Aerospace Technology Gaps and the U.S. Space Force

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Executive Summary

As more and more nations across the globe begin to express their interest in establishing themselves in the space domain, the influence the United States once had no longer carries the same weight it did previously. As such, the United States Space Force (USSF) was formed in order to handle any and all space-related threats to the US. Due to the fact that the USSF's creation is rather recent, we have identified a need to assess how well current technology meets (or does not meet) the objectives and goals of the USSF. We are a group of 3rd-year undergraduate engineering students at The University of Texas at Austin performing this semester-long, extracurricular research through The Center for Space Research. The following report focuses on the technological gaps faced by the Space Force and how they may impact its ability to achieve its objectives. With the focus on propulsion and satellite communications technology, this report will assist the understanding of how the currently available technologies may hinder or aid the completion of missions.

A specific methodology was created and utilized for our research. After inferring important Space Force objectives from relevant documents, different mission profiles were hypothesized to meet the said goals. The technologies and equipment needed to successfully complete the missions were then identified. Finally, after detailed research and documentation, gaps in the available technology that may set the Space Force back were identified and listed. We applied this methodology to two identified aerospace technologies: in-space propulsion and satellite communications with the idea that future work could extend this research to other/all technologies for a more comprehensive picture.

From the results of the research and analysis, several conclusions were drawn and recommendations made. We found that although we have capability today, specific to these two technologies, to meet initial USSF goals, significant investment and research is needed to meet long term goals and outpace our adversaries to achieve and sustain space superiority.

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Introduction

Research Objectives

The objective of this research study was to derive a methodology for identifying technological gaps that may prohibit the USSF from defending the space domain. The USSF is an institution that has only existed for a few years, but has already set ambitious objectives for itself; these objectives are discussed later in this essay. The USSF aims to perform complicated operations in the space domain, which may require advanced technology that has not been developed yet. Therefore, this research group was tasked with identifying aerospace fields and then assessing whether current technology is adequate to fulfill the Space Force's objectives. Since there is a large amount of technology that is of relevance to the USSF, we decided to focus on creating a methodology to identify technological gaps. We then tested our methodology on two different aerospace fields: in-space propulsion and communications; this allowed us to prove that our methodology is an effective tool that can be used in future research projects.

Literature Reviewed

The research group looked at several different kinds of sources to produce this analysis. The first kind we examined were what we termed our 'foundation documents', which are current primary sources from the USSF itself. The foundation documents were chosen in order to determine what the current position of the force is, how it's organized, and what its objectives are presently. These documents include the USSF's first capstone publication [18] and the Comprehensive Plan for the Organizational Structure of the USSF [2]. Additionally, we consulted Air Force Space Command (the USSF's precursor) memoranda discussing what long-term challenges the new branch will face, how to mitigate certain risks to U.S. space hardware, and a white paper from the AFSPC proposing how Space Force soldiers will be trained [14]. These documents are listed in Appendix A.

Other sources we consulted were several different conferences and think-tank organizations that have produced reports about the strategic landscape of the space domain. These reports aim to make determinations about the present, and what challenges and risks the U.S. is currently encountering from other powers [12] , or speculations about how that landscape will change in the future [17]. We also reviewed a large number of news reports on current space events, and the progress of the U.S. and other countries' space programs. We looked at said articles with a focus of how current events will impact the USSF and where said developments will lead in the future. These articles also helped provide us with a more nuanced perspective of the geopolitical position of the USSF and other space forces, to complement the strategic perspective. These resources are also referenced in Appendix A.

Finally, we reviewed multiple published technical papers to better understand the in-space propulsion and communication technologies. Each technology area we chose to write about has a multitude of potential improvements/solutions. To make recommendations, we aimed to understand the technologies that have already been developed as much as possible, along with what potential solutions are being worked on currently, or what technologies may be possible in the coming decades.

In-Space Propulsion

In-Space Propulsion encompasses the technology that is directly related to providing spacecraft with thrust to navigate through space. Note that the “in-space” term is significant, as our study does not include launch vehicle propulsion. Having efficient and adequate thrust is of extreme importance to the USSF; without effective propulsion technology, our access to space is severely limited. Our research group tested our methodology of identifying technological gaps on the in-space propulsion field, and we successfully identified some areas of which the USSF should be aware.

Communications

Communications covers all technology that is used for sending, receiving, and processing information via satellites. Satellite communications (SATCOM) are essential for the rapid dissemination of information, which is needed for various USSF applications such as command and control, crisis management, and intelligence, surveillance and reconnaissance (ISR). A fast, reliable SATCOM infrastructure allows for effective and efficient responses to many situations. Our research group identified multiple technological gaps in the field of SATCOM that could be brought to the attention of the USSF.

Historical Background

Ever since the beginning of orbital launches in the 1960s, the space domain has been of interest to many nations across the world. The potential for exploration, scientific discovery, resource extraction, and colonization surpasses any previous historical event in its magnitude. As our technology has advanced over the past 60 years, humanity’s presence in space has significantly increased, and our reliance on our space assets has now reached a point of criticality.

What was once an untapped domain has become the home of critical United States assets. Losing any of these systems, such as our GPS constellation, would have major implications for our national security, and it is of strategic importance that the US be able to defend them. In addition to government programs, the commercial sector is also rapidly expanding its influence in space. SpaceX has become the first private company to develop a manned orbital launch system. Blue Origin and Virgin Galactic are developing commercial manned suborbital launches. Countless others are working on their own launch vehicles to reduce the costs of sending material into orbit. In order to promote economic growth, the US must also continue to defend the commercial sector and guarantee freedom of trade, movement, and action.

Global Trends

After the Cold War ended, the United States led an expansive coalition of nations that together had no rival. This introduced one of the most stable global periods in history with significantly reduced levels of conflict and increased global cooperation. In the space domain, the International Space Station is a product of this international collaboration, and still stands today as a symbol of unity and peace. Despite these impressive advancements, governmental interest in the space domain did decrease over this period. This is primarily due to the lack of space competition and funding remaining relatively stagnant over this period [19]. Therefore, space security was often a neglected issue in US foreign policy.

In recent years, the dominance of the United States on the international stage seems to be decreasing. We came to this conclusion for a number of reasons. First, the rapid economic growth of the PRC signals the first time since the Cold War that a nation has had comparable economic activity to that of the US. China has used this wealth to expand its influence across all of Asia, and is openly opposed to the United States. In addition, Russia has also increased its regional influence, and still retains significant power in the space domain. The Soyuz, a Russian launch vehicle, is still the most common method of delivering astronauts to the ISS. Furthermore, Chinese-Russian relations have steadily warmed over the years [10]. This indicates that a new power block may be forming in Eastern Europe and Asia, one that could challenge US global dominance.

In addition to these geopolitical developments on Earth, these nations are also looking to establish power in space. China is rapidly advancing its space program, and is looking to launch its own space station later this year [15]. Such a station would be in direct competition with the ISS. China is also expanding its spy satellite network [13], using the space domain to gather intelligence on its enemies. China's anti-satellite capabilities are well known [12], and they are capable of threatening any US asset in LEO. Russia has also been capable of destroying US assets in space since the 1970s. Recently, Russia has been testing new anti-satellite weaponry, which reintroduces concerns about the safety of US satellites. Worryingly, China and Russia have also recently agreed to construct a Lunar Research Station [9]. This cooperation of our potential rivals is concerning, even if they claim that the station will only be used for research.

"The Future of Space 2060" document details a thorough analysis of different scenarios for what the space domain could look like in the year 2060 [17]. These scenarios are bookended by the most favorable to the US ("Star Trek" scenario) and least favorable ("Dark Skies" scenario) and are useful to help determine what the USSF needs to be prepared for to meet its objectives. From recent space-related events, we hypothesize that by 2060 that we are most likely to be in a variation of the “Wild Frontier” scenario. “Wild Frontier” details a world in which there is no clear power in space, but there is large governmental and commercial activity compared to today with limited human presence.

Taken together, we inferred the following conclusion from current events. In the near future, it's likely that the American, Russian, and Chinese spheres will compete in space activities. These countries will try to increase their influence in the space domain with other countries who are not space powers. There is a potential for more extensive Chinese-Russian cooperation with projects such as a lunar research station, but that depends on whether each country sees a way to benefit from the partnership. It may be that Russia occupies a less formal middle ground, maintaining its extensive working relationship with NASA while also attempting to cooperate with the CNSA. The only alteration to the “Wild Frontier” scenario we are applying as our conclusion is that we expect there will be two powers in space: one coalition led by the United States, and another coalition led by China and Russia. We expect that these powers will be in direct competition for influence and dominance in the space domain.

Establishment of the USSF

Due to the slowly decaying influence of the US coalition in the space domain, the DoD realized that changes had to be made to combat the increasing threat to our space assets. In February 2019, the President signed a directive instructing the DoD to develop a “United States Space Force,” which would operate as the sixth branch of the Armed Forces [2]. This branch would be charged with the general mission of establishing supremacy and security in the space domain. By December of 2019, the USSF was officially established, and efforts on organizational design began.

The USSF is still an extremely new development in the DoD, and therefore little is set in stone about how this branch will operate. The funding for the USSF is still significantly smaller than all the other branches, limiting its current capabilities [2]. Over time, as the USSF grows in size and its defense capabilities increase, it will become an equal with the other branches and be solely responsible for defending the space domain.

Research Significance

The USSF is a very ambitious program, and its mission lies on the boundary of our current technological capabilities. To develop a comprehensive operation that defends the space domain requires advanced spacecraft and systems that we may not currently be able to develop. This research paper is a step towards identifying what the USSF may lack in technology to fulfill its requirements. This information is critical to developing a strategy going forward. By identifying the current limitations of the USSF’s capabilities, the DoD will know what technologies it should be developing. This information could also be used to formulate a strategy that could reduce the consequences (or even eliminate) the effects of our technological limitations.

Methodology

In order to develop consistent and accurate conclusions from our research, we followed a rigorous and detailed procedure by which we did our research. This process was applied in both our Propulsion and Communications research. Using this procedure is advantageous as it allows us to clearly outline the steps that we took to reach our conclusions. Therefore, if an inaccurate or ill-advised conclusion is discovered, we can quickly trace the error back to its source. This allows our research to be improved or expanded through future iterations. In addition, the following methodology is easily repeatable, and can be applied to a variety of technologies, not just Propulsion and Communications. This allows our methodology to be utilized in future USSF technology research. The research procedure we used is shown below.

Research Procedure

1. **Derive USSF Objectives**. This step requires the determination of the purpose and goals of the USSF. This information can be acquired from a variety of documents, and this high level information is relatively consistent among various sources. It is important to clearly outline what the USSF is trying to accomplish, so that its mission does not get mixed with other space organizations, such as NASA. By determining these objectives, the scope of the research can be narrowed to focus on technological needs of the USSF.
2. **Create Hypothetical Mission Profiles**. In order to determine what technology is required by the USSF, we must know what operations the USSF is performing. This step is a thought exercise in which we devise and design hypothetical missions that the USSF would need to perform to achieve its objectives from **step (1)**. Once some example mission profiles have been determined, we can better understand what technology is needed to complete those missions. Having a comprehensive set of missions is important, otherwise some technology requirements might be missed.
3. **Infer Technology Requirements**. Using the mission profiles from **step (2)**, we can now narrow down what the aerospace field in question needs to be capable of to complete the USSF's missions. This step is critical, as it provides a clear set of requirements to compare against current aerospace technologies.
4. **Perform Technology Research and Analysis**. This step is where the majority of the research is done. After determining the field's requirements, we can start determining what the current field is capable of. This step requires determining what technologies exist, and its current advancement level (Mission Proven, In-Development, Concept, etc.) By the end of this step, there will be comprehensive findings that detail the current and future technological capabilities of the aerospace field in question.

5. **Determine the technological gaps between steps (3) and (4)**. Finally, we can see how well the technology analyzed in **step (4)** fulfills the requirements detailed in **step (3)**. By performing this comparison, we can determine if there are any current or future inadequacies in technologies needed to fulfill the USSF's objectives. First we compare the technology to each requirement individually, seeing if the technology will be able to meet each requirement on its own. Second, we pair up the requirements from **step (3)**, determining if we can hit all the requirements simultaneously. We then identify and record all the technological gaps found for each aerospace field.

Using this procedure above, we can thoroughly and effectively determine the technological gaps in any aerospace field significant to the USSF. Notice that steps (1) and (2) are not specific to an aerospace field. This means that the research done at this high level can be reused and applied to other aerospace fields This is an inherent advantage of our research procedure that reduces the time required to reach our conclusions.

Research Results

USSF Objectives

After an extensive analysis of the 'foundation documents' that we discussed in the "Literature Reviewed" section of this paper, we were able to successfully create a detailed list of the long and short-term goals of the Space Force. The long-term goals include achieving space superiority and determining a proper space domain awareness. On the other hand, the short-term goals include establishing space operations and supporting them with efficient space mobility and effective information transfer. The research and investment into newer and more effective technologies is now becoming one of the Space Force's top priorities.

With the rising dependence on space as an asset in the military field, it is imperative that the USSF establishes itself as a superior presence in order to better protect America and its assets. To achieve this said space superiority, the USSF must have the means to provide security to their personnel in outer space and must be properly equipped to perform various methods of orbital warfare, some examples being kinematic, electromagnetic, and nuclear warfare. The combat abilities of America must surpass the abilities of its competitors. Additionally, the defensive capabilities of extra-terrestrial assets must also be improved. Satellites and other pieces of equipment must have cutting-edge mobility abilities. The capability to send and recall troops and equipment promptly may prove to be the advantage needed to establish the USSF as the superior space presence. Finally, the gathering of military intelligence is also of great importance to achieve proper space awareness. The cyber operations that would be conducted may involve tasks from communication surveillance and spoofing to radio jamming and message interception.

However, in order to achieve these long term goals, the short-term goal of developing advanced technologies must first be met. The USSF must be able to provide its assets with the proper mobility, offensive and defensive facilities, and state-of-the-art surveillance gear. American science and technology entities must work to continue their innovation and research and we believe it is the type of research presented here that is needed to help focus our ingenuity for the largest gains.

Mission Profiles

Following the research procedure described above, with USSF objectives defined, we now move on to developing mission profiles. Based on our research and readings we identified the following example profiles:

- The protection of space assets from destruction or damage,
- Offensive operations to defend USSF assets from potential threats,
- The surveillance of planetary and non-planetary targets of interest, and
- The transportation of Guardians to and from Earth, the moon, or any other space stations.

Since there has yet to be any absolute control of the space domain, there are many dangers to any USSF assets that may be trying to establish themselves in space. From terrestrial threats to environmental dangers (asteroids, space debris, etc.), it is up to the USSF to protect its satellites and dissuade others who seek to challenge their control. Defensive missions can include profiles such as missile defense from the planet's surface or other satellites. They can also include protection from existing objects in space like asteroids and other forms of space debris. On the other hand, potential offensive actions include the utilization of the Space Force's projectiles as well as radio jamming and spoofing of potential enemies. In the cases where engagement is not necessary, the surveillance of enemy assets in space or on the planet's surface is also important. The last category of possible missions is transportation. The USSF will be required to send and collect Guardians and their equipment from different locations. Travel between space assets will become just as crucial as travel to and from space itself.

After creating these mission profiles, we now focus on the technologies and capabilities needed to achieve these missions. As stated above, for the purpose of our research we focused on in-space propulsion systems and satellite communication (SATCOM) technologies.

In-Space Propulsion

Propulsion Requirements

From the mission profiles detailed above, we now derive a set of requirements that USSF spacecraft must be able to meet. The requirements detailed here are directly reliant on propulsion technology. Using these requirements, we then evaluate if our current technology is capable of meeting these requirements, and if the current technological trends put us on track to meet these requirements in the future.

Requirement 1: Spacecraft must be capable of performing **Impulsive Maneuvers.** Impulsive maneuvers are defined as orbital maneuvers that can be approximated as an instantaneous change in velocity. Of course, it always takes time to change a spacecraft's velocity, so large accelerations are needed to make this a good approximation. Impulsive maneuvers are important for USSF spacecraft, because they allow for quick change in orbital elements. This helps to make spacecraft more maneuverable, especially in cislunar space. There are a number of scenarios where impulsive maneuvers may be important. Evasion of hostile spacecraft or space debris would require impulsive maneuvers for security. Transportation of people through space may also require impulsive maneuvers, to help reduce mission time and therefore required supplies. Having spacecraft capable of making these maneuvers is essential to protecting our space assets and being adaptable to changing conditions in the space domain.

Requirement 2: Spacecraft must have **Attitude Controls** and be capable of performing **Orbital Maintenance**. Attitude control allows spacecraft to maintain or rotate to the desired orientation. This is essential for a variety of mission types. For surveillance satellites, pointing accuracy is important to ensure you are surveying the correct location. In order for solar panels to be oriented optimally to face the sun, attitude control is important to generate maximum power. Although many smaller spacecraft use reaction wheels for attitude control, the focus of this topic will be on propulsive control. Orbital Maintenance refers to a spacecraft's ability to maintain or make small adjustments to an orbit. Due to atmospheric effects, varying gravity fields, and other perturbations in the space domain, spacecraft need to make small adjustments to continue to fulfill their mission requirements. Attitude Controls and Orbital Maintenance are grouped together in these requirements, because a single system often is used for both purposes.

Requirement 3: A spacecraft's **Longevity** must be adequate to fulfill its mission. For many mission types, spacecraft must be able to last for ten years or more. This is important to reduce costs and ensure that there is always an adequate number of assets ready to defend the space domain. Although there are many aspects to increasing a spacecraft's longevity, we will be focusing on the limiting factor of propulsion. A spacecraft cannot complete its mission without fuel, and the USSF must ensure that its spacecraft have a supply of fuel that exceeds its mission duration. This can be a very difficult requirement to meet.

Requirement 4: Spacecraft must be equipped with a **Deorbiting Ability**. Space debris is a major threat to all spacecraft in orbit. The conditions are only getting worse as massive constellations of satellites are beginning to populate cislunar space, such as Starlink. A single satellite can potentially lead to damage or the destruction of several more. In order to prevent the accumulation of space debris, USSF spacecraft should be able to deorbit at the end of its lifespan.

Propulsion Technology

Now that propulsion-specific requirements have been defined, the current technology in the propulsion field must be assessed. Through our research, we broke down in-space propulsion into three technologies: Chemical Propulsion, Electric Propulsion, and Nuclear Propulsion. In addition, we also studied the effects of Solar Sails, Electrodynamic Tethers, and Aerodynamic Drag as miscellaneous propulsion sources. The basic technical specifications, history, and technological development are assessed below.

There are two technical specifications we are particularly concerned with regarding propulsion performance. The first is thrust, which is a measure of the force output of a propulsion system. Depending on mass, some spacecraft require larger thrust, while smaller spacecraft can get away with less. Therefore, the thrust-to-mass ratio of a spacecraft is essential to determine if it can perform impulsive maneuvers, one of our requirements. Specific Impulse (ISP) is another important measure for propulsion performance. ISP is defined as the exit velocity of a propellant divided by a gravitational constant, usually 32.2 ft/s^2. Since thrust is proportional to the exit velocity of a propellant, a higher exit velocity indicates that a propulsion technology uses its propellant more efficiently. As we will discuss below, achieving a high ISP and a high thrust simultaneously can be very difficult.

Chemical Propulsion

Chemical propulsion involves the use of chemical reactions to provide thrust. There are many types of chemical propulsion but they are all capable of producing large forces (on the order of tons) at the expense of significant amounts of fuel. Most chemical propulsion have an ISP of less than 350 seconds, which is less than most other propulsion types [23]. Although chemical propulsion is more often used for launch vehicles and orbital insertion, we will be focusing on its application for in-space propulsive maneuvers.

Monopropellants are a type of chemical propulsion that uses a single propellant to generate thrust. Hydrazine is the most common chemical used, and these systems have been used since the 1960s on countless spacecraft. Historically the systems have been used for both attitude control and orbital maneuvers, and are an extremely reliable technology. Hydrazine does have some problems with toxicity and intensive design requirements, so there has been a push from NASA to use “green” monopropellants such as LPM-103S and AM-F315E. All monopropellants do suffer from low ISP (less than 250 seconds), but benefit from requiring simpler design than some other propulsion technologies [23].

Bipropellants are a step up from monopropellants, and require two propellants instead of one: liquid oxidizer and liquid fuel. Just like monopropellants, bipropellants are capable of producing larger thrust, but also have a higher ISP (sometimes up to 450 seconds). However, the use of two propellants requires two tanks, significantly increasing the complexity and expense of the propulsion system. Bipropellants are commonly used in industry for launch vehicles and orbital maneuvers. One recent example is the Curie Engine from Rocket Lab, which is used for orbital insertion for its payload. Such a system indicates that this technology will continue to be used in the future for in-space propulsion [23].

Solid Motors are a propulsion system that mixes fuel and oxidizer into a solid fuel grain. The most famous example of this are the Space Shuttle’s side boosters. This method of propulsion is more simple than bipropellants, but has very low ISP (~250 seconds at most) and has little potential for reusability. In addition, solid motors cannot be turned off once started, making them less useful for in-space applications. Hybrid propulsion involves combining the use of a solid fuel grain with a liquid or gaseous oxidizer. While this significantly reduces the complexity from a bipropellant system, it also reduces the potential for reusability. Although the technology is in early development and only has seen hotfires so far, the ISP for such systems can be as high as 450 seconds, which is comparable to bipropellants. Due to the reduced complexity, JPL has expressed interest in such a system though its Mars Ascent Vehicle Concept. Their concept vehicle would be easier to manufacture and more flexible to varying temperatures, making it a great option for lunar/mars launch vehicles far in the future.

Cold and warm gas thrusters use the expansion of pressurized gas to produce thrust. These systems are very easy to manufacture, but cannot produce much thrust and have the lowest ISP of any chemical system. Typically these systems are used for attitude control, smaller lunar landers, and by astronauts [23].

Electric Propulsion

Electric propulsion involves the use of electric or magnetic fields to propel an object. Electric propulsion has been in use for nearly as long as chemical propulsion, and is often the go-to choice for smaller spacecraft. Electric propulsion methods are known for performing at extraordinary ISP levels, an order of magnitude higher than that of chemical propulsion [23]. However, these systems also consume significant amounts of power, which limits their thrust potential to a few pounds at best. Electric propulsion methods can generally be split into three categories: electrothermal, electrostatic, and electromagnetic.

Electrothermal systems are used to heat a propellant, often through the use of electromagnetic fields. This is often used in conjunction with a chemical propulsion system to increase the energy of propellant, increasing ISP to over 500 seconds [23]. This technology has been used for decades, making its debut on Russian satellites in the 1970s. This technology, which does require significant power, does have limitations on thrust (usually under 0.25 lbf). However, it remains a solid improvement for attitude control systems and small spacecraft maneuvering, due to its improved efficiency. Aerojet Rocketdyne is one of the most prominent manufacturers of electrothermal systems, and can provide reliable and well-tested products for the foreseeable future [1].

Electrostatic propulsion uses the Coulomb force, which is created by electric fields, to accelerate propellant. This term is often used interchangeably with ion propulsion, as the propellant must be ionized before electric fields can induce acceleration. The power requirement for these systems is intense, but the ISP is an order of magnitude higher than chemical propulsion. Hall-Effect Thrusters. (HETs) are one of the oldest forms of ion propulsion, and have been flight demonstrated over 300 times [23]. These thrusters typically use xenon or krypton gas as propellant, and are considered extremely reliable. Modern HETs were demonstrated by NASA in 1998 as part of the Deep Space 1 (DS1) mission [22]. Typically HETs can reach an ISP of near 2000, but with extremely tiny thrust. For example, DS1 had a maximum thrust of 0.02 pounds, requiring 2.3 kW for operation. However, DS1 only used 50 pounds of fuel for a 3 year long mission, indicating impressive efficiency. More recently, Starlink and OneWeb both use HETs on their respective constellations, indicating that this technology is increasingly popular among industry [7]. Gridded Ion Thrusters, though a common form of ion propulsion, is not as developed as HETs. Although the technology was developed in the 1960s, the intense power requirements (more than HETs) turned the space industry away from this technology. However, some recent NASA missions plan to use Gridded Ion technology, due to the extraordinary ISP potential, which currently can go as high as 3000 seconds. In the future, the specific impulse is expected to be even higher. If the power requirements for this technology can be satisfied, Gridded Ion can be the future of micropropulsion [6].

Nuclear Propulsion

Nuclear Propulsion involves the use of nuclear energy to generate thrust. In general, nuclear propulsion can be classified into two categories: Nuclear Thermal and Nuclear Electric. Nuclear Thermal utilizes the energy from Nuclear Fission to generate the heat required for thrust. This technology is in the early stages of development and has never been flown on a spacecraft before. However, the technology is very promising, as it can provide substantial thrust at a higher

ISP than Chemical Propulsion. Due to its promise, the push to develop this technology has increased significantly over the last few years. In 2019, Congress granted NASA $125 million to develop Nuclear Thermal Propulsion [5]. The US Military has also invested funds into development of this technology [21]. With these new developments, the USSF should have reliable access to this method of propulsion by the year 2060.

Nuclear Electric uses Nuclear energy to generate the power for an electric propulsion system, such as an Ion Thruster. Since these systems are used in conjunction with electric propulsion systems, the thrust is low, but the ISP is high. This power is generally provided either through Nuclear Fission or radioisotopes. Radioisotopes allow radioactive substances to decay over long periods of time. This decay generates heat, which can be converted into electricity. Deep space missions often use radioisotopes as the power source [22], as it can essentially provide power for as long as the mission needs. This power output is very small however, and can only be used for smaller spacecraft. Nuclear Fission can provide a much higher power output, but does not last as long as radioisotopes.

Fulfillment of Requirements

After thoroughly analyzing each of the propulsion technologies, we determined how well our current technology meets the needs of the USSF, which are listed in the "Propulsion Requirements" section. We identified technological gaps that may prohibit the fulfillment of these needs, and determined what future technologies need to be developed to mitigate these technological gaps. First, we determined if we could meet each individual need. Next, we synthesized these needs together to discover any additional technological gaps that may exist. For propulsion, we came to the conclusion that we are able to meet the majority of the USSF's needs, but there are a few gaps that could potentially limit our ability to operate in space.

1. Impulsive Maneuvers: Requirements met

We determined that we are capable of performing Impulsive Maneuvers with the technology currently available to us. The majority of spacecraft require medium or high thrust to perform these maneuvers, making the various forms of chemical propulsion an excellent solution. There is already a historical precedent that Bipropellants and Monopropellants are a preferred way of maneuvering quickly in space, so our research aligns well with industry understanding. For much smaller spacecraft, electric propulsion methods such as HETs may also be viable. The thrust output of these systems are very small, but if a spacecraft's mass is reduced enough, such systems may be able to provide impulsive maneuvers as well. That being said, chemical propulsion is the best method currently available. Nuclear Thermal is an excellent solution that could be used in the future. However, this technology is still in development.

2. Attitude Control/Orbital Maintenance: Requirements met

There are a number of systems that allow us to meet this need. On the chemical propulsion side, monopropellants and cold/warm gas systems have historically been used for such purposes. Electric propulsion systems are also an excellent option, as the low thrust output generally is not a problem in this sort of application. As reducing propellant loads is a desirable quality for spacecraft, electric propulsion systems likely will be used far into the future in this application.

3. Longevity: Requirements met

Longevity requires that a spacecraft be able to operate in space for as long as the mission requires, if not longer. One main proponent that reduces longevity is fuel consumption, which should be minimized to meet this need. Electric propulsion systems can be used due to their superior ISP to chemical propulsion systems. Radioisotopes can be used in conjunction with these systems to further improve a spacecraft's longevity. Nuclear Thermal systems are a possible solution in the future, given that their potential thrust and ISP are impressive. Chemical propulsion systems generally cannot fulfill this need, as their ISP is often a limiting factor.

4. Deorbiting Ability: Requirement met

There are many methods of deorbiting spacecraft that do not require the use of a proper propulsion technology. Aerodynamic drag or electrodynamic tethers can be used to reduce the momentum of a spacecraft, ultimately resulting in its deorbit. However, these solutions are uncontrolled, and it is difficult to determine the landing area should the spacecraft not burn up in the atmosphere. Take the recent deorbit of the Chinese rocket (Long March 5B Y2). This was an uncontrolled deorbit, and posed significant risk if it did not burn up upon reentry. Electric propulsion is an excellent solution for deorbit if a controlled solution is desirable, as it does not require much extra fuel for this purpose.

Now that each individual need has been analyzed, these needs were synthesized. By grouping the individual needs together, we identified some technological gaps that the USSF may face in the future. Not every grouping is listed below, as there are too many to include in this report. The majority of groupings are also insignificant to the conclusions of this study. Therefore, only the groupings that suggested technological gaps are listed below. For in-space propulsion, there is only one grouping that we could not fulfill with our current technology.

Impulsive Maneuvers (Requirement 1) and Longevity (Requirement 3) not met

With our current propulsion technology, we do not have the ability to perform impulsive maneuvers without significantly decreasing the lifespan of our spacecraft. This is because chemical propulsion methods are generally required to perform impulsive maneuvers and they do not fulfill the longevity need since the ISP is too low. This raises a problem, especially for larger spacecraft which require higher thrust. Nuclear Thermal Propulsion can potentially help with this issue, due to its higher ISP than chemical propulsion. However, even with Nuclear Thermal, the ISP is only about twice as high as bipropellant systems, meaning there is still a technological gap present. In-space refueling, although requiring a significant amount of investment, would be an excellent way to remove this technological gap. This allows spacecraft to reduce their fuel constraints by having consistent refueling access. The importance of Nuclear Thermal Propulsion and In-Space Refueling can be seen from our research, and we recommend that both methods be developed into solutions to support near and long term USSF objectives.[1]

Communications

Satellite communication systems are essential to creating information mobility, providing space support to operations, and expanding space domain awareness.

Communications Requirements

A set of requirements that USSF SATCOM must meet was derived from the mission profiles above. These requirements were used to determine if currently available technology is capable of achieving USSF objectives. These requirements were also used to assess if technology currently in development is on track to meet USSF objectives

Requirement 1: A SATCOM device used by the USSF must be **Secure and Confidential**. For a SATCOM device to be secure and confidential it must be immune to enemy attempts to obtain information. When an enemy is able to intercept information transmitted via SATCOM, vital information could fall into the wrong hands. Therefore, security and confidentiality is not only a requirement of SATCOM systems, but a priority.

Requirement 2: SATCOM devices must foster **Information Mobility**. Information mobility is best described as transmissions that are timely, reliable, and accessible. Communications must not only be fast and dependable, but also accessible in all environments, including the contested, degraded, and operationally limited environment of space. A SATCOM system that achieves information mobility is capable of effectively supporting space operations by providing the communication network necessary to orchestrate large-scale tasks.

Requirement 3: A SATCOM network must be **Resilient** in order to remain operable in the face of adversity. For a SATCOM network to be resilient, it must be able to withstand attacks,

[1] Events since original writing: DARPA, as part of the DRACO program, has selected contractors to perform a LEO technology demonstration of Nuclear Thermal Propulsion. This demonstrates that there is interest in developing this method of propulsion in the US military, which supports the findings of our research.
Source: https://www.darpa.mil/news-events/2021-04-12

unexpected damage, or other disruptions to one or more SATCOM devices and retain operability. A fragile SATCOM network or device makes for an obvious target for potential enemies. If a large disruption occurs in a SATCOM system due to failure or destruction, a lack of communication capabilities could prevent USSF personnel from receiving necessary information. Thus, resiliency is a requirement of SATCOM devices.

Communications Technology

With the requirements for SATCOM systems defined, current and upcoming SATCOM technology can be evaluated to see if it meets these requirements. During this study, three overarching categories of SATCOM technology were taken into consideration: Radio Frequency (RF) Communication, Optical Communication, and Data Processing. The performance of current and upcoming technologies in these categories were judged based on how well they are able to meet the above requirements

RF Communication

RF communications are the most common medium of SATCOM seen today. This type of technology uses wireless electromagnetic signals in the radio frequency range to communicate information. The radio frequency range of the electromagnetic spectrum is broken up into different frequency ranges called bands. Commonly used bands for RF communications include the L, S, C, X, Ku, and K bands, as well as the newer Ka band [16]. Depending on what frequency band is being used, RF communications can be further categorized into wideband communications (S, C, X, K, Ku, and Ka bands), narrowband communications (L and S bands), and protected communications.

Wideband communications provide the global connectivity necessary to support operations. The high data rates offered by wideband communications are used for the execution of various tasks, such as command and control, crisis management, and intelligence data transfer [16]. Narrowband communications carry less information than wideband channels, but require less power to do so [3]. Protected communications are a different form of communications that offer secure, jam-resistant communications at the cost of lower throughput than wideband channels. Currently, protected communications are only supported by the Milstar and AEHF satellite constellations [16].

Optical Communications

Optical communications are an up and coming medium of SATCOM technology. This technology uses light to communicate information as opposed to radio frequency electromagnetic waves. Optical communications have the potential to address some of the shortcomings of conventional RF communications and improve upon them in other areas. Because light is used instead of radio waves, optical communications could alleviate electromagnetic spectrum congestion. Additionally, higher data rates can be achieved. Furthermore, optical communications offer greater security than RF communications. This is because optical communications cannot be picked up by spectrum analyzers or RF meters, which makes interception difficult. On top of this, light cannot penetrate walls, which prevents eavesdropping. However, optical communications currently face problems with absorption and dispersive effects from the atmosphere.

Data Processing

For the purposes of this paper, data processing technologies encompass the set of technologies responsible for sending, receiving, and interpreting communications. This can include various technologies such as antennas, encryption, uplinks/downlinks, etc. It is important to note that antennas are currently a technological bottleneck in SATCOM development. Current antenna technology is not advanced enough to combat growing problems with RF communications (like electromagnetic spectrum congestion). However, there are a few different types of upcoming antennas that show promise, such as metamaterial antennas, 3D-printed antennas, and fractal antennas.

Fulfillment of Requirements

After analyzing each of the categories of SATCOM technologies, it was determined if current technology is capable of meeting the inferred requirements of the USSF. These requirements are the same requirements listed above in the “Communications Requirements” section. First, it was determined if each individual need could be met. Next, these needs were synthesized together to see if further technological gaps could be identified through a combination of requirements

1. Security and Confidentiality: Requirement met

It was determined that the Security and Confidentiality needs of the USSF are met with current SATCOM technology. This is thanks to encryption technology such as the Protected Tactical Waveform, which allows for transmissions with data protection and anti-jamming. However, protected communications are limited, as they are only supported by the Milstar and AEHF satellite constellations. One way Security and Confidentiality could be improved is through quantum cryptography. In theory, Quantum Key Distribution could be used as a more secure encryption method. Additionally, quantum cryptography could be necessary to defend against enemy quantum computers, which would be capable of cracking conventional cryptographic methods and keys. However, quantum computing theory is currently far ahead of hardware, and full-blown quantum computing is a long way off. Another way Security and Confidentiality could be improved is through advancements in optical communications, which are difficult to intercept and impossible to eavesdrop.

2. Information Mobility: Requirement not met

It was determined that the Information Mobility needs of the USSF are not met with current SATCOM technology. The ever increasing demand for bandwidth requires improvements upon conventional RF technology to combat electromagnetic spectrum congestion. A potential solution to this problem could be using higher frequency bands or optical communications. Using higher frequency bands could mean expanding RF communications to commonly use Q, V, W, or Tremendously High Frequency (THF or THz) bands. Both optical communications and these relatively unused bands could relieve electromagnetic spectrum congestion. Additionally, both offer greater bandwidth and higher data rates. However, both require advances in data processing technology, such as antennas and satellite to ground links. On top of this, both suffer from absorption and dispersive effects from the atmosphere, so advances in these technologies must first be made before they can satisfy the Information Mobility needs of the USSF.

3. Resiliency: Requirement not met

It was determined that the Resiliency needs of the USSF are not met with current SATCOM technology. Military SATCOM currently relies on a small number of large, multipurpose satellites, which were put into space during the Cold War era. In this era, the US knew attacks on these satellites would be unlikely, as an attack from Russia on one of these satellites would mean mutually assured destruction of both Russia and the US. Because the US was conscious of this global dynamic, the decision to use large, multipurpose satellites made sense. However, global dynamics are much different today. Because there are only a small number of satellites, an attack on one of these satellites could have a large impact on communication capabilities of the USSF. This makes these satellites obvious targets for adversaries. A potential solution to this problem could be disaggregation. Disaggregation consists of having a larger number of small satellites with dispersed functions that are spread across multiple orbital planes. A disaggregated satellite network bolsters resiliency by providing redundancy and increasing target diversity. A strategy of disaggregation could resemble the trend that is observable today of LEO small satellite constellations (such as Starlink, OneWeb, Telesat, and China's Hongyan constellation).

Security and Confidentiality (Requirement 1) and Information Mobility (Requirement 2): ot met

It was determined that the combined needs of Security and Confidentiality and Information Mobility are not met with current SATCOM technology. This is because protected communications are currently very limited in capacity. A potential solution to this problem is the development and implementation of optical communications. Optical communications are more secure than RF communications, and the required technology is more readily deployed. On top of this, when compared to RF communications, optical communications offer significant power savings and lower mass requirements.

Conclusion

Research Findings

The first conclusion that can be drawn from this research is that modern in-space propulsion technology is adequate to meet most USSF objectives. Individually, the inferred in-space propulsion requirements are met through conventional chemical and electrical propulsion. However, to accomplish more ambitious goals like deep space exploration and a Martian outpost, large spacecraft must see improvements in longevity and high thrust/ISP propulsion.

Building on this point, the next conclusion drawn is that the biggest technological gap in the field of in-space propulsion is the lack of high thrust, high ISP solutions for large spacecraft. Chemical propulsion provides high thrust but low ISP. If chemical propulsion were to be used to try and meet this need, an expansive in-space refueling network would be required to make up for its inefficiency. Electric propulsion provides high ISP but very low thrust. Great strides must be made with power sources if electric propulsion is to provide significantly greater thrust. Nuclear propulsion could address this problem, but this technology requires much more development.

The next conclusion drawn is that RF spectrum congestion and increasing bandwidth demands pose a growing problem for the USSF. Therefore, advances in either optical communications or higher frequency bands are critical. Both of these technologies offer a solution to this problem accompanied by higher bandwidth and data rates.

The last conclusion that can be drawn from this research is that older space systems that prioritize size and capability are high-value, easily identifiable targets. With today's global dynamic of increasing competition in space, this type of satellite is clearly outdated. Relying on these satellites is a liability and could pose large problems if a conflict were to arise.

Recommendations

Based on this research, a number of recommendations are provided below.

First, the development of small spacecraft should be prioritized in the short term. The limits of our propulsion technology affect the ability of larger spacecraft to complete their missions. Therefore, working to fulfill as many USSF objectives as possible with small spacecraft is advisable. This will allow our spacecraft to last in space much longer, which reduces costs in the short term.

Next, investments should be made in nuclear thermal propulsion. Eventually, large spacecraft will most likely be necessary to meet the future goals of the USSF, and nuclear thermal propulsion could fill the gap of a missing high thrust, high ISP solution. However, the use of nuclear thermal propulsion does not completely eliminate the longevity issue for large spacecraft. Although nuclear thermal propulsion has high ISP, it is still well below the levels of electric propulsion. We recommend that in-space refueling capabilities be developed as well, to help our larger spacecraft stay in space for longer.

Next, attention should be focused on the development of antenna technology to cover new frequency bands, including optical frequencies. Currently, antennas are a sort of technological bottleneck facing the SATCOM field. Efforts should be made to reduce cost and power consumption while increasing miniaturization and efficiency. Additionally, antennas are critical in combating the effects of the atmosphere that prevent new frequency bands from being used.

Lastly, disaggregation should be implemented sooner rather than later. Large satellites from the Cold War era must be replaced by a network of smaller satellites with dispersed functionality. This greatly increases redundancy and target diversity, both of which are essential for a resilient SATCOM network.

Finally, as was mentioned earlier in this report, our research focused on two of many different aerospace technologies including launch systems, advanced materials and space structures. For a comprehensive assessment of aerospace advancements needed to fulfill USSF mission objectives we recommend applying the research methodology presented here to these other fields.

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