Space Operations

IN-SPACE SUSTAINMENT

AN INTERNATIONAL CIVILIAN-LED LOGISTICS ARCHITECTURE

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American policymakers are grappling with ensuring the ability of the US Space Force to project power in space while avoiding either explicitly militarizing space beyond geostationary orbit or by implying the establishment of sovereignty over celestial objects, actions which have the potential to alienate Allies and partners and alarm adversaries. An international civilian-led logistics architecture provides policymakers, military leaders, and proponents of civil exploration an opportunity to cooperatively pool their resources and achieve their objectives. An international civil and military partnership can be used to create shared standards, interfaces, and interoperability procedures to achieve strategic modularity, a fundamental requirement of a sustainment architecture and a paradigm leveraged by the petroleum industry but nearly absent from spacecraft systems engineering.

Allied grand strategy should pursue a future in space that is managed by rule of law (in the Western liberal sense, rather than the Chinese philosophy of legalism), where capitalism flourishes and people can live and work in space. This is the ideal vision of the future outlined by Air Force Space Command in 2019.[1] To achieve this future, the strategy requires a balanced trio of "ends, ways and means." Colin Gray asserts that when preparing for war, economics and logistics—the "means"—underpin strategy. "The economic resources of a polity supply and move a military machine that is directed by a strategy making organization, recruited, armed, and trained by military administration, ordered in accordance with intelligence information, educated and drilled respectively by strategic theory and doctrine."[2]

That is, the intelligence warfighting function informs maneuver, which itself informs the concept of support. Unfortunately, the US Space Force finds itself in an

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1. Air Force Space Command (AFSPC), *The Future of Space 2060 and Implications for U.S. Strategy: Report on the Space Futures Workshop* (Colorado Springs, CO: AFSPC, September 5, 2019), 6–9, https://aerospace.csis.org/; Namrata Goswami, "Explaining China's Space Ambitions and Goals through the Lens of Strategic Culture," Space Review, May 18, 2020, https://www.thespacereview.com/; and Yuri Pines, "Legalism in Chinese Philosophy," in Stanford Encyclopedia of Philosophy, November 16, 2018. https://plato.stanford.edu/.
2. Colin S. Gray, *Modern Strategy* (Oxford: Oxford University Press, 1999), 31.

unprepared theater (logistically speaking) and in an unprepared domain, and has yet to conduct set-the-theater tasks in space. Set-the-theater tasks are a prerequisite for developing a concept of support. Army doctrine defines these tasks as a

> broad range of actions conducted to establish the conditions in an operational area for the execution of strategic plans. . . . Planners leverage whole-of-government initiatives such as bilateral or multilateral diplomatic agreements to allow US forces to have access to ports, terminals, airfields, and bases within the AOR [area of responsibility] to support future military contingency operations.[3]

The envisioned Artemis basecamp on the lunar south pole and the International Space Station are the closest approximation of logistics infrastructure in space. Although the Space Transportation System and its space station was originally envisioned as permanent logistics infrastructure and as the first part of a network enabling access to deep space, the resulting International Space Station became a destination rather than a logistics hub.[4]

The American way of war highly depends upon the use of civilian logistics infrastructure to sustain and project forces.[5] This article discusses some policy, technical, and military considerations needed to establish a reliable network of in-space logistics assets. Gray asserted that "strategy requires the use or development of scarce economic resources."[6] Right now, the US Space Force finds itself contemplating power projection in an unprepared domain: power projection is necessary to maintain security, but power projection is dependent upon the sustainment of its forces.

In a resource-constrained environment, it is necessary to consider utilizing a "live off the land" mentality in space. NASA has researched in-situ resource utilization for decades but for the specific goal of use at the resource extraction location rather than with the intent of storing or further distributing the resources. Fortunately, the basic technology necessary to store and transport propellant has also been researched for decades.[7] The development of the space resources economy and the establishment of an in-space sustainment infrastructure are necessary to achieve Air Force Space Command's vision of the future and prevent the darker futures they envisioned in 2019 from arising.[8]

Challenges to the creation of a space-resources-based sustainment system are primarily bureaucratic or paradigm shifting rather than technical. These challenges

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3. Headquarters, Department of the Army (HQDA), *Sustainment*, Army Doctrine Publication (ADP) 4-0 (Washington, DC: HQDA, July 31, 2019), 2-18, https://armypubs.army.mil/.

4. Space Task Group, *The Post-Apollo Space Program: Directions for the Future* (Washington, DC: National Aeronautics and Space Administration (NASA), September 1969), 14–15, https://www.hq.nasa.gov/.

5. Rose Lopez Keravuori, "Lost in Translation: The American Way of War," Small Wars Journal, November 17, 2011, https://smallwarsjournal.com/.

6. Gray, *Modern Strategy*, 31

7. Alexander Jehle and George F. Sowers, "Orbital Sustainment and Space Mobility Logistics Using Space Resources," Space Force Journal 2, no. 4 (June 2021), https://thespaceforcejournal.com/; and George F. Sowers, "The Business Case for Lunar Ice Mining," *New Space* 9, no. 2 (June 2021), https://www.liebertpub.com/.

8. AFSPC, *Space 2060*, 8–9.

include physical, legal, and fiscal constraints surrounding maneuver in space and utilizing space resources; refueling space systems; finding a suitable terrestrial model; and establishing a civilian-led framework.

Ultimately, a propellant-distribution system will be necessary to support the distribution of raw materials and manufactured goods throughout cislunar space. The establishment of a complete sustainment system—not just that of propellant—should be the overarching goal of an in-space logistics commission. Establishing an economy in space gives future US, Ally and partner-nation planners increased means to execute national strategy in space. Recognizing the necessity of utilizing space resources to fulfill strategic and functional objectives, the United States, its Allies, and its partners should create space-resources-based in-space sustainment architecture.

Physical, Legal, and Fiscal Constraints

Operations in the space domain are constrained by physics, national and international law, and fiscal policy. The cislunar operational environment includes the orbits immediately around Earth and extends to the edge of the Earth's gravity well, the area in which Earth's gravitational pull is greater than that of the Sun's. Cislunar key terrain includes the Moon, geostationary orbits, and the five Lagrange points (points of relative stability where the gravitational pull of the Earth, Moon, and Sun balance to create stable orbits relative to the Earth and the Moon orbits).[9]

Physical Constraints

Movement in space is inherent to an orbit—objects are constantly falling towards the central body. But the orbits are predictable. Yet a satellite without the ability to change its orbit may as well be a stationary target, falling prey to electronic or physical fires from an adversary satellite with maneuver capabilities.[10] Moreover, satellites cannot merely move around the battlefield, they need to be moving with a purpose: establish a position of advantage over the adversary, or at a minimum avoid a position of disadvantage by disrupting an adversary's kill chain. Unfortunately, satellites are currently constrained by the amount of propellant they are launched with. Once a satellite runs out of propellant, it can no longer maneuver.

The fundamental argument for in-space refueling is based on the physics of maneuvering in space and can be found in the rocket equation. The rocket equation results in an exponential requirement for propellant as the need for change in velocity (ΔV) increases.

9. M. J. Holzinger, C. C. Chow, and P. Garretson, *A Primer on Cislunar Space*, AFRL 2021-1271 (Wright-Patterson Air Force Base, OH: Air Force Research Laboratory, 2021), https://www.afrl.af.mil/.

10. Emma Helfrich, "Russian Military Satellite Appears To Be Stalking a New U.S. Spy Satellite," The Drive, August 3, 2022, https://www.thedrive.com/; Todd Harrison, Kaitlyn Johnson, and Makena Young, *Defense Against the Dark Arts in Space: Protecting Space Systems from Counterspace Weapons* (Washington, DC: Center For Strategic and International Studies, February 25, 2021), https://www.csis.org/; and HQDA, *Operations*, ADP 3-0 (Washington, DC: HQDA, July 2019), https://armypubs.army.mil/.

> This is the reason rockets leaving Earth consist mostly of fuel, and that a rocket going to the Moon and back must be the size of a Saturn V used in Apollo or the SLS currently in development. However, if you can refuel enroute, and reuse the propulsion system through multiple refuelings, you can break the tyranny of the rocket equation. The exponential increase of propellant with ΔV becomes linear.[11]

A reliable network of in-space logistics assets is an enabler for the mobility of all spacecraft, not just military spacecraft. Providing low-cost or nearly free propulsion will enable the transport of other materials and all other warfighting functions in space. Among all spacepower competencies, in-space sustainment holds the greatest potential to link the typically interconnected and international character of military, civil, and commercial space activities. Using space resources for in-space sustainment will facilitate large-scale access to low-cost, sustainable propellant for the space economy.[12]

Legal Constraints

Existing and upcoming human exploration missions to cislunar space and Mars are built on models of international cooperation such as the International Space Station agreement signed by 15 states in 1998.[13] The lunar Gateway is also being planned and executed by an international space agency consortium consisting of NASA, the European Space Agency, JAXA (the Japan Aerospace Exploration Agency), and the Canadian Space Agency with bilateral memoranda of understanding.[14] Such endeavors serve as legal models for an in-space sustainment infrastructure and could also serve as customers who would benefit from the delivery of space-sourced water and its constituent elements (oxygen and hydrogen) for human sustainment, propulsion, or radiation shielding.

The possible interconnections between international space activities and an internationally operated in-space sustainment network are evident in light of a new international civil space exploration agreement. The October 2020 Artemis Accords, with 23 state signatories by December 2022, represents the zeitgeist of international commitment to shape the future of human space exploration and counter adversarial norm-setting in space.[15]

Utilization of space resources is a core aspect of the agreement, which specifies international governance according to standards established in the five major space treaties and monitored by the United Nations Committee for the Peaceful Use of Outer Space (COPUOS). "The Signatories intend to use their experience under the

11. Sowers, "Lunar Ice Mining."

12. Sowers; and Jehle and Sowers, "Orbital Sustainment."

13. International Space Station Intergovernmental Agreement, Can.-European Space Agency member states-Jap.-Rus.-U.S., January 29, 1998, T.I.A.S. 12927 (1998), https://www.state.gov/.

14. Jeff Foust, "NASA and Japan Finalize Gateway Agreement,"Space News, January 13, 2021, https://spacenews.com/.

15. The Artemis Accords: Principles for Cooperation in the Civil Exploration and Use of the Moon, Mars, Comets, and Asteroids, Aus., Can., Jap., Ita., U.S., Lux., U.K., U.A.E., October 13, 2020, https://www.nasa.gov/.

Accords to contribute to multilateral efforts to further develop international practices and rules applicable to the extraction and utilization of space resources, including through ongoing efforts at the COPUOS."[16]

A year prior, on November 12, 2019, The Hague International Space Resources Governance Working Group adopted the *Building Blocks for the Development of an International Framework on Space Resource Activities*.[17] The framework outlines a potential legal framework surrounding property rights, responsibilities, and limitations for governments to coordinate, extract, and use space resources, and it establishes a forum and procedures to prevent and resolve disagreements consistently with existing treaties, including the Moon Agreement.

The Hague *Building Blocks* and multilateral space agreements provide policy and legal examples for establishing and maintaining an international in-space sustainment infrastructure. This spirit of international cooperation can be harnessed for defense-related purposes, but its primary use should be for establishing an in-space sustainment infrastructure and for building the space economy in general. A civilian-led in-space sustainment infrastructure, used by both government and private civil and commercial entities, will support the fulfillment of peaceful international political goals in space.

Moreover, commercial services built on the foundation of the described infrastructures will service military spacecraft but will also generally decrease the costs of spacefaring. This infrastructure will facilitate commercial space activities beyond low-Earth orbit (LEO) for all space players, amplifying digital services, communication, and connectivity on Earth, and ultimately benefiting all consumers of space-based services.[18]

Commercial space activities supported by an in-space sustainment infrastructure provide broad economic benefits to the average person on Earth. They increase the individual consumer's quality of life by reducing the cost of critical services; they lower the cost of doing business for companies operating in space or tangential to the space industry; and they lower the costs to governments that use space capabilities to govern and preserve their defense. An in-space sustainment architecture, then, can serve as a roadmap for Ally and partner governments to invest in this area while adhering to their commitments to international space law. The most prominent treaty, the Outer Space Treaty (1967), emphasizes that space activities "shall be carried out for the benefit and in the interests of all countries . . . and shall be the province of all mankind."[19]

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16. The Artemis Accords.

17. The Hague International Space Resources Governance Working Group (HISRGWG), *Building Blocks for the Development of an International Framework on Space Resources Activities* (The Hague: HISRGWG, November 2019), https://www.universiteitleiden.nl/; and Olavo O. Bittencourt Neto et al., eds., *Building Blocks for the Development of an International Framework for the Governance of Space Resource Activities: A Commentary* (The Hague: Eleven International, 2020) 1.

18. HISRGWG, *Building Blocks*.

19. Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies (Outer Space Treaty), U.S., U.K., U.S.S.R., January 27, 1967, 18 U.S.T. 2410, art. I, https://www.unoosa.org/;

In-space sustainment is a support function with significant dual-use potential that supports ideals reflected in the Outer Space Treaty. Although essential to military operations, it is not inherently aggressive or threatening. It can, however, be an ideal focus point to maintain and promote positive norms and standards for international precedence in the context of the treaty. An opportune moment has now arrived in the light of the international activities of American space policy initiatives. The new space coalition has a common interest in an in-space sustainment infrastructure from strategic and operational perspectives.[20] Accordingly, this is a unique opportunity to spark a demand signal for the space resources industry.

Fiscal Constraints

Military space strategies must be derived from political and economic goals on Earth and in space and are thereby constrained by the economic means available to the planners. Although a consensus on the necessity of international cooperation in space is coming to fruition, not all stakeholders have a long-term strategic mindset. America's Allies and partners must evaluate their interest in participating in international space defense activities from a strategic perspective. Moreover, including these stakeholders from the beginning will allow for the creation of internationally accepted standards, ensuring the willingness of Allies and partners to follow US leadership in space. Civil space exploration programs accompanied by commercial opportunities emphasize international cooperation. In fact, the Artemis Accords explicitly deals with the utilization of space resources.

Several national space strategies must be coordinated into an overall model for international space defense cooperation. Cultural differences regarding the standing of space defense within national priorities, including budgets and the role of military space activities in overall national space activities, should not be underestimated. Unlike the United States, an operational demand for space is still nascent in many nations. Within NATO, space was accredited as an operational domain only in 2019, whereas the United States considered the 1991 Persian Gulf War to be its first space war.[21]

Although states might be relying on large-scale commercial and scientific activities to maintain influence in space, the implications for defense and national security often remain unperceived outside the direct spheres of influence of military institutions.

A low national priority for space results in limited spending. Revenue for military government satellites in Europe amounted to a predicted $12 billion for the two decades from 2008-2017, while North America spent $60 billion.[22] Yet commercial, civil,

20. Rachel S. Cohen, "Building the New Space Coalition," *Air Force Magazine*, March 26, 2021, https://www.airforcemag.com/.

21. NATO, "NATO's Approach to Space," NATO (website), October 6, 2022, https://www.nato.int/; and B. Chance Saltzman, interview by Brookings Institution, "Remembering the First 'Space War,': A Discussion with Lt. Gen. B. Chance Saltzman, March 19, 2021, https://www.brookings.edu/.

22. Euroconsult, *Satellites To Be Built and Launched over the Next Ten Years*, 21st ed. (France: Euroconsult, November 12, 2018), 132, https://www.euroconsult-ec.com/.

and scientific space activities massively outweigh defense applications in most countries. Among Ally nations, only the United States has a significant portion of its space budget dedicated to the defense sector. As one US Space Command official noted, "not all space partnerships are created equal. Where wealthier countries may have more established national security space needs, others may only have the budget or desire to pursue civil and commercial space programs. The United States is learning to meet everyone where they are."[23]

Unlike most other nations, the US Space Force and NASA have broad bipartisan political and economic support and standing that enable US leaders to formulate strategies relevant to national space activities. For many Ally and partner nations, the civil, military, and commercial space sectors do not garner political interest that directly translates into budgets comparable to that of the United States.

In 2018, US government spending on space dominated global government spending ($47.5 of $82.9 billion, or 57 percent of global government spending on space), and over half of that spending was military related (the National Reconnaissance Office, the Missile Defense Agency, and the US Air Force).[24] Yet the commercial satellite industry dominated the space economy ($260 of $344.5 billion, or 75 percent, in global spending), with benefits spread across the world in the form of telecommunications, position, navigation and timing, and weather forecasting. [25] These services support global terrestrial industries including cell phones and internet, transportation, and banking services and are generally outside of direct government control. Consequently the United States and its Allies and partners must collaborate where interests best coincide.

Ultimately, in-space sustainment enhances spacepower with ancillary, dual-use benefits—it develops the space economy while sustaining the principles of free and fair use of all. Additionally, because of its budgetary heft, as compared to its Allies and partners, the United States should encourage adoption of wider cost-sharing opportunities. For example, the US military can develop a space mobility command reminiscent of the Air Mobility Command or the military Surface Deployment and Distribution Command and offer any standards it develops for input and sharing with its Allies and partners.

The Challenge of Refueling

The functional use cases of refueling space vehicles closely mirror space propulsion activities: space launch, rendezvous, and station keeping. These three activities represent the how-to of conducting the movement half of maneuver in space and are a fundamental

23. Cohen, "New Space Coalition."

24. Federal Aviation Administration Office of Commercial Space Transportation (FAA AST), *The Annual Compendium of Commercial Space Transportation: 2018* (Washington, DC: FAA, January 2018), https://www.faa.gov/.

25. FAA AST, *Annual Compendium*.

part of conducting space operations. They are also foundational to sustainment activities necessary to conduct space access mobility and logistics activities.

For each activity, this article considers how refueling expands the space vehicle's mission envelope, the associated cost savings (if known), and resulting new mission opportunities. An overarching theme is that assured propellant resupply enables space vehicles to consume up to all their propellant on a single mission or set of missions without asset loss, that is, without incurring a so-called soft kill. Satellites have traditionally been designed to perform their intended mission until they run out of propellant and are then deorbited or placed in a safe graveyard orbit. Assured propellant resupply in space eliminates the soft-kill outcome, maintaining the space vehicle's design life and expanding its mission profile.

Space Launch

Launch vehicles' upper stages can be refueled in a geostationary transfer orbit or beyond geosynchronous orbits (GEO) to extend their reach and reduce the cost of placing a payload into the destination orbit. Refueling upper stages at geostationary transfer orbit for delivery of payloads to GEO (instead of using GEO satellites propulsion systems) could save up to 20 percent for the launch vehicle. Conceivably, this could eliminate GEO satellites' need for an apogee kick motor and associated propellant mass (~2000 kg, or nearly half the satellite's mass). This could free up mass budgets for other functions.

For missions beyond GEO, potential savings increase. Transportation from Earth to the lunar Gateway would see a 50 percent reduction in cost; transportation to the lunar surface or a Mars mission would cost approximately 66 percent less. A round trip from low Earth orbit to low lunar orbit (LLO) requires approximately 12,000 meters per second (m/s). Without in-space refueling, well over 300,000 kg of propellant would be needed (for a payload constrained by the assumed structure mass fraction of 0.92), sourced from Earth, at the start of the mission in low Earth orbit.[26] With one refueling, this is reduced by nearly an order of magnitude, to 40,000 kg; a 260,000 kg propellant savings.[27]

Upon mission completion, the upper stage is then either disposed of, or in the case of SpaceX's planned Starship, returned to Earth and reused. The upper stage could be refueled in space and repurposed for other missions including cryogenic propellant storage or bulk propellant delivery.[28] The upper stage could also be modified to provide in-space transportation services, including repositioning space vehicles or maneuvering space vehicles from GEO to other destinations within the cislunar

26. Sowers, "Lunar Ice Mining."
27. Jehle and Sowers, "Orbital Sustainment."
28. Jehle and Sowers.

system. This would essentially be a bulked-up version of final-leg delivery services provided by companies such as Bradford Space or Momentus.[29]

The Mars Ascent Vehicle (MAV) will be the first launch vehicle to depart an object in the solar system other than the Earth and the Moon (disregarding Osiris Rex's "Touch and Go" maneuver on the asteroid Bennu).[30] The vehicle was originally envisioned to use Martian in-situ resources to make its own propellant as part of the Martian Sample Return Mission that includes the Perseverance Rover.

The MAV team considered using oxygen sourced from Mars's atmosphere combined with liquid methane brought from Earth. Theoretically, this would have reduced the cost and amount of propellant needed to launch the vehicle from Earth. NASA later decided to use solid propellants while still successfully demonstrating oxygen extraction from Mars's atmosphere with MOXIE, the Mars Oxygen In-Situ Resource Utilization Experiment, one of the Rover's payloads.[31]

The MAV team will still have to contend with ensuring the launch vehicle can survive its entire mission profile: Earth launch, deep-space storage for eight months, Mars landing, and propellant storage on Mars for 2–6 years before a successful launch of the return mission.[32]

Future Mars missions, especially those with human participants, would benefit from local propellant generation and distribution. A round trip from LEO to low Martian orbit costs around 11,000 m/s. This budget compares to the LEO-to-low Lunar orbit mission previously discussed but would not have the benefit of in-space refueling without a dedicated, assured, in-space propellant resupply in the vicinity of Mars. A robotic propellant depot and distribution architecture established for cislunar space would need to be modified to account for the different environment of the Martian or other destination body's orbit, including differences in incident sunlight and latency for remotely controlled operations.[33]

29. "Logistics Services," Bradford-Space (website), n.d., accessed January 3, 2023, https://www.bradford-space.com/; and Debra Werner, "Momentus Reports Success in Testing Water Plasma Propulsion," Space News, September 25, 2019, https://spacenews.com/.

30. Brittany Enos, NASA's OSIRIS-REx Begins Its Countdown to TAG, NASA (website), September 24, 2020, https://www.nasa.gov/.

31. Stephen Clark, "NASA Narrows Design for Rocket to Launch Samples Off of Mars," Space Flight Now, April 20, 2020, https://spaceflightnow.com/; John Strickland, "Solving the Expendable Lander and MAV Trap," Space Review, October 19, 2015, https://www.thespacereview.com/; Stephen Clark, "Northrop Grumman to Supply Solid Rocket Motors for First Mars Ascent Vehicle," Space Flight Now, March 29, 2021, https://spaceflightnow.com/; and "MOXIE," NASA (website), n.d., accessed January 3, 2023, https://mars.nasa.gov/.

32. "Mars Sample Return Mission," European Space Agency (website), n.d., accessed January 3, 2023, https://www.esa.int/.

33. James R. Wertz, David F. Everett, and Jeffery J. Puschell, *Space Mission Engineering: the New SMAD*, (Torrance, CA: Microcosm Press, 2011), 282.

Rendezvous

Rendezvous missions (1) insert satellites into a specific point in a constellation; (2) inspect operational satellites; (3) service operational satellites; (4) intercept satellites (as a kinetic antisatellite weapon); and (5) avoid collisions. A satellite launched into a geostationary transfer orbit uses its own propulsion system for orbital insertion (utilizing its apogee kick motor). Upon successful insertion, the satellite could be refueled, providing it with an additional 1,700 m/s of delta-V to be used for collision avoidance, repositioning within the GEO belt, or even to fully deorbit rather than enter a graveyard orbit.

Space-based space surveillance missions such as those performed by the Geosynchronous Space Situational Awareness Program (GSSAP) rendezvous with natural motion circumnavigation or forced motion circumnavigation orbits around satellites in the GEO belt to inspect or observe satellites for intelligence purposes. One estimate suggests the GSSAP program could save nearly the entire cost of a replacement satellite—$114 million—by refueling GSSAP assets.[34]

Finally, programs such as the Defense Advanced Research Projects Agency's Robotic Servicing of Geosynchronous Satellites provide rendezvous capabilities with satellites to conduct repairs such as deployment assistance, swap out payloads, inspect environmental damage, and conduct retail-level refueling of satellites' propellant or cryogenic coolants.[35]

Station Keeping

Station-keeping maneuvers are performed to maintain a satellite within its assigned orbital slot. For geosynchronous Earth orbit satellites, this assignment is critical to maintain as the orbital slots are tightly allocated by the International Telecommunications Union to deconflict frequency use and mitigate collisions. The ability to refuel a GEO satellite's station-keeping propellent would enable that satellite to either extend its mission beyond what it was originally fueled for or enable it to launch with a minimal amount of propellant. Savings would be mission dependent, but water extracted from the Moon could cost as little as $1100/kg at Earth-Moon Lagrange Point-1 and only slightly more in GEO: this is a tenfold savings over propellant launched from Earth.[36]

A Terrestrial Petroleum Logistics Model

No single company or government agency including NASA or the US Space Force will be able to independently dictate standards for a widely adopted in-space logistics

34. Jehle and Sowers, "Orbital Sustainment."

35. On-Orbit Servicing, Assembly, and Manufacturing (OSAM) National Initiative, *OSAM State of Play*, 2021 ed. (Washington, DC: NASA, 2021), https://ntrs.nasa.gov/.

36. Sowers, "Lunar Ice Mining"; George Sowers et al., *Thermal Mining of Ices on Cold Solar System Bodies: NIAC Phase I Final Report* (Golden, CO: Colorado School of Mines, February 2020), 78, https://space.mines.edu/.

infrastructure. Instead, the Defense Logistics Agency, as the executive agent for bulk petroleum, manages bulk petroleum distribution to the US Department of Defense. In this capability, it coordinates with combatant commands, industry, and host nations. Additionally, each branch of military service retains its service-specific acquisition and employment strategies to support its environment and mission-unique operational and tactical needs (fig 1.)[37]

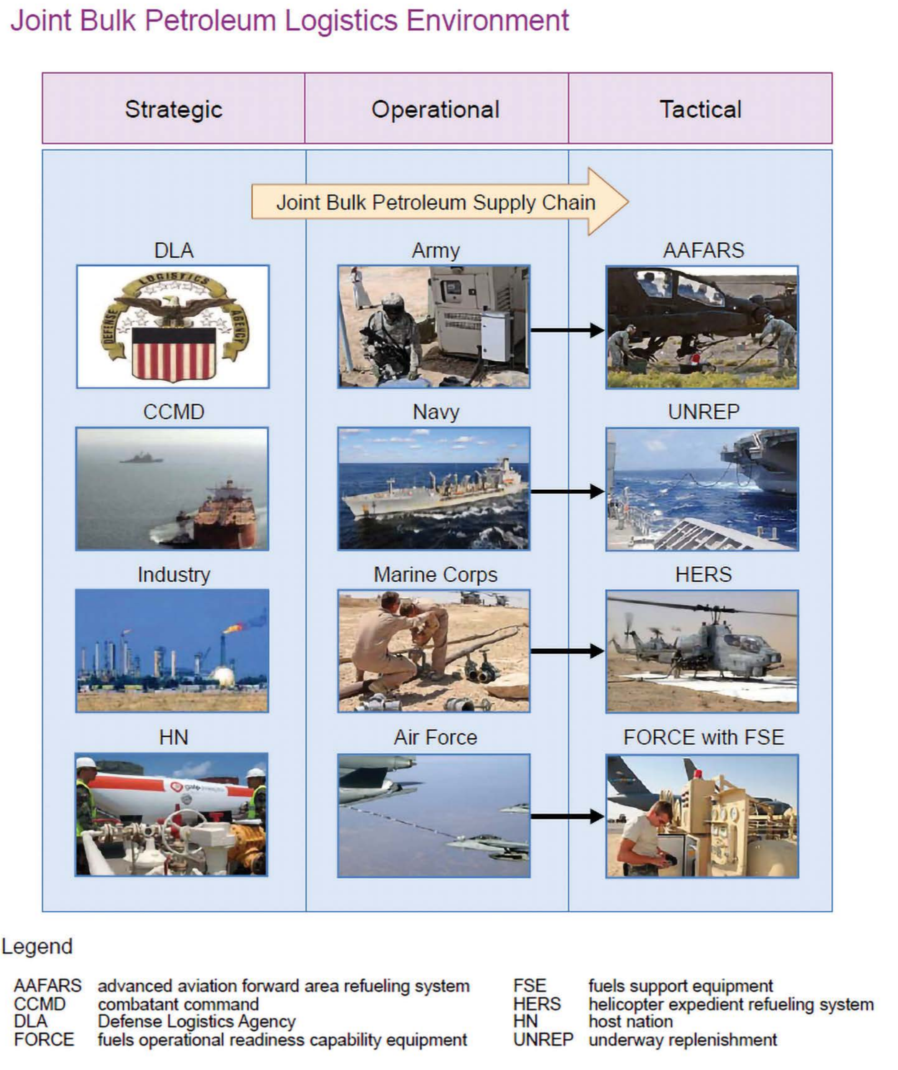

Figure 1. Joint bulk petroleum logistics environment, Joint Publication 4-03

37. Chairman of the Joint Chief of Staff (CJCS), *Joint Bulk Petroleum and Water Doctrine*, Joint Publication 4-03 (Washington, DC: CJCS, November 30, 2017), I-4, https://www.jcs.mil/.

In the petroleum industry, multiple companies are involved in the petroleum value chain, which includes prospecting, extracting, product refinement, bulk distribution, retail distribution, and final delivery to the customer. Gas stations are often privately owned franchises that lease directly from a retail fuel supplier. Those suppliers are subcontracted from bulk distributors that use pipelines or ocean-going vessels and own multiple bulk storage nodes.

A space-resources-based propellant value chain will closely mirror that of the terrestrial petroleum industry, which is global in nature. It, too, will include prospecting, extracting, processing, storage, and delivery nodes. A recent report thoroughly considers the space resources prospecting and extraction portion of the value chain but was intentionally vague about the aggregation, storage, and distribution of propellants.[38] Since that report's release, significant work has gone into prospecting, mining, and extracting water from the Moon and asteroids and transferring cryogenics in space.[39]

Northrop Grumman's Mission Extension Vehicle series has operationalized retail satellite servicing. Additional space resources value chain capability gaps still exist but are being identified and are starting to be filled in by researchers and a robust ecosystem.[40] Yet significant gaps remain including lunar-surface logistics infrastructure and in-situ resource utilization for other lunar and Martian resources.[41] NASA has been taking several steps to close these gaps, launching multiple strategies including public engagement programs like the "Break the Ice Challenge."[42]

Incorporating space resource extraction technologies, the example of DLA's civil-military partnership, and the fact that all active, thrust-producing propulsion systems require propellant, in 2021, researchers proposed a single propellant architecture

38. David Kornuta et al., "Commercial Lunar Propellant Architecture: A Collaborative Study of Lunar Propellant Production," *REACH* 13 (March 2019), https://doi.org/.

39. Justin Cyrus, "Prospecting, Extraction, and Processing of Lunar Resources Utilizing Swarms of Lunar Outpost's Mobile Autonomous Prospecting Platform (MAPP) Rovers" (paper presented at the Space Resources Roundtable, Colorado School of Mines, Golden, CO, June 11–14, 2019); Joel Sercel, "Asteroid Provided In-Situ Supplies (Apis™) Mission Architecture and Progress" (paper presented at the Space Resources Roundtable, Colorado School of Mines, Golden, CO, June 11–14, 2019); Robert Jedicke et al., "Optimized Continuous-Thrust Round-Trip Trajectories to Ultra-Low Δv ISRU Targets," *Planetary and Space Science* 211 (February 2022), https://doi.org/; and Sowers et al., "Thermal Mining."

40. Robert P. Mueller et al., "Lunar Mega Project: Processes, Work Flow, and Terminology of the Terrestrial Construction Industry versus the Space Industry," in *Earth and Space 2021*, Conference Proceedings for the 17th Biennial International Conference on Engineering, Science, Construction, and Operations in Challenging Environments, April 19–23, 2021 (Reston, VA: American Society of Civil Engineers, April 15, 2021), https://ascelibrary.org/.

41. International Space Exploration Coordination Group (ISECG), "In-SITU Resource Utilization Gap Assessment Report," (ISECG, April 21, 2021), https://www.globalspaceexploration.org/.

42. "NASA Break the Ice Lunar Challenge," NASA (website), November 18, 2020 https://www.nasa.gov/; and Molly Porter, "NASA Awards $500,000 in Break the Ice Lunar Challenge," NASA (website), August 18, 2021 https://www.nasa.gov/.

based on water distribution.[43] Nuclear thermal propulsion, an excellent and promising advanced propulsion technology, uses nuclear power to generate electrical or thermal energy to heat and accelerate a propellent—preferably hydrogen.[44] Past research has shown that water ice reserves on the Moon could be sourced and processed into propellant for in-space refueling in a commercially viable way, potentially within 10 years, supporting further space resource extraction and utilization.[45] A corresponding architecture has been proposed to distribute water (fig 2).[46]

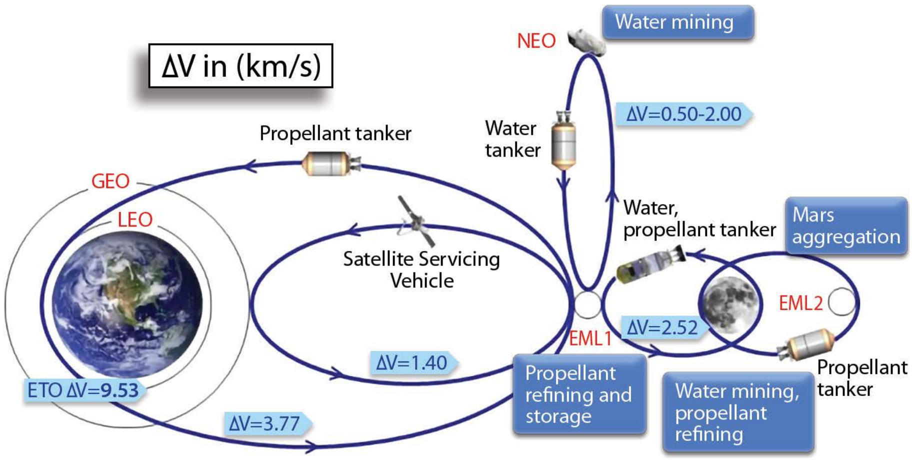

Figure 2. Water and LO2/LH2 propellant logistics architecture in cislunar space[47]

As a system-of-systems engineering problem, interfaces need to be specifically defined and adopted for the environment(s) and position(s) across the value chain in which they connect and serve. Environmentally, this includes the thermal environment for power generation and thermal management, the radiation environment for radiation hardening or to shield components, and day/night cycling for objects orbiting or based on a celestial body, among other considerations.

Value chain considerations include the total volumetric flow rate of the cryogenics being transferred; material selection; mechanical connections considering impact velocities,

43. Matthias Kößling et al., "The Space Drive Project—Thrust Balance Development and New Measurements of the Mach-Effect and EMDrive Thrusters," *Acta Astronautica* 161 (August 2019), https://doi.org/10.1016/; Jehle and Sowers, "Orbital Sustainment"; and Sowers, "Lunar Ice Mining."

44. Alex Gilbert, "Enhancing Military and Commercial Spacepower through Nuclear Thermal Propulsion," Space Force Journal 2 (June 2021).

45. Jehle and Sowers, "Orbital Sustainment"; Sowers, "Lunar Ice Mining"; and Luxembourg Space Agency, *Opportunities for Space Resource Utilization Future Markets and Value Chains: Study Summary* (Luxembourg: Luxembourg Space Agency, December 2018), https://space-agency.public.lu/.

46. Jehle and Sowers, "Orbital Sustainment."

47. Jehle and Sowers.

forces, and vibrations; electrical and data interfaces (both wired and wireless); thermal interfaces,; cycling and aging; weathering; and operational practices and protocols.[48]

Several companies are already developing and promoting their own interfaces in the hopes of achieving early and wide adoption. Some companies are promoting their interfaces as unrestricted (in the case of NovaWurks, both International Traffic in Arms Regulation–and intellectual property-free). Making an interface standard and open does not preclude intellectual property rights. As an example, the computer USB interface is still proprietary, and the owning organization sells licenses for under $10,000 to hardware developers.[49]

Eta Space, Lockheed Martin, SpaceX, and ULA were all awarded tipping point contracts by NASA to demonstrate large-scale, in-space, cryogenic propellant transfer. These demonstrations and the interfaces developed to support them would be critical to upstream propellant transfer—propellant transfer from a wholesale manufacturer to a storage depot or from a storage depot to a bulk transfer vehicle. These transfers are volumetrically high: SpaceX and ULA are specifically planning on demonstrating in-space refueling of launch vehicle upper stages.[50]

NovaWurks, Obruta, OrbitFab, SkyCorp, iBOSS (GmbH), AstroScale, and Northrop Grumman's Space Logistics have independently developed competing interfaces, visions, and standards for conducting satellite servicing. At one end of the spectrum, the Mission Extension Vehicle docks to and remains attached to the serviced satellite for the duration of its services and is relatively interface agnostic, attaching to a satellite's apogee kick motor. At the other end, NovaWurks's Space Lego concept uses its interface to facilitate in-space assembly, including for the exchange of internal propellant tanks between orbits and space systems (in the model of barbecue propane tank exchanges).[51]

Any system actively maneuvering and conducting rendezvous proximity operations and docking must be a fully functioning satellite that can independently maneuver, communicate, and survive in space; while small, the interface is an essential part of both the individual and system-level solutions. In order to achieve strategic modularity, these critical interfaces need to be agreed upon by the relevant stakeholders throughout their international value chain.

A Civilian-Led Framework

A propellant distribution system as outlined above could support the distribution of raw materials and manufactured goods throughout cislunar space. The establish-

48. Alexander Kossiakoff et al., *Systems Engineering Principles and Practice*, 2nd ed. (Hoboken NJ: John Wiley and Sons, 2011), 62.

49. "Getting a Vendor ID," USB (website), https://www.usb.org/.

50. "2020 NASA Tipping Point Selections," NASA (website), October 14, 2020, https://www.nasa.gov/.

51. "Space Logistics," Northrop Grumman (website), https://www.northropgrumman.com/; Sarah Scoles, "Now Entering Orbit: Tiny Lego-like Modular Satellites," December 29, 2019, https://www.wired.com/; and Talbot Jager, founder and CTO of NovaWurks, interview with author, July 29, 2021.

ment of a complete sustainment system—not just that of propellant—should be the overarching goal of an in-space logistics commission. Establishing an economy in space gives future US, Ally, and partner planners increased means to execute national strategies in space. Recognizing the necessity of using space resources to fulfill strategic and functional objectives, the new space coalition should contribute to the creation of a space-resources-based in-space sustainment architecture. The Artemis Accords presents an ideal structure to grow the inevitable military stakeholdership in space resources utilization in adherence to international space law while partnering with civil and commercial stakeholders.

Three areas of technological emphasis will facilitate the development of a space-resources-based sustainment network—strategic modularity, space resources utilization technologies, and orbital servicing and assembly technologies. These technology areas underpin the establishment of a celestial line of communication connecting the Moon to the Earth and facilitating the inclusion of the Moon into our economic sphere. In all three areas, an in-space logistics commission should coordinate among all stakeholders in the sustainment system-of-systems. Stakeholders will span the space resources value chain, from resource prospecting and extraction companies, through companies providing storage, processing, and distribution, to the governments, companies, and organizations that are the end in-space consumers of propellants, goods, and services.

First, strategic modularity—a systems engineering management approach that seeks a middle ground between top-down dictates of the interfaces (strangling necessary innovation) and a completely hands off approach leaving individual program managers free to select their own interfaces—needs to be achieved across a new space coalition. An in-space logistics commission could coordinate stakeholders to adopt common practices, technologies, and procedures to ensure the interoperable sustainment of their civil and military space capabilities. The commission could also map and functionally partition the components of the logistics system, specify the interfaces, and then freeze those interfaces to establish technical stability for the overall system-of-systems.[52]

If left without system-of-system level guidance, program managers may adopt the first interface that successfully meets their system's needs, achieving "technical modularity."[53] The absence of a collective interface requirement will lead to multiple standards, which increases the engineering requirements for the sustainment system-of-systems. The sustainment system-of-systems would then be required to support each standard, increasing mass and reducing efficiency. Ultimately not adopting a single standard or well-thought-out set of standards increases the cost for every system.

52. Ron Sanchez, "Modularity in the Mediation of Market and Technology Change," *International Journal of Technology Management* 42, no. 4 (2008) 338–39.

53. Ron Sanchez and Joseph Mahoney, "Modularity and Economic Organization: Concepts, Theory, Observations, and Predictions," in *Handbook of Economic Organization*, ed. Anna Grandori (Northampton, MA: Edward Elgar, 2013) 387.

Strategic modularity should be designed into any future space logistics system rather than engaging back-office, technical modularity, which has traditionally been used by the satellite industry.

An in-space logistics commission should also focus on the development of space resources utilization technologies. Technologies surrounding prospecting, extraction, processing, and distribution need to be matured in the context of civil space exploration programs. Until lunar- and near-Earth-object-sourced propellant can be transported through an in-space sustainment architecture, Earth-sourced propellants can be used to test existing and upcoming alternatives for storing and distributing propellant in space.

Finally, the commission should promote investment in orbital servicing assembly and manufacturing technologies such as space tugs (offering space mobility in the form of LEO-GEO orbital lifts), Earth-launched refueling missions, and Robotic Servicing of Geosynchronous Satellites. These missions form experimentation building blocks, mature concepts of operations, and refine the technology for international standards adoption.[54]

Conclusion

Establishing an in-space propellant sustainment architecture is both legal and necessary. Space resource law is rapidly maturing toward adopting a common framework for managing the use and extraction of celestial object resources and the property rights, responsibilities, and limitations of the countries and companies manufacturing products from them. Maneuver in space is inextricably tied to the use of propellant; reliable resupply will enhance national spacepower by reducing the cost of all other space activities.

This architecture will enable cheaper space exploration missions and lay the foundation for a material-based (an addition to the existing data-based) space economy. A new space coalition's space forces need to be prepared to leverage these new logistics capabilities, as it will extend their operational reach in cislunar space and enable maneuver without regret in the space domain.

An international coalition under the Artemis Accords should establish a civilian-led in-space logistics commission to map out the functional component of space logistics centers and networks, identify the common interfaces and procedures, and freeze those interfaces to create technical stability. An in-space logistics capability requires deliberate but decentralized coordination among its partner constituents, and strategic modularity is a prerequisite. Technical modularity, which emerges through individual program manager coordination, will not suffice, as it will increase complexity and hinder full interoperability. *Æ*

54. Elizabeth Howell, "Space Tug Company Names DARPA Military Veteran as New President," Forbes, September 15, 2020, https://www.forbes.com/; and Jeff Foust, "Orbit Fab and Benchmark Space Systems to Partner on In-Space Refueling Technologies," Space News, February 23, 2021, https://spacenews.com/.