Chapter 4:

Real Constraints on Spacepower

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Any discussion of the bases and tenets of spacepower must begin with a solid understanding of the governing physical laws, environment, advantages, and difficulties inherent in space systems and their operations.[1] While conferring significant advantages on those who can operate there effectively, space presents unique challenges and high development costs, both monetarily and experientially. After all, it *is* rocket science. Beyond the equations, too, there exist the complex systems definition and engineering needed to "operationalize" space and bring its effects to the user in a timely and affordable fashion. From definition of the basic need to delivery of a given capability, the variety of technical, programmatic, and acceptable risk issues that must be defined before any spacepower can be sustained or developed is daunting. Theorists and users must realize that, even on the strategic level, there are irreducible sets of knowledge, understanding, and trades that form the foundation of space competency. The purpose of this chapter is to highlight these key concepts, serving as a review for some readers, an overview for others, and (we hope) a motivation for all to continue to hone their space expertise.

Advantages of Space

Getting into space is dangerous and expensive. So why bother? The five primary advantages space offers for modern society are:

- global perspective
- clear view of the heavens
- free-fall environment
- abundant resources
- unique challenge as the final frontier.

While each of these benefits plays a role in defining a nation's space-power, they may not be equally valued.

Clearly, the global perspective provided by space is a primary motivator for deploying commercial, civil, military, and scientific systems there. Space takes the quest for greater perspective to its ultimate end, allowing access to large areas of the Earth's surface depending upon orbital specifics. Orbiting spacecraft can thus serve as "eyes and ears in the sky" to provide a variety of useful services.

The high ground, once achieved, makes possible several other capabilities that may reinforce a nation's space and economic power. Scientifically, space offers a clear view of

the heavens. From the Earth's surface, the atmosphere blurs, blocks, and disturbs (scintillates) visible light and other electromagnetic radiation, frustrating astronomers who need access to all the regions of the electromagnetic spectrum to explore the universe. Spacecraft such as the Hubble Space Telescope and the Gamma Ray Observatory overcome this restriction and have revolutionized our understanding of the cosmos.

Space offers a free-fall environment enabling manufacturing processes not possible on the Earth's surface. Though certainly not exploited to date for other than experimental value, the potential to manufacture exotic compounds for computer components or pharmaceutical products exists.

Further downstream, space offers abundant resources. While spacecraft now use only one of these abundant resources—solar energy—the bounty of the solar system offers an untapped reserve of minerals and energy to sustain future exploration and colonization. In the not-too-distant future, lunar resources, or even those from the asteroids, might fuel a growing space-based economy.

Finally, space serves simply as a frontier. The human condition has always improved as new frontiers were challenged. As a stimulus for technological advances and a crucible for creating economic expansion, space offers a limitless challenge that compels national and global attention. The act of exploration—across oceans or prairies in the past, and in this case pushing back the frontiers of space—has long been a wellspring of pride and an expression of power.

Turning Need into Capability

From an engineer's perspective, spacepower can be viewed as the exploitation of space-based systems (and the natural laws governing them) to achieve national political or economic ends. Maintaining and expanding a nation's spacepower hinges on the ability to define the need for new systems and turn those needs into capabilities that policymakers and war-fighters can exploit. The purpose of the space systems acquisition process is to translate those needs into capable systems. The technical foundation of space systems acquisition is systems engineering. Fundamentally, the space systems engineering process leverages one or more of the advantages of space outlined above to turn needs, as defined by policymakers and warfighters, into operational capabilities. The more clearly the needs for these systems are articulated in terms of performance, cost, and schedule goals, the better systems engineers can make realistic tradeoffs to achieve those goals with acceptable risk.

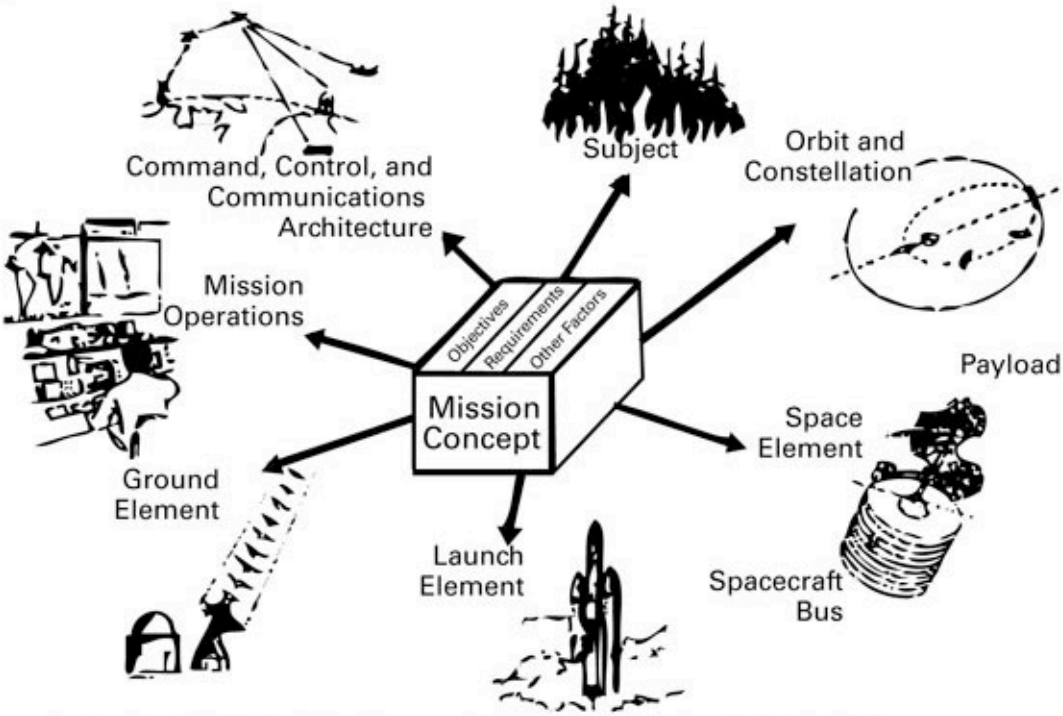
Ultimately, the intended goals and objectives of the system become defined in terms of *requirements*—single, testable *shall* statements that define what the system will be or shall do and how well. Bounding the universe of possible solutions for any problem are *constraints*. The difference between a requirement and a constraint is really a matter of perspective. One person's requirement for a given mechanical interface as defined by a specific bolt pattern becomes a constraint from the standpoint of the designer of the

interface plate. Some requirements are imposed on a system for practical, political, or economic reasons and are arguably negotiable at some pay grade, while some constraints, such as the laws of physics or the real state of the art, are not subject to negotiation. The remainder of this chapter will focus on understanding the source of requirements and constraints on space systems—and thus ultimately on spacepower—that form the realm of the possible. Fortunately, this realm is vast, offering many asyet-untapped capabilities. But the better we understand the limits of this realm, the better we will manage scarce resources to achieve best systems— and hence capabilities—to enhance spacepower.

Mission Architectures

The increasing complexity and interoperability of space systems have lead to discussions of "systems of systems" or, more broadly, *mission architectures*. A space mission architecture includes all of the space and ground elements needed to make the mission successful. A mission architecture includes the spacecraft (including payload and bus), operating in a specific orbit, interacting with some subject (see figure 4–1). The spacecraft is placed into orbit by a launch vehicle and is operated using a defined communication architecture that uses ground stations and operators. At the heart of the architecture are the objectives, requirements, and other factors that define the mission concept.

Figure 4–1. Mission Architechture



Source: James R. Wertz and Wiley J. Larson, eds., *Space Mission Analysis and Design*, 3d ed. (Dordrecht, Netherlands: Kluwer Academic Publishers, 1999).

Defining Requirements, Understanding Constraints

As stated earlier, the need desired by the policymaker or warfighter must eventually be articulated as a set of design-to, build-to, and test-to requirements by the systems engineer during the acquisition process. If we consider only technical requirements (the focus of this chapter), we can divide these requirements into a number of basic categories (similar to those specified by Military Standard-961c, "Preparation of Military Specifications and Associated Documents"). Within these broad categories, we can further define a number of typical requirements identified for military missions. These requirements are in turn specified by some number of detailed performance parameters. Finally, these parameters are constrained by a number of factors (see table 4–1). The point of this exercise is to distill the broad operational requirements normally levied on space systems down to a handful of constraining factors that affect them. The reader will notice a number of recurring themes that affect myriad types of requirements—for example, orbital mechanics. The balance of this chapter will explore these constraining factors to understand the possibilities and limits they pose on spacepower capabilities.

Table 4–1. Space Mission and Constraints

Requirement Category	Typical Requirement	Specified by	Constrained by
Performance	Resolution	Spatial resolution Spectral resolution Radiometric resolution Temporal resolution	Orbital mechanics Remote sensing physics
	Data rate	Bits per second	Communication physics
	Coverage	Latitude/longitude ranges	Orbital mechanics
	Maneuverability	Delta-V	Orbital mechanics Space launch and rocket propulsion
Interfaces	Spacecraft-to-launch vehicle	Mechanical bolt pattern, connectors pin in/out description	Space launch and rocket propulsion
	Spacecraft-to-ground segment	Data rates, frequencies, modulation schemes, encryption methods	Communication physics
	Spacecraft-to-spacecraft	Data rates, frequencies, modulation schemes, encryption methods, Doppler shifts	Communication physics
Physical Characteristics	Spacecraft mass, volume Constellation Description	Mass, volume, number of satellites, number of orbit planes, spacing of orbit planes	Spacecraft state of the art Orbital mechanics
Operational Environments	Launch environment Space environment	Vibration, thermal, acoustic, radio frequency gravitational, vacuum, neutral atmospheric, charged particles, radiation, micrometeoroid/orbital debris	Space launch and rocket propulsion Space environment
System Quality	Lifetime operability	Reliability Orbit lifetime Autonomy, interfaces	Spacecraft state of the art Orbital mechanics Space launch and rocket propulsion

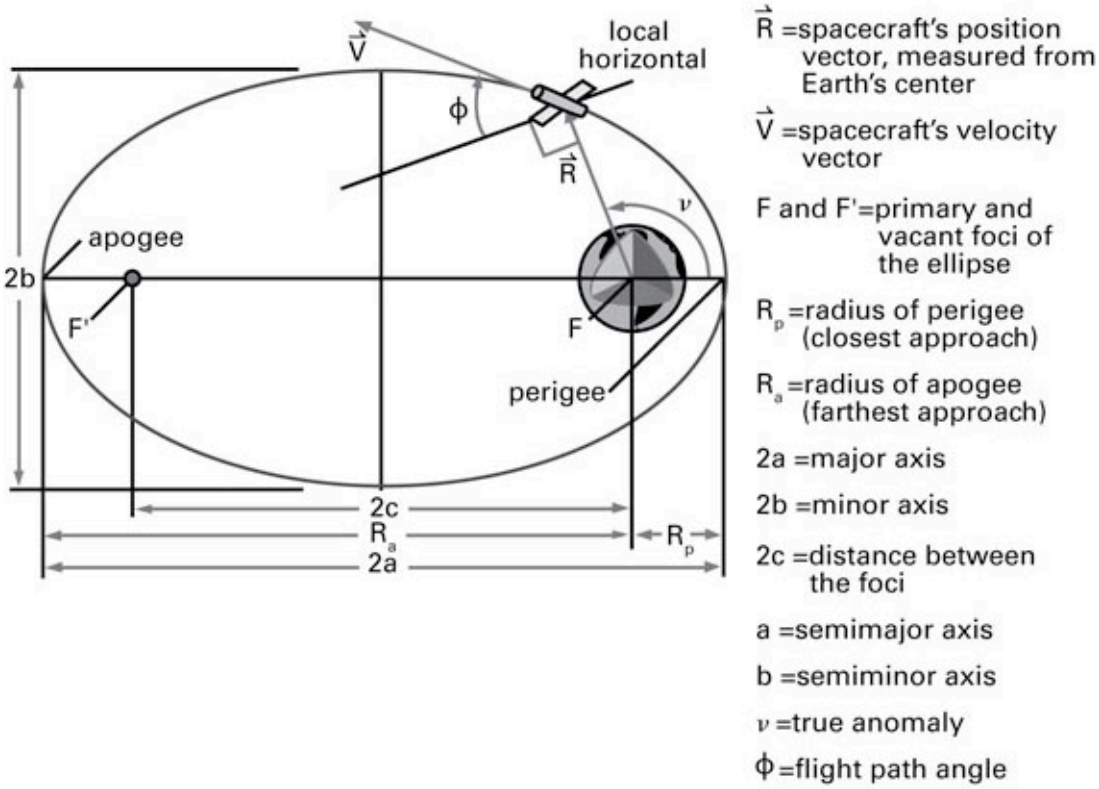
Orbital Mechanics

Simply put, an orbit is achieved when an object is moving fast enough that the Earth's curved surface is falling away from it faster than the object itself is pulled to the Earth by gravity. The velocity of the object (or spacecraft, for our purposes) and its position relative to the Earth define the specific orbit in which it moves. At ground level, an object would need a velocity of approximately 7.9 kilometers (km) per second (tangent to the Earth's surface) to effectively "fall" around the Earth—neglecting aerodynamic drag, of course. This motion is governed by Newton's second law of motion and law of gravitation and assumes that the spacecraft acts as a constant point mass, its mass is insignificant relative to the Earth's, the Earth is a perfect sphere, and no other forces (drag, thrust, solar, or lunar gravity, and so forth) are acting upon our spacecraft. These assumptions represent the requirements for the "restricted two-body problem," for which Newton's solution describes the spacecraft's location using two constants and a polar angle and represents a general relationship for any conic section (circle, ellipse, parabola, or hyperbola).

Describing Orbits

For the most useful case in this study, we consider the elliptical Earth orbit defined by the parameters shown in figure 4–2.

Figure 4–2. Elliptical Orbit Parameters



Source: Jerry J. Sellers et al., *Understanding Space: An Introduction to Astronautics*, 3d ed. (New York: McGraw-Hill, 2005), figure 4–33.

With no other forces acting upon the satellite, both total mechanical energy and angular momentum of the spacecraft remain constant throughout its orbit—consistent with Newton's laws of motion and the fact that gravity is a conservative force field. While in elliptical orbit, then, the satellite is constantly exchanging potential energy and kinetic energy, moving from apogee to perigee and back. At *apogee*—the highest point in an orbit—the satellite is moving slowest, while at *perigee*, the lowest point, it is moving fastest.

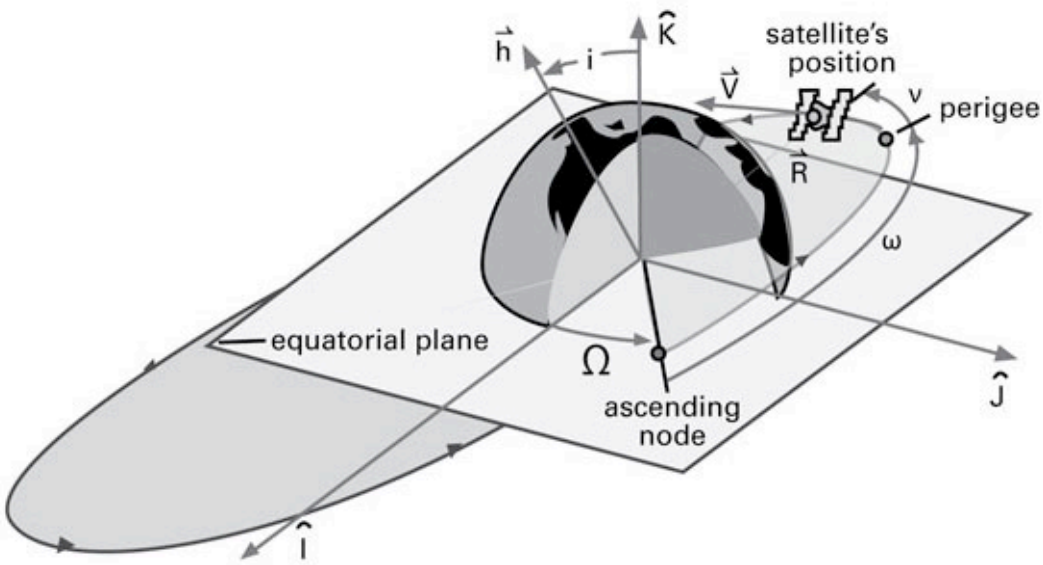
Operational orbits can be described in terms of six classical orbital elements (COEs) that describe their physical properties (see figure 4–3):

- semimajor axis, a (orbital size)
- eccentricity, e (orbital shape)
- inclination, I (orientation of the orbital plane with respect to the equatorial plane)
- right ascension of the ascending node, **Ω** (orientation of the orbital plane with respect to the Earth-centered reference frame)
- argument of perigee, **ω** (orientation of the orbit within its orbital plane)
- true anomaly, n (spacecraft's location in its orbit).

Note in the figure that *all* elliptical orbits *must* cross (or contain) the equatorial plane and have the center of the Earth at one focus of the orbital ellipse.[2] It is *not* possible to have a

natural orbit that forms a "halo" above the Earth's pole or that appears motionless ("hovering") over any spot not on the equator.

Figure 4–3. Classical Orbital Elements for Earth Orbits

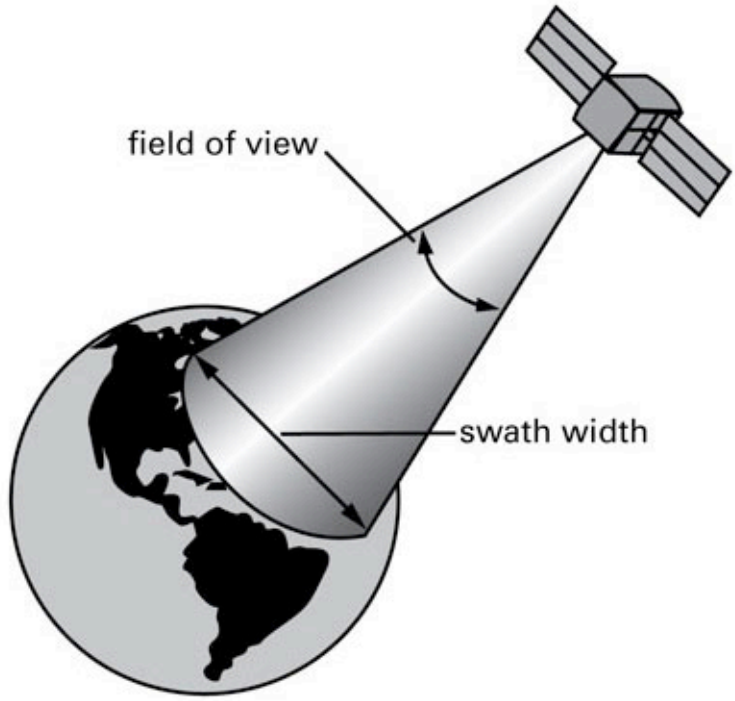


Source: Jerry J. Sellers et al., *Understanding Space: An Introduction to Astronautics*, 3d ed. (New York: McGraw-Hill, 2005), figure 5–9.

Earth-orbiting space missions supporting civil, commercial, and military objectives generally fall into one of four categories: communications, remote sensing, navigation and timing, and scientific. The previously presented physical laws governing spacecraft motion form the realm of the possible for which specific mission requirements can be met. The orbit's size, shape, and orientation determine whether the spacecraft payload can observe its target subjects and carry out other mission objectives. The orbit's size (height) determines how much of the Earth's surface the spacecraft's instruments can see, as well as how often it might pass overhead. Naturally, the higher the orbit, the more the total area that can be seen at once. But just as our eyes are limited in how much of a scene we can see without moving them or turning our head, a spacecraft payload has similar limitations. We define the payload's *field of view* as the cone of visibility for a particular sensor (see figure 4–4). Depending on the sensor's field of view and the height of its orbit, a specific total area on the Earth's surface is visible at any one time, with the linear width or diameter of this area defined as the *swath width*. Some missions require continuous coverage of a point on Earth or the ability to communicate simultaneously with every point on Earth. When this happens, a single spacecraft may not be able to satisfy the mission need, requiring a constellation of identical spacecraft placed in different (but often similar) orbits to provide the necessary coverage. The global positioning system (GPS) mission requirement, for example, requires a constellation of satellites because the mission requirements call for every point on Earth to be in view of

at least four GPS satellites at any one time—an impossibility with only four satellites at any altitude.

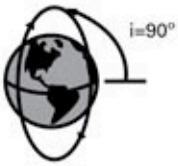
Figure 4–4. Satellite Field of View



Source: Jerry J. Sellers et al., *Understanding Space: An Introduction to Astronautics*, 3d ed. (New York: McGraw-Hill, 2005), figure 1–25.

Figure 4–5 and table 4–2 show various types of missions and their typical orbits. A geostationary orbit is a circular orbit with a period of about 24 hours and inclination of 0°. Geostationary orbits are particularly useful for communications satellites because a spacecraft in this orbit appears motionless to an Earth-based observer, such as a fixed ground station. Geosynchronous orbits are inclined orbits with a period of about 24 hours. Ground-based observers above about 70° latitude (north or south) cannot see a satellite at geostationary altitude as it is actually below the horizon. A semisynchronous orbit (used by the GPS constellation) has a period of 12 hours. Sun-synchronous orbits are retrograde (westbound) low Earth orbits (LEOs) typically inclined 95° to 105° and most often used for remote sensing missions because they pass over locations on Earth with the same Sun angle each time. A Molniya orbit is a semisynchronous, eccentric orbit used for missions requiring coverage of high latitudes, those that cannot access a geostationary orbit as described above.

Figure 4–5. Types of Orbits and Their Inclinations

Inclination	Orbital Type	Diagram
0° or 180°	Equatorial	
90°	Polar	
0° ≤ i < 90°	Direct or Prograde (moves in the direction of Earth's rotation)	
90° < i ≤ 90°	Indirect or Retrograde (moves against the direction of Earth's rotation)	

Source: Jerry J. Sellers et al., *Understanding Space: An Introduction to Astronautics*, 3d ed. (New York: McGraw-Hill, 2005), table 5–2.

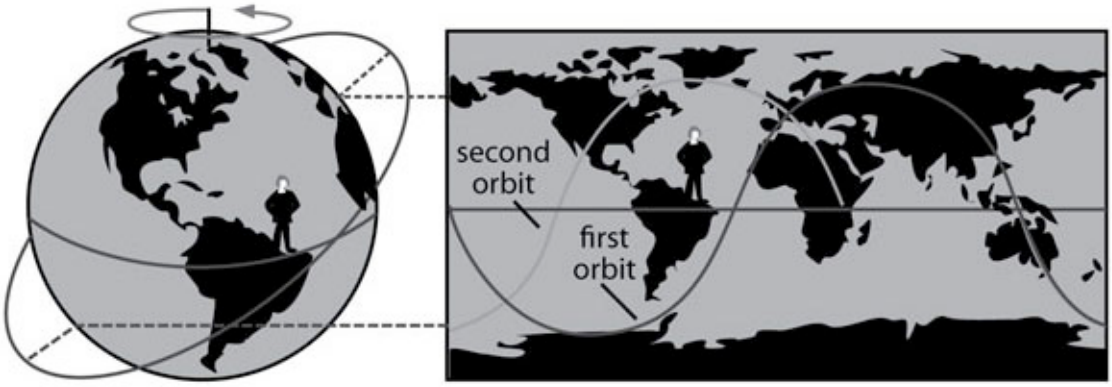
Table 4–2. Satellite Missions and Orbits

Mission	Orbital Type	Semimajor Axis (Altitude)	Period	Inclination	Other
Communication Early warning Nuclear detection	Geostationary	42,158 km (35,780 km)	~24 hr	~0°	$e \cong 0$
Remote sensing —Weather	Sun-synchronous Geostationary	~6,500–7,300 km (~150–900 km) 42,158 km (35,780 km)	~90 min ~24 hr	~95° ~0°	$e \cong 0$ $e \cong 0$
Navigation —GPS	Semi-syn-chronous	26,610 km (20,232 km)	12 hr	55°	$e \cong 0$
Space Shuttle	Low-Earth orbit	~6,700 km (~300 km)	~90 min	28.5°, 39°, 51°, or 57°	$e \cong 0$
Communication/ intelligence	Molniya	26,571 km (R_p = 7,971 km; R_a = 45,170 km)	12 hr	63.4°	$\omega = 270°$ $e \cong 0.7$

Source: Jerry J. Sellers et al., *Understanding Space: An Introduction to Astronautics*, 3d ed. (New York: McGraw-Hill, 2005), table 5–4.

Spacecraft users often need to know what part of Earth their spacecraft is overlying at any given time. For instance, remote sensing satellites must be over precise locations to get the coverage they need. A spacecraft's ground track is a trace of the spacecraft's path over the Earth's surface while the Earth rotates beneath the satellite on its axis. Ground tracks are presented to the user on a flat (Mercator) projection of the Earth (see figure 4–6).

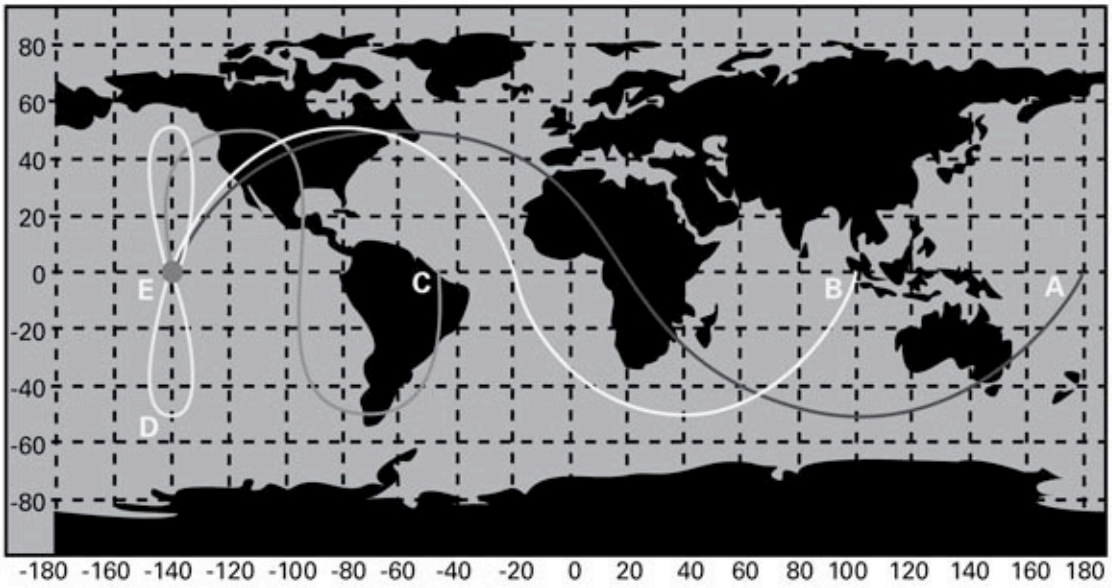
Figure 4–6. Satellite Ground Tracks



Source: Jerry J. Sellers et al., *Understanding Space: An Introduction to Astronautics*, 3d ed. (New York: McGraw-Hill, 2005), figure 5–33.

The impact of variation in orbital elements such as semi-major axis, inclination, and argument of perigee is shown in figures 4–7, 4–8, and 4–9.[3]

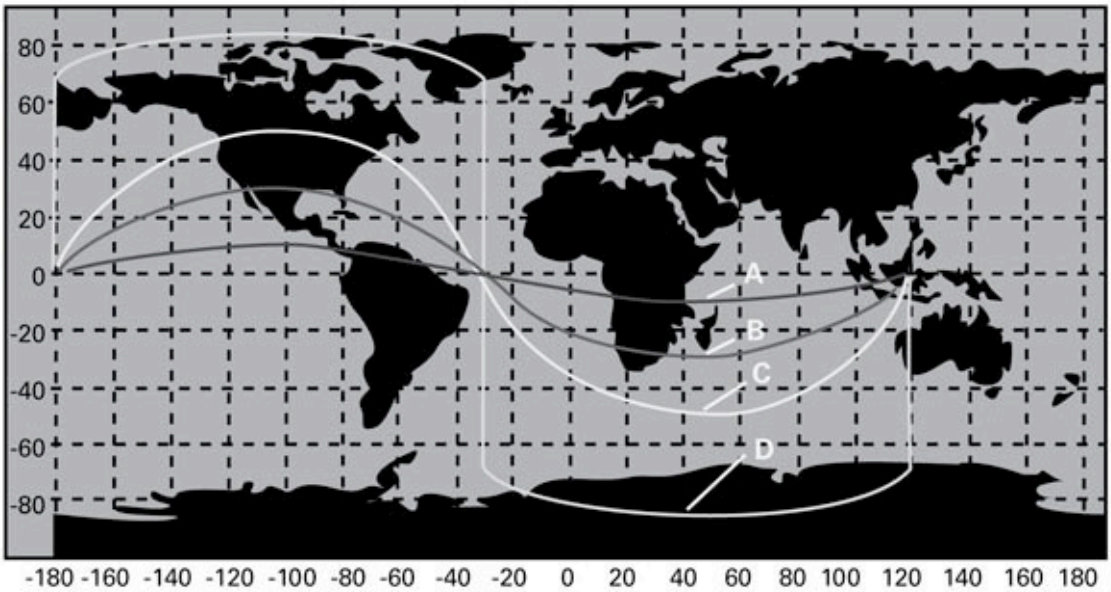
Figure 4–7. Orbital Ground Tracks with Different Periods



A = 2.67 hours; B = 8 hours; C =18 hours; D = E = 24 hours.

Source: Jerry J. Sellers et al., *Understanding Space: An Introduction to Astronautics*, 3d ed. (New York: McGraw-Hill, 2005), figure 5–33.

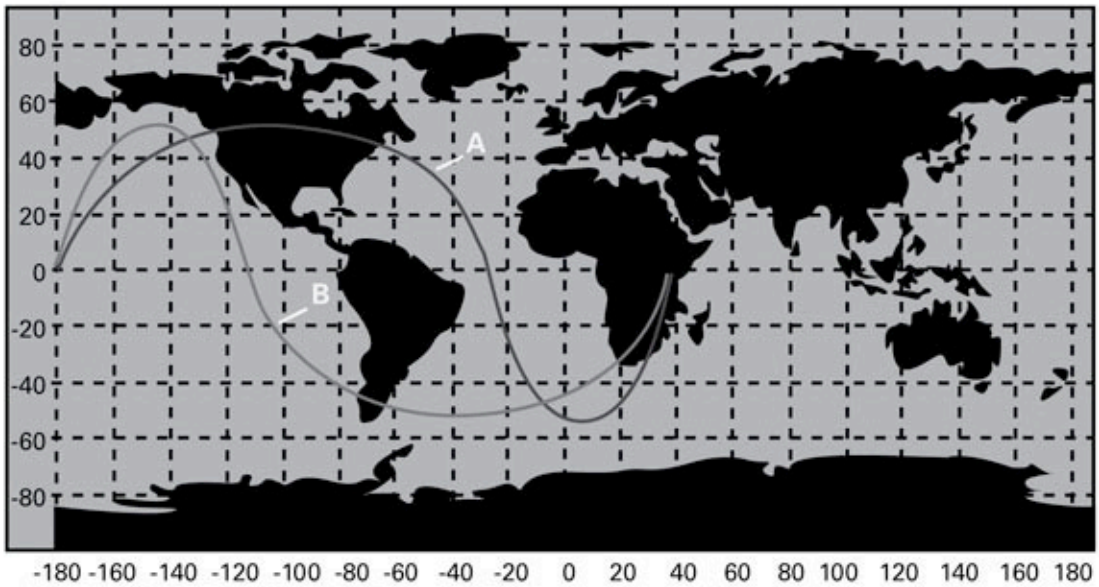
Figure 4–8. Orbital Ground Tracks with Different Inclinations



A = 10°; B = 30°; C = 50°; D = 85°.

Source: Jerry J. Sellers et al., *Understanding Space: An Introduction to Astronautics*, 3d ed. (New York: McGraw-Hill, 2005), figure 5–35.

Figure 4–9. Orbital Ground Tracks with Different Perigee Locations



Both orbits have period of 9.3 hours, inclination of 50°, highly elliptical; orbit A perigee is in Northern Hemisphere, orbit B perigee is in Southern Hemisphere.

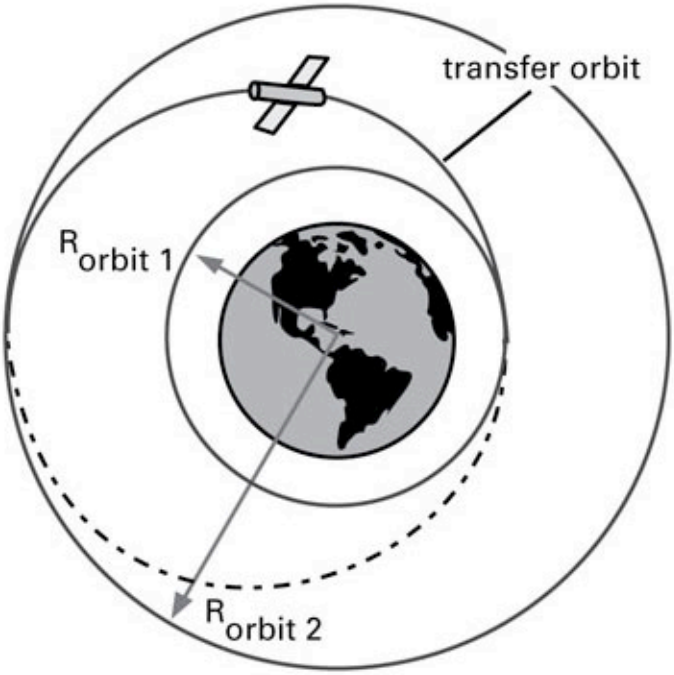
Source: Jerry J. Sellers et al., *Understanding Space: An Introduction to Astronautics*, 3d ed. (New York: McGraw-Hill, 2005), figure 5–36.

Maneuvers and Rendezvous

The ability to maintain a desired orbit and orientation within that orbit, to maneuver to possibly more useful orbits, or to rendezvous with other objects in space can be critical to overall space capability and survivability. Once a spacecraft achieves its assigned, desired orbit, it seldom remains there. Most space missions require changes to one or more of the classic orbital elements at least once. Geosynchronous satellites, for example, are sometimes first launched into a low perigee (~300 km) "parking orbit" due to launch vehicle limitations before transferring to their final orbit, requiring a large change in semi-major axis as well as shifting the satellite's inclination from that of the parking orbit to 0°. After achieving their desired mission orbit, many satellites regularly make small adjustments to compensate for small perturbations (for example, drag, solar wind, gravitational variations) to stay in that orbit. Spacecraft may also need to perform maneuvers to rendezvous with other spacecraft, as when the space shuttle maneuvers to dock with the International Space Station. The ability to maneuver in space differentiates more capable space systems from simpler buoy-like satellites with limited operational flexibility—but these extra capabilities come at some cost.

Spacecraft maneuvers, beyond simple adjustments to maintain a current orbit, can be classified as in-plane, out-of-plane, and combined, referring to the orbital plane into which the maneuver is executed. In-plane maneuvers primarily affect the semi-major axis of an orbit, enlarging or reducing the "size" of the orbit and therefore increasing or decreasing the orbit period. In either case, the spacecraft expends energy—usually in the form of burned rocket propellant. Generally, this change in energy takes the form of a change in velocity (ΔV) executed tangentially to the satellite's flight path. The most well known of these maneuvers, the Hohmann transfer, is a combination of two such "burns" that moves a satellite from one circular orbit to another using minimum energy (see figure 4–10).

Figure 4–10. Hohmann Transfer



Source: Jerry J. Sellers et al., *Understanding Space: An Introduction to Astronautics*, 3d ed. (New York: McGraw-Hill, 2005), figure 6–4.

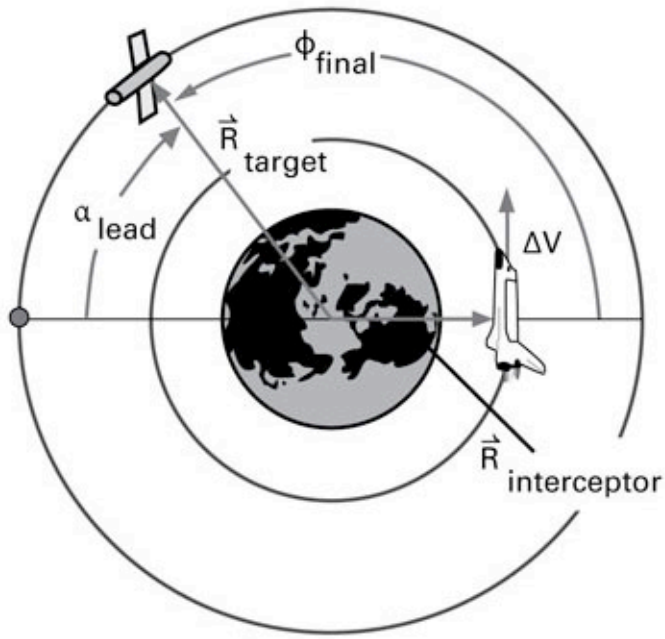
For the case where a satellite is moved from a lower to a higher orbit, the first burn (all burns are assumed to be impulsive) moves the satellite from the initial orbit to the point of perigee in the transfer orbit. The transfer ellipse's semi-major axis is the average of the semi-major axes of the initial and target circular orbits, and the ΔV needed to accomplish this first phase is the difference in the velocity at that point between the circular and elliptical orbits. Once the satellite reaches apogee of the transfer orbit, another burn is required to circularize its path into the final orbit. Again, this ΔV will be the difference between the velocity of the two orbits (transfer and final) at that point, and the total ΔV required for the mission is the sum of these two burns.[4]

Operationally, relatively small in-plane adjustments can change overhead passage time of LEO satellites by changing orbital period, can be used for collision avoidance, or can extend the on-orbit life of a LEO satellite whose orbit has slowly degraded due to atmospheric drag. Conversely, maneuvers can accelerate reentry by dropping the perigee of a satellite into a region where atmospheric drag increases, park an unused or nearly dead satellite into a safe orbit away from other operational systems, or initiate rendezvous with another spacecraft.

On-orbit rendezvous or interception maneuvers fall into two general categories: co-planar and co-orbital. In the former, a Hohmann transfer approach combines with appropriate phasing in order to time the burns correctly. The initial phase angle between the

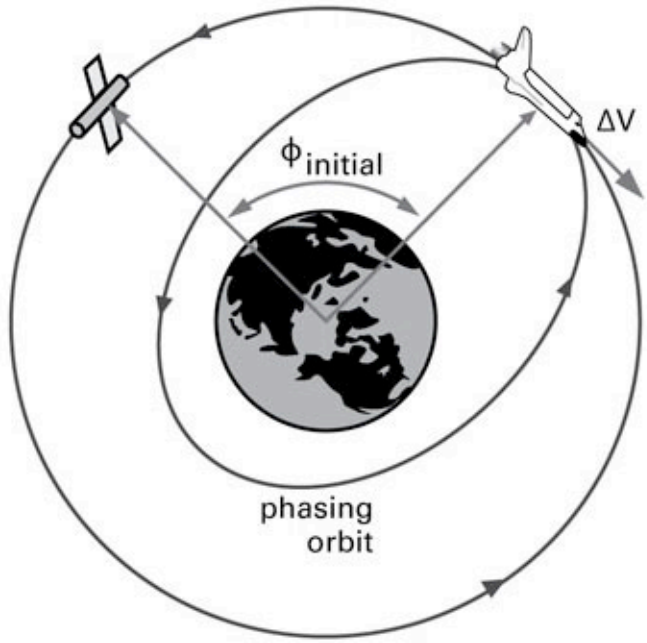
interceptor and target as well as the different speeds of each spacecraft in its particular orbit determines timing of the maneuver (see figures 4–11 and 4–12).

Figure 4–11. Coplanar Rendezvous



Source: Jerry J. Sellers et al., *Understanding Space: An Introduction to Astronautics*, 3d ed. (New York: McGraw-Hill, 2005), figure 6–12.

Figure 4–12. Co-orbital Rendezvous

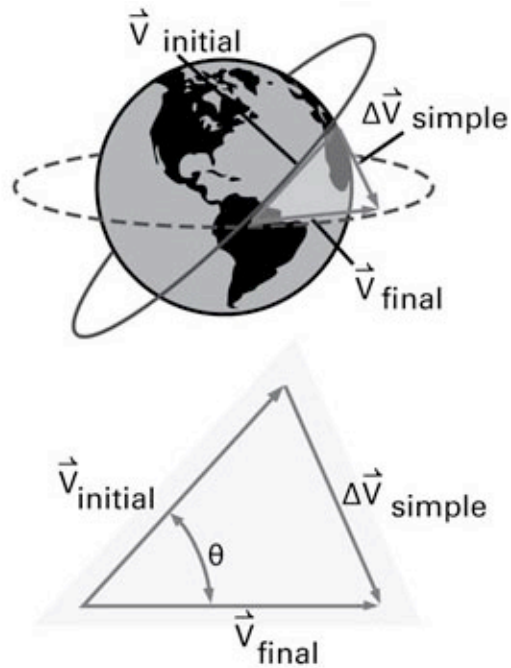


Source: Jerry J. Sellers et al., *Understanding Space: An Introduction to Astronautics*, 3d ed. (New York: McGraw-Hill, 2005), figure 6–14.

Co-orbital rendezvous occurs when both the target and interceptor are in the same orbit, though at different positions (true anomaly). In this case, the interceptor must maneuver into a phasing orbit, "speeding up to slow down" (or the converse) in order to meet the target after completing one phasing orbit. In both cases (co-planar and co-orbital), the interceptor must burn again at rendezvous to maintain its position near the target and not remain in its intercept or phasing transfer orbit.[5]

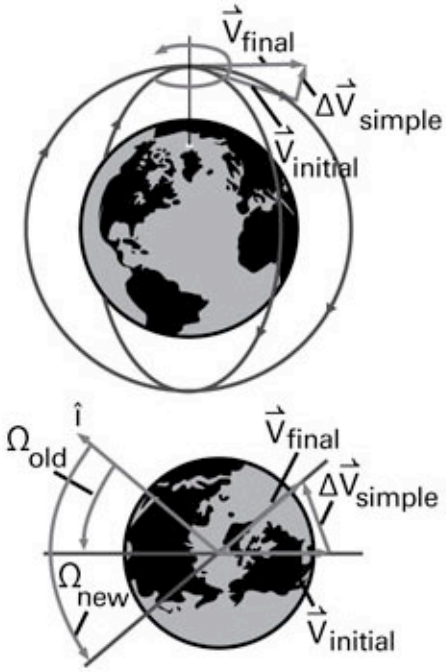
Out-of-plane maneuvers, or plane changes, occur when the satellite's direction of motion changes—usually by a nontangential burn. Operationally, plane changes to adjust the inclination of an orbit (see figure 4–13) are most commonly used when satellites launched into parking orbits from nonequatorial launch sites maneuver into geostationary orbits (a = 42,160 km, i = 0°). The plane change itself often combines with the apogee burn that circularizes the satellite's orbit at that altitude. For satellites in high inclination orbits (such as polar or Sun-synchronous), plane changes executed over one of the poles change the right ascension of the ascending node for the orbit (see figure 4–14), thus altering the overhead passage time and sun angle for that satellite. Since the burn is performed perpendicular to the spacecraft's flight path, the magnitudes of the spacecraft's initial and final velocities are identical.

Figure 4–13. Simple Inclination Plane Change



Source: Jerry J. Sellers et al., *Understanding Space: An Introduction to Astronautics*, 3d ed. (New York: McGraw-Hill, 2005), figure 6–7.

Figure 4–14. Simple Plane Change



Source: Jerry J. Sellers et al., *Understanding Space: An Introduction to Astronautics*, 3d ed. (New York: McGraw-Hill, 2005), figure 6–8.

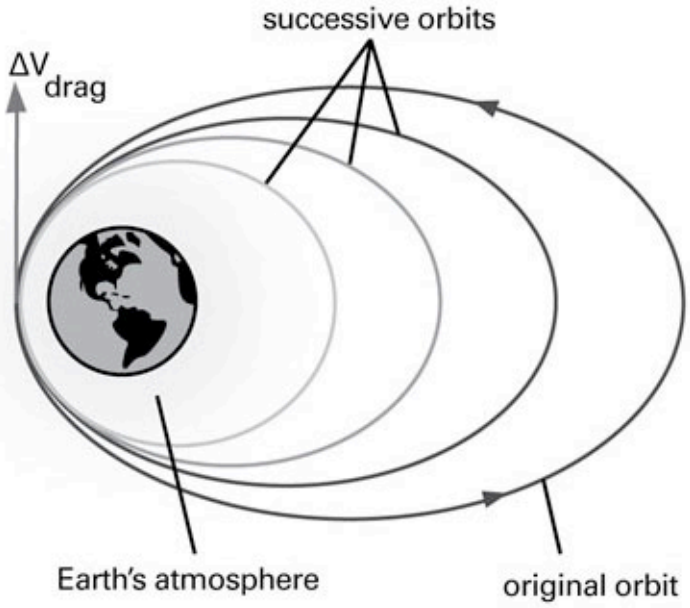
Orbit Perturbations

If some of the original simplifying assumptions for orbits are changed to include a more complete view of the forces acting on a spacecraft, COEs other than just the true anomaly will begin to change over time. The primary perturbations to simplified, classical orbital motion are:

- atmospheric drag
- Earth's oblateness (or nonsphericity in general)
- solar radiation pressure
- third-body gravitational effects (Moon, Sun, planets, and so forth)
- unexpected thrusting—caused by either outgassing or malfunctioning thrusters; can perturb orbits or cause spacecraft rotation.

While the Earth's atmosphere gets thinner with altitude, it still has some effect as high as 600 km. Because many important space missions occur in orbits below this altitude, this very thin air causes drag on these spacecraft, taking energy away from the orbit in the form of friction on the spacecraft. Because orbital energy is a function of semi-major axis, the semi-major axis will decrease over time. For noncircular orbits, the eccentricity also decreases since the drag at lower altitudes (near perigee) is higher than at apogee (see figure 4–15).

Figure 4–15. Effects of Drag on Eccentric Low Earth Orbit

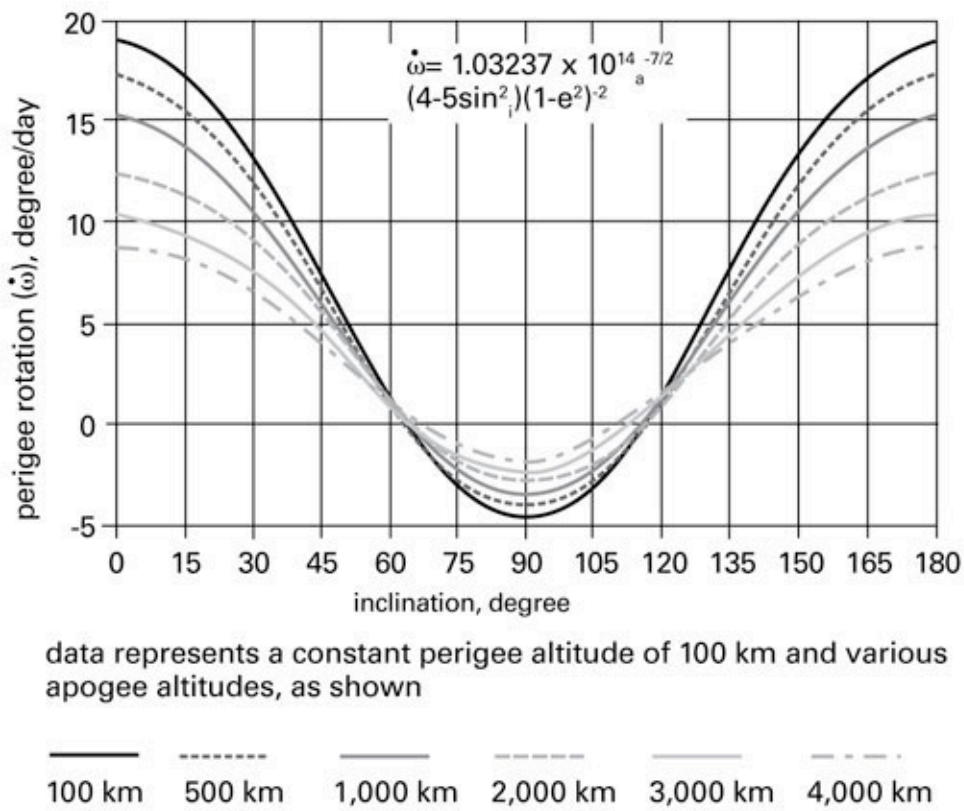


Source: Jerry J. Sellers et al., *Understanding Space: An Introduction to Astronautics*, 3d ed. (New York: McGraw-Hill, 2005), figure 8–7.

Factors such as the Earth's day-night cycle, seasonal tilt, variable solar distance, and fluctuating magnetic field, as well as the Sun's 27-day rotation and 11-year cycle for sunspots, make precise real-time drag modeling nearly impossible. Further complicating the modeling problem is the fact that the force of drag also depends on the spacecraft's coefficient of drag and frontal area, which can vary widely depending upon spacecraft orientation.

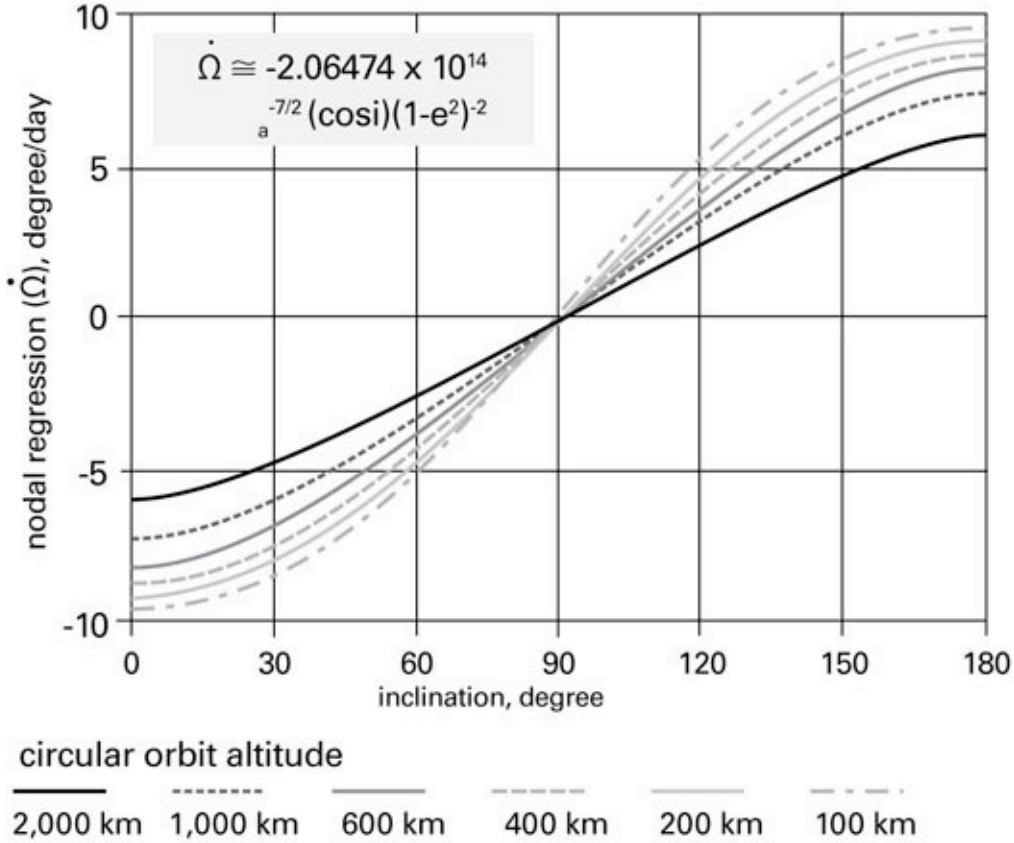
In addition, the Earth is not a perfect sphere, affecting the earlier point mass assumption. The most pronounced nonspheroidal characteristic is oblateness, meaning that the Earth bulges at the equator and is somewhat flattened at the poles, modeled using the constant J2. Unlike drag, which is a nonconservative force, the J2 effect is gravitational and does not change a spacecraft's total mechanical energy (that is, constant semi-major axis). Instead, J2 acts as a torque on the orbit since the Earth's gravitational pull is no longer directed from the Earth's exact center, causing the right ascension of the ascending node (RAAN, or **Ω**) to shift or precess with each orbit[6] and the perigee to rotate through an elliptical orbit. J2 effect is a function of orbit inclination and altitude as shown in figures 4–16 and 4–17 describing its effect on RAAN and argument of perigee.[7]

Figure 4–16. Perigee Rotation Rate



Source: Jerry J. Sellers et al., *Understanding Space: An Introduction to Astronautics*, 3d ed. (New York: McGraw-Hill, 2005), figure 8–11.

Figure 4–17. Nodal Regression Rate



Source: Jerry J. Sellers et al., *Understanding Space: An Introduction to Astronautics*, 3d ed. (New York: McGraw-Hill, 2005), figure 8–10.

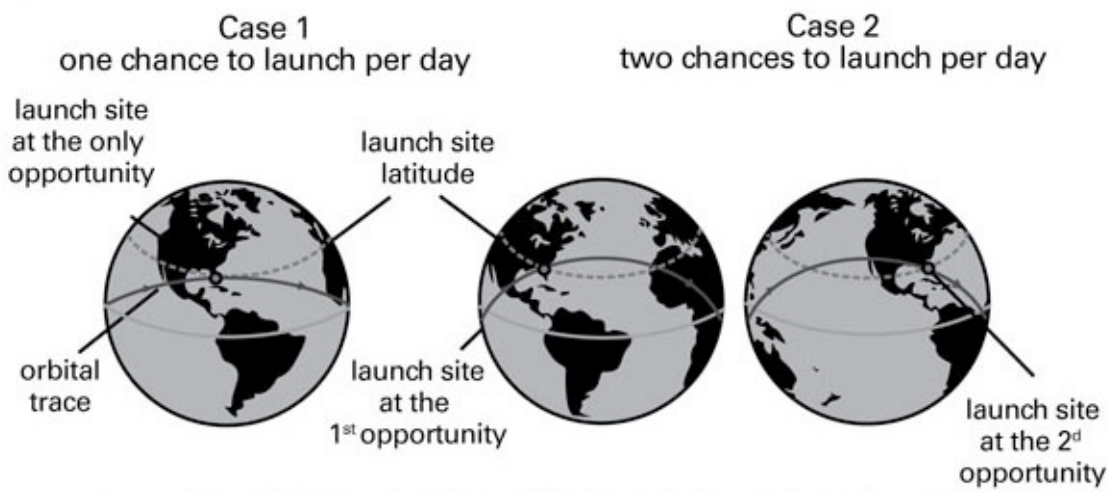
Other, smaller perturbing forces also affect a spacecraft's orbit and its orientation within it, including solar radiation pressure, third-body gravitational effects (Moon, Sun, planets, and so forth), and unexpected thrusting—caused by either outgassing or malfunctioning thrusters. The importance of each perturbation is a function of the spacecraft's mission and need for orbital and attitude accuracy.

Space Launch and Rocket Propulsion

For most space missions, the spacecraft must be placed into a specific orbit, requiring a launch at a particular time and in a specific direction. A "launch window" is a period when a spacecraft can be launched directly into its initial orbit from a given launch site, and it corresponds to the time when the chosen orbit passes over the launch site. In practice, a launch window normally covers several minutes or even hours around this exact time since mission planners have some flexibility in the orbital elements they can accept, and launch vehicles usually can steer enough to expand the length of the window somewhat. However, to launch directly into an orbit, the launch site and orbital plane must intersect at least once per day. Physically, that means that the inclination of the

desired orbit must be equal to or greater than the latitude of the launch site. If the two are equal, then there will be one launch opportunity per day. If the inclination is greater than the latitude, there will be two potential opportunities since, in this case, the spacecraft may be launched toward either the ascending or descending node (see figure 4–18). However, due to practical restrictions at a given launch site, only one of these opportunities may be used. For example, launches from Cape Canaveral are restricted to the east and northeast only due to overflight considerations.

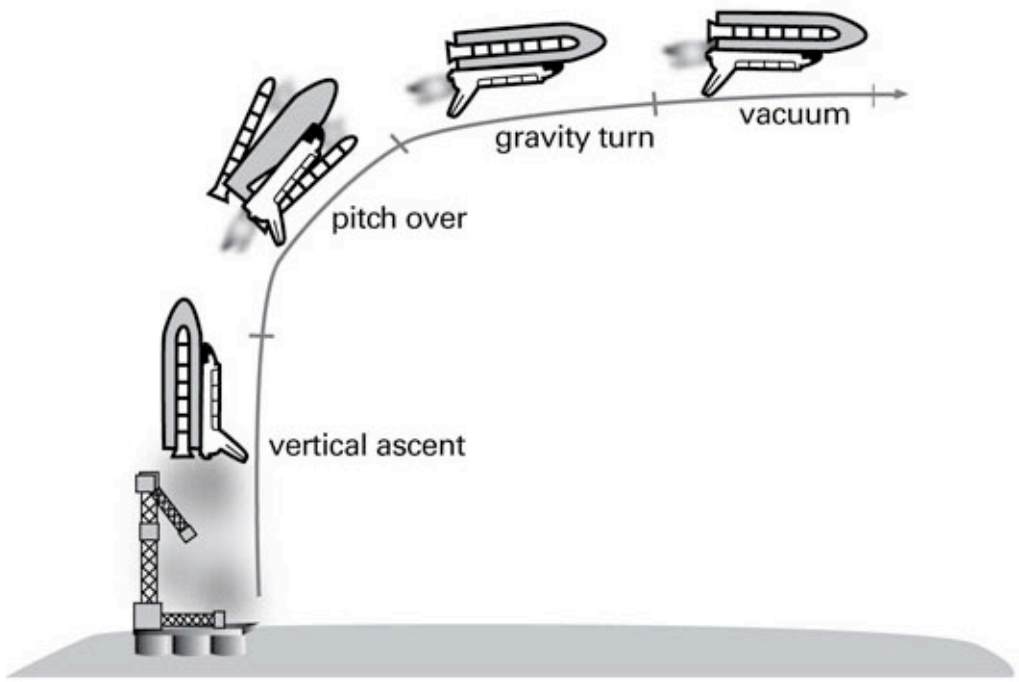
Figure 4–18. Launch Windows



Source: Jerry J. Sellers et al., *Understanding Space: An Introduction to Astronautics*, 3d ed. (New York: McGraw-Hill, 2005), figure 9–7.

During liftoff, a launch vehicle goes through four distinct phases from the launch pad into orbit (see figure 4–19). During vertical ascent, the vehicle gains altitude quickly to escape the dense, high-drag lower atmosphere. The vehicle then executes a slow pitch maneuver to gain velocity downrange (horizontally), followed by a turn in which gravity pulls the launch vehicle's trajectory toward horizontal. In the final vacuum phase, the launch vehicle is effectively out of the Earth's atmosphere and continues accelerating to gain the necessary velocity to achieve orbit. The vehicle's on-board flight control system works to deliver the vehicle to the desired burnout conditions: velocity, altitude, and flight-path angle. The velocity needed to get to orbit consists of the launch vehicle's burnout velocity and the tangential velocity that exists at its launch site due to the Earth's rotation.

Figure 4–19. Phases of Launch Vehicle Ascent



Source: Jerry J. Sellers et al., *Understanding Space: An Introduction to Astronautics*, 3d ed. (New York: McGraw-Hill, 2005), figure 9–14.

The closer a launch site is to the equator, the greater the velocity assist provided to the launch vehicle from the Earth's rotation when launching eastward.[8] A given launch vehicle can launch a larger payload due east from a launch site at a lower latitude. For westerly launches into retrograde orbits, this same tangential velocity reduces launch capability.

Determining the total velocity needed to launch a spacecraft is a very complex problem requiring numerical integration in sophisticated trajectory modeling programs that incorporate launch vehicle properties, atmospheric density models, and other factors. To determine the overall design velocity, the mission designer must consider velocity needed to overcome gravity and reach the correct altitude, inertial velocity needed at burnout for the desired orbit, velocity of the launch pad due to Earth's rotation, and velocity losses due to air drag, back pressure, and steering losses. The difference between the launch vehicle's actual design velocity for a specific payload mass and the design velocity is the launch margin.

Rocket propulsion is responsible for not only launching spacecraft into orbit, but also maneuvering them once they are in space and adjusting their attitude to accomplish their mission as needed (see table 4–3). While there are many forms of rocket propulsion, they all depend upon Newton's laws to apply forces (thrust) or moments (torque). Rockets operate by expelling high-speed exhaust in one direction, causing the spacecraft to accelerate in another. The only types of rockets currently in use are thermodynamic and electrodynamic. Thermodynamic rockets rely on heat and pressure to accelerate a

propellant (for example, the chemical reaction of fuel and oxidizer burning, or the heat generated by electrical heating or a nuclear reaction) using converging/diverging nozzles to convert the thermal energy to kinetic energy. Examples of thermodynamic rockets include chemical (liquid, solid, and hybrid); nuclear-thermal; solar-thermal; and electro-thermal. Electrodynamic rockets use electric and/or magnetic fields to accelerate charged particles to high velocities and include ion or electrostatic, Hall effect, and pulsed plasma thrusters.

Table 4–3. Rocket Propulsion Types and Performance Comparison

Type	Propellant Examples	I_{sp} (sec)	Thrust Range (N)	Advantages	Disadvantages
Thermodynamic					
Chemical					
Liquid					
Bipropellant	LO_2/LH_2 LO_2/Kerosene Hydrazine/ Nitrogen Tetroxide	334–455	$10–10^6$	• High I_{sp} • Throttleable • Restartable	• Must manage two propellants • Requires thermal control for chamber and nozzle
Mono-propellant	Hydrazine Hydrogen Peroxide	180–240	10–1,000	• Simple • Large flight heritage • One propellant to manage	• Lower I_{sp} than bipropellant • Toxic
Solid	Ammonium Perchlorate/ Aluminum/Binder	300	$1–10^6$	• Simple, reliable • No propellant management needed • Higher thrust	• Modest I_{sp} • Susceptible to propellant grain cracks • Difficult to stop; can't restart
Hybrid	Hydrogen Peroxide/ Polyethylene	333	$10–10^6$	• Simpler than bipropellant • Safer, more flexible than solids; restartable	• Limited heritage • Modest I_{sp}
Nuclear-thermal	H_2	1,000	$1–10^6$	• Long-term energy supply • Refuelable, reusable • High I_{sp}, high thrust	• No flight heritage • Environmental/ political concerns
Electro-thermal	Ammonia (NH_3)	800	0.1–1	• Simple, reliable • High I_{sp}	• Requires large amounts of on-board electrical power • Low thrust
Solar-thermal	Ammonia	800	0.1–10	• High I_{sp} • Long-term energy supply	• Requires solar energy collection • Low thrust
Electrostatic					

In all cases, the efficiency of a rocket is measured in terms of specific impulse (I_{sp}). Specific impulse gives us an effective "miles per gallon" rating as it relates the amount of thrust produced for a given weight flow rate of the propellant. Higher I_{sp} rockets produce more total ΔV for the same amount of propellant than low Irockets. However, high Irockets (such as ion thrusters) are typically low thrust and not suited for some uses. The Rocket Equation[9] relates the initial and final masses of a spacecraft with the specific impulse of the propulsion system to determine the total ΔV available. It is the mission designer's job to determine a space mission's many propulsion needs and select the appropriate system for each phase.

The total cost of a specific spacecraft's on-board propulsion system includes several factors, in addition to the bottom-line price tag, before making a final selection.[10] These factors include mass performance (measured by I_{sp}), volume required, time (how fast it completes the needed ΔV), power requirements, safety costs (how safe the system and its propellant are and how difficult it is to protect people working with the system), logistics (system and propellant transport to launch), integration cost with other spacecraft subsystems, and technical risk (what flight experience does it have or how did it perform in testing). Different mission planners naturally place a higher value on some of these factors than on others. A complex commercial mission may place high priority on reducing technical risk—for example, a new type of plasma rocket, even if it offers lower mass cost, may be too risky when all other factors are considered.

A basic understanding of rocket propulsion informs mission planners and space experts who next consider one of the most obvious manifestations of spacepower—space launch systems. While more widely open international access to launch has provided some level of space presence and power to dozens of nations, a space launch capability defines a unique level of spacepower and is possessed by many fewer states. Requirements for an operational launch system are technical, geographic, and financial. Development of a new space launch system consumes hundreds of millions to many billions of dollars[11] and requires broad expertise in propulsion systems, avionics, logistics, manufacturing, and integration processes. Testing during system development also requires extensive infrastructure and range facilities (often consisting of thousands of square miles of controlled airspace) that can assure public safety, while operational launch facilities must also include payload processing and mission control centers.

The physical, financial, and technical difficulties of launch are evident in the relatively small number of launch vehicles developed in the world's 50 years of space launch experience. Contrasted with the first 50 years of powered atmospheric flight, today's launch vehicles represent relatively small advances in capability from the Russian and American boosters of the late 1950s and early 1960s that trace their development to intercontinental ballistic missiles of the Cold War. All based on chemical (liquid and/or solid) propulsion, today's boosters can lift little more than 4 percent of their lift-off mass to LEO and much less than half that amount to geosynchronous transfer orbit from which a final apogee burn can place a spacecraft into a geostationary orbit. All vehicles use a

minimum of two stages to achieve orbit (and some as many as four) with costs on the order of $10,000 per pound to LEO and $12,000 per pound to geostationary orbit.

Several attempts to incrementally or drastically reduce launch costs and improve responsiveness have not significantly altered the status quo. The space shuttle, originally intended as a "space truck" to access space routinely and cheaply, suffered from its immense complexity, resulting in enormous per-launch cost growth. After completing its support of the International Space Station construction in 2010, it will be retired, largely due to safety and high cost of ownership. Small launch vehicles such as Orbital Sciences' Pegasus air-launched vehicle (~$22 million per launch for about 500 kilograms [kg] to LEO) have served niche markets without reducing overall costs, as have refurbished Russian and American intercontinental ballistic missiles (for example, Minotaur). SpaceX's Falcon 1 (with an advertised cost of roughly $6 million per launch as of this writing) and the larger follow-on Falcon 9 may achieve some cost savings, but nothing near the order of magnitude or greater savings that might transform space access to a more aviation-like paradigm. More exotic attempts to change the launch industry—such as the NASA-funded/Lockheed Martin–developed VentureStar single-stage-to-orbit, fully reusable launch vehicle—have not been successful beyond the PowerPoint slide.[12] In fact, current technology makes it very difficult to reduce space launch costs or turnaround time for launch vehicles or to build cost-effective reusable launch systems. With no new rocket propulsion technologies for space launch available in the foreseeable future, savings in launch costs and processing time will be incremental and depend on gains in reliability, manufacturing techniques, and miniaturization of payloads.

Whatever the state of launch, mission planners and space experts considering launch systems must consider the following factors:

- performance capability (whether the launch vehicle can take the desired mass to the mission orbit)
- vehicle availability (whether the vehicle will be available and ready to launch when needed)
- spacecraft compatibility (whether the payload will fit in the launch vehicle fairing and survive the launch environment imposed by the launch vehicle) cost.

Space Environment

Once in space, the unique environment presents several challenges to mission accomplishment, affecting not only spacecraft but also the signals received and transmitted in the course of that mission. The primary space environmental challenges are:

- free-fall gravitational conditions
- atmospheric effects
- vacuum
- collision hazards
- radiation and charged particles.

The free-fall environment gives rise to problems with fluid manage-ment—measuring and pumping—typically related to on-board liquid propulsion systems. For manned spaceflight, the physiological issues can be quite severe, marked by fluid shift within the body (lower body edema), altered vestibular function (motion sickness), and reduced load on weight-bearing tissues resulting in bone decalcification and muscle tissue loss.

In addition to the effect of drag on spacecraft (mentioned earlier as a perturbation), the upper reaches of the atmosphere contain atomic oxygen caused when radiation splits molecular oxygen (O_2). Much more reactive than O_2, atomic oxygen can cause significant degradation of spacecraft materials, weakening components, changing thermal characteristics, and degrading sensor performance.

The vacuum of space creates three potential problems for spacecraft: outgassing, cold welding, and heat transfer. Outgassing occurs when materials, such as plastics or composites, release trapped gasses (volatiles) upon exposure to vacuum—particularly problematic if the released molecules coat delicate sensors, such as lenses, or cause electronic components to arc, damaging them. Prior to launch, spacecraft are usually tested in a thermal-vacuum chamber to reduce or eliminate potential outgassing sources. Cold welding occurs between mechanical parts having very little separation between them. After launch, with the small cushion of air molecules between components eliminated, parts may effectively "weld" together. The potential for cold welding can be mitigated by avoiding the use of moving parts or by using lubricants carefully selected to avoid evaporation or outgassing. Heat transfer via conduction, convection, and especially radiation may also complicate spacecraft operation—for example, causing temperatures to drop below acceptable operating levels—and must be considered in any spacecraft design.

The chances that a spacecraft will be hit by very small pieces of debris (natural or manmade) grow with each new space mission. Twenty thousand tons of natural materials—dust, meteoroids, asteroids, and comets— hit Earth every year, and estimates of the amount of manmade space debris approach 2,200 tons.[13] Air Force Space Command, headquartered in Colorado Springs, Colorado, uses a worldwide network of radar and optical telescopes to track more than 13,000 baseball-sized and larger objects in Earth orbit, and some estimate that at least 40,000 golf ball–sized pieces (too small for the Air Force to track) are also in orbit,[14] not including smaller pieces such as paint flakes and slivers of metal.

The energy of (and thus potential damage caused by) even a very small piece of debris hitting a spacecraft at relative speeds of up to 15 km per second makes the debris environment in Earth orbit a serious issue.[15] For a spacecraft with a cross-sectional area of 50 to 200 square meters at an altitude of 300 km (typical for space shuttle missions), the chance of getting hit by an object larger than a baseball during a year in orbit is about 1 in 100,000 or less.[16] The chance of getting hit by something only 1 millimeter or less in diameter, however, is about 100 times more likely, or about 1 in 1,000 during a year in orbit. The collision between two medium-sized spacecraft would result in an enormous amount of high-velocity debris, and the resulting cloud would expand as it orbited,

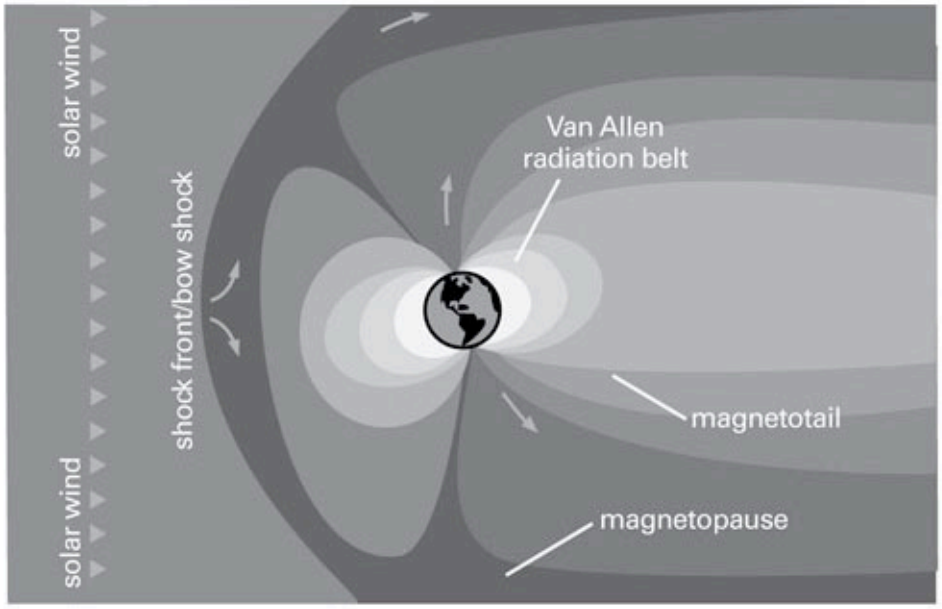
greatly increasing the likelihood of impacting another spacecraft. The domino effect could ruin an important orbital band for decades.

Electromagnetic (EM) radiation from the Sun, while primarily in the visible and near-infrared parts of the EM spectrum, also contains significant higher energy radiation, such as X-rays and gamma rays. While solar cells generate needed electrical power from this radiation, spacecraft and astronauts well above the atmosphere face negative consequences from it depending on the wavelength of the radiation. The Sun's radiation heats exposed surfaces, which can degrade or damage surfaces and electronic components, and the resulting solar pressure can perturb orbits. Prolonged exposure to ultraviolet radiation degrades spacecraft coatings and is especially harmful to solar cells, reducing their efficiency and possibly limiting the useful life of the spacecraft they power. In addition, during intense solar flares, bursts of energy in the radio region of the spectrum can interfere with onboard communications equipment. Solar radiation pressure, though only 5 Newtons of force for 1 square kilometer of surface, can also disturb spacecraft orientation.

Perhaps the most dangerous aspect of the space environment is the pervasive influence of charged particles caused by solar activity and galactic cosmic rays. The Sun expels a stream of charged particles (protons and electrons) at a rate of 10^9 kg per second as part of the solar wind. During intense solar flares, the number of particles ejected can increase dramatically. Galactic cosmic rays are similar to those found in the solar wind or in solar flares, but they originate outside of the solar system—the solar wind from distant stars and remnants of exploded stars—and are much more energetic than solar radiation.

The solar wind's charged particles and cosmic particles form streams that hit the Earth's magnetic field. The point of contact between the solar wind and the magnetic field is the shock front or bow shock. Inside the shock front, the point of contact between the charged particles of the solar wind and the magnetic field lines is the magnetopause, and the area directly behind the Earth is the magnetotail (see figure 4–20). In the electromagnetic spectrum, many lower energy solar particles are deflected by the Earth's magnetic field, while some high-energy particles may become trapped and concentrated between field lines, forming the Van Allen radiation belts. Additionally, high-energy gamma and X-rays may ionize particles in the upper atmosphere that also populate the Van Allen belts.

Figure 4–20. Interaction between Solar Wind and Earth's Magnetic Field



Source: Jerry J. Sellers et al., *Understanding Space: An Introduction to Astronautics*, 3d ed. (New York: McGraw-Hill, 2005), figure 3–29.

Whether charged particles come directly from the solar wind, indirectly from the Van Allen belts, or from the other side of the galaxy, they can harm spacecraft in four ways: charging, sputtering, single-event phenomenon, and total dose effects. Spacecraft charging results when charges build up on different parts of a spacecraft as it moves through concentrated areas of charged particles. Discharge can seriously damage surface coatings, degrade solar panels, cause loss of power, and switch off or permanently damage electronics. Sputtering damages thermal coatings and sensors simply by high-speed impact, in effect sandblasting the spacecraft. Single charged particles penetrating deeply into spacecraft electronics systems may cause a single event phenomenon. For example, a single event upset (SEU) or "bit flip" results when a high-energy particle impact resets one part of a computer's memory from 1 to 0, or vice versa, causing potentially significant changes to spacecraft functions. Total dose effects are long-term damage to the crystal structure of semiconductors within a spacecraft's computer caused by electrons and protons in the solar wind and the Van Allen belts. Over time, the cumulative damage lowers the efficiency of the material, causing computer problems. Orbits that pass through an area of higher radiation levels known as the South Atlantic anomaly increase the total dose damage during a spacecraft's lifetime. Spacecraft shielding and the use of hardened components offer some protection for these effects, as does software coding to negate the SEU effects by storing each bit multiple times and comparing them during each read operation. But all of these steps come at a cost of increased weight, testing requirements, and development time and cost.

Spacecraft State of the Art

A spacecraft consists of a payload and its supporting subsystems, also known as the bus. Overall payload requirements are defined in terms of the subject with which it must

interact, and its components are designed to make this interaction possible. Using a remote sensing example, the payload could consist of a single simple camera to detect light from some ground-based phenomenon or could include a collection of sensors, each tuned to detect a particular characteristic (such as wavelength) of that light. The number and type of sensors chosen, and how they work together to form the spacecraft's payload, determine the spacecraft's design, which in turn generates requirements for the spacecraft bus that dictate:

- payload accommodation mass, volume, and interfaces
- spacecraft pointing precision
- data processing and transmission needs
- electrical power needs
- acceptable operating temperature ranges.

Spacecraft Subsystems

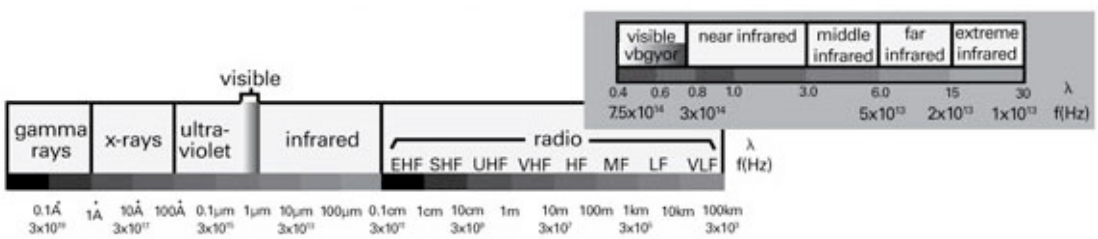
Mission designers define these requirements in terms of subsystem performance budgets such as the amount of velocity change, electrical power, or other limited resource that it must "spend" to accomplish some activity (for example, achieving operational orbit or turning on the payload). Six distinct spacecraft bus subsystems support the payload with all the necessary functions to keep it healthy and safe:

- space vehicle control: "steers" the vehicle to control its attitude and orbit, attaining and maintaining its operational orbit as well as pointing cameras and antennas toward targets on Earth or in space; on-board rockets control the orbit, while rockets and other devices rotate it around its center of mass to provide stability and precise pointing
- communication and data handling: monitors payload activities and environmental conditions, tracks and controls spacecraft location and attitude, communicates with ground controllers or other spacecraft, and warns of anomalies; communication requirements analysis produces a link budget that specifies communications parameters and the data rate
- electrical power: converts and conditions energy sources (such as solar) into usable electrical power and also stores energy to run the entire spacecraft; electrical power requirements for each of the other bus subsystems determine the total electrical power budget
- environmental control (and life support for manned missions): regulates component temperatures for proper operation, transferring or eliminating heat energy as needed; for manned missions, astronauts must be protected from the harsh space environment; provides a breathable atmosphere at a comfortable temperature, humidity, and pressure, along with water and food to sustain life
- structure and mechanisms: protect the payload and subsystems from high launch loads; deploy and maintain orientation of spacecraft components (such as solar panels and antennas)
- propulsion: produces thrust to maneuver the spacecraft between orbits and control its altitude; highly dependent on altitude and orbital control needs.

Remote Sensing and Communications Physics

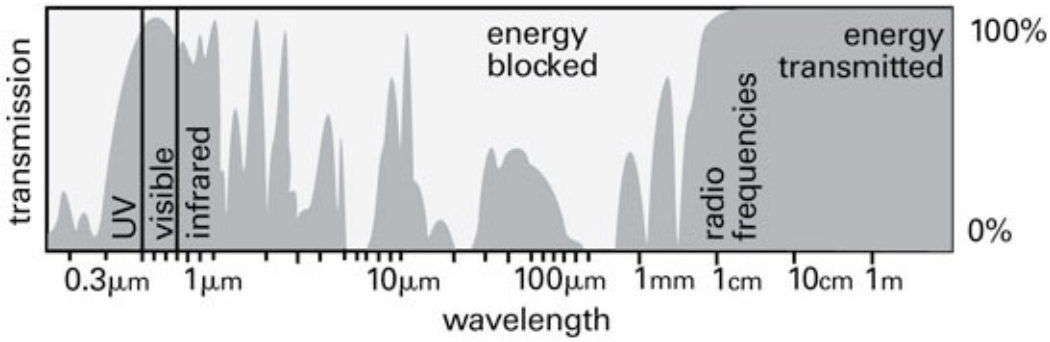
The most common general categories of spacecraft payloads perform remote sensing and communications missions and, as such, represent the variety of technical and operational trades and constraints typically found in space mission design. Remote sensing systems collect EM radiation reflected or emitted from objects on the Earth's surface, in the atmosphere, or in space—including space-based astronomy and space surveillance. Radio waves (also EM) are used to communicate to and from the Earth's surface, through the atmosphere, and between objects in space. For missions involving Earth sensing or communications, then, the transmission characteristics of the Earth's atmosphere—which frequencies are blocked, attenuated, or pass freely—drive payload performance and design decisions. Figures 4–21 and 4–22 describe the electromagnetic spectrum (in terms of EM wavelength and frequency) and the transmission of that spectrum through the atmosphere.

Figure 4–21. Electromagnetic Spectrum



Source: Jerry J. Sellers et al., *Understanding Space: An Introduction to Astronautics*, 3d ed. (New York: McGraw-Hill, 2005), figure 11–29.

Figure 4–22. Atmospheric Windows



Source: Jerry J. Sellers et al., *Understanding Space: An Introduction to Astronautics*, 3d ed. (New York: McGraw-Hill, 2005), figure 11–32.

While some wavelengths (such as visible light) are completely transmitted, others are almost completely blocked. Spacecraft instruments have access to Earth from space through various atmospheric windows—wavelength bands in which 80 to 100 percent of

the available energy is transmitted through the atmosphere. The most notable atmospheric windows are the visible, infrared, and radio wavelengths.

Passive remote sensing systems depend on reflected or emitted EM radiation passing through the atmosphere to the space-based sensor. Because objects reflect different wavelengths of EM radiation, measuring the amount and type of radiation can describe characteristics such as soil properties, moisture content, vegetation types, and many other important details. Objects also emit EM radiation at different wavelengths depending on their material properties and temperature. The relationship between temperature and wavelength of peak emission is well known,[17] and coupled with knowledge of the total energy output from the target object,[18] payload sensors can be designed to sense particular phenomena.

Given the physics of EM radiation, a workable sensor can then be designed. To observe an object, however, the spacecraft sensor must be able to point the sensor at the target, collect EM radiation from the target, transform the detected radiation into usable data, and process the usable data into usable information. First, the object must fall within the sensor's field of view—defined as the angular width within which the sensor can see. Projected onto the Earth's surface, the field of view translates into the swath width, the size of which is determined by the sensor's field of view and the spacecraft's altitude (as shown in figure 4–4). Next, the resolution of the sensor—the size of the smallest object it can detect—is a function of the wavelength of the radiation sensed, the sensor's aperture diameter, and the distance between the sensor and the target.[19]

Active remote sensors such as radar transmit their own radiation that reflects from the target and returns to the sensor for processing. Space-based radar, for example, permits accurate terrain measurement of features to construct a three-dimensional picture of a planet's surface. Because resolution relates directly to the wavelength of the transmitted and reflected signal, shorter wavelengths yield better resolution than longer wavelengths. Optical sensors measure EM wavelengths on the order of 0.5 micrometers (mm), while radar systems operate at about 240,000 mm. Thus, for optical and radar systems with the same size aperture, the optical system has almost 500,000 times better resolution. For conventional radar to have the same resolution as an optical system, the size of the radar's aperture must be increased.[20]

Space communications systems serve as the backbone for all other space missions in addition to being a mission in their own right. The primary goal, of course, is to get data to the users, whether that means relaying remote sensing data obtained from space sensors to ground systems and users, sending and receiving command and control data between spacecraft and ground control centers, or acting as a relay to receive and then transmit data from one point on the globe (or in space) to another. Communications payloads use a transmitted EM signal to carry data to a receiver. The communications link—what happens between the transmitter and the receiver—is the critical feature of any communications systems and is characterized by several critical parameters:

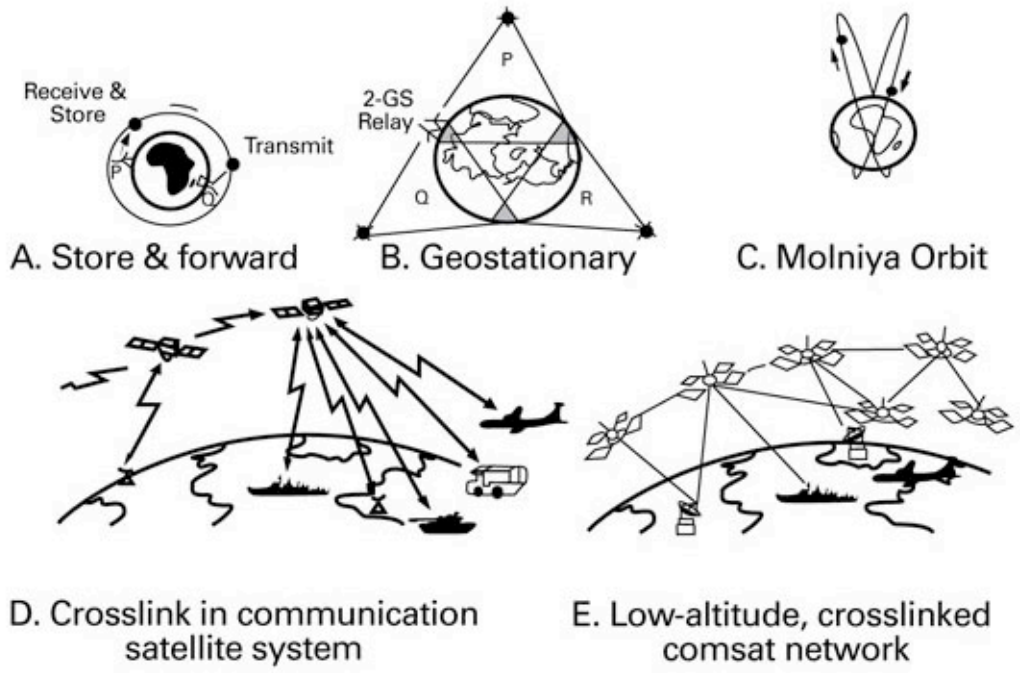
- signal-to-noise ratio

- bit error rate (signal quality)
- coverage
- data rate
- signal security.

The signal-to-noise ratio (SNR) is a function of transmitter power and gain, receiver bandwidth, temperature and gain, signal wavelength, and range between transmitter and receiver. For effective communication, SNR must be greater than or equal to one.[21] The bit error rate (BER) defines the likelihood of misinterpreting bits in a data stream, typically expressed in terms of single bit errors per power of 10 bits.[22] Increasing signal strength improves BER and can be accomplished by increasing transmitter power and antenna size, increasing receiver antenna size, improving receiver characteristics, using higher frequencies, or reducing the distance between the transmitter and the receiver. All of these factors impact the overall cost of the system. The system designer must investigate all available alternatives to obtain the desired signal-to-noise ratio at minimum system cost.

Coverage directly affects communications availability and is a function of satellite altitude and orbit, elevation angle of communicating satellites, satellite constellation configuration (number of satellites, orbital planes used, and so forth), ground station (receiver) location, and cross-linking capability. The simplest satellite communications architecture uses a "store-and-forward" approach (figure 4–23, case A) whereby it transmits or receives data only passing overhead of a single ground station. Between passes, it stores any collected data to be transmitted at the next pass. Adding well-placed ground stations improves coverage, as does adding satellites with a cross-link capability that would forward data to one or more ground stations, effectively increasing the frequency of overhead passes (figure 4–23, case D). Geostationary architectures employ three or more satellites along with terrestrial ground sites and cross-linking for global coverage (except for high latitudes) (figure 4–23, case B), while Molniya orbits with two or more satellites can provide stable, continuous coverage of polar regions (figure 4–23, case C). At low altitudes, larger numbers of cross-linked satellites in a properly arranged constellation can provide continuous coverage of the Earth (figure 4–23, case E), with the most well-known example being the Iridium satellite telephone system.

Figure 4–23. Satellite Coverage Strategies



Source: James R. Wertz and Wiley J. Larson, eds., *Space Mission Analysis and Design*, 3d ed. (Dordrecht, Netherlands: Kluwer Academic Publishers, 1999).

Data rate is the number of bits per second of information that must be transferred over the communications link and is a function of the signal frequency—higher frequency signals can better support higher data rates. Enhanced capabilities to support global operations such as unmanned aircraft systems, video teleconferencing, or simply providing Super Bowl broadcasts to deployed troops create greater demand for higher and higher data rates. Signal security and availability include communications security—disguising the actual transmitted data and typically including data encryption—and transmission security—disguising the transmitted signal, usually by generating security keys and variables that support spread spectrum techniques. Availability, on the other hand, depends upon the environment's effect on the transmission channel. Communications links are typically designed to create an SNR that produces the required BER for the anticipated environment (no hostile effects on the transmission channel). Link margin is then added to compensate for other expected (and unexpected) operating conditions. Signal jamming is an intentional means of corrupting the otherwise benign environment by introducing noise into the communications path, resulting in an SNR of less than one. Of course, simple interference from other systems operating at the same frequency may have a similar, less sinister effect on communications, making frequency deconfliction an important factor in insuring effective communications.

All of these factors will impact the overall cost of the system. The system designer must investigate all available alternatives to obtain the desired signal-to-noise ratio at minimum system cost. Current trends in space communications focus on using more power, higher frequencies, and phased-array antennas to point the beam more precisely to make the signals less susceptible to jamming and interference and to increase data rates.

Conclusion

Space offers society advantages that have revolutionized modern life since the launch of Sputnik 50 years ago and has motivated scientific investigation and dreams of adventure for millennia. The global perspective has allowed worldwide communications and remote sensing (in many forms) and transformed navigation and timing for civil, military, and industrial uses. The challenge of space as a final frontier has lured huge investments by nations seeking to increase their international stature while improving their ability to provide services to their citizens, motivating the technical progress and patriotism of those same citizens, enlarging their international economic influence, and, in many cases, increasing their military power. The clear view space provides causes astronomers and other scientists to dream of future discoveries about the fundamental nature of life and our universe, while the unlimited and largely untapped wealth of space tantalizes citizens of the Earth, who are increasingly aware of finite terrestrial resources.

Realizing these advantages and leveraging the power conferred on those who best exploit them, however, require an appreciation of the physics, engineering, and operational knowledge unique to space, space systems, and missions. It is precisely because so few citizens of Earth have first-hand experience with space—unlike previous terrestrial, maritime, and aeronautical "frontiers"—that we must stress some technical understanding of these characteristics of space. This chapter may serve as a summary or review of some of the key concepts necessary for a firm understanding of the realm of space. Further in-depth study, beginning with the references cited within, is de rigueur for anyone interested in a better understanding of space policy and power and is especially important for space decisionmakers. Making policy and power decisions without this understanding would be akin to formulating a maritime strategy using a team of "experts" who had never seen the ocean or experienced tides, had no concept of buoyancy, or seen sail or shore.

Notes

1. For in-depth development of the concepts introduced in this chapter, refer to Jerry J. Sellers et al., *Understanding Space: An Introduction to Astronautics*, 3d ed. (New York: McGraw-Hill, 2005), from which much of this material has been excerpted or summarized. The classic text in this field is Roger R. Bate, Donald D. Mueller, and Jerry E. White, *Fundamentals of Astrodynamics* (New York: Dover Publications, 1971). Another excellent reference geared toward those not technically trained is David Wright et al., *The Physics of Space Security: A Reference Manual* (Cambridge: American Academy of Arts and Sciences, 2005).
2. Kepler's First Law applied to Earth-orbiting satellites: the orbit of each planet is an ellipse with the Sun at one focus.
3. Sellers et al., 182–184.
4. A simple example: to move a satellite from a circular orbit at an altitude of 300 km (a = 6,678 km, V total= 7.726 km/sec) to a higher, 1,000 km altitude orbit (a = 7,378 km, V = 7.350 km/sec) requires a ΔV total of 378 m/sec. For a 1,000 kg satellite (initial mass on orbit), this would require approximately 155 kg of fuel using a common monopropellant rocket propulsion system.

5. The same process can be used to disperse several satellites placed into an initial, identical orbit by a single launch vehicle—the effective reverse of a rendezvous maneuver. The satellites each perform well-timed "speed up and slow down" maneuvers to establish a constellation of equally spaced satellites (in time and angle) that might provide near-continuous coverage over the Earth.
6. RAAN precession occurs westward for direct orbits (inclination < 90°), eastward for retrograde orbits (inclination > 90°), and zero for polar orbits (inclination = 90°) and equatorial orbits (inclination = 0°).
7. Earth oblateness gives rise to two unique orbits with very practical applications: sun-synchronous and Molniya. The first case uses the eastward nodal progression when i > 90°. At i ≈ 98° (depending on spacecraft altitude), the ascending node moves eastward at the same rate as the Earth around the Sun (about 1° per day), keeping the spacecraft's orbital plane in the same orientation to the Sun throughout the year such that the spacecraft will always see the same Sun angle when it passes over a particular point on the Earth's surface. This is important for remote-sensing missions (such as reconnaissance) because observers can better track long-term changes in weather, terrain, and manmade features. The Molniya (in Russian, *lightning*) orbit is usually a 12-hour orbit with high eccentricity (e ≈ 0.7), perigee location in the Southern Hemisphere, and i = 63.4. At this inclination, the perigee does not rotate, so the spacecraft "hangs" over the Northern Hemisphere for nearly 11 hours of its 12-hour period before it whips quickly through perigee in the Southern Hemisphere. Molniya orbits can provide communication coverage to areas of high latitude that could not practically use geostationary orbits.
8. For example, the European Space Agency's launch site at Kourou (4°N latitude) gives launch vehicles an assist of 0.464 km/sec versus 0.4087 km/sec for the Kennedy Space Center at 28.5° latitude.
9. $\Delta V = I_{sp} g_o ln$ mi/mf where g_o is the gravitational acceleration constant (9.81 m/sec^2); m_i is the initial mass of the spacecraft (fully fueled); and m_f is the final mass (fuel empty).
10. Jerry J. Sellers et al., "Investigation into Cost-Effective Propulsion System Options for Small Satellites," *Journal of Reducing Space Mission Cost* 1, no. 1 (1998).
11. Recent bounding examples in the United States are Space Exploration (SpaceX) Incorporated's Falcon I vehicle (~1,000 pounds to low Earth orbit) on the low end and the two families of Evolved Expendable Launch Vehicles (EELV), Lockheed-Martin's Atlas V and Boeing's Delta IV. While exact figures on these are not available, low estimates for Falcon I are probably $100 million, while EELV developmental funding was several billion dollars.
12. The VentureStar program was canceled in March 2001 after NASA canceled the suborbital X–33 technology demonstrator meant to reduce risk for full VentureStar development. NASA expenditures for X–33 totaled $912 million.
13. Sellers, *Understanding Space*, 84.
14. James R. Wertz and Wiley J. Larson, eds., *Space Mission Analysis and Design*, 3d ed. (Dordrecht, Netherlands: Kluwer Academic Publishers, 1999).
15. The French Cerise spacecraft became the first certified victim of space junk when its 6-meter gravity-gradient boom was clipped during a collision with a leftover piece of an Ariane launch vehicle in 1996.
16. Wertz and Larson, 1999.
17. Given by Wien's Displacement Law, $\lambda m=2898/T$, where λ_m is the wavelength of maximum output in micrometers (mm) and *T* is the object's temperature in degrees Kelvin.
18. Given by the Stefan-Boltzmann equation, $q_A = \varepsilon\sigma T^4$, where q_A is the object's power per unit area (W/m^2), ε is the object's emissivity ($0 \le \varepsilon \le 1$), s is the Stefan-Boltzmann constant (5.67 x 10^{-8} W/m^{2}K^4), and *T* is the object's temperature in degrees Kelvin.
19. Resolution = $2.44\lambda h/D$ where λ is the wavelength of the sensed radiation, *h* is the distance between the sensor and the target, and *D* is the instrument's aperture diameter.
20. A conventional radar operating at a wavelength of 240,000 mm would need an aperture of more than 480 km (298 miles) to get the same resolution as an optical system with a mere 1-meter aperture! Fortunately, signal-processing techniques that enable synthetic aperture radar—effectively enlarging the radar aperture—can achieve much higher effective apertures and thus higher resolutions.

21. $SNR=(P_tG_t/kB)/(\lambda/4\pi R)/(G_r/T)$ where P is transmitter power, G_t is transmitter gain, k is Boltzmann's constant, B is the receiver system's bandwidth, λ is the signal wavelength, R is the range to receiver, G_r is the receiver gain, and T is the receiver system's temperature.
22. For example, a bit error rate of 10–3 implies an error rate of 1 bit out of every 1,000 bits; typical bit error rates are ~10–5 for voice and ~10–14 for data.