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THE PHYSICS OF SPACE WAR: HOW ORBITAL DYNAMICS CONSTRAIN SPACE-TO-SPACE ENGAGEMENTS

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Summary

As the United States and the world discuss the possibility of conflict extending into space, it is important to have a general understanding of what is physically possible and practical. Scenes from *Star Wars*, books, and TV shows portray a world very different from what we are likely to see in the next 50 years, if ever, given the laws of physics. To describe how physics constrains the space-to-space engagements of a conflict that extends into space, this paper lays out five key concepts: satellites move quickly, satellites move predictably, space is big, timing is everything, and satellites maneuver slowly. It is meant to be accessible to policymakers and decisionmakers, helping to frame discussions of space conflict. It does not explore geopolitical considerations.

Introduction

Movies portray wars in space much as they do wars on Earth. Starfighters dogfight with unlimited maneuverability and range. Troop transports drop from orbit to celestial surfaces to deliver space marines. But that is not how a real war in space would look for decades, if ever. The space-to-space engagements in a modern conflict would be fought solely with un-crewed vehicles controlled by operators on the ground and heavily constrained by the limits physics imposes on movement in space.

At the beginning of the Space Age, there was the assumption that military personnel would live and work in space, just as they do in all other domains. As an extension of a human in the cockpit, the Air Force pursued a crewed spaceplane, the Dyna-Soar program.[1] However, adapting techniques that work for an airplane into the vacuum of space proved beyond their capabilities. Instead, the focus shifted to basing people in space and focusing on crewed reconnaissance platforms. The Air Force pursued a Manned Orbiting Laboratory and the Soviets worked on the Almaz space station, which carried an externally mounted machine gun cannon to defend against American astronaut attacks. Unfortunately, people require a lot of support: food, water, even air, all of which must be launched from Earth. Eventually, both programs faltered. Instead, improvements in technology and data transmission—the same developments that ultimately underpin our modern connected life—made possible satellites that perform the same military functions envisioned for the earlier crewed programs. Since then, activity in space is dominated by these “un-crewed” satellites, which provide amazing capabilities and influence almost every aspect of modern military operations. These same capabilities are also attractive targets for adversaries in future warfare.

This paper aims to describe what that war would look like, with an emphasis on space-to-space engagements, due to the constraints imposed by physics, rather than a treatise on why or whether a war should be fought in space; what strategy or doctrine should be used to fight or avoid a war in space; or what threats adversaries are fielding in space.[2] It is not even about how one might fight in space. Its focus is only to help those of us bound to Earth understand the counterintuitive forces that drive movement and maneuver in space.

To describe how physics would constrain space-to-space engagements, this paper describes five key concepts: satellites move quickly, satellites move predictably, space is big, timing is everything, and satellites maneuver slowly. Building upon these concepts are explanations of how competing spacecraft can engage each other kinetically,[3] as well as contrast how electronic warfare, directed energy, and cyberattacks might play in a space fight. Finally, these basics are further illuminated via a discussion of how debris created by these engagements can affect later engagements.

Movement in space is counterintuitive to those accustomed to flight within Earth's atmosphere and the chance to refuel. The focus here is on what is counterintuitive, specifically on the space-to-space fight with a limited discussion on ground-to-space capabilities. Still, even by establishing only the basic understanding, one can better understand how a war in space might occur. Space-to-space engagements would be deliberate and likely unfold slowly because space is big and spacecraft can escape their predictable paths only with great effort. Furthermore, attacks on space assets would require precision because spacecraft and even ground-based weapons can engage targets in space only after complex calculations are determined in a highly engineered domain. This is true because physics puts constraints on what happens in space. Only by mastering these constraints can other questions such as how to fight and, most importantly, when and why to fight a war in space, be explored.

How to Think about a Space War

Warfighting on Earth typically involves competitors fighting to dominate a physical location. Opposing military forces fight to control the land, sea, and air over a certain part of Earth to expand influence over people or resources. Space warfare does not follow this paradigm; satellites in orbit do not occupy or dominate a single location over time. Instead, satellites provide capabilities, such as communications, navigation, and intelligence gathering, to Earth-based militaries. Therefore, to "control space" is not necessarily to physically conquer sectors of space but rather to reduce or eliminate adversary satellite capabilities while ensuring one retains the ability to freely operate their own space capabilities.

There are several potential objectives for an attacking force in a space war:[4]

- Deceive an enemy so that they react in ways that hurt their interests
- Disrupt, deny, or degrade an enemy's ability to use a space capability, either temporarily or permanently
- Destroy completely a space-based capability
- Deter or defend against a counterattacking adversary, either in space or on Earth

The weapons used to achieve these goals can be either ground-based or space-based and can be reversible or irreversible. Furthermore, space weapon types range from kinetic weapons, which must physically affect a target, to standoff weapons, which can reach a target many miles away. This paper will cover most of these weapon categories, with a detailed discussion of physics constraints on space-to-space movement and maneuver. Regardless of how they are employed, the use of space weapons is not only constrained by system design but also by physics.

Satellites Move Quickly but Predictably

The fact that satellites move quickly and that they move predictably are two separate and equally important concepts. However, it is easier to discuss them together. Objects move through space differently than they move through Earth's atmosphere. Objects orbiting Earth have a strict relationship between altitude and speed. Orbital mechanics dictate that objects at lower altitudes will always move more quickly than those at higher altitudes. Any attempt to add or reduce a satellite's speed will always lead to a change in altitude. Compare this relationship between speed and altitude to an aircraft, which often changes speed without affecting its altitude, and vice versa.

Space Domain Awareness

Being able to find and track satellites is fundamental to space operations. This is known as *space domain awareness*. Because satellites can be thousands of miles away, large, powerful ground and space-based radars and telescopes are used to monitor where a satellite is, when within view of the sensor. Each time a radar or telescope detects a satellite, the data is sent to a cataloging agency (usually a military organization or company) where it is combined with previous observations to estimate the satellite's orbit. The orbit information is then cataloged in a central database where observers can use it to predict where the satellite will be in the future.

The catalog not only contains active satellites, but all objects that have been launched into space, including rocket bodies, inactive satellites, and debris. Checks are made for each object to make sure that the orbits are matching previous predictions.

And that speed is fast. Satellites in commonly used circular orbits move at speeds between 3 km/s and 8 km/s (6,700 mph and 18,000 mph), depending on their altitude. In contrast, an average bullet only travels about 0.75 km/s (1,700 mph).

Satellite orbits are also constrained in the direction of movement. Unlike an aircraft, which is free to change where it is heading at any time, a satellite in orbit generally follows the same path and goes in the same direction without additional propulsive maneuvers. These paths can be circular or elliptical[5] (i.e., shaped like a watermelon) but must revolve around the center of Earth. Also, because a satellite's speed is tied to its altitude, a satellite will return to approximately the same point in its orbit at regular intervals (known as its period), regardless of the orbit's shape and absent a maneuver to change the orbit. Satellites in circular orbits maintain a constant altitude and speed. Elliptical orbits vary in altitude, with the satellite traveling slower as it moves higher and faster as it moves lower in altitude.

This relationship between altitude, speed, and orbit shape makes satellite paths predictable. There are external factors that create an imperfect relationship (e.g., atmospheric drag for satellites at lower altitudes [below 600 km or 375 mi.] and the fact that Earth is not a perfect sphere). However, these factors can be reasonably accounted for, making it easy to track and predict the trajectory of satellites for those with access to space domain awareness data. To deviate from their prescribed orbit, satellites must use an engine to maneuver. This contrasts with airplanes, which mostly use air to change direction; the vacuum of space offers no such option.

Furthermore, the orbit of a satellite does not depend on its mass—both small satellites and large satellites move at the same speed for a given altitude. This is fundamentally different than our experience on

Earth, where motion is driven by adding energy and large objects tend to move more slowly than smaller objects when using the same amount of energy. Thus, a large passenger airliner requires more energy to fly as fast as a small corporate jet.[6]

Table 1 shows characteristics of common orbit regimes, highlighting the predictable relationship between altitude and speed. Satellites in low Earth orbit (LEO), including the International Space Station at an altitude of 400 km (250 mi.), are relatively close to Earth and thus move the fastest. This is akin to the distance between Washington, D.C., and New York City but, at a satellite's speed, you would get there in less than one minute. A satellite in a geostationary Earth orbit (GEO), which includes satellite TV and communications satellites, are orbiting at an altitude of 35,786 km (22,236 mi.)—almost the same distance as a complete trip around the world at the equator.

Satellites move very differently from anything we are accustomed to on Earth; however, the motion is far more predictable than most familiar vehicles. That predictability will have significant implications for how to engage satellites in space.

Space Is Big

The volume of space between LEO and GEO is about 200 trillion cubic kilometers (50 trillion cubic miles). That is 190 times bigger than the volume of Earth. Furthermore, because a satellite is moving quickly, it has a lot of inertia. Consequently, changing or repositioning a satellite in its orbit, known as a *maneuver*, can require significant time and energy.

Because space is very big and coupled with the tight natural relationship between a satellite's speed, altitude, and direction, changing an orbit requires both ΔV and time. Maneuvering a satellite in space is very different from maneuvering an airplane or other Earth-bound vehicle. Because the satellite travels at high speeds, attempting to change its course through space requires expending energy to generate ΔV. This is done usually by burning chemical propellants or expelling accelerated gases through a propulsion system. If no ΔV is used, a satellite cannot be moved from its trajectory.[7] A terrestrial comparison to a satellite in this regard is the maneuvering of a train, which is only free to move in the one direction defined by its tracks.

Table 1: Characteristics of Common Orbit Regimes

	Altitude	Speed	Period
Low Earth Orbit (LEO)	160–2,000 km (100–1,250 mi.)	7–8 km/s (15,000–18,000 mph)	1.5–2 hours
Medium Earth Orbit (MEO)	2,000–35,000 km (1,250–22,000 mi.)	3–7 km/s (6,700–15,000 mph)	2–23.5 hours
Geosynchronous Earth Orbit (GEO)	35,786 km (22,236 mi.)	3 km/s (6,700 mph)	24 hours
Highly Elliptical Earth Orbit (HEO)	Varies (noncircular)	1.5–10 km/s (3,300–22,000 mph)	12–24 hours

Delta-V (∆V): A Limiting Factor

One of the biggest constraints on any warfighting vehicle, whether a satellite, an airplane, or a tank, is the amount of energy needed to move it. Fighter planes have indicators showing how much fuel is left onboard, which limits the range of the aircraft. Similarly, maneuvers in space are measured by the amount of velocity change required. The magnitude of these velocity changes, provided almost exclusively by onboard propellants, is known as *Delta-V* (denoted: ∆V) and is measured in meters per second.[8] When a satellite uses ∆V it is known as a *burn*. A satellite is designed with a specific ∆V budget that acts as the satellite's fuel gauge. Just as a pilot will know how far they can fly on a tank of gas by looking at the fuel gauge, a satellite operator will plan satellite maneuvers based on how much ∆V is left in the satellite's budget. Importantly, unlike an airplane that can be refueled, once a satellite is launched, it currently does not have the ability to increase its ∆V budget. Although on-orbit servicing, or the ability to add ∆V to a satellite that has depleted its on-board propellant, has recently been demonstrated,[9] a new satellite is still required. No effective orbital "gas station" exists to replenish a satellite's spent ∆V.

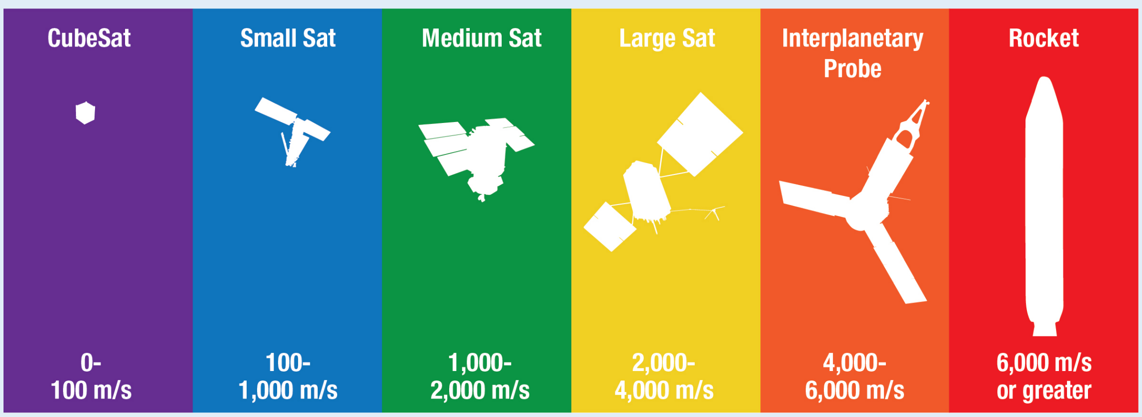

Figure 1. Conceptualizing ∆V Budgets (also serves as the color key for Figures 3, 4, and 7 through 9).

Figure 1 illustrates the capacity of different ∆V budgets. The left end corresponds to small ∆V budgets (0 to 100 m/s), which can be compared to the capacity of shoebox-sized satellites known as *CubeSats*.[10] Because of their small size, CubeSats generally cannot carry enough propellant to do more than a few maneuvers (e.g., adjusting orbit due to atmospheric drag) throughout their lifetimes, if they carry propellant at all. The right end corresponds to rockets that use large ∆V budgets to loft satellites to the vast distances required to orbit Earth. Generally (but not always), satellites have larger ∆V budgets as they grow in size.

There is a practical limit to how much propellant a satellite can carry. For very large maneuvers (above about 4,000 m/s, such as interplanetary travel or launch), satellites require the use of outside sources of ∆V. This includes the use of launch vehicles and custom modules that can attach to satellites and be jettisoned later when emptied. Some interplanetary probes will use flybys of certain planets to change their speed to reach distant objects. Whatever is used, the ∆V required for the maneuvers exceeds the satellite's capacity and must be provided through external means. ∆V is an important concept to understand when dealing with satellites and their ability to maneuver because it means engagements in space are fuel limited.

One common maneuver is the plane change, where the satellite's orbit plane is tilted relative to its original orientation without changing the satellite's altitude (Figure 2). This is comparable to moving a train to an intersecting set of tracks without changing its speed. Because satellites travel so fast and have so much momentum, it takes a lot of ΔV to perform even small plane changes, but it does not take a lot of time. See Figure 3 to see how much ΔV is needed for different plane changes. For example, in 2018, a GEO satellite was inserted into an orbital plane 17 degrees higher than intended. Reducing the angle to its intended mission orbit consumed about 40 percent of its lifetime ΔV budget.[11] For this reason, a satellite is launched into an orbit as close to its intended orbit plane as possible. To change orbital planes, a single burn, where ΔV is applied to the satellite's orbit, is needed to do a plane change. However, this burn must occur at the exact spot where the current orbit plane and the desired plane meet, meaning that some transit time may be required to wait for the right time to maneuver. At worst, this requires waiting the duration of half an orbital period (or a maximum of about 1 hour in LEO, about 12 hours in GEO).

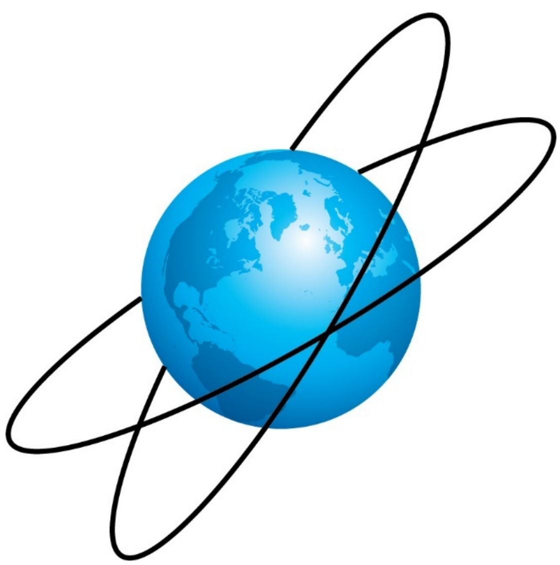

Figure 2: Orbital Planes: Each loop is a different orbital plane.

Satellites may also be required to change altitudes during their mission. This often occurs for satellites that operate in high altitude orbits, such as GEO, if the rocket is not powerful enough to go the entire way. Like a train that must climb a mountain, a satellite making large changes in altitude requires a significant amount of ΔV. At least two burns are required for an altitude change maneuver. The first burn puts the satellite on a new orbit that has one point at the old altitude and another point at the new altitude. The last burn moves the satellite completely onto the desired orbit. These burns are done only at certain points of the orbit where the satellite is either closest or farthest from Earth.[12] Furthermore, unlike a plane change, which occurs within minutes, an altitude change may take hours or days to complete. Figure 4 shows the time required to reach certain altitudes. For example, moving from LEO to GEO requires over five hours to complete, at a minimum. Altitude changes are often combined with any required plane changes to minimize the ΔV required.

Figures 3 and 4 convey both the time and ΔV budgets required to maneuver (plane change and altitude, respectively) in space. For both figures, the ΔV required is denoted by the color with Figure 1 being the color key. As with airplanes, tanks, and ships, satellites have finite fuel tanks. Therefore, even for satellites with large ΔV budgets, only a limited number of maneuvers are available. Because space is big, many satellites are simply unable to reach the orbits of other satellites within their ΔV budgets. Purpose-built space weapons may require larger-than-typical ΔV budgets to enable maneuver to their intended targets.

Space is big, which means that a space-to-space engagement is not going to be both intense and long. It can only be one or the other: either a short, intense use of a lot of ΔV for big effect or a long, deliberate use of ΔV for smaller or persistent effects. Due to the distances involved, planning for a kinetic satellite attack requires accounting for both the time

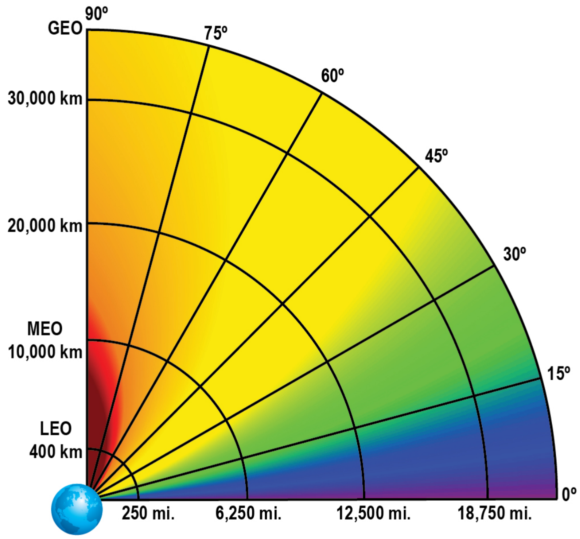

Figure 3: Plane Change ΔV Budget: Assuming circular orbits, the approximate ΔV needed to change planes about Earth. *A minimal time delay exists for all plane changes. The colors correspond to the ΔV budgets outlined in Figure 1.*

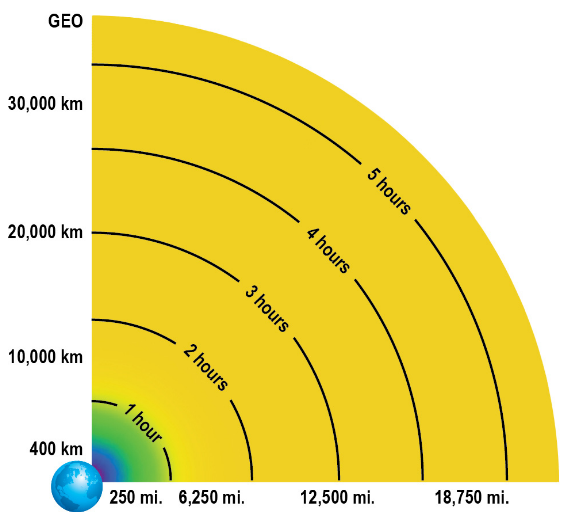

Figure 4: Altitude ΔV and Time Budget: Starting from a 500 km circular orbit, the approximate time and ΔV needed to raise a spacecraft to a higher orbit. *These times assume the use of Hohmann transfers orbits, a commonly used orbit transfer method that minimizes transfer ΔV costs. The colors correspond to the ΔV budgets outlined in Figure 1.*

and ΔV needed to execute the mission. Operators of an attack satellite may spend weeks moving a satellite into an attack position during which conditions may have changed that alter the need for or the objective of the attack. Additionally, if an attacking satellite must perform costly maneuvers to match planes with its target, it may not have the reserves needed to respond if the target performs its own maneuver to avoid the attacker.

Timing Is Everything

Within the confines of the atmosphere, airplanes, tanks, and ships can nominally move in any direction. They can move in a straight line, make a circle, zigzag, etc. Satellites do not have that freedom. Due to the gravitational pull of Earth, satellites are always moving in either a circular or elliptical path, constantly in free-fall around the Earth. When one satellite tries to move close to another, its motion—whether circular or elliptical—becomes important. And therefore, timing is everything.

The nature of conflict often requires two competing weapons systems to get close to one another. Aircraft carriers maneuver to get close enough to enemy ships so that their aircraft can reach them. Jets maneuver to get their missiles close enough to other jets. For space, this means two satellites must be near the same physical location at the same time. Getting two satellites to the same altitude and the same plane is straightforward (though time and ΔV consuming), but that does not mean they are yet in the same spot. The phasing—current location along the orbital trajectory—of the two satellites must also be the same. Since speed and altitude are connected, getting two satellites in the same spot is not intuitive. Therefore, it requires careful planning and perfect timing.

One way to get close to another satellite is to perform a flyby. A flyby occurs when one satellite nearly matches the other satellite's position without matching its orbit. Because the satellites are in different orbits, they will appear to speed past each other. These maneuvers are useful for inspection missions where the goal is not to destroy the target but to image it. Flybys often require minimal ΔV for an attacking satellite to perform since it can use natural intersection points of the two orbits to come close to its target. A related operation, known as an *intercept*, involves intentionally trying to match positions with the target, leading to the destruction of both satellites.

For two satellites in the same orbit, a common maneuver known as a *phasing maneuver* is required for one satellite to catch the other satellite. A phasing maneuver involves changing the satellite's position in its orbit plane, either moving it ahead or behind of where it would normally be, similar to a train increasing or decreasing its speed to arrive at a destination sooner or later. Unlike a train, which can speed up or slow down without changing tracks, a satellite that changes speed also changes its altitude. This leads to the satellite entering into a new orbit known as a *transfer orbit*, an orbit used temporarily to move a satellite from an original orbit to a new orbit.

Therefore, a phasing maneuver is a two-burn sequence. The first burn will move the satellite into either a higher or lower transfer orbit. The satellite is now traveling at a different speed relative to its original spot. A higher orbit has a slower speed, which moves the satellite *backward* relative to its original position in the orbit. A lower orbit increases the speed of the satellite, moving the satellite

Relative Velocity

Space is mostly empty, and this makes it difficult to have points of reference. On Earth, many objects exist to help orient both your position and speed. (For example, you can direct people to turn left at Starbucks, and you generally do not think of Starbucks as moving.) To reference movement between satellites, we use the idea of relative velocity. The relative velocity of two objects (A and B) is the velocity of object A as seen from object B.

As an analogy, imagine driving down the highway at 60 mph. If a car is in the next lane also traveling at 60 mph (in the same direction), the relative velocity is zero (that is, both cars appear stationary to each other). Say, instead, you pass a car traveling at 50 mph. Since both cars are traveling in the same direction, you are traveling 10 mph faster than that other car, and you appear to slowly pull away. If a car is traveling in the opposite direction at 60 mph, your relative velocity is the addition of your separate speeds (120 mph). In this case, the other car appears to fly by very quickly.

In the car analogy, it would be much worse if you were hit by a car driving at the same speed (or even a bit slower) but in the opposite direction, as opposed to getting hit by a car driving in the same direction, even if they are going a bit faster. If you want to intercept a satellite, you need to understand how speed is dependent on altitude, that satellites follow an elliptical trajectory, and how relative velocity works. If you want to inflict physical kinetic harm to a satellite, these are key principles to keep in mind. In short, hitting a satellite head-on will inflict more damage and generate more debris than hitting it from behind. However, any collision at orbital speeds is likely to effectively end a satellite's life.

forward relative to its original spot. When the satellite has reached the new location, a second burn is applied to return the satellite into its original orbit. Both burns are roughly the same magnitude in terms of ΔV. See Figure 5 for a schematic of both a backward- and forward-phasing maneuver.

Figure 6 is a schematic overview of rendezvous and proximity operations (RPO)—or how satellites maneuver to get close. A *rendezvous* requires two or more satellites to match their altitude, plane, and phasing. A *proximity operation* is when two or more satellites maneuver around each other. The final state can include, but does not require, docking or physically touching. In Figure 6, the far-left panel (panel 1) shows the attacking satellite (green orbit) at a different altitude than its target (orange orbit). The attacking satellite enters a transfer orbit (panel 2) that causes it to approach the target in a series of loops, as viewed from the target (panel 3). The looping motion is due to the changing altitude and speed of the approaching satellite as it rises to the target orbit and falls back to its starting orbit. When the satellite finally approaches its target (panel 4), it performs a final burn to complete the rendezvous.

A critical component of RPO is *plane matching*. Plane matching refers to maneuvering a satellite such that its orbit plane is aligned with a target. Once an attacker's space-to-space weapon system has matched planes with a target, it has options. If the weapon is not limited by ΔV, the attacker can choose the time and location of the engagement.

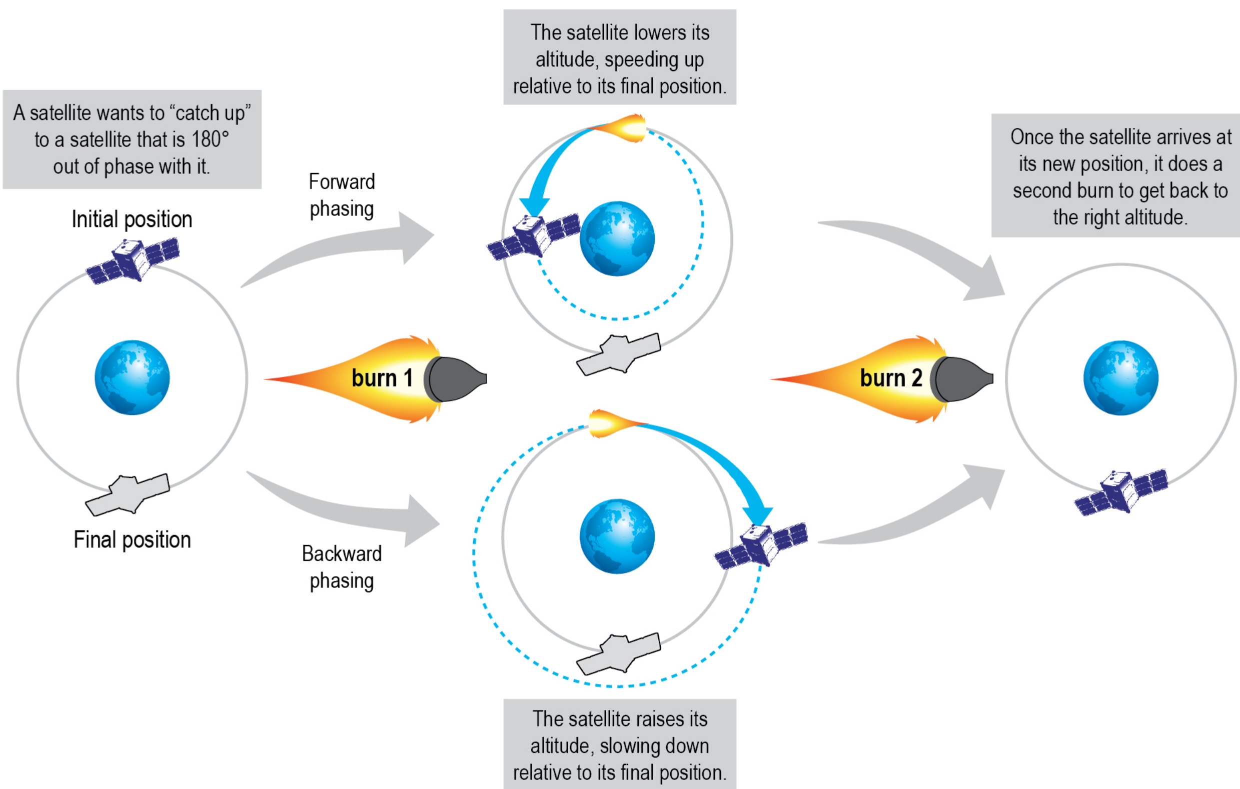

Figure 5: Phasing Maneuvers: How satellites can change their position within their current orbit. *This is akin to "catching up" to a satellite that is in the same orbit. Note, the direction of the satellite's motion around Earth is the same at all points. The different directions of the arrows indicate relative velocity (see the sidebar on this topic). When a satellite raises its orbit and slows down, it appears to be moving backward relative to its initial orbit and altitude.*

Rendezvous and Proximity Operations

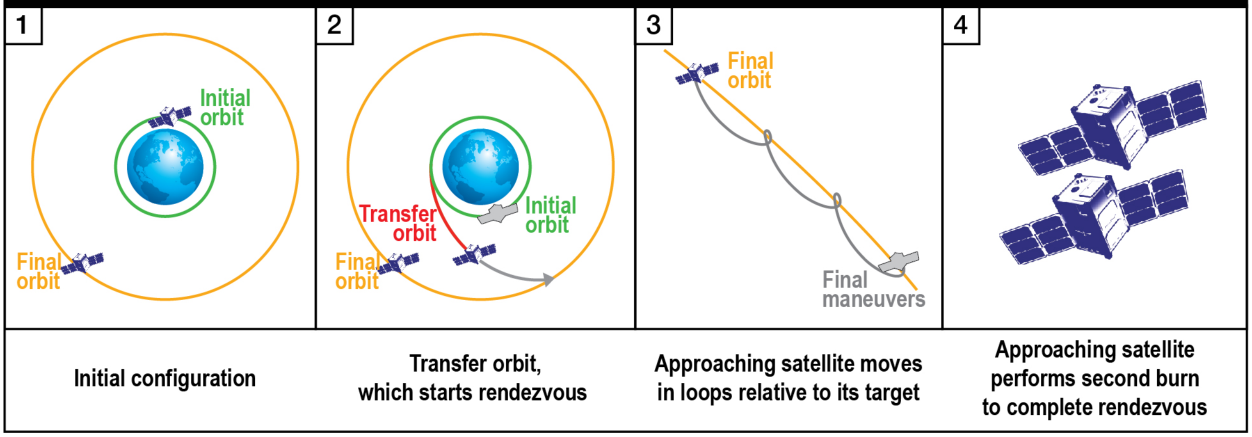

Figure 6: Rendezvous and Proximity Operations: Maneuvering a satellite to perform a rendezvous with a target.

Because the attacker matched planes, it now has the initiative and can dictate when an engagement occurs. By not initiating threatening maneuvers immediately, an attacker may try to seem harmless while waiting for an optimal time to attack. The target satellite could defensively maneuver to avoid the attacker, but such maneuvers use ΔV and thus decrease the target's ability to perform future maneuvers. Furthermore, defensive maneuvers often temporarily take the satellite out of its primary mission, achieving the same result the attacker was seeking in the first place.

There are multiple ways to get close to another satellite. Satellites may come into close proximity through purposeful action (maneuvers) or through happenstance (orbits may intersect naturally). What constitutes small or close distances is a judgement call depending on the satellite operators. For example, a GEO satellite may be able to tolerate 50 km (30 mi.) of separation between other satellites, but a crewed space station may not allow any satellite to approach within 150 km (90 mi.). For an attacker intentionally maneuvering a spacecraft, there are three points to consider:

1. **Threats can maneuver to naturally intersecting points of orbits.** Because of the natural intersection of some orbits, two satellites may periodically get close to each other without any plane matching involved. These opportunities can be exploited by an attacker. For example, two satellites in orbits at the same altitude but in different planes will intersect twice, as shown in Figure 2. A hostile satellite can then use small phasing maneuvers to position itself to intercept its target at one of these intersection points, similar to an army using choke points such as a mountain pass to ambush an enemy patrol. These attacks will produce high relative velocities that are useful for destructive kinetic attacks, which are explained in more detail in a later section.

2. **Plane matching can create regular, low relative velocity rendezvous opportunities.** A satellite may plane match to create regular attack opportunities. If the satellite is positioned with a slight altitude offset to its target, the attacking satellite will have a slight speed offset. The speed difference between the two satellites will cause the attacking satellite to make low relative velocity passes on the target, either by being slower or faster than the target. These types of passes are used by satellites on rendezvous missions, such as delivery missions to the International Space Station or inspection

missions where the goal is to observe and characterize the target.

3. **A seemingly "safe" approach provides opportunities for low-ΔV intercept trajectories.** The previous two methods involve maneuvering an attacking satellite to a point that is close to its target. However, a satellite intent on doing RPO may be placed in an orbit that does not come extremely close to the target object in an effort to disguise its approach as a natural, coincidental pass. Similar to point 2, a hostile satellite would match planes, but instead of attempting a close approach of, for example, 10 km (6 mi.), an operator may position the satellite to approach at 100 km (60 mi.). In spite of this larger separation, because the hostile spacecraft has already matched planes, only small ΔV maneuvers would be required to move the satellite onto an engagement trajectory. Functionally, this is like sending a bomber on a patrol route over a region. Even though it remains on a set path, only a small effort is required to divert the aircraft to a nearby area to attack.

Understanding how to position satellites allows for discussions about using them for hostile intent. The physics of space dictate that kinetic space-to-space engagements be deliberate with satellites maneuvering for days, if not weeks or months, beforehand to get into position to have meaningful operational effects. But once an orbital threat has matched planes and set up the timing through precise orbital phasing, many opportunities can arise to maneuver close enough to engage a target quickly.

Satellites Maneuver Slowly

While satellites *move* quickly, space is big, and that makes purposeful maneuvers seem relatively slow. The following subsections highlight this with specific examples for satellites in LEO and GEO.

Maneuvering in LEO

LEO is an interesting place to examine due to its proximity to Earth and the subsequent behavior of satellites in that orbit. LEO is also where many satellites are located, meaning it would be likely to be a key battleground in a space war. In LEO, satellites move at around 8 km/s (17,000 mph), circling Earth approximately every 90 min. They are also spread out over many different orbital planes.

While this is the orbit in which satellites both move the fastest and have the shortest distance to travel to complete a revolution around Earth, it still takes a lot of time to do a phase change. That means if an attacker wants to "catch up" to a satellite that is at the same altitude and plane, but at a different point along the trajectory, it can be time consuming to do. There are many reasons to catch up to another satellite during a space conflict, from monitoring and surveying to inflicting harm or otherwise interfering with its function. There are also many ways to do so, including those mentioned in the above section. However, there are challenges with catching up to another satellite in an orbit. Because space is so big, catching up to a target takes careful planning and a long time to execute.

If Satellite A wants to catch up or change the phase of its orbit to match with Satellite B (which is on the other side of Earth, 180 degrees out of phase), it has multiple options to achieve this. Note, this would be a worst-case scenario as military planners are likely to target a closer satellite. As discussed in Figure 5, it can go *forward* or *backward* to maneuver. However, certain physical limitations exist. As shown in Figure 7, if the satellite in a 500 km (310 mi.) circular orbit is to be moved *forward* in the orbit, no single burn can exceed about 115 m/s; otherwise, the satellite will descend too far into Earth's atmosphere and immediately reenter.[13] Note, a burn of this magnitude would cause a notable change in the orbit and use a substantial portion of a LEO satellite's ΔV budget, comparable

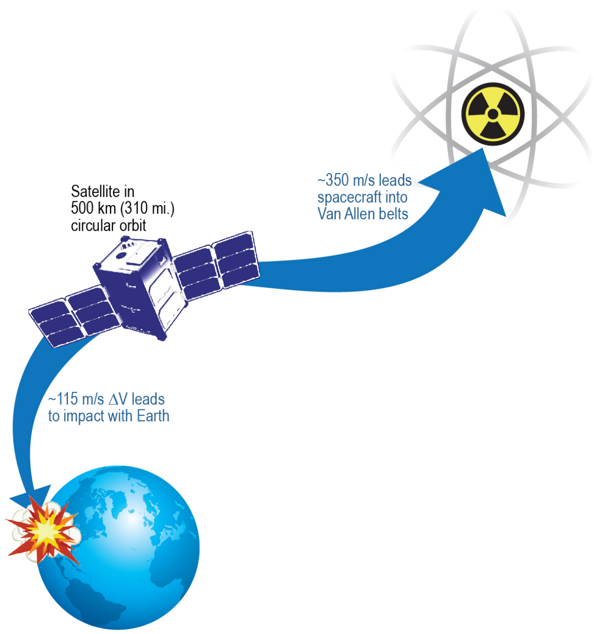

Figure 7. Bounding Cases for Phase Maneuvers in LEO: *If a satellite performs a forward phasing maneuver with a first burn of 115 m/s or more of ΔV, it will reenter Earth's atmosphere and burn up. Similarly, if the satellite performs a backward phasing maneuver with a first burn of 350 m/s or more of ΔV, it will experience high radiation in the Van Allen belts. These two facts create natural bounds for how quickly a satellite can maneuver in LEO (500 km or 310 mi.).*

to a jet aircraft using its afterburner to increase its speed at the expense of greatly increased fuel use.

There is also a limit to how high Satellite A should reasonably try to go to phase *backward* in its orbit. Once it reaches about 2,000 km (1,250 mi.) in altitude, the Van Allen radiation belt[14] becomes a problem. While not quite as devastating as crashing into Earth, the radiation belt is harmful to satellites and is generally avoided. Satellites in LEO are generally not designed to survive long exposures with these belts; however, satellites at higher orbits that must cross through the belt will have shielding to reduce the effects of the radiation as they transit the belts.

Phasing options less extreme than those highlighted in Figure 7 exist. Ultimately, it is a trade between how quickly the operator wants to get there and how much ΔV they are willing to use. Recall, using ΔV limits the number of total maneuvers available for the satellite. Figure 8 shows three potential phasing maneuvers (two-burn maneuvers) for Satellite A in a 500 km (310 mi.) low Earth orbit.

As shown in Figure 8, Satellite A can catch up to Satellite B by doing a backward phasing maneuver in 4 or more hours. Doing the maneuver in 4 hours requires both the highest total ΔV and Satellite A to temporarily go to a relatively higher altitude than the slower 12- and 24-hour options shown. If Satellite A instead wants to do a forward phasing maneuver, it will take a minimum of about 18 hours. In 4 hours, it could only travel 22 percent of the way there; in 12 hours it could get 67 percent of the way there.

This means a LEO fight will be complicated because of the large number of satellites that are moving very quickly and are spread over many orbital planes. However, as explained in this section, even satellites in LEO maneuver slowly. A "quick-strike" rendezvous attack in LEO would require a very large ΔV budget for the attacking satellite—and would not be quick. In addition to performing the right phasing maneuver, the attacker and the target must be in the same orbit plane. Any plane change maneuver performed by the attacker will be costly, as shown in Figure 3. Targets may be spread out over many planes, meaning that one attacker may not have the ΔV to reach multiple targets in different planes. Thus, an RPO attacker in LEO would probably launch directly into its target plane and make small maneuvers over many days to move itself closer to its target before attacking.

Maneuvering in GEO

The GEO belt has several characteristics that make it an interesting place to consider for kinetic engagements. Satellites in this orbit are "stationary" above a fixed point on Earth over the equator. That means a satellite in this orbit takes 24 hours to move

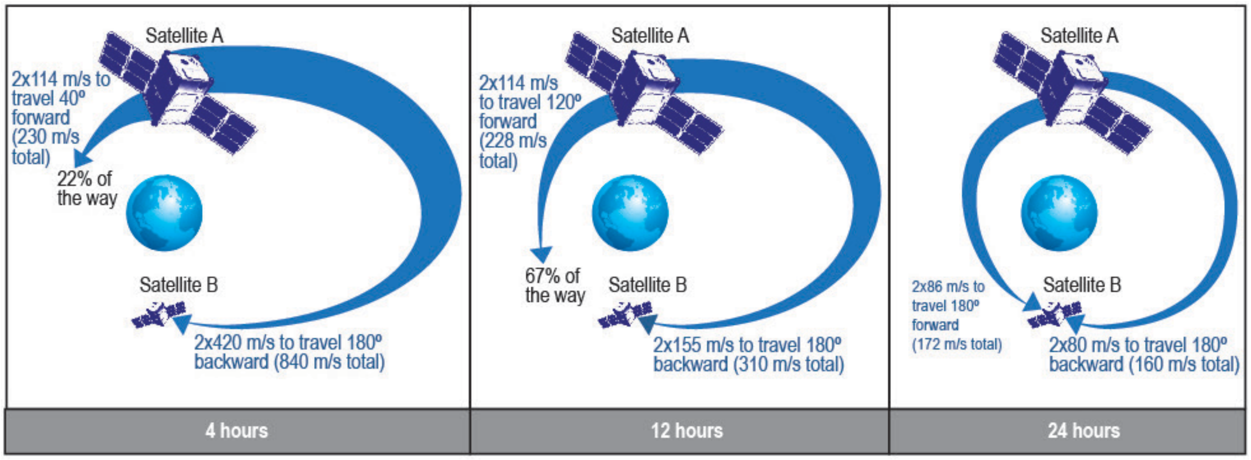

Figure 8: Catching up in LEO: *Each panel depicts how far Satellite A in LEO (at 500 km/310 mi. altitude) could travel in 4, 12, and 24 hours, respectively, and the corresponding ΔV required.*

around Earth. Changing locations (called *slots*) along this orbit means changing which point on Earth the satellite is constantly above. The allotment of slots is regulated by an international organization such that movement to other slots would be readily noticed. The circumference of this orbit is 225,000 km (140,000 mi.), or about five times Earth's circumference, and each slot can be as narrow as 75 km (45 mi.) in length along the orbit.

If an object is to move to a different slot, it can use either forward or backward phasing, as described in Figure 5. Figure 9 depicts different time and ΔV budget options for moving to the opposite side of the GEO belt. Note that to phase 180 degrees in an orbit, which corresponds to moving about 112,000 km (70,000 mi.), can require multiple days even for large phasing maneuvers. Most commercial satellites in GEO will use only a few meters per second of ΔV to move into another slot, making these repositioning events take up to several weeks. An attacking satellite that uses larger burns to move faster will therefore be conspicuous.

Because GEO satellites travel large distances during each orbit and the relative speed between satellites

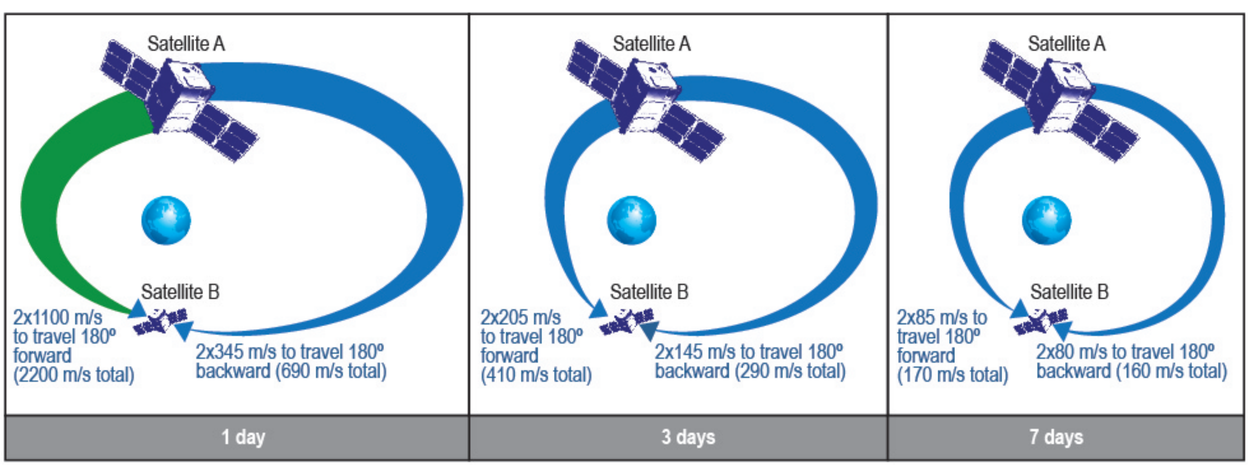

Figure 9: Catching up in GEO: *Each panel depicts how far Satellite A in GEO (at 35,786 km/22,236 mi. altitude) could travel in 1, 3, and 7 days, respectively, and the corresponding ΔV required.*

can be small, it can take a long time to position a weapon to engage a target. It can take days or weeks to get a weapon into an appropriate attack position. That means any space-to-space engagements in GEO will unfold over days, not minutes, resulting in slow and deliberate engagements. The majority of the satellites in GEO are in the same plane, providing more opportunities and targets to attack. However, an attacking satellite is unlikely to have its motion go unnoticed since many operators will be maintaining space domain awareness around their satellites.

Types of Kinetic Engagements

The previous sections outline the key concepts necessary to understand how objects move in space. What do these key principles mean in the context of a kinetic conflict in space? Just like in terrestrial warfare, one objective of an attack is the physical destruction of a target, known as a *kinetic impact attack*. There are two types of kinetic impact weapons for space warfare: ground-based anti-satellite (ASAT) missiles, and on-orbit weapons (kinetic kill vehicles or orbital ASAT). [15]

Ground-based ASATs are missiles that rely on a rocket to deliver a small warhead to impact with a satellite. Because the rocket has a large ΔV capacity, the warhead itself is placed in the correct intercept trajectory and requires little propellant to reach its target—this makes them more intuitive as they behave more like traditional missiles. Unlike orbital ASATs, it does not require extensive setup time to be operational—if the target is within range, the missile can be used. Flyout times can be less than 10 minutes to LEO and less than 5 hours to GEO, leaving the target little time to detect and react to an attack. Once the missile launches, the warhead separates some distance from the target and uses onboard seekers and thrusters to refine its approach. If the missile delivers the warhead in the proper trajectory and if the target has not significantly changed its position relative to the attacker's predictions, the warhead likely will successfully intercept the target. However, if the target maneuvers, or if the missile does not deliver the warhead on the correct path, the ASAT will have limited ΔV to move to the correct intercept path.

In contrast, an orbital ASAT is basically a satellite that purposefully destroys other satellites. This can be done either with an RPO intercept or with onboard weapons. Unlike the ground ASAT missile, which can be launched without warning and at a moment's notice, an orbital ASAT may be launched months to years ahead of a potential conflict. Furthermore, since the ASAT itself is a satellite (or is carried by a satellite), the weapon must be placed in an orbit that has access to the target. This could be the same orbit (same altitude and orbit plane) or an orbit that crosses the target's orbit, either of which increases the prospect of the target's operators identifying the potential threat. The orbital ASAT must then maneuver into position to launch its attack which, as shown above, takes time and ΔV. One advantage of an orbital ASAT is that it can more readily pursue a maneuvering target than can a rapidly approaching ASAT missile.

There are several ways a kinetic ASAT can attack a satellite:

1. **Head-on collision.** A head-on collision from a kinetic weapon yields the highest relative velocity (just like two cars on a freeway hitting head-on). However, a head-on collision also minimizes the time available to course correct if the target moves contrary to the weapon's calculations. The ASAT weapon must be launched into the same orbit plane as the target but going in the opposite direction. This practically limits attacks using head-on collisions to a missile, given that maneuvering an orbital ASAT weapon into the proper trajectory

would require thousands of m/s of ΔV.[16] Head-on collisions generate lots of debris, which may pose dangers to other satellites in the orbit.

2. **T-bone collision.** A collision that comes from two orbits crossing each other, which is like a car being "T-boned," also yields high-impact velocities and offers little time to make any trajectory corrections. Unlike a head-on collision, a T-bone collision only requires that the target and the attacker are in the same location at the same time. No plane matching is required. Thus, an attacker could come from a different orbit plane with different altitudes but crosses the target's plane at the point of impact. This attribute is particularly attractive for orbital ASAT weapons, since attacks can be masked as harmless orbit intersections up until the time of impact.[17] However, for a T-bone collision to succeed, the attacker must accurately place the interceptor at the intersection point at the exact time the target is there, which can be difficult. The 2009 accidental collision of the Iridium 33 and Cosmos 2251 satellites is a real-life example of the damage done by two satellites that impact at an orbit crossing. Like the head-on collision, large amounts of debris are generated by a T-bone collision.

3. **Tail-on collision.** A tail-on collision allows for more time for the weapon to adjust its approach orbit to better track the target. However, the impact velocities in this configuration will be lower, which leads the attacker to either apply extra ΔV to engage kinetically or deploy onboard weapons to finish the attack. The lower-impact velocities also decrease the amount of debris generated by the attack. A tail-on collision also requires the target and attacker to have matched planes. GEO is an especially good location for a tail-on collision by an attacking satellite, as all satellites in GEO are already in nearly the same plane and orbit in the same direction, making it easy to pass off an attacking satellite as a nonaggressive satellite like other satellites in the orbit.

The engagements discussed here are limited to attacks on a single satellite. Given the size of space and the distance between satellites, kinetic attacks will be constrained to focus on individual satellite targets. This is analogous to using a sniper rifle, rather than a machine gun, in a terrestrial battle. One caveat to this is the generation of debris, discussed in a later section, which would put multiple satellites at risk.

Electronic Warfare, Directed Energy, and Cyberattacks

RPO and kinetic threats require coming close to a target satellite. However, there are also ways to attack from a distance. Some counterspace threats utilize the electromagnetic spectrum to inflict either temporary (reversible) or permanent (irreversible) harm. These threats are attractive because the attacks happen from a distance, which adds a measure of deniability and lessens the burden of getting physically close. Intentional jamming can also be quite difficult to distinguish from unintentional interference, making attribution more challenging.[18] There are two major types of electromagnetic threats, which can be delivered by satellites, or ground or airborne units:

1. **Electronic warfare** includes using radio frequencies to overwhelm an opponent's signals with random noise (jamming) and the purposeful mimicking of an opponent's signals to send harmful commands or data (spoofing). Electronic warfare attacks are considered reversible attacks as they do not inflict permanent damage to a satellite. The principles of electronic warfare have been known since the early twentieth century and have been used extensively in ground, naval, and air battles since World War II. Jamming satellites is a natural extension of these earlier efforts.

2. **Directed-energy weapons** use concentrated radio frequencies (high-power microwaves) or light (lasers) to interfere with a satellite's operations. Effects from directed-energy weapons can be either reversible or nonreversible. Lasers can be used to either temporarily blind optical sensors and cameras (dazzle) or permanently damage sensitive onboard equipment. High-power microwaves interfere with onboard electronics, with effects ranging from temporary malfunctioning to melting of critical components and other permanent damage. These are the same effects that airborne and other systems experience when attacked by directed-energy weapons.

To understand how these effects could play in a conflict, there are a couple of key points to understand.

1. **Intensity dissipation.** As an electromagnetic signal, whether radio frequencies or light, is emitted from a source, the intensity of the signal decreases with the square of the distance from the source. The farther away, the weaker it is. An object 10 km from a source will experience only 1 percent of the intensity of an object next to the source. For satellites in orbit, where distances are often measured in hundreds or thousands of kilometers, a threat would need high-power levels to successfully engage with electronic warfare or directed-energy weapons.

   Signals in a vacuum only lose strength due to distance. However, when a signal goes through the atmosphere, gases such as water vapor and oxygen absorb some of the intensity. Liquid water also degrades signal strength at many frequencies. This means that a ground-to-space or space-to-ground attack will require more power than a space-to-space attack of the same distance. If a space-based attacker's line-of-sight to its target goes through the atmosphere, there will be additional signal losses compared with a clear (no atmosphere) attack path. Figure 10 shows these effects.

2. **Precision.** Electronic warfare requires a large degree of precision to execute. In this context, *precision* refers to how well an attacker can match the signal of or focus on its target. For a jamming attack to be successful, the attacker must transmit a jamming signal that matches the signal of the target's receiver, either through jamming a large block of signals in hopes of hitting the right signal (known as *brute force jamming*) or through specifically matching the targeted signal. Matching a signal is a combination of achieving the right frequency, polarization, and signal strength. The frequency of the signal refers to the number of times the signal oscillates through space and is correlated to the amount of data that can be carried. Polarization describes the direction the signal travels as it moves through space. Signal strength is important because a jamming signal must be at least equally strong as the targeted signal to cause interference. A jamming signal that does not match in all three areas (for example, if it matches frequency and signal strength but not polarization) will not be effective. The precision needed for electronic warfare is not unique to satellites. However, because satellites move in predictable paths, it is easier for an attacker to characterize a target's signal and change its jamming broadcast accordingly. This is especially true for attacking spacecraft that are operating in proximity to their targets.

   Spoofing attacks require even greater precision. In addition to matching a signal's frequency, polarization, and signal strength, a spoofer must also broadcast the right type of information on the signal. As an example, suppose an attacker wishes to use spoofing techniques to transmit false troop locations to a targeted system. For the attack to work, the spoofer must know what signal to broadcast and give data that is close

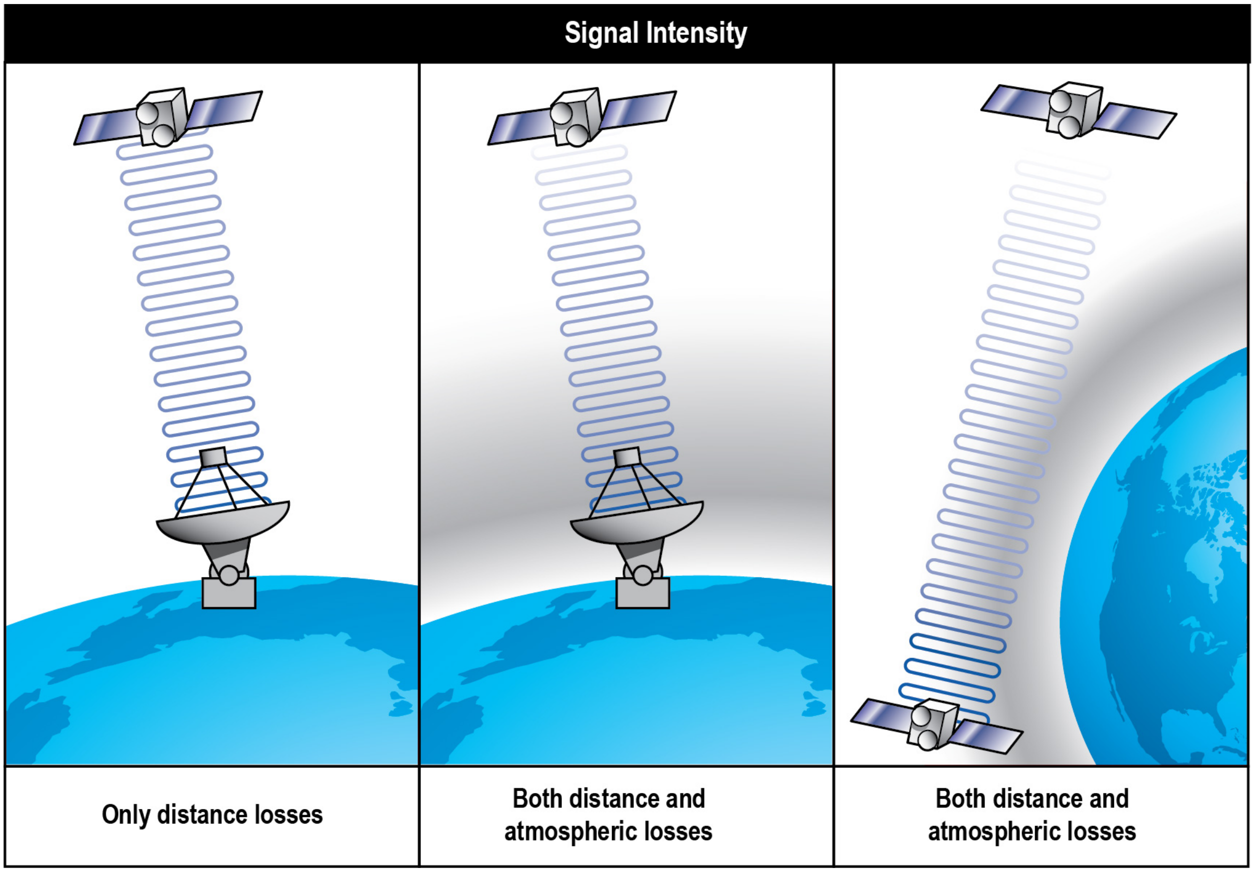

Figure 10: Signal Intensity Dissipation: *Comparison of the intensity dissipation in vacuum to that of additional atmospheric losses for three different scenarios. For a signal sent from a ground station on Earth to a satellite at medium Earth orbit (MEO), the signal strength is reduced to a trillionth of its original power due to distance alone (left panel). The signal loses an additional 90 percent of its strength through interactions with the atmosphere (middle panel). If a satellite must reach another satellite by going through the atmosphere (right panel), signal intensity is reduced by about 99 percent compared with the signal strength resulting from distance loss alone. This is due to the longer path through the atmosphere in the right panel as compared to the center panel.*

enough to the truth as to be believable. The attacking spoofer must thoroughly understand both the signal itself and how the signal is interpreted by the targeted system to be effective.

While electronic attacks involve interfering with a satellite's radio frequency signals, cyberattacks target the data used and transmitted by a satellite. Just like terrestrial cyberattacks, cyberattacks on satellites involve exploiting hardware or software weaknesses in the communications link between a satellite and its ground network to either steal data or to inject malicious code into the system. A cyberattack on a satellite can result in loss of information needed to perform its mission, or even loss of control of the vehicle itself.

There are two general approaches to conducting a cyberattack against a satellite: target ground stations it communicates with or target the satellite directly. A cyberattack on a ground station is like a cyberattack on any other land-based network. However, there is a delay in the satellite receiving the bad or malicious signal, as it has to be in view of and/or communicate with the ground station to be compromised. A satellite could also be directly targeted by a ground station set up by a bad actor, as opposed to the ones it was designed to communicate with. Alternatively, a satellite can also be cyberattacked by another satellite. Exactly how close it needs to be depends on the specific capability of the attacking satellite but will likely need to be nearby and, thus, would execute an RPO maneuver to get close and then employ the attack.

Electronic warfare, directed energy, and cyberattacks greatly increase the number of shots an aggressor might take, making them more akin to a machine gun than a sniper rifle. Additionally, they have the potential to deliver effects far faster than the deliberate pace of space-to-space engagements. These factors mean they are likely to be an important aspect of space war. Even though many of these effects are reversible, they can severely degrade capabilities during a fight.

The Complication of Debris

During any kinetic conflict there may be secondary concerns to consider in engagement planning. Blowing up a bridge may prevent enemy tanks from escaping, but it will also hinder the pursuing army. Because it is so far removed from other human activities, space does not have too many secondary concerns. But it does have a big one: debris.

Space debris is created when two objects collide (whether intentional or accidental) or if a satellite explodes (due to battery failure or pressurized tank rupture, for example). Debris is especially harmful in space given the speed at which objects move, regardless of their mass. A piece of debris as small as the size of a coin, traveling at orbital speeds, could destroy a satellite.[19]

That means what one does to another's satellite can have dramatic—even fatal—consequences for one's own satellites.

Recently, three countries have performed successful ASAT missile tests: China (2007), the United States (2008), and India (2019). In all three cases, ASATs were launched from Earth's surface and successfully intercepted and destroyed a satellite in LEO. Both the Indian and Chinese tests were head-on collisions though not perfectly so like a head-on car crash. Instead, the ASAT came slightly from below but still in the plane of the satellite. Figure 11 compares longevity of debris from the three tests, with the resulting debris cloud densities of the three tests plotted as a function of altitude. Red denotes areas of high debris density, while blue shows low debris densities. Black represents areas of no debris. The Indian test is similar to the U.S. test, with very short-lived debris clouds for both events due to their low intercept altitudes (less than 300 km or 190 mi.). In contrast, in 2007, the Chinese intercept of FY-1C, a nonoperational Chinese weather satellite, occurred at an intercept altitude of 856 km (532 mi.) and, therefore, created debris likely remaining in orbit for decades.[20]

While the U.S. and Indian tests saw large dropoffs in debris densities after 60 days, the Chinese test had no noticeable density dropoff. Over time, satellites in these higher-density areas will have a higher probability of a catastrophic debris impact. However, even in the densest debris cloud, an individual satellite's probability of hitting debris remains low. But a debris impact would affect the functionality of space-based capabilities during a conflict—for both a ground fight and space fight—and could be devastating.

Figure 12 illustrates the evolution of the debris cloud created during the 2019 Indian test. Aerospace models predict the creation of 297,000 debris fragments greater than 1 cm (0.5 in.) in size.[21] Regions of high debris density show up in orange and red, low debris densities are shown in blue. Although the initial impact produces a localized debris cloud, it only takes about a day for the debris cloud to form rings around the entire Earth. Even though the density of the debris ring is relatively low

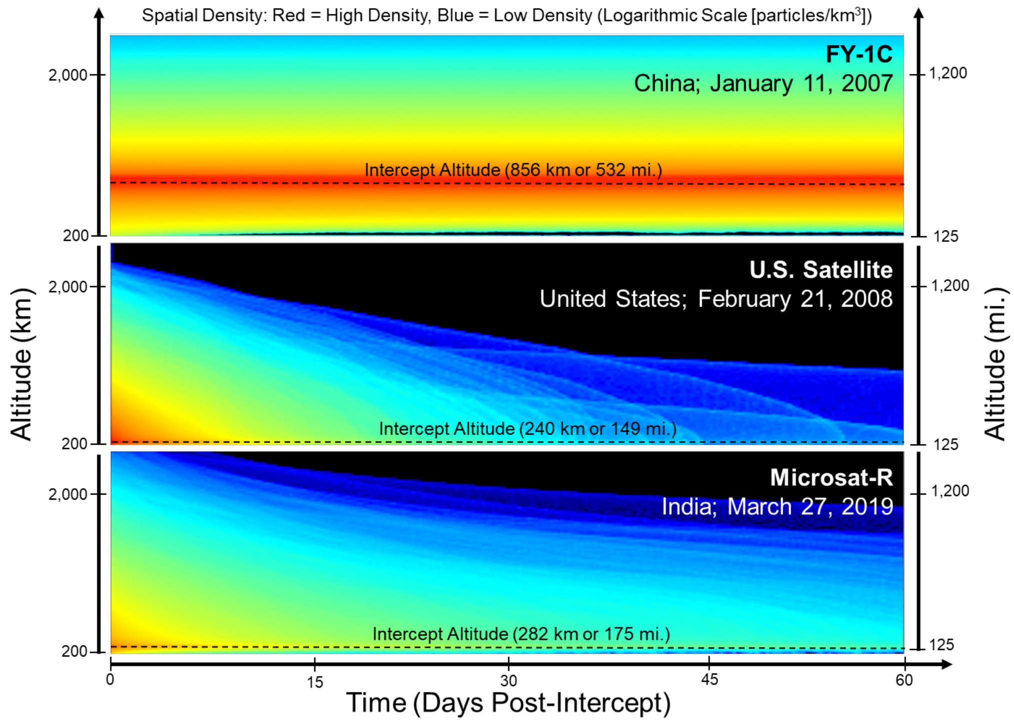

Figure 11: Debris Comparison of Three ASAT Tests:[22] *The density of debris is compared at different altitudes as a function of time after the ASAT intercepted (made contact with and destroyed) the target satellite. The Chinese test happened at a much higher altitude (856 km or 532 mi.) than the other two, creating long-lasting debris.*

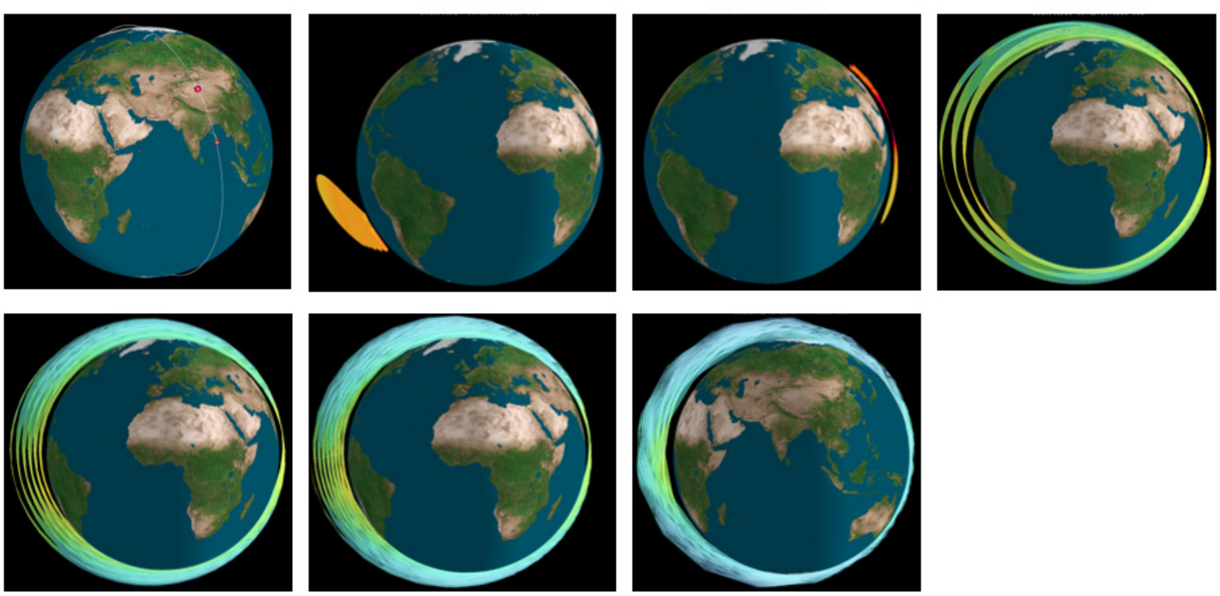

Figure 12. Indian ASAT Debris Cloud: *Time progression of the debris cloud. Starting in the top left, the images correspond to post-intercept time: 5 min., 45 min., 90 min., 1 day, 2 days, 3 days, and 6 days.*[23]

after one day, the region affected by the test has become greatly expanded.

Debris clouds propagate quickly, which has immediate consequences for further engagements. If an adversary threatens a satellite by being in the same plane, there are few good options for the target. Kinetically destroying the adversary satellite may create debris that then threatens the very satellite being protected. Furthermore, other spacecraft will have to fly through the debris cloud. Debate continues on how many engagements would make space unusable.[24]

While this discussion focused on ground-to-space ASAT tests, similar outcomes could be expected for orbital kinetic engagements (space-to-space).

Additionally, any debris generated in space could have a lasting effect on the space environment, especially for orbits at higher altitudes, such as GEO. Many other publications cover this topic in more detail.[25,26,27,28]

Conclusion

Because the way things move in space is not intuitive to most of us, it is important to take the time to understand what makes the space domain unique if we are to understand the practical constraints on space-to-space engagements. Five key principles have been presented here: satellites move quickly, satellites move predictably, space is big, timing is everything, and satellites maneuver slowly.

The space-to-space portions of conflict in space would be uniquely limited. Until there are gas stations in space, maneuvering requires careful ΔV budgeting, limiting the number of maneuvers a given satellite could do. Between ΔV limitations and the likely desire to minimize detection, properly positioning an orbital weapon into an appropriate attack position will often take days or weeks.

Since space-to-space engagement timelines tend to be lengthy due to the physics of orbits, there is a strong incentive for an aggressor to consider alternative weapon systems among ground-based ASATs, electronic warfare, directed energy, and cyber. These alternatives to space-based weapons could shorten attack timelines and increase the number of targets that can be attacked in short order.

However, not everything about conflict in space would be unique. Satellites being jammed or spoofed is a natural extension of electronic warfare that has existed for decades. However, the distances involved and the predictability of satellite motion does introduce new considerations.

Most space activities are for peaceful purposes: science missions, human exploration, communication, environmental monitoring. Because of the broad range of space applications, the effects of conflict in space would affect most everyone on the planet. The possible generation of debris is the most obvious example. However, operating in a less benign environment might change how civil and commercial stakeholders operate.

While there has never been a battle in space, we can still gauge what a war in space might look like. It would not be like the movies with intense dogfights. Instead space-based threats would be un-crewed and require slow and deliberate planning to get into position. Compared with the timing and flexibility limitations of on-orbit weapons, ground-based threats afford substantially shorter engagement execution timelines and the prospect of more numerous shots. The more we can internalize these insights, the better we can understand the stakes of a geopolitical fight in space.

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[3] *Kinetic* military action refers to the use of physical force. This contrasts with diplomacy, sanctions, the use of the electromagnetic spectrum to hinder or harm, or cyberattacks.

[4] Joint Publication 3-14, "Space Operations."

[5] Satellites can also follow parabolic or hyperbolic orbits that carry the satellite out of Earth orbit and into an orbit around the sun. This paper assumes that military satellites will stay in Earth orbit.

[6] However, the larger satellite requires more energy and, in general, a bigger, more expensive rocket to get to a given orbit than does a smaller satellite. Once there, they have the same energy per unit mass and the same speed.

[7] Ignoring the effects of drag and other perturbations

[8] ΔV is measured in metric units even in the United States, which primarily uses English units.

[9] https://spacenews.com/northrop-grummans-mev-1-servicer-docks-with-intelsat-satellite/

[10] CubeSats are defined in 10 cm (4 in.) cubes and are often used as student engineering projects due to their simplicity and low cost.

[11] https://www.seradata.com/al-yah-3-arrives-in-geostationary-orbit-but-has-lost-part-of-its-expected-lifespan/

[12] These points are known as "perigee" and "apogee," respectively.

[13] This leads to a practical upper limit of 10 degrees per hour (40 degrees in 4 hours, 120 degrees in 12 hours) to phase Satellite A forward in its orbit. The reentry-imposed ΔV limit indicated here will be different for orbits at other altitudes.

[14] There are two main concentric loops/bands around Earth full of charged particles. These particles largely originate from solar winds and are captured and held in place by Earth's magnetic field.

[15] Kinetic impact attacks can be launched from air, sea, and ground assets.

[16] Or that it be launched in a retrograde (direction opposite of the direction of Earth's rotation) orbit.

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[18] https://ontheradar.csis.org/issue-briefs/satellite-jamming/

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[21] Ibid.

[22] Ibid.

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