification of orbital regimes analogous to low Earth orbit (LEO), medium Earth orbit (MEO), geostationary orbit (GEO), or highly elliptical orbit (HEO) to serve as fixed points of reference in our astrographic framework. From an operational perspective, operators seeking to maintain a predictable satellite trajectory through this region must perform frequent station-keeping maneuvers, thereby limiting satellite lifetime to the quantity of fuel on board. Accordingly, any useful map of multibody gravitational systems would naturally highlight possible locations at which spacecraft might maintain their positions with minimum fuel expenditure.

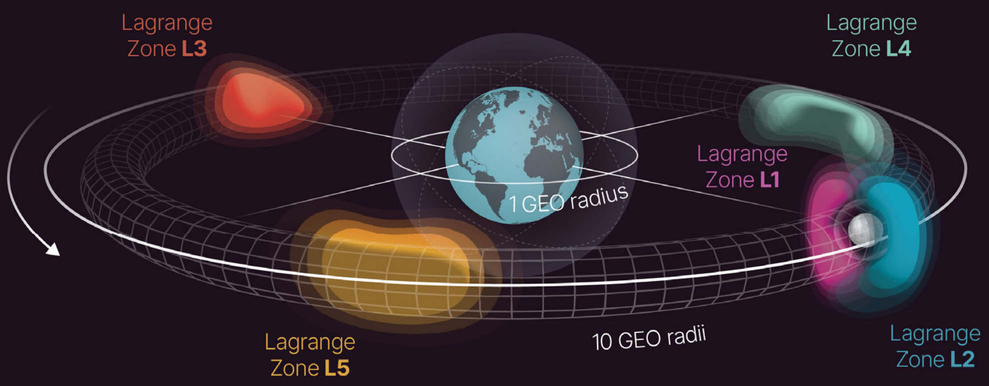
In Cislunar Space, as for any circular-restricted three-body gravitational system, this sort of location is embodied by the five Earth-Moon Lagrange (EML) zones.[14] Traditionally, EML zones are described as specific, mathematical points in space in which the combined gravity from the Earth and the Moon "cancel out," resulting in discrete locations wherein satellites would not move with respect to these bodies (see Figure 2.2). In actuality, there exist vast zones around these theoretical points composed of large quantities of overlapping orbits across a wide variety of distances. Many such trajectories extend far beyond their associated Lagrange point centers, with the intervening space occupied by still more orbits—accordingly, we adopt the phrase *Lagrange zones* in place of *Lagrange points*.[15] Numerous families of orbits exist around the different EML zones, each offering their own flavor of quasi-periodic behavior and, therefore, the promise of orbits requiring significantly reduced station-keeping to maintain. To represent this reality, Figure 2.3 employs amorphous shapes with diffuse boundaries to illustrate the indefinite extent of the various orbit families that each Lagrange point plays host to.

Figure 2.2 | Earth-Moon Lagrange Points

[14] A *three-body system* can refer to three larger objects, such as the Sun-Earth-Moon, or two larger objects and one much smaller object, such as the Earth-Moon-satellite (Wang Sang Koon, Martin W. Lo, Jerrold E. Marsden, and Shane D. Ross, *Dynamical Systems, the Three-Body Problem, and Space Mission Design*, California Institute of Technology, April 2011).

[15] We first observed discussion of the concept of a Lagrange region or volume in Jessy Kate Schingler, Victoria Samson, and Nivedita Raju, "Don't Delay Getting Serious About Cislunar Security," *War on the Rocks*, July 6, 2022.

Figure 2.3 | Notional Lagrange Zones



Future work to definitively identify all families and instances of quasi-periodic orbits throughout Cislunar Space would pay dividends for planning future Cislunar and Deep Space operations. In the meantime, NASA's Jet Propulsion Laboratory hosts the Three-Body Periodic Orbit Catalog, which contains a large quantity of pre-computed Cislunar orbits.[16] Similar Lagrange zones exist in any three-body environment, and Sun-Earth Lagrange zones are commonly discussed as part of future Cislunar and Deep Space operations.

Reference Frames

Lagrange zones highlight the importance of another key concept for mapping space: the need for a common basis for comparing the positions and movements of objects in space. Often taking the form of Cartesian coordinate systems, reference frames establish a common basis for tracking motion in space. The International Celestial Reference System is the celestial reference system adopted by the International Astronomical Union for high-precision positional astronomy.[17] Careful definition is crucial because reference frames also end up shaping how operators conceive of their freedom of action.

One critical example of how reference frames shape the understanding of Cislunar Space is the use of a rotating coordinate system. Up to this point, our discussion has implicitly assumed that Earth is the center point of comparison for all other objects, including the Moon. Under this assumption, objects in GEO appear to an Earthly observer as stationary—hence the monikers *geostationary* or *geosynchronous*. However, from the perspective of the Sun, objects in GEO are constantly in motion, rotating both around Earth and the Sun. By employing a rotating coordinate system—as in one centered on Earth's center of gravity and rotating with the Moon—operators greatly simplify their conception of Cislunar Space.

[16] Jet Propulsion Laboratory, Three-Body Periodic Orbit Catalog, database, undated.

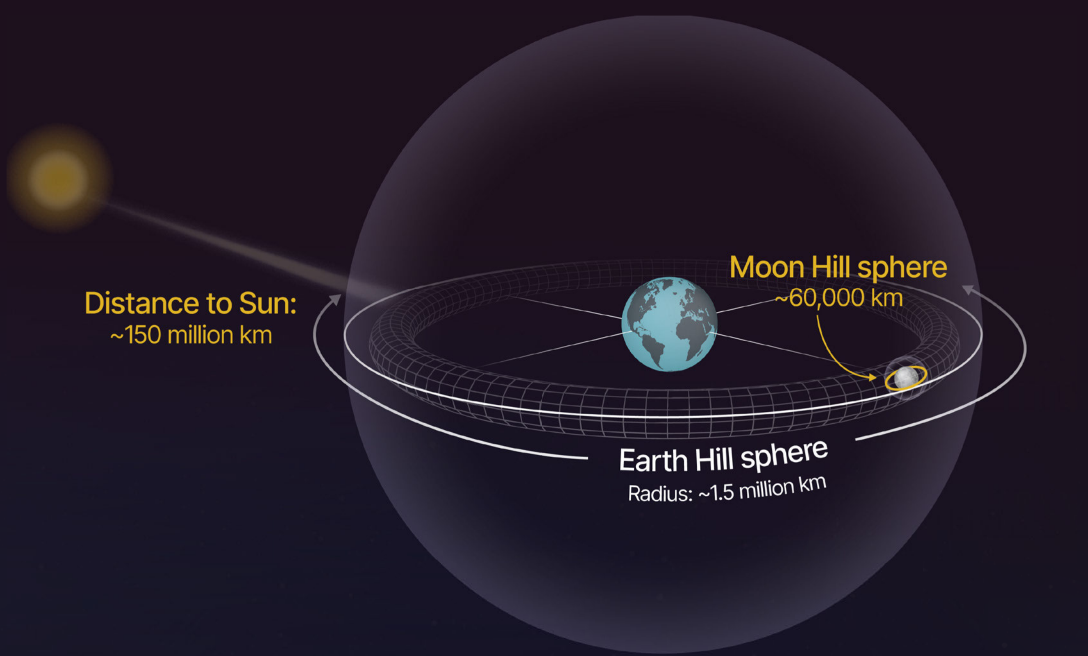
[17] Astronomical Applications Department, U.S. Naval Observatory, "International Celestial Reference System (ICRS)," webpage, undated.

Hill Spheres

Hill spheres may be thought of as gravitational spheres of influence, providing a physics-based reference for defining the boundaries of systems. These theoretical boundaries mark the region of space in which a smaller planetary body's gravity will dominate over a neighboring larger body's gravity owing to proximity. Hill spheres may be approximated by determining the distance at which the gravitational force of the smaller body equals that of the larger body (i.e., their shared Lagrange point).

In the case of Earth's influence relative to the Sun (see Figure 2.4), the radius of Earth's Hill sphere is placed at approximately 1.5 million km from its center of gravity. For the Moon relative to Earth, the boundary extends approximately 60,000 km.

Figure 2.4 | Earth and Moon Hill Spheres



CHAPTER 3

Defining Four Astrographic Regions

Drawing on established mapping principles and durable physics-based terrain features to delineate regional boundaries, we define four distinct astrographic regions: surface environment, near-body space, celestial neighborhood, and deep space. As the next stage of humanity's outer space activities, we select the Earth-Moon space region as an example application of mapping these four regions to a real-world gravitational system, although these definitions should apply to any celestial body and its associated gravitational system.

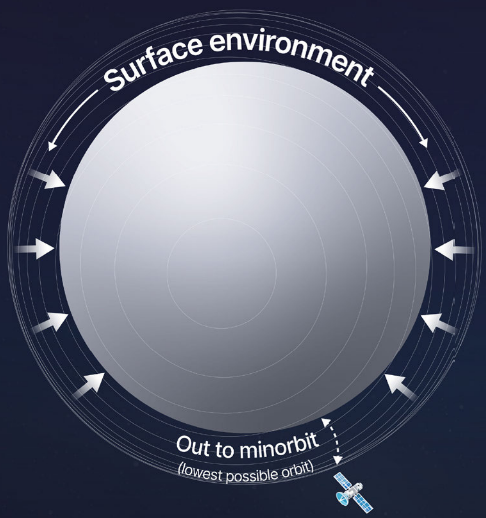
Surface Environment

We define *surface environment* as the volume contained within a celestial body's minorbit sphere, being the lowest stable orbit around the given celestial body (Figure 3.1).

Applied to the Earth, the surface environment—which we refer to as the *Terrestrial Environment*—encompasses the Earth's subsurface, surface, and gaseous atmosphere out to its minorbit sphere. For atmospheres like the Earth's, the exact location of the space-facing boundary is constantly in flux as gases ebb and flow into outer space. To define the bounds of the Terrestrial Environment in an accessible way, we focus not on the exactness of this ever-changing boundary but on a reasonable estimation. Accordingly, we define the outer bounds of Earth's Terrestrial Environment as the Kármán line, located 100 km above MSL. This definition is the widely, though not universally, accepted boundary between the aeronautic and astronautic regimes and aligns our astrography with existing civil policy and military doctrine, as in the Fédération Aéronautique Internationale and U.S. Space Command, respectively.[18]

In applying the surface environment definition to the Moon, we introduce the *Lunar Environment*. Because the Moon lacks a gaseous atmosphere, one might assume that the Lunar Environment's outer boundary would coincide with the physical surface itself. However, as previously discussed, Lunar mascons complicate the location of this boundary by perturbing the orbit of satellites at certain inclinations. Lunar mascons effectively result in a minorbit sphere of approximately 100 km above the mean lunar surface, and this altitude serves as the upper bound of the Lunar Environment.

Figure 3.1 | Surface Environment



[18] Fédération Aéronautique Internationale, "Statement About the Karman Line," November 30, 2018; Joint Publication 3-14, *Space Operations*, U.S. Joint Chiefs of Staff, August 23, 2023.

Near-Body Space

Just outside the surface environment lies the next astrographic region: near-body space. This term describes a celestial body's immediate orbital environment, the volume sandwiched between the minorbit sphere and a second sphere containing all of that body's Keplerian orbit families.

In Cislunar Space, we apply this definition to describe *Near-Earth Space*. This region begins at the Earth's minorbit sphere—100 km above MSL—and extends to encompass all the traditional orbital regimes around Earth, including LEO, MEO, GEO, and HEO (Figure 3.2). At their farthest distance from Earth, certain HEOs could extend to more than 47,000 km above MSL.[19] To establish a practical, accessible definition of Near-Earth Space, we round the outer boundary of this region to 50,000 km above MSL.[20]

Figure 3.2 | Near-Earth Space and Canonical Orbits Around Earth

[19] Zhenlong Li, Timothy J. Schmit, Jun Li, Mathew M. Gunshor, and Frederick W. Nagle, "Understanding the Imaging Capability of Tundra Orbits Compared to Other Orbits," *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 59, No. 11, November 2021.

[20] This first application of the definition relies on demonstrated applications. More-distant Keplerian orbits may exist, in which case the boundary should be updated.

Applied to the Moon, we define *Near-Lunar Space* as the region of outer space immediately surrounding the Moon, from its minorbit sphere out to the farthest extent of its theoretical Keplerian orbit families (Figure 3.3).

The inner boundary of Near-Lunar Space is contingent on the perturbing effects of the Moon's mascons, which influence the trajectories of orbiting objects at lower-than-expected altitudes. As a result, the Moon's minorbit sphere is found at 100 km above the Moon's mean surface. Without a robust heritage of demonstrated lunar orbits, the outer boundary of the region is set according to the theoretical limit of Keplerian orbits, being the Lunar Hill sphere at approximately 60,000 km from the Moon's center of gravity.

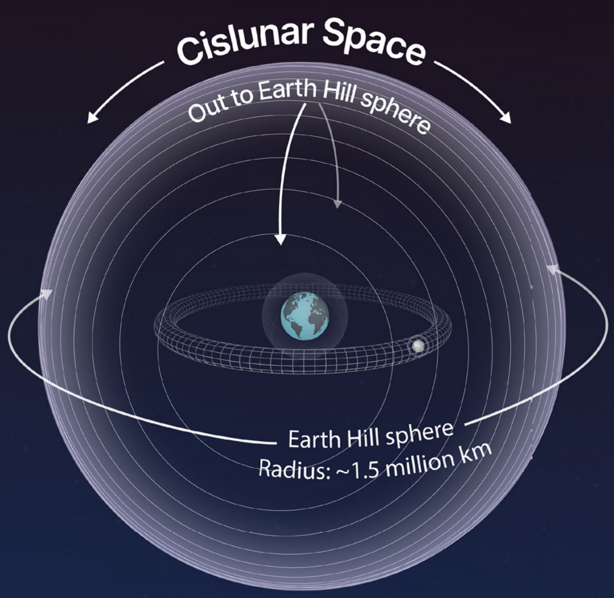
Figure 3.3 | Near-Lunar Space

Celestial Neighborhood

A celestial neighborhood encompasses the volume of outer space primarily influenced by the gravity of the constituent bodies of a given gravitational system. Applied to the neighborhood of the Earth-Moon system, this celestial neighborhood is *Cislunar Space*. Cislunar Space's outer boundary is set to be coincident with Earth's Hill sphere at about 1.5 million km distant (Figure 3.4). Cislunar Space does not include the volumes contained within Near-Earth and Near-Lunar Space; rather, Cislunar Space is akin to the ocean in which these smaller regions float.

In the case of Cislunar Space, as for other multibody gravitational systems, the operational implication of the region's complex gravitational environment is that satellite behavior is very different compared with Near-Earth Space. Depending on a satellite's placement within the regime, small maneuvers can effect exceptional changes to satellite location with little indication of the ultimate endpoint. This implies far easier access to distant locations within Cislunar Space, as well as Near-Earth and Near-Lunar Space, once a satellite has reached Cislunar Space.

Figure 3.4 | Cislunar Space



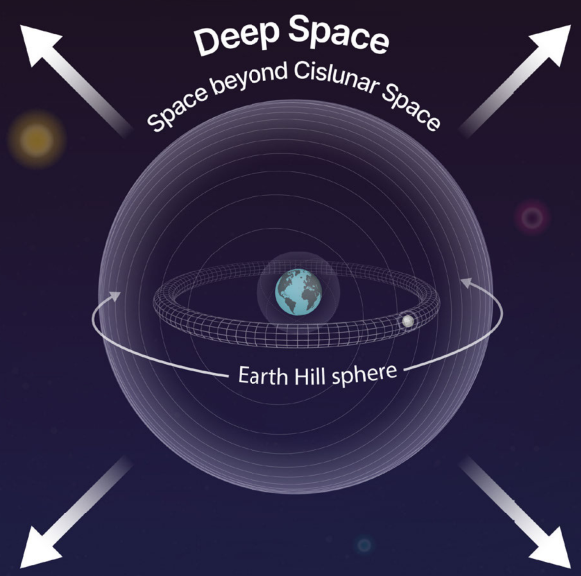
Deep Space

Deep space refers to the remainder of the known universe outside the boundaries of a given celestial neighborhood. Unlike the other regions, its exact definition depends on the perspective of the celestial neighborhood in question.

In the context of Cislunar Space, deep space (Figure 3.5) includes celestial bodies, such as the Sun and planets, that cannot be perturbed from their natural orbits, as well as smaller objects, such as asteroids and comets, that can in principle be moved and therefore may not fall within the legal definition of celestial body.[21]

Our discussion focuses on Cislunar Space, but future efforts may apply these concepts to any other gravitational system. Deep Space comprises innumerable celestial bodies, many nested within larger systems, just as the Earth-Moon system exists within the Solar System. In designing an astrographic framework that is simple and enduring, we hope that the concept proves generalizable to future space activity distant across both time and space.

Figure 3.5 | Deep Space



[21] Title 42 of the U.S. Code defines Near-Earth, Cislunar, and Deep Space (U.S. Code, Title 42, The Public Health and Welfare; Chapter 159, Space Exploration, Technology, and Science; Section 18302, Definitions).

CHAPTER 4

Opportunities for Enhancing the Astrographic Framework

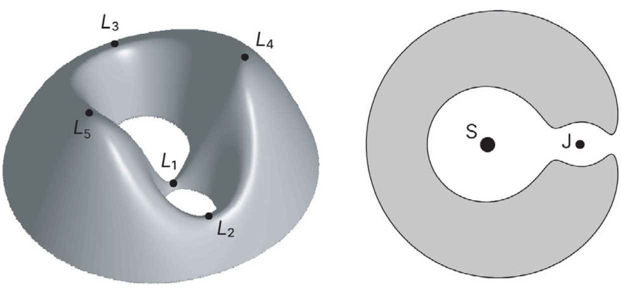
We have discussed the rationale for establishing accessible terms and definitions pertaining to mapping astrographic regions and proposed an approach sufficient for current and near-future space operations. However, given the rapid progress expected in spaceflight over the coming decades, it is important to look ahead to mid- and long-term horizons to ensure that this initial approach can be expanded as needed. We identify three opportunities for enhancing our astrographic framework: differentiating areas governed by two-body versus three-body (or more) orbital dynamics, deploying tools for multidimensional representations of astrography, and incorporating additional astrographic regions as humanity's cosmic activities expand in scope.

Three-Body Dynamics in Cislunar Space

In practice, space operators need to distinguish between areas in which traditional two-body orbital dynamics dominate, such as in Near-Earth Space, and areas in which the influence of a third body, such as the Moon, will have a meaningful impact on an object's trajectory.[22] The specific threshold for what counts as *meaningful* in this context will depend on mission type and operational requirements, but no matter the definition, the resulting boundary will be a complex three-dimensional shape that distinguishes regions governed by two-body orbital dynamics from those influenced by three-body dynamics. This complexity is evident in Figure 4.1, which plots gravitational potential energy (on the left) and inaccessible zones (on the right) for a notional three-body environment.

The intent of Figure 4.1 is to demonstrate the loss in understanding wrought by simplifying complex three-dimensional regions down to two dimensions. Space operators may use quantitative modeling and simulation to determine this boundary and visualize it in three dimensions; such visualizations will need to balance accessibility with mathematical precision according to the intended audience and application.

Figure 4.1 | Example Potential Surface and Hill Region Illustrating the Complexity of These Shapes



SOURCE: Reproduced from Koon et al., 2011, p. 11.
NOTE: The three-dimensional figure on the left plots gravitational potential energy in the vertical, so that the peaks evident at Lagrange Zones L3, L4, and L5 represent areas of higher potential than the enclosed circular regions in which the primary celestial bodies would be located. The figure on the right shows a two-dimensional representation of a similar gravitational system as the figure on the left, although it instead plots shaded exclusion zones in which a launched satellite would not physically be able to enter, owing to its Jacobi constant.

[22] At an altitude of approximately 2.7 times GEO, there is a "fuzzy" transition from two- to three-body orbital dynamics for Near-Earth Space. This is sometimes referred to as the *Worden line*, and it may prove to be an important astrographic concept (David Buehler, Eric Felt, Charles Finley, Peter Garretson, Jaime Stearns, and Andy Williams, "Posturing Space Forces for Operations Beyond GEO," *Space Force Journal*, No. 1, January 31, 2021). For an overview of three-body orbital dynamics, see Koon et al. (2011).

Multidimensional Mapping

Humans evolved in a gravitational environment that bound them to movement in two dimensions, and this perspective is reflected in our approaches to mapping—even most airspace maps are two-dimensional.[23] Furthermore, terrestrial topography typically does not change much over operationally relevant time frames, and thus static mapping is usually sufficient. In space, however, the third dimension is essential, and time also needs to be considered for some astrographic representations, adding a fourth dimension.

Although any higher-dimensional representation can be projected onto a two-dimensional surface in the vein of the traditional approach to mapping, computer-based immersive three-dimensional displays are much more intuitive, especially to users without deep expertise, and allow for efficient and interactive exploration of operationally relevant topographies, including time-variant ones. Thus, there is a need for tools that allow for the interactive, dynamic three-dimensional visualization of space topographies (not just trajectories), both for individual users and as a collaborative capability. Such tools are being developed already, although none of the examples we reviewed are optimized for operational purposes.[24]

[23] Charles F. Fuechsel, "Map," *Encyclopaedia Britannica*, last updated April 10, 2025.

[24] Solar System Scope, homepage, undated.

Expanding Astrographic Regions

Our four main astrographic regions should prove sufficient for describing at a high level a wide variety of gravitational systems, but space planners and operators may one day require more granular divisions. As examples, consider the following subregions at the boundary between the Terrestrial Environment and Near-Earth Space:

- **Very Low Earth Orbit** is the portion of Near-Earth Space in which Earth's atmosphere still has a significant impact, ranging from the outer edge of the Terrestrial Environment (100 km above Earth MSL) to approximately 150 km altitude. Objects in this region can still orbit, but even those with a high ballistic coefficient will be affected by the residual atmosphere and will therefore require frequent reboosts to avoid rapid reentry. However, there is operational utility in these low altitudes.

- **Suborbital Flight Envelope** is defined not by spatial coordinates but temporarily established around the trajectory of a suborbital or ballistic vehicle that ascends above the 100-km boundary and can thus affect objects in orbit.

Similarly, Cislunar Space could be subdivided into two parts:

- **Two-Body Cislunar Space** is where the gravitational influence of the Moon can be neglected for most missions.

- **Three-Body Cislunar Space** refers to the Lagrange zones and other areas between Near-Earth Space and Near-Lunar Space in which the Moon's gravity must be considered.

CHAPTER 5

Conclusion

As technological capabilities advance and humanity ventures deeper into space, the need for a shared lexicon to delineate and describe distinct space regions has become increasingly important. To address this emerging need, this report offers a starting point for developing a novel, coherent framework to define clear astrographic regions. Our goal is to provide a model that is accessible to a wide audience, durable over time, and generalizable beyond the Earth-Moon celestial neighborhood. In realizing these guiding principles, we aim to reduce the risk of misinterpretation by equipping decisionmakers and space operators with a shared understanding of space regions.

We present four astrographic regions—surface environment, near-body space, celestial neighborhood, and deep space—as an initial effort to foster dialogue on how best to delineate space in a practical and meaningful way. In doing so, we emphasize the importance of applying clear definitions and thresholds. Among the concepts that inform our approach, we identify minorbit spheres, mascons, Lagrange zones, reference frames, and Hill spheres as valuable features that future researchers can use to define analogous regions in other gravitational systems.

Recognizing that this framework represents an early-stage effort, we anticipate that future work will refine these definitions and incorporate additional concepts not covered here. We view this effort as an invitation to broader collaboration in shaping a framework that meets the guiding principles of accessibility, durability, and generalizability. We encourage future iterations to explore expanded concepts—including three-body dynamics in Cislunar Space, multidimensional mapping, and additional astrographic subregions—while also accounting for emerging use cases and developments in national security and international norms of behavior. Enabling humanity's expansion beyond our celestial home will be a full team effort.

Abbreviations

EML	Earth-Moon Lagrange
GEO	geostationary orbit
HEO	highly elliptical orbit
LEO	low Earth orbit
mascon	mass concentration
MEO	medium Earth orbit
minorbit	minimum orbit
MSL	mean sea level
NASA	National Aeronautics and Space Administration

Glossary

celestial neighborhood	Volume of primary gravitational influence by the constituent bodies of the gravitational system
Cislunar Space	Volume of space contained within Earth's Hill sphere (1.5 million km from Earth's center), minus Near-Earth and Near-Lunar Space
deep space	Remainder of space outside a given celestial neighborhood
Hill sphere	Region of space in which a smaller planetary body's gravity will dominate over a neighboring larger body's gravity owing to proximity
Lagrange zones	Areas of gravitational equilibria between any two celestial bodies
mass concentrations (mascons)	Highly dense pockets of mass distributed across a celestial body that disproportionately perturb the trajectory of orbiting satellites
minimum orbit sphere (minorbit sphere)	The lowest altitude at which stable orbit around a celestial body can be achieved, marking the transition between the body's surface environment and its orbital regime
near-body space	A celestial body's immediate orbital neighborhood, from its minorbit sphere to its farthest practical orbit
reference frame	A system used as a common basis for comparing the positions and movements of objects in space—oftentimes a Cartesian coordinate system
surface environment	Volume contained within a celestial body's minorbit sphere
three-body dynamics	Gravitational interactions in which three celestial objects influence orbital paths, such as in the Earth-Moon Lagrange zones
two-body dynamics	Orbital mechanics influenced primarily by the gravitational interaction between two objects, commonly used to model near-Earth or near-Lunar scenarios

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About This Report

As scientific, commercial, and geopolitical activities accelerate beyond near-Earth, existing delineations of deeper space are proving to be insufficient; often, they are highly technical, inconsistently applied, and inaccessible to many decisionmakers. In this report, we build on existing geographical and cartographical precedent to propose four clear astrographic regions—surface environment, near-body space, celestial neighborhood, and deep space—each grounded in durable physical thresholds or established conventions. Designed to be accessible, durable, and generalizable, the framework aims to support discourse among a wide variety of space professionals. We also highlight opportunities for further improving this framework, including the incorporation of multibody gravitational boundaries, four-dimensional mapping, and additional space regions and features as space activities continue to evolve.

RAND National Security Research Division

Funding for this research was provided by Founders Pledge and conducted within the International Security and Defense Program of the RAND National Security Research Division (NSRD). NSRD conducts research and analysis for the Office of the Secretary of Defense, the U.S. Intelligence Community, the U.S. State Department, allied foreign governments, and foundations.

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Acknowledgments

We express our gratitude to those individuals whose contributions were instrumental in the development of this report. Peter Garretson, Todd Pennington, and select members of the U.S. Air Force Academy Astronautical Engineering Department, especially Colonel Luke Sauter, Lt Col Luke Hagen, and Blair Thompson, generously lent their time and expertise, providing invaluable feedback that shaped the report's direction and refinement. Daniel Suarez served as the external quality assurance reviewer, offering thoughtful suggestions and notes that elevated the report's overall quality and accessibility. Our RAND colleague David Glickstein worked closely with the research team to bring our concepts to life through the visualizations featured throughout the report. Finally, Joel Sercel acted as an expert sounding board and a source of inspiration for some of the ideas explored in this work. We are deeply appreciative of these and many other individuals for their time and inputs. All errors are our own, and we welcome feedback on how to improve the framework.

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$20.00

ISBN-10 1-9774-1548-2
ISBN-13 978-1-9774-1548-6

52000

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RR-A4003-1