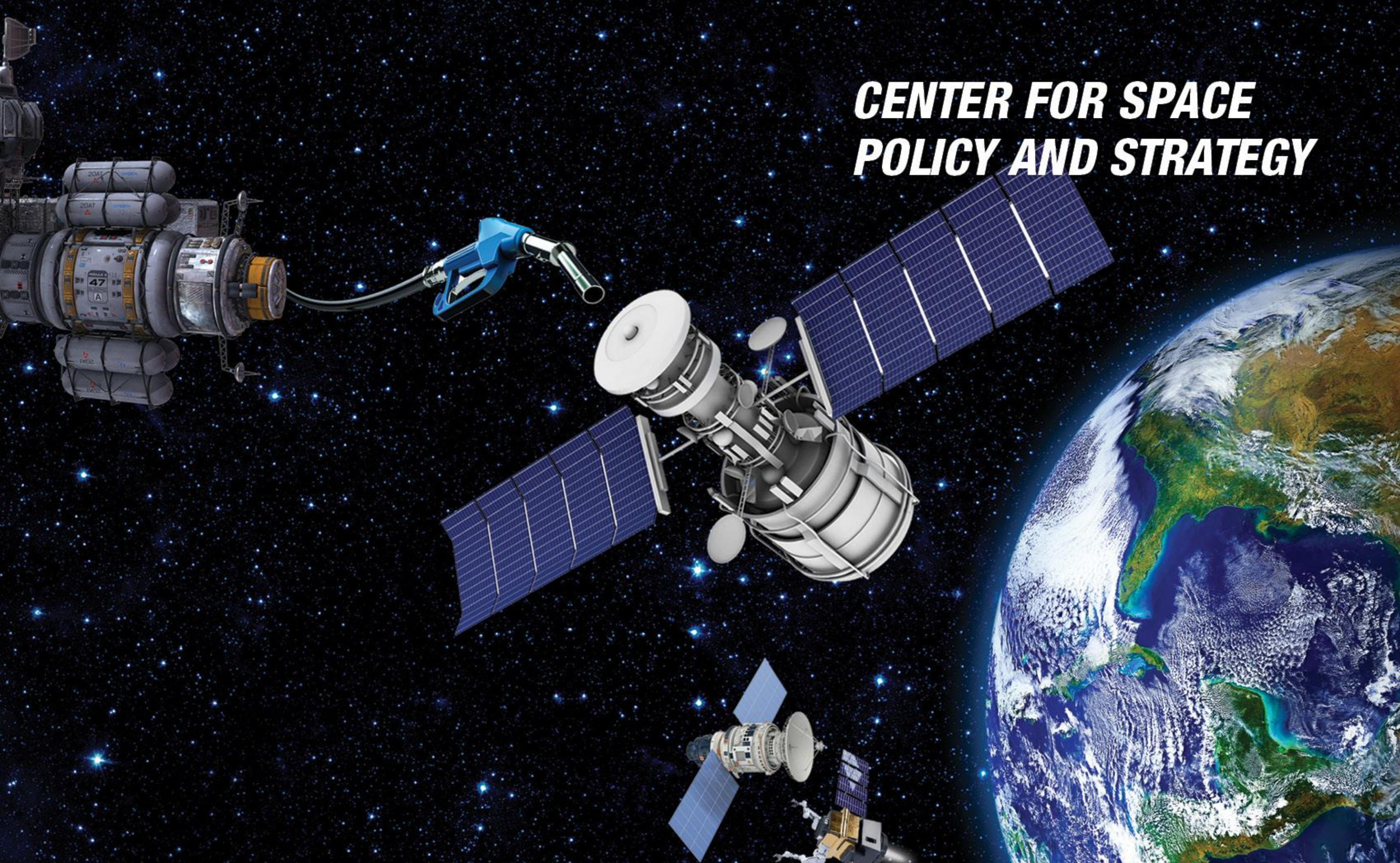

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ENABLING A NEW SPACE PARADIGM: HARNESSING SPACE MOBILITY AND LOGISTICS

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Summary

For the U.S. Space Force to emerge as a twenty-first century space warfighting force, certain new capabilities need to be fielded. The Space Capstone Publication *Spacepower* emphasizes the point especially when introducing the Core Competency of Space Mobility and Logistics. Space Mobility and Logistics encompasses capabilities meant to make spacecraft more maneuverable, adaptable, and resilient, including inspection, materiel logistics, orbit modification, refueling, client augmentation, and active debris removal. For each of these capability areas, the Space Force can adopt one or more of four general approaches: as a *Participant* in a wider market with standard services, a strategic customer utilizing the wider market for *Customized* services, an *Anchor Tenant* for a capability with future commercial promise, or as a full *Owner* of a unique capability. The features of each of these capabilities, along with the current state of space technology and commercial industry, dictate different approaches for each. This paper provides an approximation of the most favorable approach for each capability for fielding in a generic national security space application in the next five years. Funding constraints will encourage U.S. Space Force stakeholders and policymakers to adopt the participant approach where possible, so some methods of driving capabilities toward this approach are outlined. These findings are meant to aid the difficult process of transforming policy into reality and best equip the space warfighter for the future.

Introduction

Space Mobility and Logistics (SM&L) has recently been declared a core competency by the U.S. Space Force (USSF). The concept itself is far from new; many of the operations the concept embodies have been demonstrated over several decades: the ability to conduct rendezvous and proximity operations, dock with a spacecraft, refuel a spacecraft on-orbit, repair, and even assemble objects.[1] Space Force leaders seek to expand upon these demonstrations and leverage the capabilities initiated by commercial companies in these areas to solve military problems. If the USSF fully exploits these demonstrations and converts them into military utility, it will mark another step on its maturity as a military service. But USSF cannot use a single approach to capitalize on these commercial capabilities. Each of the capabilities is at a different stage of development, with some proven but others still early in the conceptual and developmental phase. Each of the capabilities has different promise when fully developed: some will be commercially viable while others will be unique to military operations. To adapt to these different circumstances, this paper lays out four approaches by which USSF can mature SM&L capabilities: a *Participant* approach that becomes viable with wider commercial availability, a *Customized* approach that relies on strategic partnership with vendors to adapt commercial developments to government unique needs, an *Anchor Tenant* approach for capabilities that have future commercial promise, and an *Owner* approach for capabilities that are neither commercially viable nor appropriate. These approaches are uniquely tailored to SM&L and provide a clearer roadmap to allow USSF to build a mature SM&L architecture.

"If USSF is successful in implementing the sets of capabilities laid out under Space Mobility and Logistics, then it will be well positioned to protect and defend current and future U.S. global and in-space interests in a way that would be impossible without this new set of capabilities."

USSF as a nascent force has an opportunity to respond to the changing space environment in a meaningful way by establishing the mobility and logistics capabilities which do not readily exist in space today. The publication of *Spacepower* and other Department of Defense (DOD) and federal government documents, along with an evolving and growing threat, give USSF the impetus to acquire the suite of SM&L capabilities to enable a new paradigm to propel the Space Force forward as the predominant military space power while strengthening the United States' commercial space sector. If USSF is successful in implementing the sets of capabilities laid out under Space Mobility and Logistics, then it will be well positioned to protect and defend current and future U.S. global and in-space interests in a way that would be impossible without this new set of capabilities.

It has long been understood that logistics are vital to military success. A quote attributed to General Pershing acknowledges "[i]nfantry wins battles. Logistics wins wars."[2] This paper aims to assist decisionmakers in appreciating the scope and applications of SM&L and understanding what approaches are available and viable to attain those capabilities.

Making SM&L Central to USSF

USSF knows the importance of SM&L to its future and the future of space warfighting. In June 2020, the Space Capstone Publication *Spacepower* articulated the governing theories for how the USSF could maintain preeminence of the titular subject. Among these are a list of five core competencies necessary for the USSF to execute this role. Nestled in the middle of the list is the core competency of "Space Mobility and Logistics."[3] Doctrinally, USSF has clearly stated the importance of SM&L to its future, though it will take work to match that aspiration with reality until SM&L provides true militarily useful mobility in space.

This gap between aspiration and reality is illustrated in the definition of mobility. *Spacepower* defines SM&L collectively as "the movement and support of military equipment and personnel into the space domain, from the space domain back to Earth, and through the space domain." Further, the concept of *orbital sustainment* is included under SM&L, which includes a host of activities—such as replenishing consumable and expendable commodities, spacecraft inspection, anomaly resolution, and system maintenance and upgrades. These domain-specific concepts can be compared to their terrestrial equivalents in the *DOD Dictionary of Military and Associated Terms*:[4]

- "mobility — A quality or capability of military forces which permits them to move from place to place while retaining the ability to fulfill their primary mission. (JP 3-36)"
- "logistics — Planning and executing the movement and support of forces. (JP 4-0)"
- "sustainment — The provision of logistics and personnel services required to maintain and prolong operations until successful mission accomplishment. (JP 3-0)"

Taken as a whole, the spirit of the generic definitions is reflected nicely in the space-specific versions. One key takeaway, though, is that the generic definition of mobility includes the provision that movement is only mobility if the primary mission can be retained.

This provision does not yet consistently hold in space. Propellant is often a life-limiting factor for spacecraft. A spacecraft cannot move without it. Traditionally, propellant has been one of the greatest contributions to weight, constraining all of a spacecraft's other functions. Because of that, propellant was limited to the minimum needed for its intended life. The few exceptions prove this point. Some maneuvering spacecraft, like USSF's Geosynchronous Space Situational Awareness Program, have been explicitly built with enough propellant to achieve mobility in the doctrinal sense.[5] Nevertheless, in most cases, propellant limitation means today's spacecraft may not technically have true military mobility. SM&L promises to change that.

Those with a civil space background might recognize these concepts as part of on-orbit servicing (OOS) or on-orbit servicing, assembly, and manufacturing (OSAM). These concepts are also gaining traction with a whole-of-government audience as evidenced by the publication of the *In-Space Servicing, Assembly, and Manufacturing (ISAM) National Strategy.*[6] While SM&L includes OOS and ISAM activities, among others, it is not synonymous because it excludes non-Earth surface activities. More importantly, it makes military utility the key factor of any argument to include SM&L in warfighting doctrine. Business as usual for the military space domain is severely limited in the inclusion of SM&L capabilities because the current understanding begins and ends with the launch vehicle. In a full-scope SM&L implementation, key benefits can only be realized after vehicle separation. Chief among these is the ability to maneuver without regret, restore and enhance capabilities, and economically move materiel through the space domain.*

*Another important concept highlighted in SM&L in the capstone publication is orbital recovery. This capability "allows for the recovery of personnel or military equipment from the space domain." Access to and recovery from orbit are key abilities of a spacefaring nation, but the focus of this paper is fixed in the space domain itself and does not examine these areas in greater detail.

Adrift at Sea and in Orbit

Just over nine days and 4,400 nautical miles ago, the champagne broke on the bow of the latest Arleigh Burke-class destroyer. After deftly handling rough seas and protecting her sailors, she now drifts aimlessly with the whims of the ocean currents. What happened? True, she was unable to respond to a distress call as it was slightly off the charted course, but the planned mission was fulfilled without a hitch. Hundreds of millions of dollars were spent to ensure the smooth and reliable operation of all the ship's systems, and they worked spectacularly. No enemy vessel was to blame either. The one flaw in the design was that the ship could not be refueled. Without more gas to carry on, the otherwise fully functional ship is adrift at sea waiting to be rolled under the waves or run aground on the shore.

This hypothetical scenario would be unthinkable for any ship on the high seas today, but it is business as usual in space. Satellites have never been designed to be refueled. Functioning, costly assets are left to drift in orbit long before the other critical systems fail. Each and every maneuver has to be carefully planned so as to not prematurely deplete the spacecraft's precious propellant. While the U.S. naval fleet can maneuver without regret, the USSF fleet does not enjoy the same benefit. This is just one of the areas where the status quo for space mobility and logistics differs dramatically from the terrestrial equivalent.

Where USSF Can Leverage Commercial Developments

USSF can leverage the capabilities the commercial sector has explored to develop a full SM&L architecture. There are six main areas ripe for exploitation: Inspection, Orbit Modification, Materiel Logistics, Refueling, Client Augmentation, and Active Debris Mitigation.

These areas are comprehensive of all on-orbit activities that could fall under the SM&L umbrella. Further, these areas, when fully implemented, will provide a complete SM&L capability to USSF and other national security space operators. This can be confirmed by comparing the coverage the described areas provide to the two operative words in the SM&L definition: movement and support.

As a precursor to movement or support, the state of the client being moved or supported must be known by the servicer. To ascertain the position, orientation, and status of the client, a high-fidelity inspection is required which makes Inspection an implicit part of nearly all SM&L activities.

To fully enable movement, the service areas of Orbit Modification and Refueling are required. Spacecraft are always moving, but this movement is a product of their environment. Much like a twig in a stream is always moving, a spacecraft in its orbit will largely follow the path of that orbit. To take control of that movement, spacecraft must use propellant. Once that propellant runs out, the movement again becomes a product entirely of the space environment. Through Orbit Modification, a servicing vehicle or module can lend its own propulsion capabilities to the client. With Refueling, the propellant of a client can be restored, which in turn restores their independent movement capability.

Spacecraft are currently designed to be self-sufficient, knowing that no support is coming for them. That effort increases the resilience of the spacecraft but at a cost of high redundancy and long design cycles. Despite this, roughly 48 percent of spacecraft failures occur within the first year of operation.[7] By harnessing the SM&L service areas of Materiel Logistics and Client Augmentation, spacecraft will have other options for support than what they packed with them. Materiel Logistics, as a service area, encompasses all of the necessary elements of a space supply chain from the launch vehicle upward. By delivering and storing materiel at space depots, the USSF space enterprise can depend on greater parts availability outside of the spacecraft bus. Materiel Logistics is also an important precursor for sustained Refueling operations. Client Augmentation is necessary to make use of the parts supplied by Materiel Logistics to maintain, repair, and upgrade the spacecraft that need them. This service area requires the use of robotics, but modularly designed spacecraft that intend to use orbital replacement units (ORUs) lower the level of complexity required for those robotics. With parts availability and augmentation servicers, SM&L dispels the image of each spacecraft as a lone ranger.

The final service area of Active Debris Mitigation is unique in that the client is not serviced directly but does benefit from an SM&L perspective. By removing debris from the space environment, either by placing it in a graveyard orbit safely away from other spacecraft or by deorbiting it to remove it from the space environment entirely, movement and support directly benefit.[8] With less debris, spacecraft can use their movements for important maneuvers as opposed to debris avoidance and will experience fewer debris strikes that need to be addressed through design or support. Space is a challenging enough place to operate in, cleaning up the junk stops it from being any harder.

Key to understanding these activities is recognizing one spacecraft will be serviced by another, just as B-52 bombers are refueled by KC-135s. The spacecraft being serviced is referred to as the client. The spacecraft providing the SM&L capability is called the servicer.

Service Area	Description
Inspection	The gathering of information on the state of a client at a distance using one or more sensors, both optically in multiple bands (visible, infrared) and electromagnetically for radio frequencies.
Materiel Logistics	The placement and storage of commodities and equipment in space for usage in a space architecture to support client operations. This includes launch and the forward placement and storage of materiel at space depots.
Orbit Modification	Change the orbit of a client vehicle, typically for specialized insertion (“last-mile delivery”), life extension, or end-of-life maneuvers.
Refueling	An activity that directly restores the propellant of a client vehicle.
Client Augmentation	The upgrade, repair, or maintenance of a client vehicle’s hardware. Repair servicers are often conceptualized as robotic-arm equipped, tool-wielding spacecraft that address client failures through restorative procedures.
Active Debris Mitigation	The relocation of junk resident space objects (RSOs) to disposal orbits.

SM&L Capability Acquisition Strategies

Since SM&L casts such a wide net, there is no one-size-fits-all approach. As such, each capability area must be evaluated separately to determine the most appropriate approach for each. To do so, this paper presents two factors that dominated the best approach. The paper then considers how these quadrants relate to other taxonomies devised to evaluate capabilities. And finally, the paper uses the framework to evaluate the status and potential of each of the six areas already discussed. This is not meant to provide *the* definitive answer but should be viewed as a well-informed starting point. Using such an approach, USSF can best determine how to nurture nascent commercial capabilities into a complete SM&L with military utility.

Two Key Factors

Two criteria are key as the dominating factors: *Commercial Viability* and *Application Agnosticity*, both of which can have either a positive or negative score, creating four quadrants.

Commercial Viability refers to the strength of the demand signal from commercial space actors for a capability in the next five years. Positive scores in this metric indicate that commercial demand signals exist or are likely to exist for a capability, whereas negative scores indicate that commercial demand signals are unlikely to arise in the near future.

Application Agnosticity is a measure of how indifferent to the application a service in a capability area would be. A commercial service or solution is defined in this context to mean any product or service utilized, but not owned, by the government.[†] A positive score in Application Agnosticity indicates that little to no augmentation would need to be made to a commercial service for DOD applications. A negative score indicates extensive augmentations or even full system redesigns of a commercial service or solution are needed for DOD applications.

A multitude of factors were considered prior to the selection of these two criteria for this paper. Potential evaluation metrics included the ability to meet unique DOD requirements, desired exclusivity of each capability, impacts on implementation and operational complexity, and upfront and recurring costs to DOD. After discussing these and others, it became apparent that all these factors were largely derivative of the two primary questions regarding *Commercial Viability* and *Application Agnosticity*. Therefore, while only two criteria are directly evaluated, each of the two encompass a range of factors of import that ultimately determines scoring.

Four Quadrants

Along these two axes now exist four quadrants of potential approaches: DOD Participant, DOD Customized, DOD Anchor Tenant, and DOD Owned (as visualized in Figure 1). These four quadrants capture the principal approaches USSF can leverage to nurture commercial capabilities.

- *A DOD Participant* approach indicates the ability to act as one of many customers in a thriving market for a capability. As such, this approach sits in the top right quadrant with positive scores for Commercial Viability and Application Agnosticity. This approach allows for the least amount of investment on behalf of the government and is indicative of the government being a customer to a robust commercial market. There is a strong desire among USSF policymakers and stakeholders to leverage this approach whenever possible in order to obtain the most capability per dollar. General Jay Raymond, Chief of Space Operations, has personally called for closer ties between the USSF and commercial space.[9]

[†]This investigation also limits the scope of commercial providers to U.S.-owned companies only.

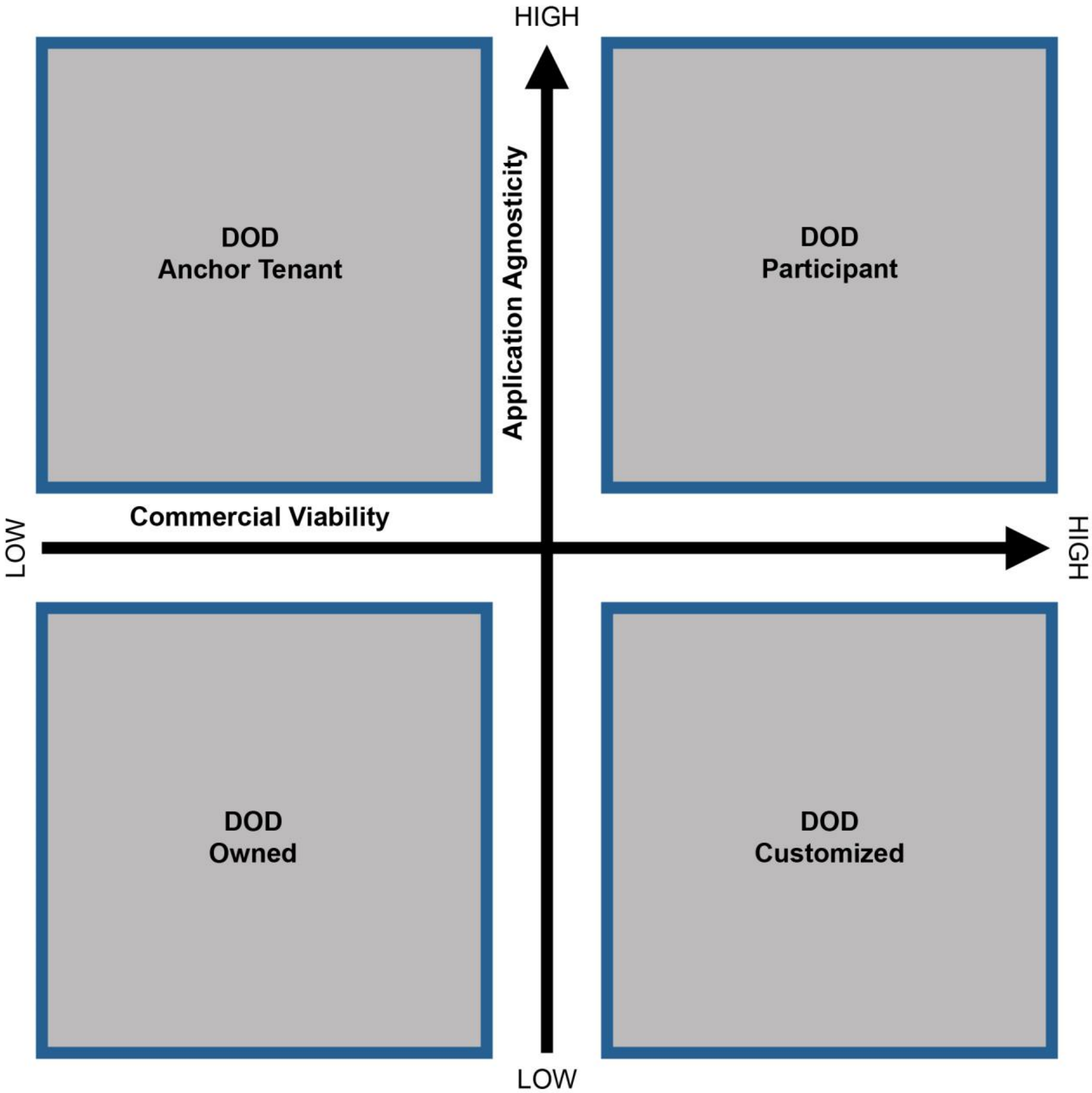

Figure 1. Visualization of approaches for the attainment of SM&L capabilities

- Underneath Participant, in the bottom right quadrant, is the *DOD Customized* approach. This approach is appropriate where a commercial market exists, but certain aspects of NSS applications require customizing the solution. This approach leverages significant commercial investment with the necessary adjustments funded by the government.

- The *DOD Anchor Tenant* approach, in the top left quadrant, is appropriate where a commercial solution could be easily integrated into a NSS context, but no commercial market exists in the near future. The last bit is key, because the potential exists in this approach that once the capability exists, there could be a commercially viable market for it. The DOD Anchor Tenant approach requires significant government funding but keeps the door open for the provider to market services for future commercial application.

- In the final quadrant is the *DOD Owned* approach. For capabilities that would never have commercial use and/or whose DOD application necessitates tight government control of the entire process, this approach is the most appropriate. While also the most expensive, the DOD Owned approach does allow DOD to optimize the capability for its purpose and reserves the capability as a national asset.

What This Framework Adds

Others have proposed frameworks by which to evaluate commercial capability for government and military use. Some approaches look at a range of relationships between government and commercial. This results in a spectrum from full government ownership and operation of an SM&L capability to full commercial ownership and operation available for the government to use as a service.[10] Where the USSF wants to land in that spectrum for a given capability is up for debate. A key consideration is the level of exclusively military utility or the level of violence involved.[11] Missions such as communications can be applicable beyond the military, but missile warning is more in line with military applications. A similar exercise can be applied to SM&L capabilities. And finally, the USSF must also explore the maturity of emerging and existing commercial capabilities. The level of market maturity can drive the role the government wants to play in leveraging the capability.[12]

This paper provides a way to incorporate these many considerations into one cohesive framework for SM&L. Our axes include one for commercial market considerations (Commercial Viability), but also include another for how suitable the application of a commercial service might be for military use (Application Agnosticity). Application Agnosticity is an important axis to evaluate against since the availability of a service does not immediately imply its suitability for direct NSS application.

Many have sought to propose ways to allow government to leverage commercial capability.[13] But SM&L is a unique field with both broader commercial application and critical, unique military utility. Using a taxonomy tailored to SM&L provides a better roadmap for how USSF can mature these capabilities and itself.

Evaluation of Approaches

Using this framework, the need for unique approaches jumps out. Each quadrant has at least one of the SM&L areas in it. And all but one of the areas neatly fit in a single quadrant. Trend arrows are included on some placements where the optimal approach was considered likely to change with increasing time (more than five years). The reasons for this change vary and are described in each capability area breakdown. Since the placements are (by necessity) generalized, the mapping of the capability areas should be used as just one tool among many for assistance in the formulation of acquisition strategies for SM&L capabilities. Some specific versions of capabilities could see different placements, and limited discussion on this is included.

Each subsection below describes the unique circumstances of each area, why it fits in a particular quadrant, and in which direction it is trending.

Inspection

Inspection resides in the Customized quadrant with no clear trending. For Commercial Viability, the score is in the mid-low positive range. The rationale behind this scoring comes from the readiness of technology and limited commercial demand for the capability. While the business case for Inspection is not well understood at the moment, a potential driver could be from spacecraft insurers looking for more detailed information on fault attribution and severity. Malinowska has an in-depth discussion of the impacts of inspection and servicing in general on the insurance of space assets.[14] The desirability of Inspection for insurance purposes is still an open question as current contracts are for loss of use with the specificity of the fault being outside of consideration. For Application Agnosticity, the score is in the slightly negative region. This scoring is due to policies regarding the handling of detailed imagery of space assets. It is possible that whatever communication and information security methods are acceptable to commercial clients would prove insufficient for handling and transmitting inspection data of DOD assets. For assets that do not require such strict information handling requirements, a Participant approach could be justified.

Materiel Logistics

As the only clear member of the Participant category, Materiel Logistics stands out as an obvious target for commercial utilization. The placement gives positive scores in both Commercial Viability and Application Agnosticity. For Commercial Viability, demand has been noted and providers are making moves already to provide access to goods on orbit. An example of this is the company Orbit Fab's investment in propellant depot prototypes in both Low Earth Orbit (LEO) and Geosynchronous Earth Orbit (GEO).[15] For Application Agnosticity, the internally contained nature of the supply chain from launch vehicle to depot reduces many of the concerns associated with information handling. This stance parallels the legacy of launch for space logistics since commercial providers, United Launch Alliance (ULA) and SpaceX, are utilized for National Security Space Launch (NSSL).[16] The capability is anticipated to further trend in Commercial Viability as the client base expands, though demands for specialized and unique services from the DOD may drive towards a Customized approach.

Orbit Modification

Straddling the line between Participant and Customized, the nuances of application to DOD missions are apparent for Orbit Modification. The simple part of this evaluation was the highest Commercial Viability score because Orbit Modification is the only capability currently being fielded commercially. This is evidenced in the last-mile delivery space tugs like Spaceflight's Sherpa and "jet pack"-style Mission Extension Vehicle (MEV) servicers from Northrop Grumman.[17] The uncertainty in the Application Agnosticity arises mainly from the risk tolerance of the NSS program. Some Orbit Modification concepts (like Sherpa) are mostly final orbit insertion stages separate from the launch vehicle upper stage that have limited and highly controlled interaction in which the clients are mated pre-flight. Other Orbit Modification concepts involve rendezvousing and docking with the client in orbit and then performing the service (like MEV). For the first type, it is possible that the servicer has no need to communicate with or image the client at all, making it highly agnostic to either commercial or DOD payloads. Additionally, the mating of the servicer and client is done on the ground and the systems typically separate before the client enters operations, which reduces risk. This type of Orbit

Modification could be a good candidate for a Participant approach. The second type of Orbit Modification is more likely to fall in the Customized quadrant as the servicer will be imaging, physically interacting with, (potentially) communicating with the client, and potentially doing all of these things after the client has entered operations. These factors could require higher levels of information control, more oversight in servicer operations, and a higher risk tolerance.

Refueling

Refueling sits in the Customized quadrant and is likely to remain there. The Commercial Viability of refueling is promising—with companies like Orbit Fab investing in refueling capabilities and the DOD already looking to incorporate their technology in future systems.[18] Some initial commercial movement has already begun as well, with the announcement of Orbit Fab signing a refueling contract for Astroscale's proposed servicer fleet.[19] A major stumbling block to the commercial development of refueling services is the lack of agreed upon standards, notably common interfaces and standard fluids. The Consortium for Execution of Rendezvous and Servicing Operations (CONFERS) is an industry group that is working on the development of just such standards, but standards development is typically a lengthy process and with often slow commercial uptake.[20] The score for Application Agnosticity is negative from factors that have been mentioned previously: information security (before, during, and after the operation), physical interaction of client and servicer, communication between client and servicer, and program risk posture.

Client Augmentation

Augmentation is the only capability area that is solidly in the Owned quadrant. Demand signals from commercial clients for this type of service are not noticeable at present and the business case for such a service remains uncertain. An event that could alter this scoring is the advent of persistent commercial hosted payload platforms, which trends this placement towards a Customized approach. A persistent platform would have the ability to host payloads and swap in new clients over time, similar to hosted payloads on the International Space Station (ISS). Preceding this development are likely specific applications for DOD programs for upgradeability and responsivity that will drive much of the initial work in this area. The Application Agnosticity is also low due to the sensitive nature of modifying hardware on a DOD asset. It is unlikely that even if a commercial service were to exist that it could be implemented for a DOD mission without significant alteration.

Active Debris Mitigation

As a unique capability area, it is somewhat appropriate that Active Debris Mitigation is on its own in the Anchor Tenant quadrant. The Commercial Viability of Debris Mitigation services is not yet established. Without regulatory incentives or penalties, debris remains a problem for all, with none willing to move towards a solution. Policy also restricts who is allowed to clean up what pieces of space junk since Article VIII of the Outer Space Treaty gives control of space objects to the originating nation in perpetuity.[21] With the rise of mega-constellations (e.g., proliferated LEO constellations such as Starlink) and increasing populations of debris, it is likely that some change will be forced in this area, as evidenced by the FFC rule change moving the de-orbit timeline from 25 years down to just five, trending the placement toward the Participant quadrant.[22] For Application Agnosticity, the mitigation of debris and defunct satellites is viewed favorably since the assets have no operational value and risk can be more easily accepted because the objects themselves pose the risk. A potential bifurcation of this placement could be with regard to debris objects and whole defunct satellites. Debris objects contain little residual value

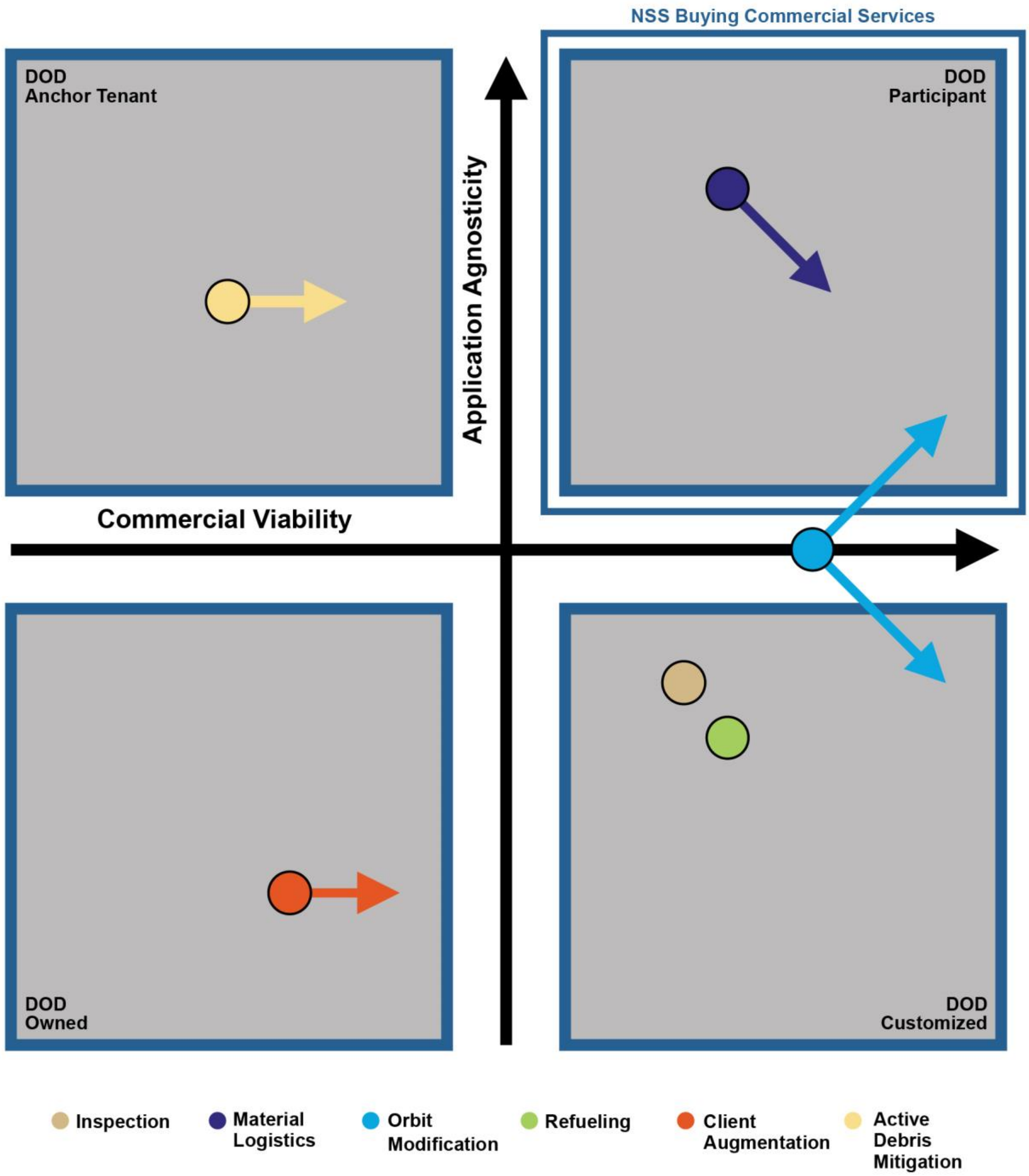

Figure 2. Placement of SM&L capabilities on the approach axes with respect to current conditions and implementation within five years.

in terms of information about the design and operation of the larger space object it originated from, but the interaction with defunct bodies, especially ones that may have prematurely ended life, may have sensitivities more similar to Orbit Modification. Additionally, using commercial services helps alleviate some of the fears of government-owned Active Debris Mitigation platforms potentially being weaponized. Further justification of this placement is the appearance of signals from the USSF for a desire to buy debris mitigation as a service from the private sector.[23]

Each of the six areas is at a different stage of maturity and will have a different role in a fully developed SM&L capability. By exploring how each area fits in each quadrant, USSF can better leverage current commercial efforts into true military utility.

Looking to the Future

With the declaration of Space Mobility and Logistics as a core competency of the USSF, it is not a question of *if* but *how* SM&L capabilities should be acquired and fielded. Answering this question, especially with regards to fielding, will require collaboration with U.S. Space Command (USSPACECOM) to ensure that operationally relevant capabilities are being developed. These capabilities are foundational, and this truth has been accepted by other governments, notably China with the recent SJ-21 mission demonstrating space tug capabilities.[24] The framework outlined in this paper should serve as a tool for both USSPACECOM and USSF leaders as they develop the future space enterprise. It can also help to educate those in industry seeking to engage with the national security space enterprise. Moreover, the primary goals of this framework are:

- To promote understanding of the current state of SM&L as it relates to implementation approaches
- To use this understanding to leverage previous investment and development effectively
- To then consider how to best influence the trending of capabilities through policy signals and funding

Given the desire of the DOD to maximize being a customer (DOD Participant quadrant), there are tangible steps that should be considered. With the growing desire for the DOD to act as a customer to a commercial market, investment, architectural, and policy decisions made today can influence the direction of the projected arrows in the future.

There are at least four areas for DOD to consider: investments, purposeful architecture design, security considerations, and regulatory issues.

For investments, look for strategic opportunities to spur the development of key commercial capabilities. Government investments and demand signals for specific capabilities made now may increase commercial investments to accelerate development of immature servicing areas, like refueling.

When considering the design of the enterprise architecture design, the USSF force design process should consider complex servicing areas, like client augmentation, as an integral element. Similarly, acquisition processes should include coordination and exploration of commercial ISAM capabilities.

Classification issues have long plagued DOD. By restricting information about capabilities, DOD also limits the number of commercially competitive companies. Policy changes in security posture may enable some servicing areas, such as inspection, to be more commercially viable.

Finally, improving the regulatory process would provide predictability and confidence to the commercial sector. Specific direction, such as federal policy on debris mitigation and end-of-life disposal, would serve as a demand signal to fuel investments and capabilities.

As the USSF considers these capability areas, and how it intends to acquire and operate these capabilities, it is important to ask critical questions. How should USSF and USSPACECOM apply different roles and responsibilities in developing SM&L? How will the role of USSF relative to commercial providers change over time as the commercial market matures? What acquisition strategies should be taken to balance enabling commercialization versus enterprise risk and resiliency? Should policies and regulations change in order to better enable USSF as a customer? How should USSF interact with industry on developing and defining critical interfaces?

"… the least optimal choice is to do nothing at all."

Conclusion

The capability areas within SM&L have unique characteristics that lend themselves more favorably to certain approaches than others. While all may be acceptable on some budget or time scale, the *Commercial Viability* and *Application Agnosticity* placements proposed reflect the realities of commercial demand and capabilities as well as unique DOD mission considerations. Though additional optimization could be done to figure out strategies and approaches for more specific applications, the least optimal choice is to do nothing at all. SM&L is required in order to transform the USSF into a twenty-first century space warfighting force.

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References

[1] Josh Davis, John Mayberry, and Jay Penn, "On-Orbit Servicing: Inspection, Repair, Refuel, Upgrade, And Assembly of Satellites In Space" The Aerospace Corporation (April 24, 2019), https://csps.aerospace.org/sites/default/files/2021-08/Davis-Mayberry-Penn_OOS_04242019.pdf; Wei-JieLi et. al, "On-orbit service (OOS) of spacecraft: A review of engineering developments," Progress in Aerospace Sciences 108 (July 2019), https://www.sciencedirect.com/science/article/pii/S0376042118301210

[2] T. T. Parish, "Infantry wins battles, logistics wins wars – Roseburg VA Supply Chain Vital During COVID-19 Fight," DVIDS (May 13, 2020), https://www.dvidshub.net/news/369929/infantry-wins-battles-logistics-wins-wars-roseburg-va-supply-chain-vital-during-covid-19-fight

[3] "Space Capstone Publication, Spacepower (SCP)" United States Space Force (June 2020), https://www.spaceforce.mil/Portals/1/Space%20Capstone%20Publication_10%20Aug%202020.pdf

[4] "DOD Dictionary of Military and Associated Terms," Office of the Chairman of the Joint Chiefs of Staff, (November 2021) https://apps.dtic.mil/sti/citations/AD1024397

[5] "Geosynchronous Space Situational Awareness Program," Air Force Space Command Fact Sheet, March 22, 2017, https://www.afspc.af.mil/About-Us/Fact-Sheets/Article/730802/geosynchronous-space-situational-awareness-program/

[6] "In-Space Servicing, Assembly, And Manufacturing National Strategy" National Science and Technology Council (April 2022). https://www.whitehouse.gov/wp-content/uploads/2022/04/04-2022-ISAM-National-Strategy-Final.pdf

[7] Mak Tafazoli "A study of on-orbit spacecraft failures," Acta Astronautica 64, Issues 2–3 (January–February 2009), https://www.sciencedirect.com/science/article/pii/S0094576508003019

[8] H. Krag, et. al, "Global Trends in Achieving Successful End-Of-Life Disposal in LEO and GEO," SpaceOps Conferences (May 5-9, 2014), https://arc.aiaa.org/doi/pdf/10.2514/6.2014-1933

[9] Nathan Strout, "Space Force chief sees larger role for commercial industry in its missions," C4ISRNet (February 25, 2021), https://www.c4isrnet.com/battlefield-tech/space/2021/02/25/space-force-chief-sees-larger-role-for-commercial-industry-in-its-missions/

[10] Alanna Krolikowski and Emmanuelle David, "Commercial On-Orbit Satellite Servicing: National and International Policy Considerations Raised by Industry Proposals," New Space 1, Issue 1 (2013), https://www.liebertpub.com/doi/pdf/10.1089/space.2013.0002

[11] Jamie Morin, Robert Wilson, "Leveraging Commercial Space for National Security" The Aerospace Corporation (2021), https://csps.aerospace.org/sites/default/files/2021-08/Morin-Wilson_Leveraging_20201113.pdf

[12] David McQuiggan and Ronald Birk, "Assessing Commercial Solutions for Government Space Missions" The Aerospace Corporation (February 17, 2022), https://csps.aerospace.org/papers/assessing-commercial-solutions-government-space-missions

[13] Jamie Morin, Sam Wilson, "Leveraging Commercial Space For National Security," Aerospace, November 2020.

[14] Katarzyna Malinowska, "RISK MANAGEMENT AND THE INSURANCE OF ON-ORBIT SERVICING. THE INSURANCE INDUSTRY AS A DRIVER OF RISKY SPACE INNOVATION," 71st International Astronautical Congress (October 12-14, 2020), https://katarzynamalinowska.eu/wp-content/uploads/2021/02/Katarzyna-Malinowska-Risk-management-and-the-insurance-of-on-orbit-servicing.-The-insurance-industry-as-a-driver-of-risky-space-innovation.pdf

[15] "Orbit Fab to Deliver Fuel in Geostationary Orbit, Via the Moon" Orbit Fab Press Release (September 24, 2021), https://www.orbitfab.com/fuelgeo

[16] "Space Force awards National Security Space Launch Phase 2 launch service contracts to ULA, SpaceX," United States Air Force (August 7, 2020), https://www.af.mil/News/Article-Display/Article/2305576/space-force-awards-national-security-space-launch-phase-2-launch-service-contra/

[17] "SpaceLogistics," Northrop Grumman, https://www.northropgrumman.com/space/space-logistics-services/; "Sherpa Program: New Orbital Transfer Vehicles Launch Smallsats to Custom Orbital Destinations," Spaceflight, https://spaceflight.com/sherpa/

[18] Sandra Erwin, "Orbit Fab gets $12 million to integrate refueling port with military satellites" SpaceNews (March 17, 2022), https://spacenews.com/orbit-fab-gets-12-million-to-integrate-refueling-port-with-military-satellites/

[19] Sandra Erwin, "Orbit Fab secures deal to refuel Astroscale's satellite-servicing robots," Space News (January 11, 2022), https://spacenews.com/orbit-fab-secures-deal-to-refuel-astroscales-in-space-servicing-robots/

[20] Jeff Foust, "Industry group working on satellite servicing standards," Space News (September 30, 2021), https://spacenews.com/industry-group-working-on-satellite-servicing-standards/

[21] "(XXI). Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies," United Nations Office for Outer Space Affairs (December 19, 1966), https://www.unoosa.org/pdf/gares/ARES_21_2222E.pdf

[22] Jeff Foust, "FCC approves new orbital debris rule," Space News (September 29, 2022), https://spacenews.com/fcc-approves-new-orbital-debris-rule/

[23] Sandra Erwin, "Space Force wants to help fund technologies to recycle, reuse or remove space debris," Space News (January 5, 2022), https://spacenews.com/space-force-wants-to-help-fund-technologies-to-recycle-reuse-or-remove-space-debris/

[24] Theresa Hitchens, "China's SJ-21 'tugs' dead satellite out of GEO belt: Trackers," Breaking Defense (January 26, 2022), https://breakingdefense.com/2022/01/chinas-sj-21-tugs-dead-satellite-out-of-geo-belt-trackers/