Space 201: Thinking About the Space Domain

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Over the past three decades, the role of outer space in military operations has risen steadily. From the inception of the space age, America's activities in space have included a large national security component. The development of satellites was not only a matter of national prestige in the ideological competition of the Cold War, but also an effort to monitor military and other developments from the strategic high ground of space. Many of the earliest satellites were engaged in the gathering of intelligence.

Due to their sensitive nature and the advanced technologies associated with them, information derived from reconnaissance satellites (sometimes termed national technical means, or NTM) has generally remained highly classified. Rumors have long abounded regarding the capabilities of American reconnaissance satellites, for example, but little of their actual resolution (what they were able to see on the surface of the planet) was revealed during the Cold War. The end of the Cold War and the subsequent use of satellite imagery in 1991 during the first Gulf War pulled back many of the curtains that had obscured the capabilities and nature of reconnaissance satellites as programs were declassified and images were disseminated more broadly.

Space-based capabilities have also evolved from being oriented primarily toward meeting national security requirements to increasingly being part of global commerce. Whereas information from satellites used to be closely held, anyone can now purchase overhead imagery through companies like Digital Globe and Skybox. Similarly, whereas satellite position, navigation, and timing (PNT) used to be employed primarily by military forces to improve weapons accuracy, it is now incorporated as standard equipment in many private cars, and the timing function is employed in myriad activities from precision agriculture to reconciling financial transactions.

It is important to recognize that this massive expansion of the role of space is a relatively recent phenomenon. The space age itself is only a half-century old, having begun on October 4, 1957, with the launch of Sputnik by the USSR.[1] Moreover, because space activities and space-derived information have long been closely held secrets, their full potential for military and civilian applications has yet to be explored. Though information from space systems has been employed in the wars of the past quarter-century, no nations have yet engaged in combat in space. Both the political and technical ramifications of such a conflict are still largely theoretical.

Key Characteristics of Space

Given the growing importance of space in security affairs, it is important to recognize certain key characteristics of the outer space domain.

Characteristic #1: Space is beyond Earth. The outer space region is generally considered to begin somewhere between 100 kilometers (62 miles) and 100 miles above the surface of the Earth and extends from there. At 100 kilometers, aerodynamic forces have minimal impact on reentry vehicles; at 100 miles, the atmosphere is no longer a meaningful presence. While "space" theoretically encompasses the entire vastness of the cosmos, the militarily significant region of space is that bounded by the Earth–Moon area, as well as certain other locations governed by the Earth–Moon relationship. The latter include the Lagrange points, the five points where the gravitational pulls of the Earth, Moon, and Sun balance each other, thus making it possible for an object placed at one of these points to remain there indefinitely with minimal expenditure of fuel.

Because space is literally beyond the Earth, it is not affected by terrestrial borders as is the case with airspace. Whereas the airspace (physical space within the atmosphere above the boundaries of a nation) is considered the equivalent of sovereign territory, the same does not apply once one enters outer space. Instead, spacecraft of all nations are allowed to transit freely overhead and have no obligation to curtail their activities in doing so. (Realistically, such activities as satellite communications and weather forecasting would be virtually impossible if there were a patchwork of sovereignty governing outer space as there is on Earth.) Ironically, this principle of "open skies" was established when the Soviet Union orbited its Sputnik spacecraft. The Soviets argued that Sputnik did not pass over countries; instead, countries rotated underneath the spacecraft.[2]

Because it is beyond Earth, outer space is also not affected by considerations of terrain. There are no features in space (at least within the Earth–Moon system) that provide concealment or otherwise can mask spacecraft operations. Therefore, there is no real ability for spacecraft to hide.

Counterintuitively, this set of considerations actually makes space situational awareness (SSA) a very complicated affair. Because there is no place for satellites to hide, all orbiting objects can be seen, given a suitable suite of sensors. At the same time, however, this means that one must track several tens of thousands of objects in space, ranging from operational and defunct satellites to spent upper stages of rockets, loose nuts and bolts, and other debris from past space missions. Today, the United States Air Force officially keeps track of over 23,000 objects, which is by no means the totality of objects currently orbiting the Earth.[3] To do so, it makes over 400,000 observations (determining where various objects are located) daily.[4]

Undertaking SSA is essential in part because space objects may be mistaken for missiles; in order to prevent false alarms and possible inadvertent escalation, it is vital to track at least the larger objects in orbit so that we can know what is normally in orbit and therefore what new object might warrant closer scrutiny. Almost as important, tracking current objects in space and determining their orbits is critical to preventing collisions between satellites, preventing collisions between orbiting objects and spacecraft that are being launched, and determining whether space objects' orbits are decaying to the point that those objects may reenter the Earth's atmosphere.

To maintain SSA, the United States (like other nations) employs a variety of means. A vital tool is a network of radars. Some are conventional radars, which can track individual targets. Others are large phased-array radars, which can track multiple objects simultaneously and maintain surveillance over large volumes of space. In addition, there are many telescopes that allow imaging of satellites, which in turn allows analysts to determine the likely functions of a given satellite more precisely. All of these are ground-based systems.

Since 2014, the United States has also deployed a series of satellites that allow it to examine satellites from orbit. The Geosynchronous Space Situational Awareness Program (GSSAP) comprises a number of satellites deployed in geosynchronous orbit.[5] These carry electro-optical sensors that provide analysts with up-close pictures of objects in orbit.

Characteristic #2: Space is a hostile environment. The reaches of outer space are some of the most difficult environments in which machines or people operate. Because spacecraft are operating under near-vacuum conditions, gases that are trapped in the material of a spacecraft may be emitted in a process known as outgassing. These gases, in turn, can condense on the surfaces of a spacecraft, damaging components, clouding lenses and sensors, or otherwise adversely affecting the spacecraft.

Because spacecraft operate beyond the protection of Earth's atmosphere, they are exposed to a variety of forms of radiation, including cosmic rays, solar radiation, and even radiation belts that encircle the Earth (for example, the Van Allen radiation belts). Prolonged exposure to ultraviolet radiation can alter the properties of various materials. Spacecraft are also subjected to wild variations in temperature in ranges of hundreds of degrees. This, in turn, can lead to expansion and contraction of materials and even to cold-welding of parts.

Finally, in addition to being potentially vulnerable to collision with other satellites and any objects in orbit, spacecraft may be hit by micrometeoroids.[6] Everything in space is moving at very high speeds. Space debris, for example, typically moves at about 10 kilometers per second on average, which translates to roughly 22,000 mph.[7] Even grains of sand traveling at such speeds can have an abrasive effect, and larger objects can damage solar panels and instrument packages.

In order to operate in such a hostile environment, spacecraft must be manufactured to very high tolerances. Many are practically hand-made, which makes them very expensive. A commercial communications satellite costs at least $200 million.[8] Military communications satellites such as the Wideband Global Satcom satellite cost upwards of $400 million each.[9] Dedicated reconnaissance satellites (spy satellites) can cost over $1 billion. Reportedly, the overall cost for four new U.S. GOES-R weather satellites will be $11 billion.[10]

The steady increase in the cost of satellites is reflected in the American Global Positioning System (GPS) constellation. When fielding of GPS began in the 1990s, each satellite cost approximately $43 million, and launch costs were about $55 million. In 2013, it was reported that the newest GPS III satellites would cost $500 million each and $300 million per launch.[11]

Given the expense, few states can afford to develop, launch, and operate satellites, much less maintain reserve satellites, either in orbit or on the ground. A satellite that is lost due to a malfunction, collision, or other problems therefore cannot be replaced easily. There will likely be gaps in service or coverage until a replacement satellite can be built and launched. Augmenting a constellation is also not something that can be done either easily or inexpensively.

For these reasons, it is in the interest of satellite operators to have satellites last as long as possible. A satellite will typically carry enough fuel to enable orbital maneuvers. These range from station-keeping in order to stay in the proper orbital track and location to altering the orbit in order to avoid collisions. Activities that adversely affect the life span of a satellite (such as extensive maneuvering) are not undertaken lightly. In particular, changing a satellite's orbital plane (angle relative to the Earth's equator) is very expensive in terms of fuel and is usually avoided.

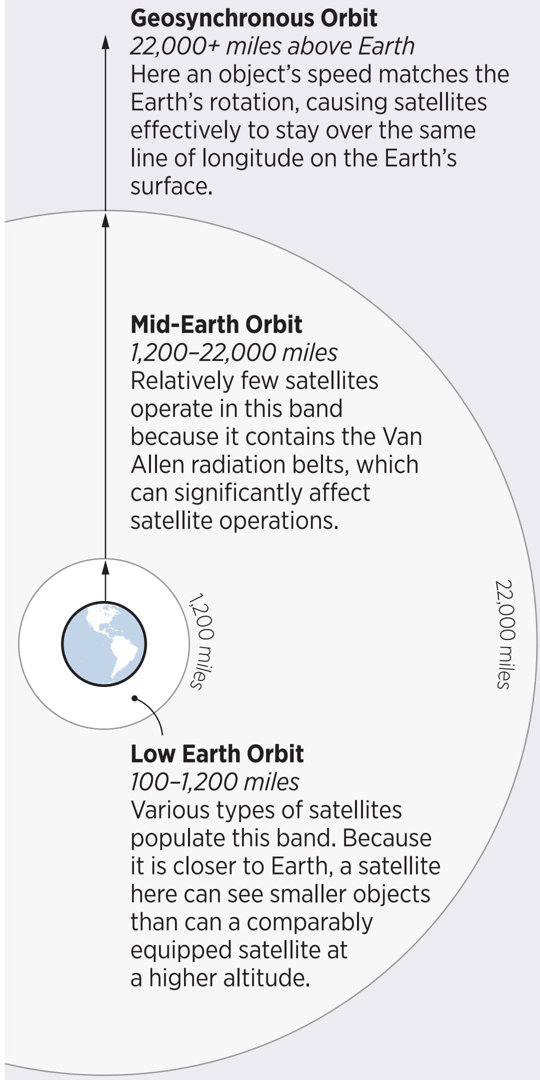
Characteristic #3: Space is difficult to reach. Not only does it take time to build a satellite; it also takes time and a great deal of infrastructure and related expense to launch it. Various capabilities are necessary to place an object into orbit. One must have a satellite and a launch vehicle. That vehicle is launched from some kind of facility that has a launch pad, a mission-control facility, and surveillance equipment with which to monitor and control the launch. There is usually an assembly or mating facility for placing the satellite payload on the rocket. Finally, other tracking sites are necessary to ensure that the payload has reached the proper orbit, has separated from the launching rocket, and is functioning properly after it has entered orbit.

All of these elements combine to make space operations expensive.[12] Until quite recently, only major countries could afford space operations, but private companies have entered the market.

The differences among these major space launch providers are the result of a number of factors, the most important of which is reliability of launch. This is no small affair when satellite payloads cost hundreds of millions or even billions of dollars. ULA has perhaps the longest track record of successful launches. SpaceX, a competing private venture, is the newest entrant and therefore does not yet have an established track record, making its reliability more of an unknown.

FIGURE 3

Types of Earth Orbits



SOURCE: Heritage Foundation research.

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Types of Orbits[13]

While there is no terrain in space, there are orbital bands that are loosely defined by their altitude above the Earth's surface. There is no clear demarcation among them, but space experts in general talk about three main orbital bands.

Low Earth Orbit (LEO). This is the part of outer space that begins at about 100 miles above the Earth and extends to 1,200 miles. A variety of satellites populate this band, including various types of reconnaissance and Earth observation satellites, some weather satellites, and various scientific satellites. Because it is closer to Earth, a satellite in LEO can see smaller objects than a comparably equipped satellite at a higher altitude can.

However, satellites in LEO have a more limited field of view. They are essentially viewing a ribbon of the Earth's surface as they orbit around the planet.[14] The closer to Earth, the narrower the ribbon, much as a flashlight's area of illumination shrinks or expands the closer to or farther away it gets from the spot at which it is pointed. Moreover, because of orbital mechanics, an object in LEO cannot hover over a given point unless it uses an enormous amount of fuel to stay in position. Therefore, satellites in this orbital band cannot maintain surveillance over any particular point on Earth. Instead, any individual satellite will pass over a given spot every few hours. Multiple satellites in a constellation can keep a given spot on Earth under constant surveillance—but at the cost of fielding multiple satellites.

Objects in LEO also have a more limited life span. Though they are operating above the bulk of Earth's atmosphere, they nonetheless are still operating within its upper reaches. This imposes atmospheric drag so that their orbit drops (or decays) over time. At 150 km altitude, a satellite begins to lose altitude within a day; at 400 km, it could remain in orbit for a year before its orbit began to decay appreciably.[15]

Medium Earth Orbit (MEO). This region stretches from 1,200 miles to 22,000 miles above the Earth's surface. Relatively few satellites operate in this band, partly because it also contains the Van Allen radiation belts, which can affect satellite operations significantly. Within this band, however, is an area where a satellite will revolve around the Earth in 12 hours, going over the same spot twice every day. Satellites orbiting at approximately 12,800 miles above the Earth's surface are said to be in semi-synchronous orbit.

Most of the satellites that operate in semi-synchronous orbits are involved with positioning, navigation, and timing. These include the American GPS satellites and their Russian GLONASS, European Galileo, and Chinese Beidou/Compass counterparts.

Geosynchronous Orbit (GEO). The geosynchronous belt is at approximately 22,000 miles above the Earth's surface. At that altitude, an object in orbit is traveling at a speed that matches the Earth's rotation. Consequently, a satellite will effectively stay over the same line of longitude on the Earth's surface, although it may drift north or south in terms of its footprint on Earth. If a satellite is located at the GEO belt at the Earth's equator, however, it will stay over the same location on the ground and is said to be geostationary.

Theoretically, satellites in a geostationary orbit can keep constant watch over one-third of the Earth's surface. Consequently, this orbital band is considered extremely valuable; GEO slots above the equator are occupied by weather satellites, communications satellites, and missile early warning satellites.

In addition to these three orbital bands, there are several other types of orbits that are militarily useful.

Polar and Sun-Synchronous Orbits. Some satellites are launched into low Earth orbits that are at a very high inclination relative to the Earth's equator, essentially traveling from pole to pole. Polar orbiting satellites will typically see the same spot on Earth twice a day, once in daylight and once at night. A particular type of polar orbit is the sun-synchronous orbit. A satellite in such an orbit will always pass over the same spot on Earth at the same time. If it takes images while passing overhead, the fact that the images are taken at the same time every day facilitates the identification of any changes that may have occurred on the ground in the interval between images.

Lagrange Points. At the five Lagrange points, the Earth, Moon, and Sun's gravitational pulls cancel out each other. As a result, an object located at these points will remain in the same location relative to the Earth even as the Earth–Moon system and the satellite itself revolve around the Sun.

Molniya Orbits. Satellites operating in geosynchronous orbit over the equator stay over the same spot, but their ability to view the extreme northern and southern latitudes is very limited. Russian scientists therefore developed the Molniya orbit, where satellites orbit as high as 24,000 miles at their apogee or highest point while dipping as low as 500 miles above the Earth's surface at their lowest point.

Because the Molniya orbit also has a period of 12 hours, the high-altitude portion of the orbit will occur over the same area of Earth twice each day. Moreover, due to the momentum of the satellite, most of the time when it is moving more slowly will be near the top of its orbit. For most satellites in a Molniya orbit, the top of the orbit will be in the Northern Hemisphere, maximizing the opportunity to observe areas of interest in the high northern latitudes.

Major Satellite Missions

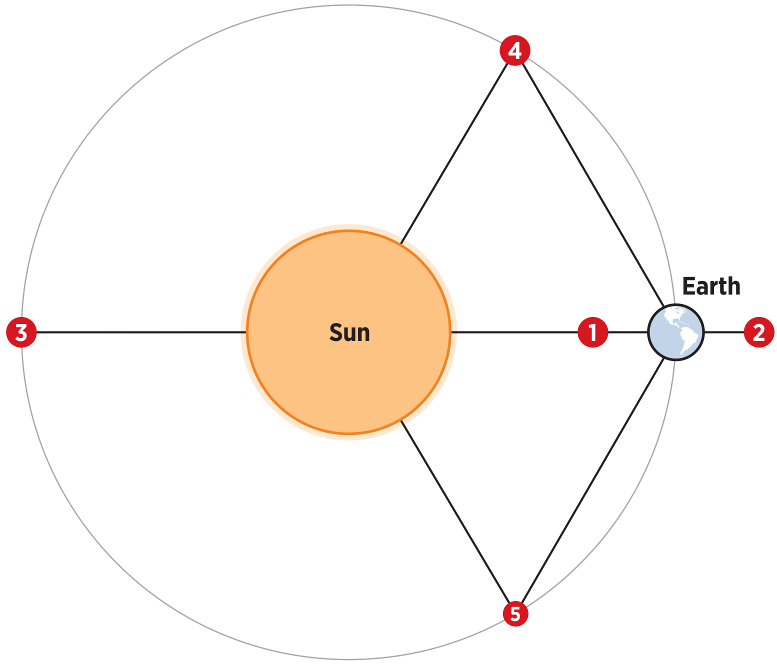
According to the United Nations Office for Outer Space Affairs (UNOOSA), more than 7,600 registered objects (a subset of the more than 23,000 that are tracked) are currently in orbit around the Earth.[16] Of these, only about 1,460 are operational satellites.[17] These satellites are engaged in a number of mission areas.

Intelligence, Surveillance, and Reconnaissance (ISR) Satellites. Satellites tasked

FIGURE 4

Lagrange Points

Lagrange Points are five locations where the gravitational pulls from the Earth, Moon, and Sun cancel each other out. As a result, an object located at any of these points will remain in the same location relative to the Earth, even as the Earth-Moon system and the satellite itself revolve around the Sun.



SOURCE: Heritage Foundation research.

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with monitoring developments in other countries have been a mainstay of space capabilities since the dawn of the space age. Both the United States and the Soviet Union sought to develop spy satellites capable of seeing into the other side's hinterlands. These satellites were initially equipped with cameras that dropped film, but those cameras were later replaced with systems that could beam their images back directly to Earth-based stations. Electro-optical satellites are unable to see through fog and clouds, so some satellites carry radars to overcome the effects of obscuring by clouds; these can often produce very high resolution images.

Imaging satellites of various sorts have been supplemented by satellites that can monitor various types of activities in the electromagnetic spectrum. Some listen to radio traffic, collecting communications intelligence (COMINT). Others are able to detect and record electronic signals, collecting electronic intelligence (ELINT). COMINT and ELINT together are referred to as signals intelligence (SIGINT). SIGINT satellites can provide insight into the types of equipment (such as radars) being deployed by countries of interest, with the information collected revealing the wavelengths the equipment houses and what types of units (such as anti-aircraft batteries and anti-ship missile forces) are being deployed.

Most ISR satellites operate in LEO.

Earth Observation and Weather Satellites. Not all information collection is necessarily focused on other countries' military and political forces and behavior. Understanding the local environment can also be important.

Earth observation satellites such as the Landsat series have been collecting information about the land and seas for decades. The resulting data are invaluable for creating maps, as well as for understanding, for example, land use and seasonal changes in ground cover like tree foliage and grasses. For both ISR and Earth observation, data from space sensors are combined with information gathered from aircraft and terrestrial sources to give a comprehensive, layered understanding of any spot or vertical column above the ground on the planet.

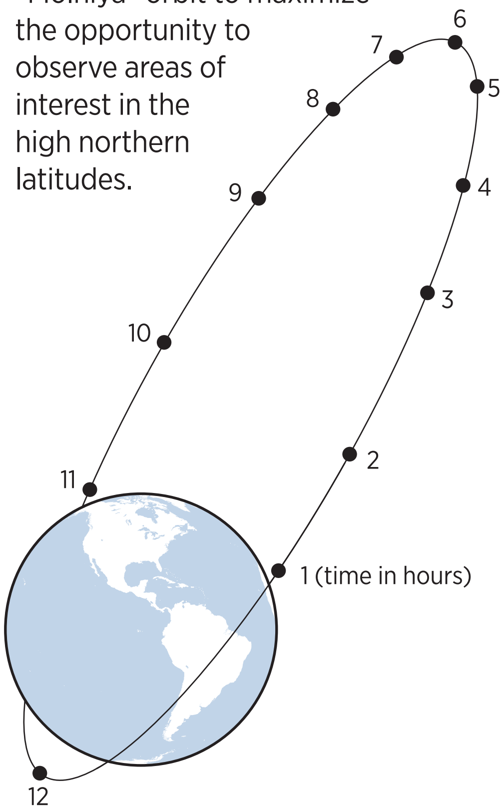
Of particular security importance among the Earth observation satellites are weather

FIGURE 5

Molniya Orbit

500–24,000 miles above Earth's surface

Russian scientists developed the "Molniya" orbit to maximize the opportunity to observe areas of interest in the high northern latitudes.



SOURCE: Heritage Foundation research.

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satellites. The ability to forecast weather accurately can have a decisive impact on military operations. Amphibious operations, for example, can be badly disrupted by storms. Similarly, the ability to undertake air operations, whether launched from an aircraft carrier or from a land base, is affected by inclement weather conditions. Aircraft launched from an airbase in the United States may have to fly to a destination thousands of miles away. Knowing weather conditions along the route is essential to safe and effective operations, whether they involve military or civilian aircraft. The better one's understanding of weather information is, the lower the risk that one has to accept to carry out a mission.

Possessing better awareness of weather conditions than is possessed by one's opponent can confer important operational advantages. This was the case in June 1944 when Allied meteorologists, unlike their German counterparts, identified an impending lull in storms that were battering the English Channel. Consequently, the Allies landed on the beaches of Normandy on June 6, while the German high command presumed that storms made such an invasion impossible.

Most Earth observation satellites operate in LEO. Some weather satellites operate in LEO, and others are deployed in GEO.

Communications Satellites. One of the earliest commercial types of satellites was the communications satellite (comsat). Because radio, television, and other communications signals travel in straight lines, their ability to connect users on the ground is often limited by the horizon. Comsats essentially serve as relays for the transmission of these signals; a transmitter sends a signal to the communications satellite in orbit, which then transfers the signal to a ground station that may be well beyond the horizon of the original transmitter. Theoretically, a constellation of three comsats at GEO would be sufficient to provide global coverage. In reality, the availability of transponders (which are the actual relays) limits the ability of any given satellite to provide coverage.

Modern communications satellites are an important link in the movement of voice communications, television signals, and data (including Internet traffic). With the growing popularity of satellite television and its potential for entertainment and distance learning, there is a growing demand for comsat services. In addition, communications satellites are a key enabler for military drone operations. From bases in the United States, operators can fly drones halfway around the world only because they are able to access comsats that bounce their instruction signals to their drones and relay information gathered by drone aircraft back to controlling or intelligence-processing stations.

Many of the world's communications satellites are run by private companies. Some of the world's largest constellations, for example, are now privately owned by companies such as Intelsat (55 satellites in 2014); Eutelsat (34); and the Canadian company Telesat (10).[18]

Many communications satellites are operated at GEO. However, the Iridium constellation that provides global satellite phone service is largely in LEO. Because of the smaller footprint for satellites operating at that altitude, more are needed to provide global coverage; the Iridium constellation comprises some 66 satellites.

Position, Navigation, and Timing Satellites. Beginning in the 1980s, the United States started to deploy satellites to provide position, navigation, and timing information.

- *Position* provides information about one's location and orientation: "Where am I?"
- *Navigation* provides information linking one's location to a desired destination: "How do I reach my intended location?"
- *Timing* provides precise, accurate time information.[19]

The position and navigation functions are outgrowths of the timing element. Timing functions on the GPS constellation are possible due to the highly accurate atomic clocks that are integrated into each satellite.

Each PNT satellite provides a unique signal indicating which satellite it is and what its orbital parameters are. A receiver (for example, a Garmin receiver in a vehicle) decodes the signal from at least three and usually four satellites to determine its distance from each satellite. This is done by comparing the time stamp signal from each satellite (provided by the onboard atomic clock) with the signals from the others in order to triangulate one's location. The result provides information in three dimensions with accuracy down to a few feet if one is using a cell phone's GPS function to a few inches with dedicated equipment. This is why a navigation application on a phone, in one's car, or aboard a ship far out at sea is able to work.

Because the PNT signal can be reached worldwide and all the clocks in a given constellation are keyed to the same system, the timing function has assumed a growing importance. American military frequency-hopping radios, for example, use the timing signal from GPS to time their jumps from frequency to frequency.

The U.S., Chinese, and European PNT constellations are in MEO, although China's system also includes a component that is based in GEO.

Tracking, Telemetry, and Control

In order to ensure that the various satellites are operating properly, a satellite operator needs a tracking, telemetry, and control (TT&C) network. This network enables the operator to control the satellite's functions.

- *Tracking* refers to the ability to locate a satellite and monitor its orbital condition and situation. This includes the satellite's distance and velocity.
- *Telemetry* is comprised of messages from the satellite that provide the operator with information about how well the satellite is operating. It is typically broken down into information about each of the satellite's subsystems. Telemetry data are distinct from payload data (the missions that the satellite is performing). The former is about the ability of the satellite to perform its mission.
- *Control* refers to the ability of the operator to adjust the satellite's operations. This might involve reorienting onboard instruments such as cameras or the entire satellite (for example, to point the spacecraft's solar panels toward the Sun). It might

involve moving the satellite to a different orbit or requests for more telemetry data.

TT&C networks often include stations in foreign countries and may also incorporate dedicated space support ships.

Space and Future Conflicts

Modern warfare is marked by the centrality of information. The ability to conduct joint air, land, and sea operations rests in part on the ability to create a common situational picture. Modern warfare requires the coordination of forces often separated by vast distances: for example, aerial tankers from one airbase, strategic bombers from another, and carrier air wings operating hundreds of miles from the front lines, along with infantry and armored forces. These forces must be able to communicate among themselves, identifying the location not only of the adversary, but also of one's own forces. All of this relies heavily on the ability to access the strategic high ground of space.

For the United States, this dependence is especially acute because American forces typically operate in an expeditionary mode, far from our own shores. By contrast, an Iran, a China, a North Korea, even a Russia is usually operating far closer to its home territory. Consequently, these states can employ a variety of non-space means, ranging from manned and unmanned aerial vehicles to radar networks, and even human observers on land and sea to provide a constant stream of information. Similarly, they have a range of communications options such as microwave, cell phones, and various types of radio systems to link their forces together—options often not available to U.S. forces because of the distances involved when deploying from home to far-flung theaters of operation.

This asymmetric dependence means that adversaries are incentivized to deny the United States easy access to space, which will affect their own operations far less than those of the U.S. armed forces. Conversely, the United States will have to maintain access to space-based systems for a variety of functions if it is to operate as it has operated in various conflicts since the end of the Cold War.

Counter-space operations, however, will not necessarily be anti-satellite systems shooting down satellites, although a number of nations have tested anti-satellite capabilities in recent years. Because space operations depend on ground-based facilities to control the satellites and obtain data from them, there is a significant terrestrial component to space operations. Similarly, both the systems that control satellites and the data that flow over satellite networks are vulnerable to cyber attacks and data manipulation. A hacked satellite that turns off its camera at key moments is as neutralized as a functioning satellite that is intercepted and destroyed by a co-orbital or ground-based anti-satellite system.

In future conflicts, both the outer space and information space domains will be central battlefields, and operations there will have as much impact as traditional activities in the air, on land, and at sea have had.

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