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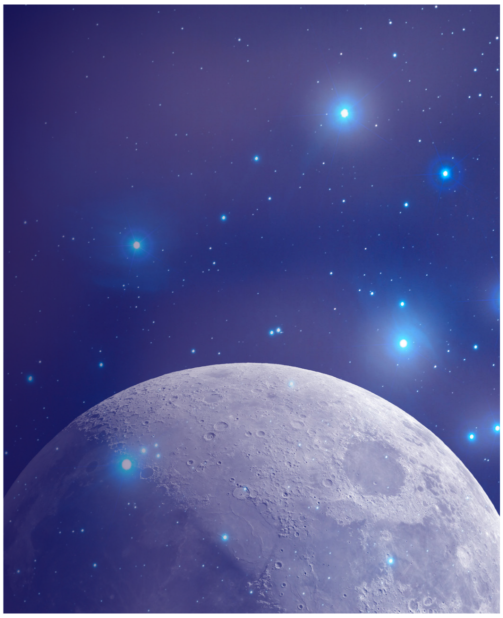
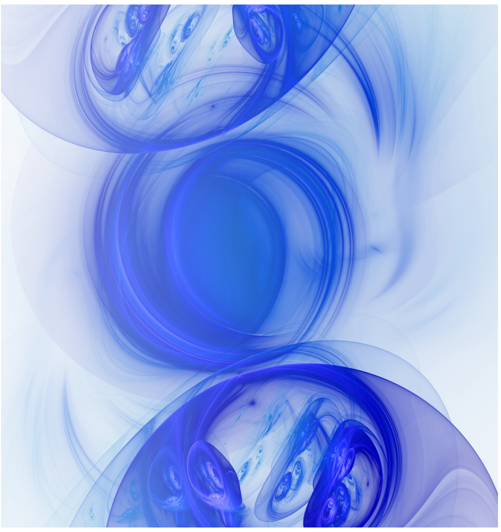
Anticipate, Innovate, Transform

Beyond Orbiting: Toward a Sustainable Space Economy

CONTENT





BEYOND ORBITING: TOWARD A SUSTAINABLE SPACE ECONOMY

BY MATTEO AINARDI AND GUILLAUME STORCK, GUEST EDITORS

For decades, the space industry was driven by national governments for their own uses, both civilian and military. Today, although government investment still makes up the bulk of space-related funding, a combination of three main factors has resulted in a foundational evolution of the industry, often referred to as "New Space."

The first factor is technological innovation, including:

- **Miniaturization** of electronic components and development of commercial off-the-shelf (COTS) components, both of which lower the cost to develop space systems and increase the speed of innovation
- Emergence of **high-cadence, reusable launchers,** significantly increasing available launch capacity and reducing its cost
- Development of **big data and artificial intelligence (AI),** allowing the extraction of valuable insight from the exponentially growing volume of space-based data

The second factor is the growth of vertically integrated space players in both satellite connectivity (e.g., Starlink) and remote sensing (e.g., Planet Labs), which is driven by clients (especially institutional ones) progressively shifting from an asset-purchase model to a service-purchase one.

The third factor is an influx of funding from private investors, such as venture capital funds and large corporations (e.g., Amazon).

New Space, resulting from the combination of these three factors, has generated an unprecedented rise in the number of space players, rocket launches, spacecraft in orbit, and volume of space-generated data. But the industry faces several challenges as it seeks to make this growth sustainable, including environmental, supply chain, and security issues:

- **Environmental.** Orbital space is not an unlimited resource and must be shared by public and private players, all of which need to efficiently track space objects and avoid space debris as part of successful spacecraft operations.
- **Supply chain.** Ensuring resilient production scale-up across the value chain is crucial as the space industry grows in new segments, requiring addressing significantly larger user bases compared to the past. Moreover, specific attention must be given to the usage of critical materials that can become increasingly rare or difficult to access.
- **Security.** Space has traditionally been the realm of intergovernmental competition, with military use beginning in the 1960s. Increased international tensions have made space a new conflict theater — not just militarized as it has always been, but increasingly weaponized, with threats ranging from cyberattacks (from both state and non-state actors) and jamming to physical destruction.

This issue of *Amplify* explores the key challenges that the space industry faces in its journey toward long-term sustainable growth and value creation.

IN THIS ISSUE

We begin this issue with Victor Heaulme, who takes a look at the space waste problem through a technology lens. He notes that the Kessler Syndrome (i.e., orbit overpopulation leading to object/satellite collisions that greatly affect space access) is becoming increasingly possible. Along with policy making, Heaulme describes technologies for more accurate tracking of space objects of all sizes, monitoring software that automates collision warnings, and technology that remotely removes objects in orbit. These include two systems that cause decaying orbits, one that uses a specialized satellite to push space objects and one that moves objects into a different orbit from Earth.

> **NEW SPACE IS THE RESULT OF EXPONENTIAL GROWTH, INCLUDING AN UNPRECEDENTED RISE IN SPACE PLAYERS, ROCKET LAUNCHES, SATELLITES IN ORBIT & SPACE-GENERATED DATA**

Next, Ronald Birk, Lori W. Gordon, and Eleanor Mitch outline the factors behind the need for a system that dynamically updates space supply chain information. Along with higher demand, there is competition among sectors, such as medical device and auto makers, for certain commodities and many rare-earth elements. The authors propose a distributed ledger technology (DLT) system called "Space supply chain Topology for Assessing Risk (STAR)" that would create a nexus for all stakeholders in the space supply chain community. STAR would include trusted partnerships via information-sharing agreements, information wells that let partners leverage an array of structured and unstructured data, a network of cloud-based platforms that enable secure processing of data among partners across the space enterprise, data integrity via DLT, and assessments of priority items to discover weak areas in space supply chains. The article describes the four key risks STAR would identify and calls for community dialogue about a space enterprise solution that "shines a light on dynamically evolving risks."

Sylvester Kaczmarek then dives into the cybersecurity issues threatening current and future space exploration. In addition to bad actors who have targeted satellites by jamming, spoofing, and data hijacking, there's the potential for spacecraft life-support, navigation, and propulsion systems to be hacked. Breaches that threaten communications between ground stations and their space assets are also possible, as is interference with the data streams that flow constantly between satellites and public and private entities. Kaczmarek advises a number of strategies for mitigating space-related cyber threats, including AI models that anticipate and prevent attacks before they occur, encryption methods resistant to quantum attacks, and international cooperation to harmonize regulations across countries.

Our fourth article comes from Moriba K. Jah, who points to a growing concern over mankind's ability to use orbital space for long-term benefit. Orbital space is not infinite; yet several companies are planning large-scale satellite launches in the next few years. When added to operating and abandoned satellites (and other space debris) in geostationary orbit (GEO), and low Earth orbit (LEO) orbits, there's the potential for "a tragedy of the commons." Jah proposes a solution guided by the tenets of traditional ecological knowledge, including recognizing space as a dynamic ecosystem in which changes in one part can impact the whole, designing satellites and spacecraft for longevity/reusability, and promoting a greater sense of accountability among spacefaring nations and commercial entities. Shifting from a linear space economy to a circular one, says Jah, would not only prevent orbital ecocide, but it would also preserve the final frontier as a resource and habitat for future generations.

Next, Matteo Ainardi, Arnaud Siraudin, and Guillaume Storck present a way for businesses to envision future space ecosystems and their associated value chains. A recent study, conducted by the EURO2MOON association (including Arthur D. Little), endeavored to understand demand drivers, value chains, and areas of uncertainly around lunar resource use. Propellant production was used as an illustration — the reaction engines needed to power vehicles on the lunar surface and traveling to/from Earth (and beyond) will need propellants. The study examined both the supply side and the demand side, developed scenarios of a future ecosystem, proposed a likely value chain, outlined use cases, and estimated those use cases' likely ranges of demand. Beyond giving a peek into lunar opportunities, the article can help businesses considering lunar-economy investment better understand how to account for inherent high levels of uncertainty.

Finally, Curt Hall takes a look at the role 3D printing can have in space exploration. From Earth-based manufacturing of spacecraft parts to tools like wrenches on the International Space Station and metal parts during a Mars mission, space could be 3D printing's killer app. Hall discusses a large number of technologies in development, including the ability to convert plastic waste from previously printed parts into feedstock that can be used to create new tools and parts. Similarly, there are projects underway to see if the Moon's regolith can be used to construct the (literal) building blocks for a moon base. Printing food, medicine, and even replacement organs for long-haul space missions is also being explored using bioprinting, a technology that could come full circle to provide tissue-based patches for the outside of damaged hearts here on Earth.

As space technologies adoption and usage keeps growing across all governmental and private sectors, these challenges must be taken into account to enable long-term, sustainable growth of the space industry. We hope this issue of *Amplify* can offer a starting point for space industry stakeholders to reflect and collaborate in addressing them.

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DECODING SPACE WASTE:

AWARENESS, CONCERN, ACTION

Author

Victor Heaulme

Humanity has been going to space since Soviet cosmonaut Yuri Gagarin led the way in 1961. We've had a permanent human presence in the International Space Station (ISS) since 2001. New satellite constellation companies appear every year. The US and China plan to reestablish human presence on the Moon by the decade's end. But our access to space is at risk — not because there aren't enough people investing in it, but because Earth's orbit is becoming too cluttered. Much like the depiction in Pixar's film *Wall-E*, if Earth's orbit becomes filled with satellites and debris, we risk not being able to leave our atmosphere at all.

To discuss this growing issue, we must understand why space is crucial to humanity, what the space waste challenge is, and how we can address it.

FIRST OFF, WHY GO TO SPACE?

One reason is that the space economy is currently valued at US $469 billion and is set to surpass $1 trillion in the next decade.[1] There's a lot of money to be made! But that's the boring answer. It also doesn't answer the pressing question: *why should we go to space?*

Investment in our presence in the stars has recently increased dramatically. It would be too easy to reduce this change to a few billionaires playing with their money. Instead of spending billions on rockets, why don't they invest in saving the planet? Healthcare? Clean energy? Artificial intelligence (AI) and quantum computing? Hunger and poverty? Connectivity? Space skeptics pose these questions — and they are all valid!

Ironically, investment in space addresses all these issues, and many more:

- Space mining replaces mining Earth for finite resources, such as rare earth metals, helium-3, and water.
- Manufacturing and travel in space can help reduce CO2 emissions.
- Extending the human lifespan and production of lifesaving drugs are key to making us a multi-planetary species.
- Clean energy like fission, fusion, and solar is essential for sustainable colonies.
- Robotics, AI, and quantum are needed to operate in space efficiently and safely.
- Earth observation satellites monitor our farms, weather, crop output, water management, and more.
- Satellite constellations connect the globe, including the 40% with little or no Internet access.

> **INVESTMENT IN OUR PRESENCE IN THE STARS HAS RECENTLY INCREASED DRAMATICALLY**

These technologies are being developed by space, for space — with real Earth applications. They are the reasons we need to invest in space, but if that isn't enough, listen to Elon Musk's words: "Fundamentally, the future is vastly more exciting and interesting if we're a spacefaring civilization and a multi-planet species than if we're not."[2]

SO WHAT'S THE PROBLEM?

We're at a turning point in the space industry, with costs to orbit having decreased by several magnitudes. NASA's Space Shuttle sent payload to low Earth orbit at a rate of $54,500/kg.[3] SpaceX sends payload for $2,800/kg with Falcon 9 and around $1,400/kg for Falcon Heavy. Starship could go as low as $50/kg when it's fully operational and optimized.[4]

Economic opportunities in orbit and beyond are flourishing, and many countries and private operators are investing in satellite constellations in orbit. In 1978, NASA scientist Donald J. Kessler predicted that Earth's orbit could eventually become so overpopulated that object/satellite collisions would lead to a chain reaction of collisions, making orbit and space access impossible. This is called the "Kessler Syndrome."

With more than 7,000 active satellites, projections to reach 100,000 by 2030, and 100 million+ objects larger than 1 mm (from flecks of paint to out-of-commission satellites) in orbit, the Kessler Syndrome is increasingly probable. To deal with collision risks, operators must carefully track and predict their satellites in orbit, accurately track objects and debris in their path, rely on accurate collision algorithms to predict their risk of collision, and act to avoid them.

Satellite operators must exponentially increase their satellite maneuvers due to collision warnings. However, collision warnings are estimations, not predictions, based on inaccurate object detection, resulting in estimations of orbits and probabilities of collisions. These are almost always false positives. NASA's threshold to maneuver a satellite is a 1 in 10,000 chance of collision, whereas SpaceX's Starlink constellation has a threshold of 1 in 100,000.

As a result, SpaceX's Starlink satellite constellation reported 25,000 avoidance maneuvers between 1 December 2022 and 31 May 2023. That number has been doubling every six months since 2019. It's expensive and getting exponentially worse as we approach 100,000 satellites by 2030. At this rate, they would have 1 million maneuvers by 2028, a hugely inefficient way to manage a satellite constellation.[5]

Government agencies are starting to prioritize efforts to accurately monitor space debris and remove it. In October 2022, the Orbital Sustainability (ORBITS) Act was passed by the US Senate to outline Space Traffic Management (STM) measures NASA must take to develop monitoring and removal capabilities, align on new debris-mitigation practices, and develop standard practices to coordinate orbit traffic.[6]

SO HOW DO WE SOLVE IT?

The first step is policy making. Before we can introduce new technologies to resolve the problem, we need to ensure it doesn't get worse. The ORBITS Act was a step in the right direction.

The ORBITS Act was passed again by the Senate in October 2023 but was not considered by the House of Representatives, requiring its reintroduction in the House in 2024. This marks the Senate's second approval of a version of the ORBITS Act (which received unanimous consent in the late 2022 Senate session but was also not addressed by the House). The proposed legislation instructs NASA to initiate a program for the removal of orbital debris. It would require collaboration among NASA, other government agencies, and the private sector to publish a list of debris objects that present the most imminent risk to the safety and sustainability of orbiting satellites.[7] The US Federal Aviation Administration (FAA) also recently proposed a rule that would limit satellite life in orbit after the end of operation to five years.[8]

On the global front, in a collaborative initiative with the European Space Agency (ESA), the World Economic Forum released its "Space Industry Debris Mitigation Recommendations" in June 2023, aimed at fostering space sustainability.[9] At the time of publication, the document had received 27 signatures from industry players in the space domain. This document, updated from its previous edition,[10] urges increased collaboration among space actors to minimize space debris, better transparency among operators, accelerated innovations in spacecraft-disposal technologies and practices, and the elimination of existing space debris in orbit. It also outlines specific objectives for post-mission disposal success and a designated time frame for an object's orbital lifespan.[11]

Within the United Nations (UN) Office for Outer Space Affairs (UNOOSA), the UN Committee on the Peaceful Uses of Outer Space (COPUOS) Working Group on the Long-Term Sustainability of Outer Space Activities addresses space debris and associated regulations and guidelines.[12] Member states share information on their space debris research annually at the committee's Scientific and Technical Subcommittee meeting. A compendium of space debris–mitigation standards can be found on UNOOSA's website.[13]

International treaties and agreements, combined with government policies and regulations, enable collaboration among nations, space agencies, and private entities to set shared standards, reduce new debris generation, and encourage responsible behavior in space.

KEY TECHNOLOGIES FOR TRACKING, MONITORING & REMOVAL

Addressing the Kessler Syndrome starts by accurately tracking everything in space, no matter how small. A 1-mm-wide fleck of paint might seem like nothing, but when traveling at 17,500 mph, it could cause severe damage to the ISS, endangering human life. Algorithms only work if they are fed good data. Table 1 lists some technologies that could help in tracking, monitoring, and removal. The following sections describe each technology.

LEOLABS

LeoLabs has developed an Earth-based, global radar network that tracks space objects in real time and populates a dynamic living map of tracked objects. Its proprietary algorithms predict and notify of potential collisions, recent

COMPANY	CATEGORY	DESCRIPTION
LeoLabs	Tracking	Earth-based, real-time radar network predicts and notifies on potential collisions
L3Harris	Tracking	Detects, tracks, and identifies all man-made objects in orbit using space-based sensors with radar
Kratos Defense & Security Solutions	Tracking	Uses RF sensors to locate satellites to within 150 meters
Deimos Space	Tracking	Surveys, tracks, and catalogs near-Earth space objects
OKAPI:Orbits	Monitoring	Compiles satellite data to automate collision warnings and maneuver recommendations
Lockheed Martin	Monitoring	Correlates data from optical, radar, and radio sensors to provide collision and maneuver recommendations
Lumi Space	Removal	Uses laser momentum transfer technology to detect and move objects in orbit from Earth
OrbitGuardians	Removal	Sends satellites into orbit to push objects into a decaying orbit

Table 1. Technologies that can help address space waste

maneuvers, and patterns throughout an object's or satellite's operational life. The radar network:

- Covers 300-2,500 km in altitude
- Tracks 250,000 objects, with >2 cm capability, 10x a day
- Focuses on radar over laser (radar is more efficient for scanning an area, laser is more effective for tracking a specific object)

MOVING A SATELLITE FOR A 1:10,000 CHANCE OF COLLISION CAN'T CONTINUE TO BE THE NORM

L3HARRIS

L3Harris provides a system that detects, tracks, and identifies all man-made objects in orbit. It combines ground- and space-based sensors with radar technologies.

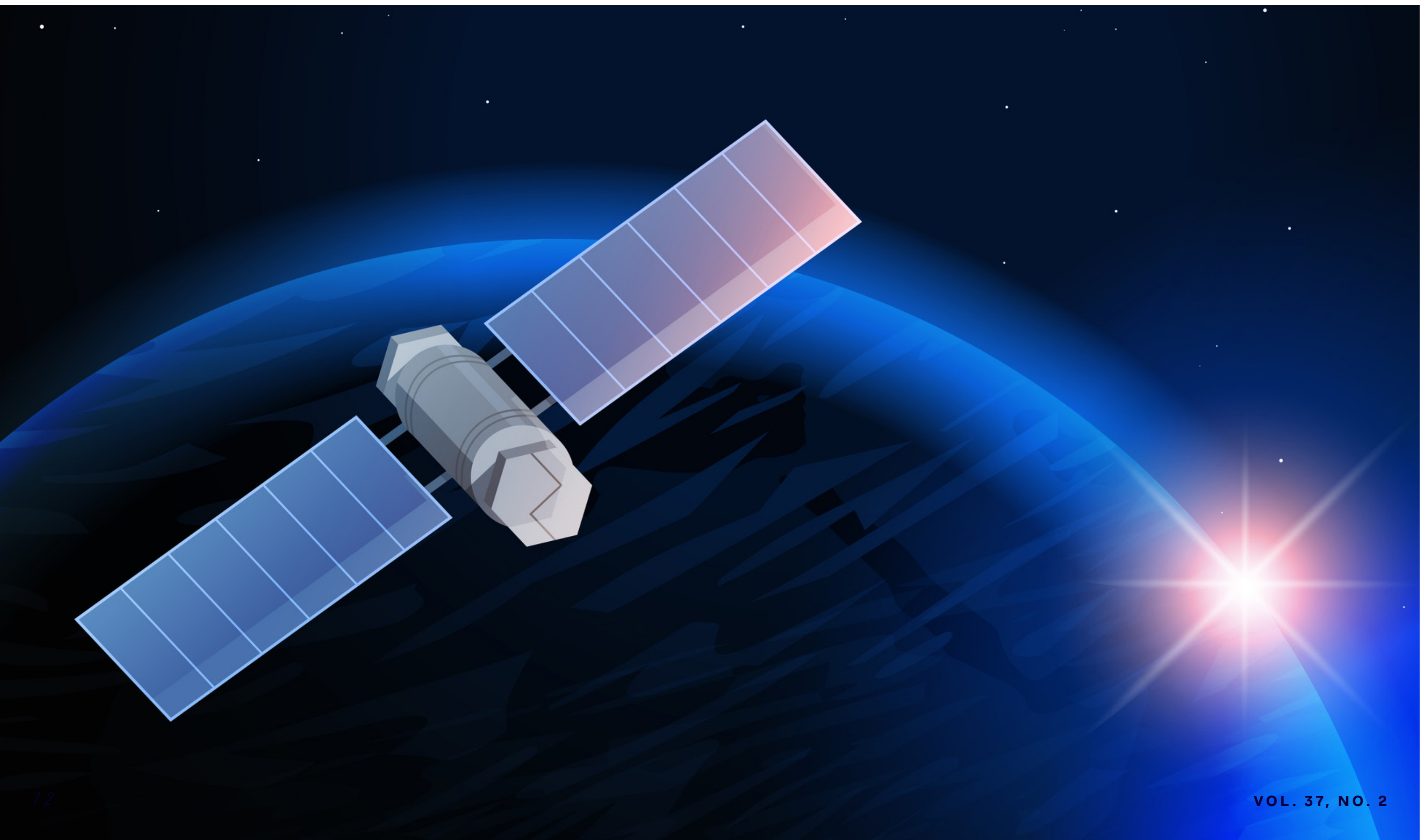
KRATOS DEFENSE & SECURITY SOLUTIONS

Kratos Defense & Security Solutions developed a system that uses radio frequency sensors to detect satellite signals and locate them within 150 meters with a rapid revisit rate (30 minutes) in all weather. This type of system is designed to address the gaps that radar/optical systems tend to have, and its higher-accuracy scans lead to better predictions of potential collisions.

DEIMOS SPACE

Deimos Sky Survey is an advanced complex used to detect, observe, survey, track, characterize, identify, and catalog near-Earth space objects. It also aids in determining the risk of collision and provides actions to prevent or mitigate collisions.

State-of-the-art 3D models and algorithms use this type of data to create usable platforms to monitor one's satellites and the objects endangering them. Moving a satellite for a 1:10,000 chance of collision can't continue to be the norm. Imagine if people driving on the highway constantly changed lanes because of these types of collision chances — it would be dangerous and inefficient!



Next, we describe a selection of software platforms that could help in monitoring potential risks.

OKAPI:ORBITS

A monitoring platform from OKAPI:Orbits compiles all data pertaining to a satellite (GPS, propulsion system, attitude, location of other objects/debris) to automate the generation of collision warnings and maneuver recommendations.

LOCKHEED MARTIN

Lockheed Martin's iSpace processes and correlates available data from optical, radar, and radio sensors to provide a real-time depiction of space objects, as well as collision and maneuver recommendations.

Next, we showcase technology tools to remotely remove objects in orbit. Some companies are launching satellites to capture old satellites and send them on a reentry trajectory (where they burn up safely upon entering our atmosphere). Some are developing ground-based technology to move objects remotely by altering their momentum.

LUMI SPACE

Laser momentum transfer (LMT) technology from Lumi Space detects and moves objects in orbit, from Earth. The object's changed momentum causes a decaying orbit that leads to it burning up in the atmosphere. LMT technology:

- Uses satellite laser ranging to precisely determine orbits
- Predicts orbits more precisely and further into the future
- Informs an API that connects to client software
- Plays a critical role in STM and laser-width adjustment (due to its adaptive optical systems)
- Provides a cost-effective solution for space debris mitigation[14]
- Clears the path for satellites, saving operators money and increasing lifespan
- Ensures space safety[15]

ORBITGUARDIANS

OrbitGuardians's system sends a satellite into orbit to rendezvous with an object and "push" (momentum transfer) it into a decaying orbit to burn up in the atmosphere. Its benefits are: (1) one satellite can be used to de-orbit hundreds of objects in one mission; and (2) it offers economies of scale (the more objects to "push" in one mission, the lower the price per push).

THIS TIME, THE SPACE RACE IS HERE TO STAY

Space exploration isn't slowing down; in fact, it's accelerating:

- Russia sent its Luna 25 lunar lander mission in 2023, the first in 50 years.
- India's Chandrayaan-3 mission landed on the lunar south pole in 2023 (becoming the fourth country to land on the Moon).
- In 2023, China sent the youngest-ever crew to its space station, with the goal of a manned lunar landing by 2029.
- In January 2024, the US sent its first lunar lander in more than 50 years (Astrobotic's Peregrine Mission One).
- Also in January 2024, Japan became the fifth nation to land on the Moon with its Smart Lander for Investigating Moon (SLIM) mission.

This time, humans are going to space to stay. But we need to ensure we do it safely, and that starts by solving the problems we've created in our own orbit.

> **SPACE EXPLORATION ISN'T SLOWING DOWN; IN FACT, IT'S ACCELERATING**

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STAR: SHINING LIGHT ON SPACE SUPPLY CHAIN RISK

Authors

Ronald Birk, Lori W. Gordon, and Eleanor Mitch

In the next 10 years, global space spending is expected to double.[1] Higher global demand will drive increased pressure on the US space-related supply chain. Companies are pivoting to high-rate production for critical national space capabilities, making supply chain efficiency more critical than ever. Other global market sectors (e.g., auto, medical device, gaming, and cloud storage industries) are competing with the US space enterprise for many of the same components, commodities, and rare earth elements.

These factors are driving the need for comprehensive, up-to-date, trusted information to expose problems in US space supply chains. Unfortunately, no trusted system exists for pulling together and disseminating the information needed to evaluate risk and inform decisions. This is particularly challenging considering the expanding diversity of the space supply chain stakeholder community, which comprises policy makers, procurement specialists, buyers and sellers of products and services, technologists, and security experts.

This article proposes a topology to aggregate and dynamically update space supply chain information, providing time-sensitive reporting along the lines of the Waze mapping application. For example, Waze has helped the US Federal Emergency Management Agency (FEMA) know where to dispatch fuel trucks to address urgent needs during disasters and has informed authorities and the public about open shelters and evacuation zones.

The space enterprise is a long way from having Waze-like solutions for space supply chains. That said, the Space supply chain Topology for Assessing Risk (STAR) would connect people, processes, and technologies via information-sharing partnerships, secure cloud-based platforms, and distributed ledger technology (DLT).[2] We recognize that stakeholders are already making connections, establishing information-sharing partnerships, and using DLT. These standalone approaches could be linked within STAR to provide a common nexus for all stakeholders in the space supply chain community.

This project will involve significant hurdles. To dynamically collect the necessary information, STAR needs buy-in from key stakeholders across the global supply chain. It would require cloud and related technologies to compile, process, and turn vast amounts of dynamically collected data into near-real-time decision support. This article does not suggest the best way to overcome these hurdles or recommend who should tackle which tasks. Our objective is to establish a community vision for STAR, stimulate discussion, and motivate the community to begin working toward it.

KINKS IN THE GLOBAL SPACE SUPPLY CHAIN

The space enterprise is transforming from producing a modest number of custom-made space systems commissioned by government organizations to an ecosystem in which many companies produce large quantities of space systems using assembly line production.

Managing the availability and delivery of large quantities of components to build these space systems is a challenge given the volume of data that must be tracked and the lack of visibility of that data. Incomplete data collections paint a fragmented picture for supply chain stakeholders. Blind spots manifest as risks for government organizations and companies; those risks are compounded by the fact that space-system component availability is affected by geopolitics, global economics, and competition from industries outside the space sector.

For example, growing demand and geopolitical crises have disrupted the supply of noble gases (neon, xenon, and krypton). Russia's illegal annexation of Crimea in 2014 disrupted Ukraine's steel industry, which was the source of as much as 90% of the global neon gas supply.[3] Effects of the pandemic and the 2022 expansion of the Ukraine-Russia war further interrupted production. Neon gas scarcity affected Taiwan Semiconductor Manufacturing Company Limited (TSMC) and others involved in semiconductor manufacturing since neon is a key input in the semiconductor manufacturing process. So, in addition to the space sector, the neon shortage affected auto industry access to semiconductor chips, illustrating the global scope of the problem.[4]

THE NEED FOR INNOVATIVE SUPPLY CHAIN TRACKING TOPOLOGY

The US space enterprise can benefit from a trusted, global, dynamically updated, enterprise view of the space supply chain. As mentioned, STAR's objective is to connect people, processes, and technologies via information-sharing partnerships, secure cloud-based platforms, DLT, automation, and evolved analytical techniques.[5]

Once established, STAR would rely on trusted partners to provide data stored in what we call "information wells." Hosted by vetted stakeholders using cloud-based platforms, information wells would leverage technology to ensure data integrity and allow access only to authorized users. Data would be collected and processed to inform risk assessments, a primary reason for STAR.

In essence, STAR would be a network of networks. Figure 1 shows the five main elements of STAR; each element is described in more detail below.

1. TRUSTED PARTNERSHIPS

Trusted partnerships among multiple stakeholder organizations could be formalized with information-sharing agreements that include exchanging agreed-upon types of data and applying common approaches to using it. Options for sharing could include anonymizing the data to protect the business cases of the contractors involved. Trusted partnerships could be facilitated by nondisclosure agreements and through employee contract stipulations.

Since setting up agreements can be time-consuming, we recommend starting with the more straightforward task of ingesting publicly available data into information wells and then assimilating the data that members are willing to share and use. This might include business-sensitive data consistent with vetted stakeholder data access and sharing agreements. Once established, partners would be able to routinely provide data and extract information through automated or manual processes.

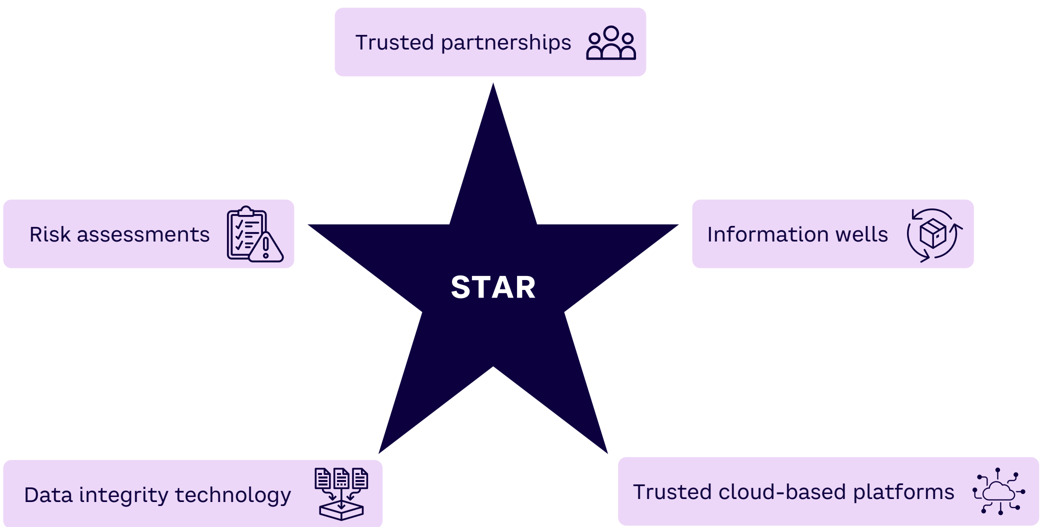

Figure 1. Five elements of STAR

Useful partnership models include the Space Collaboration Council, the NASA Electronic Parts Assurance Group, and the Space Information Sharing and Analysis Center (Space ISAC). Potential STAR sponsors and participants include Space ISAC member organizations.

Other partner-based models include Microsoft's Supply Chain Platform, Amazon Supply Chain, and Google's Supply Chain Twin.[6-8] Microsoft's platform enables organizations to use artificial intelligence, collaboration capability, security protocols, and software-as-a-service applications. Amazon's cloud application unifies data and provides machine learning for insights, collaboration, and demand planning. Google's capability allows organizations to build digital representations of their supply chains.

Another model is Supply-chain Levels for Software Artifacts (SLSA), which is led by a cross-organization, vendor-neutral steering group. SLSA comprises Google, Citibank, VMware, and others, maintaining a checklist of standards and controls to prevent tampering and improve integrity.[9] The Internet Engineering Task Force (IETF) has a working group called Supply Chain Integrity, Transparency, and Trust that creates industry standards for software bills of materials.[10]

The space enterprise can benefit from commercial know-how to help STAR gain maximum insight into the dynamics and risks associated with space supply chains. Once established, STAR would enable participants from supply chain analysts to CIOs to work together more efficiently up and down the chain to facilitate information flow about a specific space mission.

The barriers to building partnerships and information sharing include concerns related to sharing proprietary information and the risk of exposing potentially damaging information. Per the US federal government's 2023 National Cybersecurity Strategy, allies and partners should be included to ensure global supply chains for information and communications technology are secure, reliable, and trustworthy.[11] International partnerships may be constrained by International Traffic in Arms Regulations (ITAR) and other export controls. Therefore, sharing information in a trusted environment is critical. Technologies such as secure cloud-based platforms and distributed ledgers contribute to building and maintaining trust.

The economic benefits to information sharing can outweigh the costs. For example, information sharing is a major lever for increased performance and competitiveness. Sharing information promotes production responsiveness, innovation, codevelopment, and robust risk management. Analyzing data from a single organization limits these advantages. Collaboration promotes coordination and trust between partners that may be geographically, organizationally, and/or informationally distanced. As in the Waze example, the sharing of data between connected tiers or partners can help all parties improve processes and make informed decisions in response to a crisis.

It may seem counterintuitive for an organization to willingly share information that could compromise commercial advantage, but business leaders increasingly understand the degree to which increased performance follows from information sharing.[12]

> **THE SPACE ENTERPRISE CAN BENEFIT FROM COMMERCIAL KNOW-HOW TO HELP STAR GAIN MAXIMUM INSIGHT INTO THE DYNAMICS & RISKS ASSOCIATED WITH SPACE SUPPLY CHAINS**

2. INFORMATION WELLS

Information wells provide secure, traceable, transparent data management environments that promote trust by letting partners leverage a broad array of structured and unstructured data (see Appendix for a list of example data sets). Information wells would provide a holistic view of the supply chain across the space system lifecycle (design, development, distribution, deployment, and operations). Bills of materials and inventory risk report data would enable end-to-end awareness of component availability. Data would inform the search for alternative components when needed, and aggregated data would inform the detection of trends and risks.[13]

3. TRUSTED CLOUD-BASED PLATFORMS

A network of cloud-based platforms would host information wells and enable secure processing of data shared among partners across the space enterprise. Data collected from information wells would be dynamically ingested from multiple providers into the information wells residing on STAR's cloud-based platforms.

Supply chain data would be encrypted into a "hash" that is secured and distributed in a private blockchain. The information would be made available for secure sharing to various levels of user stakeholders and partners based on vetted protocols. Representative commercial cloud platforms include AWS Cloud or Microsoft Azure.

Decision support on availability for a given need at a given time and location would be informed by risk assessments based on calculations using aggregated data on how much of a commodity (e.g., krypton) is needed to meet global demand, coupled with the aggregate quantity of supply.

Eventually, the data in information wells could be analyzed using automated tools. Once these tools are developed, stakeholders would be able to run assessments to pinpoint single points of failure, such as sole-source suppliers that could affect production of multiple space systems.

4. DATA INTEGRITY TECHNOLOGY

STAR's fourth element is data integrity technology, most likely via trust-based partnerships using trusted cloud platforms that leverage trusted private DLT (e.g., blockchain for exchanging information and providing visibility into demand signals).

DLT enables data accountability by authenticating member identity and auditing data consent, access, and sharing. A key benefit of DLT is that data cannot be altered without detection. If one node is hacked, copies can provide verification of data consistency. The addition of data that violates established consistency is rejected, and data from primary sources cannot be altered. Data integrity can be traced to the primary source, where the primary source is verified and authenticated. With the use of robust cybersecurity controls and data encryption with secure sharing protocols, data privacy is protected and the risk of unauthorized access to the data is reduced.

5. RISK ASSESSMENTS

The framework calls for STAR supply chain risk assessments to be enabled by the other four STAR elements. Risk assessments indicate weak areas in space supply chains (business or technical) where malicious actors could disrupt the supply chain via access to hardware, software, or transportation vectors.

Near-real-time data would enable risk assessments of priority items, helping to mitigate uncertainty. When disruptive events occur, information well data could be updated to immediately inform rapid analysis of risks and impacts to space operations, including identifying alternative supplies. For example, although xenon provides the best performance of noble gases for ion thrusters, krypton is an acceptable alternative if a design change is made early enough in the development cycle.

STAR'S 4 RISK ASSESSMENTS

STAR's risk assessment element maps the key risk drivers of availability, cost, quality, and security, as shown in Figure 2 and discussed below. Assessments on these areas (identified through research and interviews with experts) need to be conducted on a rolling window basis, due to the dynamic nature of changes in both demand and supply.

Figure 2. STAR risk assessment elements

The information must be calculated on an ongoing basis to provide decision support in time to course correct for impact to specific supply chain components and consumables. STAR participants would conduct multi-parametric, multi-variant analyses using data provided by partners, stored in information wells, processed in cloud platforms, and secured using data integrity technologies. The following sections describe each of the four correlated risk assessments.

1. AVAILABILITY: GLOBAL PRODUCTION & SUPPLY ASSESSMENT

Global Production and Supply Assessment (GPSA) addresses availability. Using trends data on production levels and distribution channels as key metrics, GPSA analytics would extend beyond traditional availability modeling focused on next-tier components. For example, it could establish the probability of component availability according to specified space enterprise mission timelines. The results would inform decisions on mitigation plans, such as anticipating limitations of xenon gas availability to meet propulsion requirements so that a spacecraft provider can shift to use of krypton for ion thrusters.

2. COST: GLOBAL DEMAND & SPACE SECTOR COST ASSESSMENT

Global Demand and Space Sector Cost Assessment (G/SCA) addresses risk related to cost. G/SCA would assess all market segments to provide insight into differentiation, switching costs, speculation, future roadmaps, and projections. For upstream buyers, this assessment would consider a variety of factors, including price elasticity due to fluctuations in supply and demand over time and viability of market players given the viability of broad market segment. For the space sector, an additional low tier would be added for systems in the context of global demand. G/SCA assessments of space market segmentation identify the effects on demands associated with tailoring requirements for space systems. Requirements include quality assurance, testing, and related characteristics for a specific component to meet demands for space systems.

STAR'S RISK ASSESSMENT ELEMENT MAPS THE KEY RISK DRIVERS OF AVAILABILITY, COST, QUALITY & SECURITY

G/SCA assessments inform confidence in, and risk of sourcing from, trusted producers and providers in the global marketplace. For example, current global xenon production is 10 million liters,[14] of which Ukraine produces 30% or 3 million liters.[15] The space market uses approximately 36% of this global xenon supply or 3.6 million liters.[16] So, if the supply from Ukraine is disrupted, the remaining 7 million liters of xenon of varying grades (not all are appropriate for use as propellent) will be in demand by competing market segments. G/SCA will be useful for highlighting price escalation amid geopolitical conflict.[17]

3. QUALITY: SPACE APPLICATIONS QUALITY ASSESSMENT

Space Applications Quality Assessment (SAQA) addresses risk assessments related to quality. SAQA would assess the degree to which components meet quality standards and specifications for operational needs. The assessment can be reviewed to prevent issues, such as the effects of using subpar gas if xenon/neon quality does not meet space system needs. For example, purification processes for neon, krypton, and xenon gases used in semiconductor manufacturing require a technical threshold, and the Russia/Ukraine conflict has affected Ukraine's ability to deliver it.[18]

4. SECURITY: SUPPLY-SIDE INFORMATION FOR SPACE SYSTEMS SECURITY ASSESSMENT

Supply-Side Information for Space Systems Security Assessment (SSecA) addresses security. SSecA would assess multiple dimensions of security for a specific supply-side product or service. Security challenges include situations where the provider's financials infer limited ability to sustainably provide components for the duration needed or that the company has owners or investors from countries that pose national security concerns. For example, production of xenon and neon was affected by pandemic-related policies in China.[19]

Current risk assessment tools include MITRE's System of Trust Framework,[20] which addresses concerns and risks related to suppliers, supplies, and service providers.

CONCLUSION

As the number of space systems increases, so does competition for the raw materials and components needed to produce them. Supply chain information is important to sustain the production of nationally important space-based missions and services. The US and partner space organizations need information that is current, accurate, and trusted to manage supply chain risks. Recognizing these needs, this article envisions a topology called STAR to shine a light on dynamically evolving risks.

This article is intended to serve as a springboard for community dialogue to establish, build confidence in, and operationalize a STAR solution for the space enterprise. Other sectors, including the automotive and aircraft industries, have complex global supply chains with similar needs, and their experience in supply chain tracking could serve as exemplars for the space sector.

Our vision for STAR includes an approach for trusted, near-real-time risk assessments. These risk assessments can be enabled by harmonizing multiple elements. As described, STAR could be implemented through a coordinated set of community actions, such as building partnerships, pooling data in information wells hosted on cloud platforms, and applying DLT to ensure data integrity.

As the space enterprise begins producing thousands of spacecraft for deployment into low Earth orbit, the time has come to overcome policy, legal, technical, and nontechnical barriers. Secure, sustainable space supply chains are a matter of national security and economy because a chain is only as strong as its weakest link.

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APPENDIX

RISK DRIVER	ASSESSMENT	DATA FACTORS
Availability	GPSA	• Distribution readiness & capacity • Lower-tier components' access • Production readiness & capacity • Raw materials access • Transportation readiness & capacity
Cost	G/SCA	• Buyers • Economic environment • Market disruptors • New entrants • Price elasticity • Price sensitivity • Segment size • Suppliers
Quality	SAQA	• Architectural fit • Interoperability • Reliability • Requirements (operational) • Resiliency • Safety • Scalability • Security • Stability • Supplier capability • Survivability • Sustainability • Workforce availability
Security	SSecA	• Corporate ownership (level of foreign control), governance, management team, business model • Cybersecurity • Due diligence in engaging, selecting & assessing candidate commercial solution providers • Long-term capital, liquidity, solvency, operating efficiency, profitability, financial ratios, trends & intellectual property rights • Physical security • Transportation security

Table 1. Data factors in assessments

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CYBERSECURITY CHALLENGES IN SPACE EXPLORATION

Author

Sylvester Kaczmarek

The importance of cybersecurity in space exploration cannot be overstated. Spacecraft, satellites, and other space-based systems are increasingly dependent on interconnected technologies. These systems, which control aspects of space missions from navigation to life support, are potential targets for cyber threats. The ramifications of a security breach in such environments range from data loss and compromised missions to the endangerment of human life.

Artificial intelligence (AI) integration is essential for the success and safety of missions, but this reliance brings additional cybersecurity challenges. AI offers groundbreaking capabilities in automating complex tasks, analyzing vast amounts of data, and making autonomous decisions based on real-time environmental inputs. However, as AI becomes more sophisticated and autonomous, the risks evolve to include malicious AI behaviors, data integrity issues, and the exploitation of AI systems for unauthorized control or sabotage.

On the flip side, AI can be a powerful tool in enhancing cybersecurity. AI algorithms can be used to continuously monitor satellite networks and spacecraft so anomalies and potential threats can be detected in real time. AI can also aid in predictive analysis, helping identify and mitigate potential vulnerabilities before they are exploited.

Addressing these cybersecurity challenges is essential to protecting valuable space assets, ensuring their longevity, and safeguarding the future of space exploration. This article provides an overview of the cybersecurity landscape in space exploration and looks at the increasing role of AI in space exploration. Developing robust cybersecurity strategies to protect these advanced systems is essential to ensuring that mankind's journey into the final frontier is innovative and secure.

AI INTEGRATION IS ESSENTIAL FOR THE SUCCESS & SAFETY OF MISSIONS, BUT THIS RELIANCE BRINGS ADDITIONAL CYBERSECURITY CHALLENGES

CYBER-THREAT LANDSCAPE IN SPACE EXPLORATION

Space exploration's rapidly evolving cybersecurity landscape includes:

- **Cyber espionage,** which can lead to the loss of sensitive or proprietary technological data, undermining national security and economic interests
- **Sabotage of space infrastructure,** which can result in mission failure, loss of expensive equipment, and endangerment of human life

- **Ransomware and malware attacks,** which can corrupt data, disrupt operations, and cause significant financial losses
- **Increasing involvement of private companies and international collaborations,** introducing new security challenges
- **Cyberattacks** that impact research activities and scientific data integrity, hindering international cooperation in space exploration

SATELLITES ARE INCREASINGLY BEING TARGETED BY BAD ACTORS

It's difficult to determine the frequency of cyberattacks. For one thing, a significant portion of advancements and vulnerabilities in space cybersecurity, especially those tied to military or national security, are classified. Additionally, there is a considerable delay between when a new vulnerability is identified or a defense mechanism is developed and when this information is made publicly available. The delay gives space agencies and cybersecurity professionals time to implement countermeasures before vulnerabilities can be exploited.

Despite these data-access issues, there is no disputing the problem. In 1970, there were 200 operational satellites and one incident. In 2018, there were 2,100 operational satellites and 95 incidents (see Figure 1).[1] Expert predictions vary; the US Government Accountability Office (GAO) estimates there will be an additional 58,000 satellites in orbit by 2030,[2] with an accompanying rise in incidents. Many operators, facing the growing specter of these attacks and the inadequacy of their defenses, choose silence over disclosure. This underreporting not only masks the scale of the issue, it points to widespread unease about existing vulnerabilities in space systems.

SATELLITES UNDER SIEGE: JAMMING, SPOOFING & DATA HIJACKING

Satellites are increasingly being targeted by bad actors using a variety of methods:

- **Jamming.** This was evident in 2014 when a suspected Russian jamming attack disrupted GPS systems in Norway, impacting civil aviation navigation.[3] The incident demonstrated how jamming could lead to significant economic disruptions and pose risks to public safety.
- **Spoofing.** In 2013, a University of Texas at Austin team demonstrated the ability to mislead the navigation system of a yacht by spoofing GPS signals.[4] This kind of attack could lead to misdirected satellites, causing data inaccuracies or space collisions.

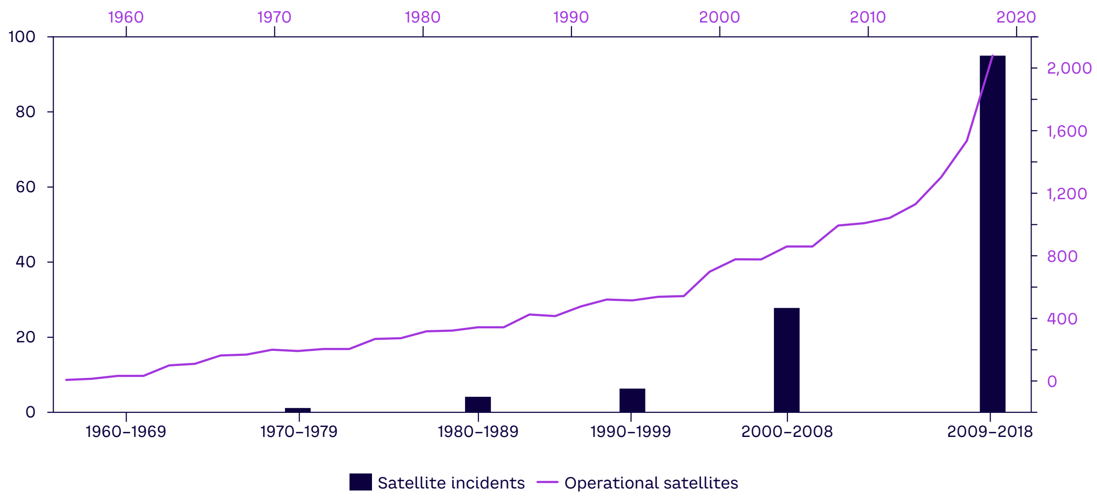

Figure 1. Satellite incidents, 1960–2018 (adapted from Manulis et al.)

- **Data hijacking.** In 1998, hackers assumed control of the US-German-UK ROSAT (short for Röntgensatellit) x-ray satellite and commanded the satellite to point its solar panels directly at the sun, causing irreversible damage. This incident underscored the potentially dire consequences of such attacks.[5]

AI's role in satellite systems magnifies these types of risks. For example, AI-driven navigation systems, if spoofed, could provide false data leading to incorrect satellite positioning. Similarly, data hijacking of AI-driven satellites could compromise the integrity of data analysis and decision-making processes, which are critical to space missions.

Implementing advanced security measures in space systems is challenging due to limited onboard processing power and bandwidth constraints. This necessitates innovative solutions that provide robust security without overwhelming the system's resources. For instance, lightweight cryptographic algorithms are being developed to secure communications without imposing significant computational loads.

SPACECRAFT VULNERABILITIES: HACKING LIFE SUPPORT, NAVIGATION & PROPULSION SYSTEMS

Spacecraft are becoming increasingly susceptible to cyberattacks, posing a significant risk to mission success and astronaut safety:

- **Life support.** If the life support system aboard a manned spacecraft is hacked, it could fail to maintain essential environmental conditions. For example, manipulating oxygen levels or temperature control systems could create life-threatening conditions.
- **Navigation.** A cyberattack on a navigation system could lead to loss of control and direction. Because these systems rely heavily on software and satellite communications, they are vulnerable to attacks that alter their trajectory enough to cause a crash. Such an event would jeopardize the mission and create space debris, creating a risk to other space assets.
- **Propulsion.** The complexity and automation of spacecraft propulsion systems create many entry points for cyberattacks, and compromising these systems could be catastrophic. If hackers alter thrust or direction, the spacecraft will deviate from its intended path and could crash.

GROUND CONTROL SECURITY: SAFEGUARDING GROUND STATIONS & NETWORK COMMUNICATIONS

Ground stations and network communications systems link space assets and their operators. Securing these channels is critical to the operational integrity of space missions:

- **Ground stations.** These are susceptible to both physical and cyber threats. The stations often use standard communications protocols, making them targets for denial-of-service attacks that can disrupt operations, leading to loss of control over space assets.
- **Communications links.** Interference with these links can lead to a loss of communications, leaving spacecraft unable to receive vital commands or transmit data back to Earth. Bad actors can target these links to intercept, manipulate, and/or disrupt the flow of information.
- **Network security.** Any breach in the security of the networks used for space communications can lead to leaks of sensitive information and/or operational disruption. Advanced encryption and secure communications protocols are necessary to protect these networks from unauthorized access.

Addressing the vulnerabilities in spacecraft systems and ground control networks requires combining physical security measures with advanced cybersecurity strategies, including regular software updates, continuous monitoring for anomalies, and robust encryption methods.

THE INSIDER THREAT: HUMAN ERROR & MALICIOUS INTENT IN SPACE SYSTEMS

Insider threats encompass both human error and intentional malicious activities. These risks stem from individuals with authorized access to space missions' critical systems and data.

Simple mistakes by staff, such as system misconfiguration or erroneous command inputs, can have drastic consequences in the highly sensitive environment of space operations. For instance, an incorrect data entry or a misconfigured network setting could compromise the safety of a spacecraft or lead to the loss of critical mission data.

Mitigation requires a combination of stringent security protocols, continuous monitoring, and regular audits of system access and activities. Employee education on cybersecurity best practices and implementing a least-privilege access policy can enhance protection.

SPACE COMMUNICATIONS: KEY VULNERABILITIES IN SATELLITE NETWORKS & SPACECRAFT

Satellite networks and spacecraft form the backbone of space communications systems. Identifying and addressing their vulnerabilities is crucial to ensuring the security and functionality of space missions.

For example, signal interference, whether accidental or deliberate (jamming), can disrupt the transmission of critical data and commands. The onboard systems of satellites and spacecraft (navigation, propulsion, and communications subsystems) are also vulnerable to cyberattacks. These systems might have outdated software or unpatched vulnerabilities that can be exploited.

Inadequate encryption of communications signals makes satellites susceptible to eavesdropping and data manipulation. This poses a significant threat, especially for military and strategic satellites. Ground stations, which control and monitor satellites, can also be attack targets, leading to the loss of control over satellites or corruption of the data being relayed.

Mitigating these vulnerabilities requires frequent updating and patching of onboard systems, employing advanced encryption techniques, and deploying robust cybersecurity measures to secure ground stations.

REAL-WORLD CYBERSECURITY INCIDENTS IN SPACE MISSIONS

Cyberattacks have been a risk for many years and are multifaceted, as the following examples show. They underscore the critical need for robust security measures in the space exploration realm.

NOTPETYA ATTACKED UKRAINIAN INFRASTRUCTURE

The 2017 NotPetya cyberattack, though primarily targeting Ukrainian infrastructure, indirectly affected satellite communications systems and their ground facilities worldwide.[6] The attack exploited vulnerabilities in terrestrial infrastructure and serves as a stark reminder of the interconnected nature of space- and ground-based systems.

The incident illuminated the vulnerability of critical infrastructure, including space-related systems, to widespread cyberattacks. It also underscored the need for the space industry to bolster cybersecurity measures, recognizing the cascading effects that terrestrial cyber threats can have on space operations.

NotPetya's impact extended to satellite companies, possibly through compromised software suppliers, highlighting the intricacies and vulnerabilities within the modern supply chains of the space sector. This aspect of the attack demonstrated the need for rigorous security protocols throughout the supply chain.

SPACEX STARLINK TERMINALS WERE JAMMED IN UKRAINE

In 2022, SpaceX's Starlink satellite communications terminals, supplied to Ukraine during the conflict, experienced targeted jamming attacks.[7] This event marked a significant instance of cyber interference in satellite communications within a geopolitical conflict zone.

The incident underlined the strategic importance and vulnerability of satellite communications systems in modern conflicts. SpaceX's prompt response demonstrated the necessity for agility and resilience in satellite communications networks against evolving cyber threats.

CHINA-BASED HACKERS INFILTRATED SATELLITE & TELECOMS

In a sophisticated campaign in 2017 and 2018, hackers based in China infiltrated satellite operators, defense contractors, and telecoms companies in the US and Southeast Asia.[8] The campaign, identified by Symantec, involved targeting computers used for satellite control and geospatial imaging software.

The focus on operational systems suggests that the attackers aimed to intercept (and possibly alter) communications traffic, which could have led to significant disruptions in consumer and business activities.

The hackers employed a technique known as "living off the land," using legitimate tools and system features to blend malicious activities with normal network operations. Key tools included PsExec, PowerShell, WinSCP, and LogMeIn, along with custom malware like Trojan.Rikamanu for data theft.

GALAXY 15 SATELLITE INTERFERENCE

In 2010, the communications satellite Galaxy 15 (also known as Zombiesat) experienced a malfunction that led it to stop responding to ground commands while continuing to broadcast signals.[9] The incident posed a risk of interference with other satellites' signals, demonstrating potential vulnerabilities in satellite control systems.

TURLA GROUP'S ESPIONAGE CAMPAIGN TARGETED SATELLITE INTERNET USERS

A sophisticated cyber-espionage group known as Turla, reportedly linked to Russia, targeted users of satellite-based Internet connections across the Middle East and Africa in 2015.[10] By hijacking the connections of these users, Turla was able to siphon sensitive information, showcasing a unique approach to cyber espionage using satellite technology.

CAN AI SECURELY PILOT SPACESHIPS & ROBOTS?

AI-driven robots are increasingly being used for tasks like satellite repair, spacecraft maintenance, and planetary-surface exploration. They are also capable of processing vast amounts of data collected during space missions, identifying patterns and insights that would be difficult for human analysts to discern — which is vital for missions that generate large volumes of scientific data. Increasingly, AI systems are being trusted with autonomous spacecraft navigation because of their ability to react faster than humans to changing conditions in space, such as avoiding space debris.

However, there is a risk of system compromise, either through cyberattacks or internal failures. Ensuring the security of AI systems that control critical aspects of spacecraft and robotic missions is paramount. The move toward AI autonomy in piloting spacecraft and robots also raises ethical questions and safety concerns. Establishing robust protocols and fail-safes to prevent unintended consequences is essential.

> **AI SYSTEMS ARE BEING TRUSTED WITH AUTONOMOUS SPACECRAFT NAVIGATION BECAUSE OF THEIR ABILITY TO REACT FASTER THAN HUMANS**

AI'S ROLE IN CISLUNAR EXPLORATION MISSIONS

AI's role in cislunar (between the Earth and the Moon) exploration missions is also increasing. AI can optimize flight paths, manage resources, and ensure mission objectives are met efficiently. On the lunar surface, AI-driven robots can conduct scientific experiments, analyze geological conditions, and even prepare for human habitation. These robots can operate autonomously, carrying out missions in harsh, unpredictable environments.

AI can also manage communications and data relay between the Earth and lunar operations, ensuring a steady flow of information even with the inherent delays in communications over such distances.

MITIGATING AI RISKS

Implementation of advanced encryption is essential to protecting AI-driven space systems from unauthorized access and data breaches. This includes encrypting data both at rest and in transit between space systems and ground stations.

Keeping AI systems up to date with the latest security patches is also vital. Given the remote nature of space missions, developing secure and reliable methods for updating software on spacecraft and satellites is a challenge. Anomaly detection systems can be used to monitor AI-driven space systems in real time, identifying and providing alerts of unusual patterns or behaviors that could indicate a cybersecurity threat.

It is also crucial to maintain a balance between AI autonomy and human oversight to prevent unintended consequences. Before deployment, AI systems should undergo rigorous testing and validation to ensure they perform as expected in the unique conditions of space. This includes testing for vulnerabilities that could be exploited by cyberattacks. Implementing redundancy in critical systems and ensuring that there are fail-safe modes can prevent catastrophic failures. In the event of a system compromise, these measures can maintain basic operational control and prevent total system failure.

Collaboration between agencies, governments, and industry partners is key to developing comprehensive security frameworks. Sharing knowledge and best practices can help create more secure AI systems for space applications. The use of AI in space systems also raises important ethical considerations. Ensuring transparency in how AI systems make decisions and maintaining clear lines of accountability in case of failures or unintended actions are essential.

OUTLOOK & RECOMMENDATIONS

As space exploration evolves, so will the cyber threats it faces. Anticipating and strategizing against these emerging threats is crucial:

- **Future defense strategies** should include advanced threat-detection systems, such as AI-driven predictive models that can anticipate and prevent cyberattacks before they occur.
- **Adaptive security architectures** that can evolve with changing threat landscapes will be essential. This includes creating systems that are both reactive and proactive in their defense mechanisms.
- **Emerging technologies** like quantum computing pose new threats to space cybersecurity. Developing encryption methods resistant to quantum attacks is essential.
- Recognizing and preparing for the possibility of space-based **cyberwarfare** is crucial for national and global security.
- **Effective policies** play a key role. Establishing standardized security protocols across the space industry can create a unified defense strategy. Implementing comprehensive regulatory frameworks can provide guidelines and best practices for securing space assets.
- **International cooperation** must be part of the solution. Developing and adhering to international treaties focused on space cybersecurity can help mitigate the risks of conflicts and attacks. Harmonizing regulations across countries can facilitate a more cohesive approach to securing space assets globally.

CONCLUSION

Propelled by advancements in AI and robotics, space exploration presents a future brimming with possibilities. It also introduces a spectrum of cybersecurity challenges that must be meticulously addressed. Key takeaways from this article emphasize the importance of robust cybersecurity measures in safeguarding space missions:

- **Cybersecurity** must be an integral part of the design and operation of space systems, not an afterthought.
- As cyber threats evolve, so must the **strategies and technologies** we use to combat them. This requires ongoing R&D and adaptation.
- The complexities of space cybersecurity necessitate a **collaborative approach**, involving governments, industry, academia, and international bodies.

The potential cost of cyberattacks on space missions, such as millions of dollars in lost research or catastrophic damage to critical infrastructure, further highlights the urgency of these efforts. Public awareness of these risks and the role of collaborative initiatives in mitigating them are important and should include supporting policies and organizations dedicated to advancing space cybersecurity and creating education programs for those interested in this subfield.

As we navigate the final frontier, the role of AI and robotics in space exploration will continue to grow. Ensuring a secure future in this realm requires:

- **Proactive cyber defense.** Proactive and predictive cybersecurity measures should be implemented to anticipate and counteract emerging threats.
- **Ethical and responsible AI use.** The deployment of AI in space must be done ethically and responsibly, with a clear understanding of potential risks and safeguards.
- **Global cybersecurity standards.** Developing and adhering to global cybersecurity standards and treaties will be crucial in maintaining the security and integrity of space missions.

Specific initiatives such as the collaborative efforts between NASA and international partners for cybersecurity research and the development of global standards for space operations are indicative of the progress being made in this field.

The future of space exploration promises great discoveries and innovations, but it demands vigilance and commitment to securing this new frontier. We must embrace these challenges and work collaboratively to ensure that our journey through space is not only innovative but also secure.

The call to action is clear: support cybersecurity initiatives, advocate for stronger policies, and contribute to the safeguarding of our cosmic endeavors. As we explore the vastness of space, let us do so with the assurance that our path is secured, safeguarding the incredible potential that space exploration holds for humanity.

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THE TRAGEDY OF THE COMMONS IN ORBITAL SPACE

TOWARD A CIRCULAR ECONOMY

Author

Moriba K. Jah

In the vast expanse of our sky, where celestial bodies dance to a delicate choreography, humanity is extending its reach into the final frontier: orbital space. Once perceived as infinite and boundless, this domain has become the stage for a complex interplay of technological advancement, geopolitical saber-rattling, and commercial exploitation. Within the tapestry of this celestial canvas lies a growing concern, one that threatens to unravel the fabric of our collective aspirations: the loss of our ability to use space to our long-term benefit.

Contrary to popular perception, orbital space is not an endless void awaiting our limitless expansion. Instead, it is a meticulously organized realm governed by the laws of physics and social science, where satellites, rocket bodies, and debris traverse specific pathways known as "orbital highways." Just as terrestrial highways accommodate a finite number of vehicles before succumbing to congestion, orbital highways have carrying capacities dictated by (1) the delicate balance of the curvature of space-time we call "gravity" and (2) humanity's need for the robots in the sky we call "satellites."

Several companies are poised to launch and operate tens of thousands of satellites on these orbital highways in the next few years. And the challenge of orbital congestion is not limited to the proliferation of operational satellites. Lurking amidst the celestial highways are tens of thousands of anthropogenic space objects. These remnants of past missions and failed ventures pose a significant threat to active spacecraft and human safety. From spent rocket stages to defunct satellites, orbital debris serves as a grim reminder of humanity's flippant attitude toward orbital stewardship.

In light of these challenges, the notion of a tragedy of the commons in orbital space looms large. Just as the overexploitation of shared resources on Earth has led to depletion and degradation, the unchecked proliferation of satellites and debris in orbital space jeopardizes the long-term sustainability and viability of space exploration and utilization.

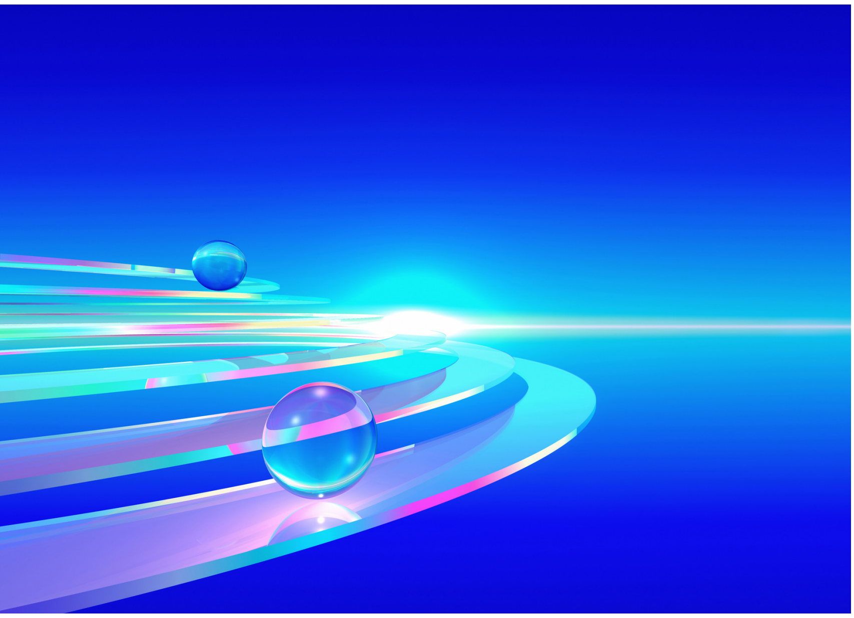
Amid the uncertainty and complexity of the orbital landscape, there's a glimmer of hope: a path forward guided by principles of sustainability, cooperation, and responsible stewardship. This article contends that the transition from a linear space economy, characterized by waste and inefficiency, to a circular one, grounded in the principles of reuse, recycling, and responsible resource management, offers a viable solution to the challenges facing orbital space.[1] This approach is inspired by the tenets of traditional ecological knowledge (TEK) currently residing (but vanishing) in sparse pockets of Indigenous people.[2]

> **CONTRARY TO POPULAR PERCEPTION, ORBITAL SPACE IS NOT AN ENDLESS VOID AWAITING OUR LIMITLESS EXPANSION**

With collaborative effort and collective action, we can ensure that the final frontier is not a battleground of neglect and exploitation but a beacon of hope and inspiration for future generations.

ORBITAL HIGHWAYS: FINITE RESOURCES IN A CROWDED SKY

The term "orbital highways" evokes a sense of order and structure in the vast expanse of space. In reality, they are not infinite expanses but carefully delineated pathways that accommodate the movement of satellites and spacecraft. Just as highways on Earth have limits, orbital highways possess finite carrying capacities.



Among the most coveted of these orbital highways is the geostationary orbit (GEO), situated approximately 36,000 kilometers above the Earth's equator. Renowned for its unique properties of stability and fixed position relative to the Earth's surface, GEO has become a "Goldilocks" destination for communications satellites, weather observation platforms, and Earth-monitoring instruments. This has led to a veritable traffic jam in space, as nations and commercial entities vie for slots.

As the number of GEO satellites rises, propelled by the insatiable demand for global connectivity and telecommunications services, the orbital highway approaches saturation. Already, concerns have been raised about the potential for congestion and collision in GEO, where a single misstep could have catastrophic consequences for the critical infrastructure of our modern society.[3]

Similarly, the low Earth orbit (LEO) represents a bustling thoroughfare teeming with satellites and spacecraft, ranging from scientific probes to commercial ventures. Situated at altitudes ranging from a few hundred to roughly a thousand kilometers above the Earth's surface, LEO is a gateway to a multitude of applications, including Earth observation, navigation, and communications. The proliferation of satellites in LEO has led to concerns about overcrowding and collision risk, particularly with the advent of mega-constellations comprising thousands of interconnected satellites.

The recent proliferation of mega-constellations, such as SpaceX's Starlink and Amazon's Project Kuiper, has raised alarm bells among astronomers and space agencies. Envisioned to provide global broadband Internet coverage, they threaten to saturate LEO with tens of thousands of satellites, transforming the night sky into a veritable minefield of bright streaks and glimmers. Moreover, their deployment poses significant challenges for space traffic management and collision avoidance, as the sheer volume of objects in LEO exceeds the capacity of tracking and monitoring systems in the absence of a global space traffic coordination and management system.[4]

Beyond immediate concerns about congestion and collision, the proliferation of satellites and spacecraft in orbital space has broader implications for long-term sustainability and viability. Each satellite in orbit represents not only an investment of resources but also a commitment to maintaining and operating that asset for its intended lifespan. However, as orbital highways become more congested, the risk of collisions grows, threatening the continued operation of active satellites and the safety of future space missions.

Just as terrestrial highways require traffic regulations and infrastructure investments to ensure safe and efficient movement, orbital highways require international cooperation and coordination to prevent a tragedy of the commons and preserve the sanctity of space for future generations.

> **THE "DARK & QUIET SKIES" MOVEMENT IS GAINING MOMENTUM AS IT ADVOCATES FOR THE PRESERVATION OF PRISTINE NIGHT SKIES**

TRACKING THE TRACES: A SKY FILLED WITH DEBRIS

As humanity explores the use of orbital space, the legacy of our endeavors manifests in both the satellites and spacecraft that grace the heavens and the debris littering the celestial highways. It serves as a stark reminder of our collective impact on orbital space and the consequences of our actions.

More than 50,000 anthropogenic space objects populate the skies, each a testament to humanity's ingenuity and ambition. Only a fraction serves operational roles, fulfilling critical functions such as communications, navigation, and scientific research; the remainder drifts aimlessly through orbital space, posing a risk to human life as spacecraft attempt to navigate through them. Among these objects are satellites no longer in use, their once-shining surfaces now reflecting sunlight. This is a significant challenge for astronomers, whose quest to unravel the mysteries of the universe relies on clear, unobstructed views of the heavens.

For Indigenous peoples and others with cultural ties to the sky, the proliferation of satellites and debris represents a desecration of sacred space — a violation of the natural order and a disruption of ancestral traditions. As the night sky becomes cluttered with artificial objects, the voices of those who hold reverence for the heavens grow fainter, drowned out by the cacophony of human endeavor.

Not surprisingly, the "Dark & Quiet Skies" movement is gaining momentum as it advocates for the preservation of pristine night skies free from the intrusion of artificial light and space debris.[5] Recognizing the importance of preserving the cultural and scientific value of the night sky, the United Nations (UN) has begun to consider Dark & Quiet Skies as a crucial aspect of space sustainability, incorporating it into discussions and initiatives aimed at mitigating the impact of human activity on orbital space.

Efforts to track and monitor space debris, which is born of past missions and failed ventures, have thus become paramount, with space agencies and organizations around the world working tirelessly to catalog the growing population of objects in orbit. Ground-based radar systems, optical telescopes, and space-based sensors provide crucial data on the location, trajectory, and characteristics of debris, enabling operators to predict potential collisions and maneuver spacecraft out of harm's way. Privateer's Wayfinder is a publicly available tool that provides multisourced evidence of our orbital clutter.[6]

Initiatives such as Space-Track and the European Space Agency's Space Debris Office are vital in coordinating international efforts to track and mitigate the threat of space debris.[7,8] By sharing data and collaborating on R&D, these organizations seek to reduce collision risk and preserve the long-term sustainability of orbital space.

Space debris poses a threat to the safety of future generations. Only through concerted international cooperation and innovation can we hope to address these challenges and preserve the sanctity of space, ensuring that the voices of astronomers and those with cultural and spiritual relationships to the sky are heard and respected.

THE VOICES OF OUR INDIGENOUS PEOPLE CAN GUIDE US

The tenets of TEK offer valuable insights and principles that can inform our approach to holistically managing and caring for orbital space. Rooted in the wisdom and practices of Indigenous cultures and communities, TEK emphasizes interconnectedness, sustainability, and respect for the natural world. By applying these principles to our interactions with orbital space, we can develop a holistic, sustainable approach to space exploration and utilization.

One key tenet of TEK is the recognition of the interconnectedness of all life and systems. In the context of orbital space, this involves understanding the complex interactions between satellites, spacecraft, space debris, and the broader celestial environment. Rather than viewing orbital space as a collection of isolated objects and resources, we must recognize it as a dynamic ecosystem in which changes to one part of the system can have far-reaching impacts on the whole. By adopting a holistic perspective, we can better anticipate and mitigate the unintended consequences of our actions in space.

Another core principle of TEK is the importance of sustainability and long-term stewardship. Traditional societies have thrived for generations by carefully managing their natural resources and ecosystems, ensuring they remain healthy and productive. In orbital space, we must adopt practices and policies that promote the sustainable use of resources and minimize our environmental impact. This includes designing satellites and spacecraft for longevity and reusability, implementing measures to mitigate space debris, and developing technologies for in-orbit recycling and resource utilization.

TEK also emphasizes the importance of respect and reciprocity in our relationships with the natural world. Indigenous communities often view themselves as stewards of the land, with a responsibility to care for and protect the environment. In the context of orbital space, this means a greater sense of accountability among space-faring nations and commercial entities. We must recognize that orbital space is a shared resource, belonging to all humanity and future generations, and act accordingly to preserve and protect it for the benefit of all.

TEK highlights the importance of community-based decision-making and collaboration. Indigenous societies have long relied on collective wisdom and consensus-building to address complex environmental challenges and sustainably manage natural resources. In orbital space, we must foster international cooperation and collaboration to address the shared challenges and risks facing the space environment, another finite resource.

By working together, sharing knowledge and resources, and respecting diverse perspectives and values, we can develop effective, equitable solutions to manage and care for orbital space.

FROM LINEAR TO CIRCULAR: A BLUEPRINT FOR SPACE SUSTAINABILITY

As humanity's footprint in orbital space expands, so does the recognition that our linear approach to space utilization poses significant risks, including the threat of orbital ecocide. The prevailing model, characterized by the launch of single-use satellites and the proliferation of space debris, resembles a one-way trajectory toward congestion, conflict, and potentially irreversible environmental degradation. To avoid this, we must transition from a linear space economy to a circular one that is grounded in principles of sustainability, stewardship, and innovation and inspired by TEK.[9]

At the core of the circular space economy lies the concept of resource efficiency and reuse. Rather than treating satellites and spacecraft as disposable entities to abandon, we must design them for longevity and reusability. Modular designs, standardized interfaces, and in-space servicing, assembly, and manufacturing (ISAM) capabilities can prolong the lifespan of existing assets, reducing the need for costly replacements and mitigating space debris proliferation.[10]

Embracing ISAM and resource use holds promise for transforming orbital space into a self-sustaining ecosystem. By tapping into the abundant resources available in space, such as solar energy and asteroid materials, we can reduce our dependence on Earth-bound supplies and pave the way for an independent and sustainable space economy. 3D printing (or additive manufacturing), for example, can facilitate the construction of large-scale structures and habitats in orbit, and technologies for extracting and refining asteroid resources offer a glimpse of a future where humanity thrives harmoniously with the environment.

The transition to a circular space economy also demands a reevaluation of space governance and regulation. Current regulations focus primarily on safety and security; a circular economy mindset requires a broader approach that prioritizes sustainability, equity, and inclusivity. International agreements and treaties must be updated to incent responsible behavior and discourage negligence. Mechanisms for space debris mitigation and remediation must be strengthened, with an emphasis on active debris removal and end-of-life disposal protocols.

Simultaneously, efforts to foster innovation and entrepreneurship in the space sector must intensify. Governments, academia, and industry should collaborate to develop and commercialize cutting-edge technologies for sustainable space exploration and utilization. Public-private partnerships offer valuable opportunities for investment and collaboration, driving the development of new capabilities and business models that support a circular space economy.

Transitioning from a linear to a circular space economy is not just about sustainability — it's about preventing orbital ecocide and ensuring the long-term viability of orbital space as a resource and habitat. By embracing resource efficiency, reuse, and innovation, we can safeguard the celestial environment and preserve the final frontier for future generations. Through collective action and a shared commitment to stewardship, we can navigate toward a brighter future where space remains a sanctuary for exploration, discovery, and human progress.

CONCLUSION

The journey through the universe, both figuratively and literally, has brought humanity to a pivotal crossroads. Our exploration and use of orbital space have unlocked unprecedented opportunities for scientific discovery, technological innovation, and economic growth. But as our presence in space expands, so do the challenges and risks that accompany it. The current trajectory, characterized by a linear space economy and unchecked exploitation of orbital resources, threatens to push us toward a tragedy of the commons in which the collective pursuit of self-interest leads to the depletion and degradation of a shared resource.

The transition from a linear to a circular space economy offers a blueprint for addressing the pressing challenges facing orbital space. By embracing principles of resource efficiency, reuse, and innovation, we can transform orbital space into a vibrant ecosystem where human activity coexists with the natural rhythms of the universe.

This transition requires bold leadership, innovative technologies, and a willingness to challenge the status quo. It demands collaboration, cooperation, and collective action from governments, industry stakeholders, and the global community. Fortunately, momentum is building, with initiatives such as the Dark & Quiet Skies movement and the UN's consideration of space sustainability highlighting the need to preserve orbital space for scientific, cultural, and environmental reasons.

As we navigate toward a circular space economy, we must be mindful of the interconnectedness of all life on Earth and in the cosmos. Just as terrestrial ecosystems rely on delicate balances and feedback loops to thrive, orbital space requires careful stewardship and management to avoid irreversible harm. By working together, we can build a future where space remains a sanctuary for exploration, discovery, and human progress.

The stars above serve as our guideposts on this journey, reminding us of the boundless potential that lies beyond the confines of our planet. Through collaboration, determination, and a shared commitment to sustainability, we can chart a course toward a future in which the stars shine bright, the skies remain dark and quiet, and the promise of the cosmos beckons us onward.

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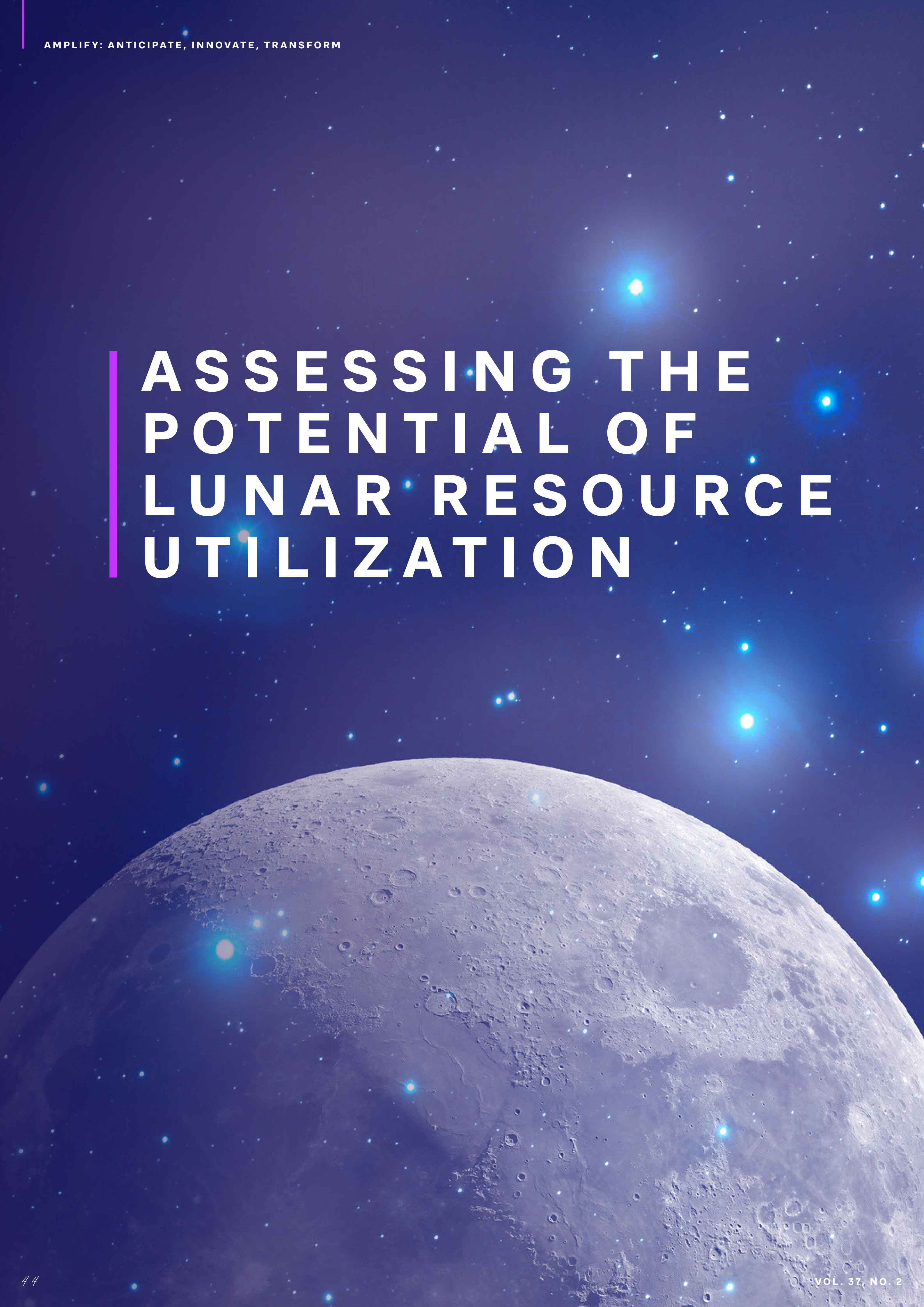
ASSESSING THE POTENTIAL OF LUNAR RESOURCE UTILIZATION



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with contribution from members of the EURO2MOON Market & Business Working Group, especially Carlos Espejel (ispace), Bertrand Baratte (Air Liquide), and Pierre-Alexis Joumel (Airbus Defence & Space)

It's not unthinkable that the headlines of 2050 could be reporting on a dynamic new economy on the Moon, with human settlers, incipient manufacturing facilities, growing transport infrastructure, and booming tourism. Or else it could be just written off as an eternal desert, far from Earth with only scientific — or military — value. Today, the jury is still out on how things will unfold.

Until recently, Moon exploration has been mainly the preserve of state-funded science. However, as the possibility of developing a future lunar economy — a self-sustaining and sustainable lunar ecosystem — starts to be taken more seriously, private investors beyond the narrow "space industry bubble" are beginning to show interest. For example, Japanese company ispace launched its HAKUTO-R M1 lunar-landing mission in 2022. Last year, well-known toymaker Tomy contributed to a lander successfully deployed from a governmental JAXA (Japan Aerospace Exploration Agency) lunar mission. More recently, US space companies Astrobotic Technology and Intuitive Machines both launched their missions to the Moon, albeit with mixed results.

Lunar economic development would require very high levels of capital investment over several decades and would reach far beyond the traditional scope of the space industry, involving sectors such as mining, telecommunications, manufacturing, farming, and others. Despite the major technical, financial, political, and even ethical issues still to be resolved, there could be great potential in growing a sustainable, peaceful, lunar economy.

Based on a recent study conducted by Arthur D. Little (ADL) with partners from Europe's leading lunar industry association, EURO2MOON, this article briefly explores the business potential of developing lunar resources. At this embryonic stage, the aim is not to provide definitive answers but rather to increase understanding of underlying demand drivers, possible value chains, and areas of uncertainty. To illustrate the issues, we focus on one of the most important potential lunar markets: propellant production. Reaction engines using propellants will be key for powering vehicles, both for operations on the lunar surface and for space travel to and from Earth and the solar system.

The study followed a well-established six-step process:

1. **Supply side.** Summarize the potentially available lunar resources.
2. **Demand side.** Identify and model the drivers for demand, including assessing impact and uncertainty.
3. **Scenarios.** Develop potential scenarios to help visualize the future ecosystem.
4. **Value chain.** Propose a likely value chain structure for propellant production.
5. **Use cases.** Outline the highest-priority use cases for each scenario.
6. **Demand projection.** Estimate the likely ranges of propellant demand for these use cases.

This article is derived from a much more detailed scientific paper presented by EURO2MOON at the *2023 Aerospace Europe Conference.*[1]

AVAILABLE RESOURCES ON THE MOON

Based on current scientific knowledge, which is still limited in extent, the Moon may be rich in resources that hold great potential for permanent settlement and commercial utilization. These include, among others, oxygen, hydrogen, aluminum, magnesium, and potentially water ice. The presence of potential water ice is perhaps surprising for nonexperts, but there is evidence to suggest it could exist in significant quantities at the Moon's poles. As well as its value in supporting human life and numerous other manufacturing applications, it can be used to generate oxygen and hydrogen for propellant production. Indeed, many of the other minerals present on the Moon may also be used for propellant production.

As well as these so-called material resources, the Moon also provides valuable "immaterial" resources, which are also a key benefit for certain potential use cases. These include: low gravity (or microgravity), which is useful for the production of certain high-quality materials; abundant solar energy for power generation; extensive land for building equipment and real estate; and hard vacuum/low temperatures, which are valuable for running cryogenic and superconducting processes.

As such, propellant production is seen as a major application for in-situ resource utilization (ISRU). By harnessing local resources, ISRU can potentially reduce the reliance on Earth for propellant resupply. This can significantly enhance the sustainability and cost-effectiveness of space missions, as well as enable long-duration space exploration and sustainable presence in space. ISRU takes advantage of the lower gravity of the Moon to achieve greater operational efficiencies and to reach other orbits with less energy than Earth. ISRU has the potential to reinvent how we think about space missions and transportation in space, even in Earth orbit.

KEY DRIVERS FOR DEMAND IN LUNAR ECONOMY

To model the drivers for economic demand in the lunar economy, a top-down approach was taken, starting with identifying the range of likely end goals. As shown in Figure 1, five generic end goals were identified (scientific exploration, resource utilization, manufacturing, construction, and tourism) together with several support activities (transportation, positioning/navigating/timing [PNT] and observation, in-orbit services, and security). The achievement of each end goal will be determined by a range of different drivers. For example, achieving the goal of lunar manufacturing would be driven by human presence, positive economic interest, and the development of the necessary technology.

For propellant production, we are primarily interested in the resource utilization end goal. Our analysis for achievement of this goal identified seven macro-level drivers as being key, shown in the dark blue boxes in Figure 2.

Each of these seven drivers has different relative levels of uncertainty and impact on the achievement of propellant production. For example, having a "high cost of transportation to/from Earth" is fairly likely, and its impact on the extent of lunar resource extraction is also high.

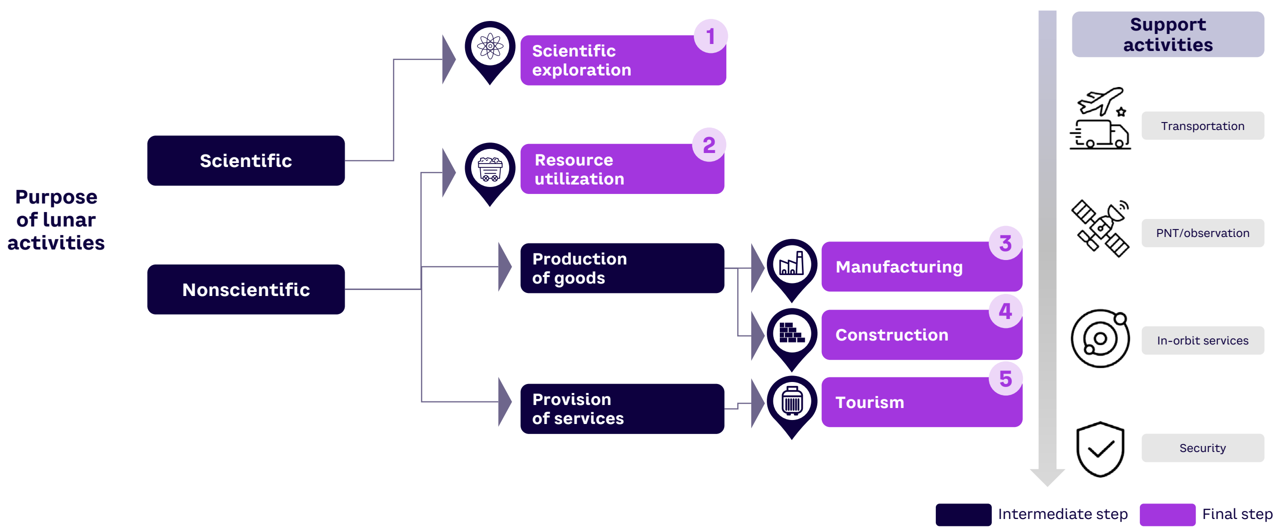

Figure 1. Five end goals driving lunar economic demand (source: Arthur D. Little)

Figure 3 shows the ranking of all these drivers based on the two axes of impact and uncertainty. As shown in the figure, human presence, availability of lunar energy, and quantity of available resources are the three macro-drivers that emerge with the combination of highest impact/highest uncertainty:

1. **Human presence.** Human presence on the Moon significantly impacts the scale and scope of all lunar activities. However, the timeline, required investment, and necessary international cooperation for establishing a sustained human presence on the Moon are all highly uncertain.
2. **Availability of lunar energy.** Beyond solar power, other energy sources such as nuclear energy will be crucial to produce the power required by other activities (e.g., mining) with a reasonable logistic footprint. However, whether these will become available, and their maturity and extent, are uncertain.
3. **Quantity of available resources.** Although there is scientific evidence of the existence of lunar resources, as described above, there is still high uncertainty around its extent, distribution, quality, quantity, and accessibility.

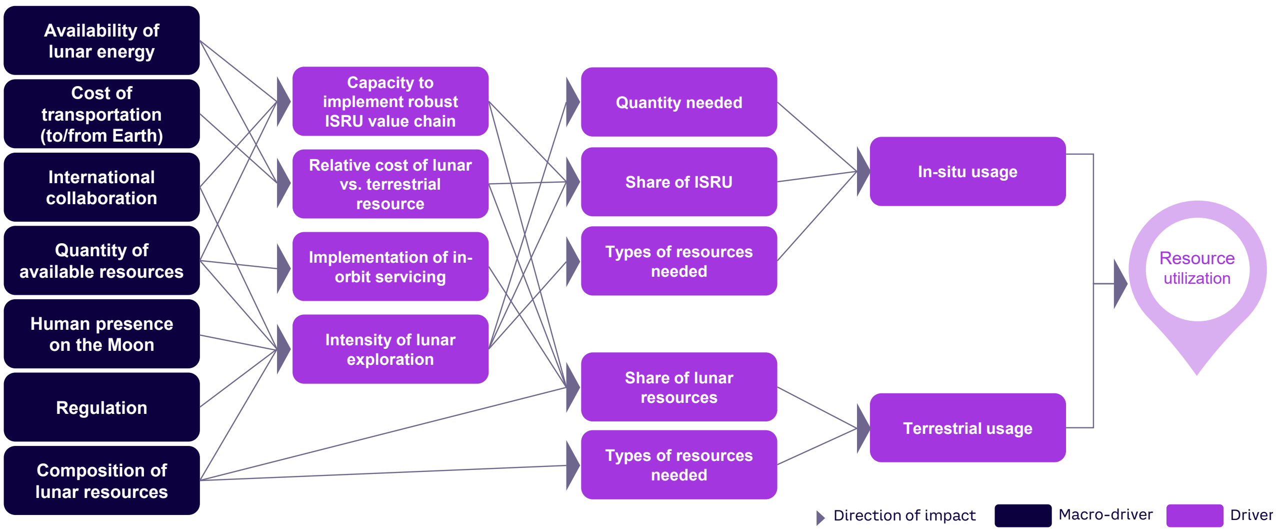

Figure 2. Seven drivers for achieving the end goal of resource utilization (source: Arthur D. Little)

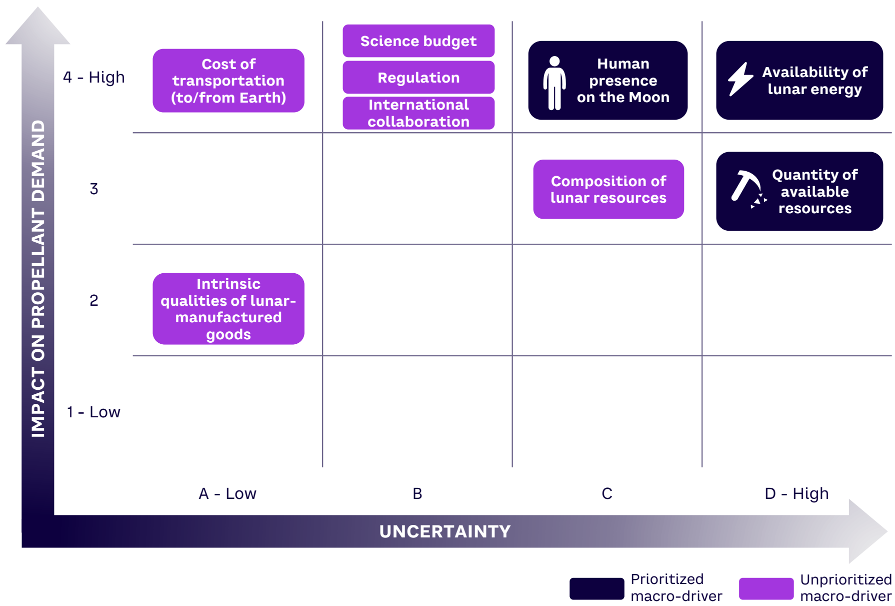

Figure 3. Prioritization of macro-drivers (source: Arthur D. Little, EURO2MOON)

5 SCENARIOS FOR FUTURE LUNAR DEVELOPMENT

The most useful future scenarios to consider for the broadest coverage are those that result from different combinations of the above three high-impact/high-uncertainty drivers. Those drivers with low uncertainty will need to be addressed in all possible futures, while those drivers with low impact are relatively less important. Five plausible scenarios emerged from the analysis (see Figure 4).

The first scenario, the *Prosperous Frontier*, is the most optimistic, with abundant energy, abundant resources for utilization, long-term habitation, and commercial trips between the Moon and Earth. In the *Thriving Amidst Scarcity* scenario, the lack of material resources restricts broader economic development, but there is still a human base supporting dynamic scientific and tourism activities. By contrast, the *Resource-Rich Wilderness* scenario envisages little, if any, permanent human settlement due to lack of energy, with activities restricted to selective utilization of rare available resources and targeting of scientific missions. *The Dawn of Lunar Energy* scenario similarly envisages restricted development, based on costly terrestrial resources. Finally, the *Desolate Horizon* scenario represents largely the current situation, with no further economic development and only occasional scientific missions.

It is immediately clear from the five scenarios that there is a huge variation in possible futures for lunar resource utilization. Nevertheless, understanding the drivers for these futures can help businesses better anticipate the implications of relevant events as they unfold over time.

WHAT WOULD A LUNAR PROPELLANT VALUE CHAIN LOOK LIKE?

To help us assess the demand for lunar propellant across different scenarios, it is necessary first to model a preliminary propellant value chain. As shown in Figure 5,[2-4] there are six main steps, beginning with resource exploration and moving through construction, extraction, processing and refinement, storage and liquefaction, and transportation.

Each of these steps would need its own enabling technologies (also shown in the figure). While some of these, such as transportation using rovers, have already been deployed on the Moon, others, such as microwave heating for lunar regolith processing, are still in the applied research and experimental development stages.

Scenario	PROSPEROUS FRONTIER	THRIVING AMIDST SCARCITY	RESOURCE-RICH WILDERNESS	THE DAWN OF LUNAR ENERGY	DESOLATE HORIZON
Drivers: Human presence on the Moon	✓	✓	✗	✗	✗
Drivers: Availability of lunar energy	✓	✓	✗	✓	✗
Drivers: Quantity of available resources	✓	✗	✓	✗	✗
Associated activities	• Abundant energy for resource utilization, manufacturing & construction for sustainable settlement • Energy supports in-situ needs & commercial transportation • Thriving lunar tourism industry • The Moon becomes a refueling station for deep space exploration, reducing dependence on Earth	• Abundant energy for life support, manufacturing, or construction with terrestrial resources • Science exploration & tourism in a life base • Supercomputing, energy storage & electrical power for vehicles or for life support	• Limited resource utilization, as there is no energy to extract it • Limited automated manufacturing or construction activities • Few scientific missions with no habitation • Utilization of rare or intrinsic-quality resources	• Supercomputing, energy storage & electrical power for vehicles or for life support • Limited automated construction for in-situ needs with terrestrial resources • Limited scientific missions with no habitation	• Business as usual • Only a few scientific missions with no long-term habitation

Human presence on the Moon · Availability of lunar energy · Quantity of available resources

Note: Three other scenarios have been built but are inconsistent.

Figure 4. Five plausible scenarios for lunar resource extraction (source: Arthur D. Little)

It is beyond reasonable doubt that this type of value chain would need to involve an ecosystem of players in different value chain positions. Understanding ecosystem roles and helping to enable ecosystem development will be important for any prospective investor or entrepreneur. One key consideration affecting attractiveness will be the extent to which innovative technologies developed for the lunar environment could be redeployed to advantage on Earth.

USE CASES FOR LUNAR PROPELLANT

The next step in the analysis was to identify and map the various use cases for lunar propellant. Using a range of sources, including EURO2MOON and ADL experts, 16 vehicle types were identified across a range of energy sources. These were classified in terms of how much power they needed and the duration of their use to fulfill their typical mission (see Figure 6).[5-7]

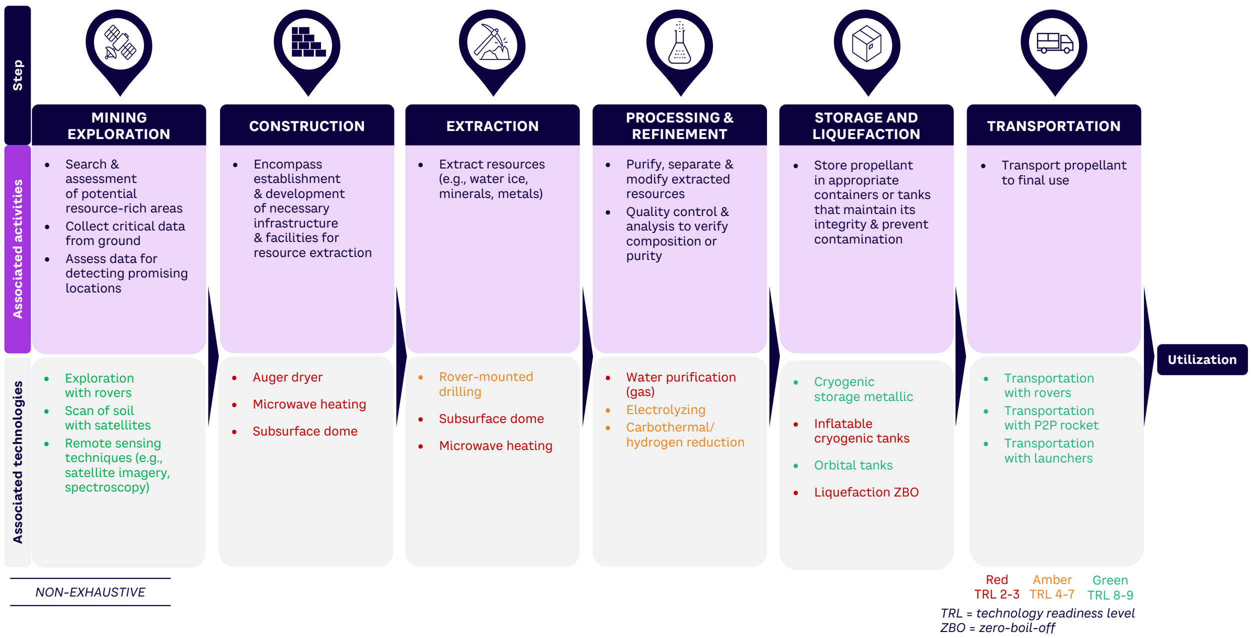

Figure 5. Preliminary, non-exhaustive lunar propellent value chain (source: Arthur D. Little, Kornuta et al., Sutton et al., Weston)

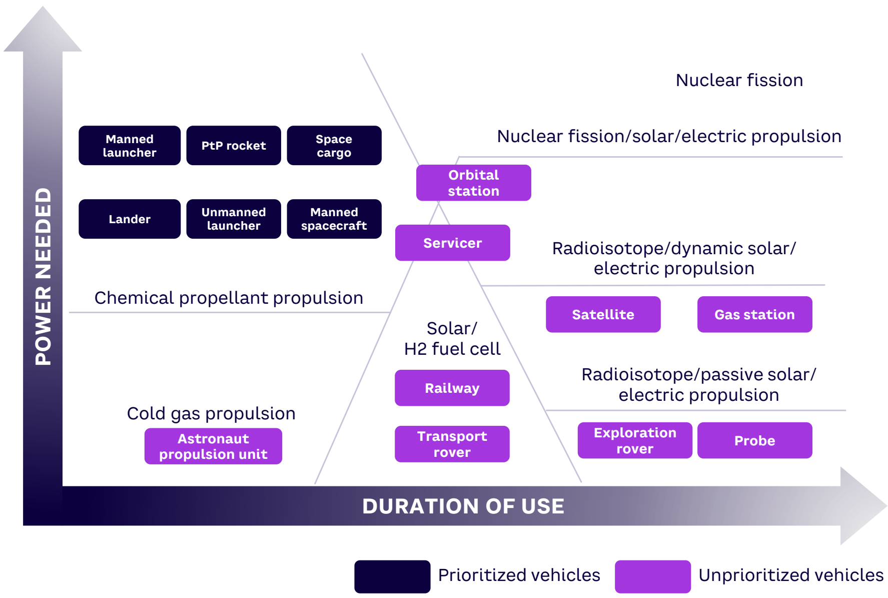

Figure 6. Vehicle types mapped by power needed and duration of use (source: Arthur D. Little, Kornuta et al., Metzger, Green/Kleinhenz)

Given that oxygen is the most abundant and available resource, we decided to focus on chemical propellant propulsion in order to make a projection of the range of likely propellant demand across the different scenarios. In Figure 6, these are the six use cases in the top-left of the matrix. They include:

1. **Manned launchers** — specifically designed to transport astronauts from the Moon to space
2. **Point-to-point (PtP) rockets** — designed to transport passengers or payloads efficiently and rapidly between different locations on the Moon's surface
3. **Space cargo** — the transportation of goods and supplies from space (orbit) to Earth, Mars, or farther in space
4. **Landers** — spacecraft designed to transport passengers or payloads from orbit to surface
5. **Unmanned launchers** — space vehicles designed to deliver payloads into space from Moon without the presence of human operators or crew onboard
6. **Manned spacecraft** — specialized vehicles designed to transport astronauts from space (orbit) to Earth, Mars, or farther

PROJECTED PROPELLANT DEMAND

The final step in the analysis was developing a projection for propellant demand (in this case, oxygen). This was done by summing the individual demands from each of the six use cases and making adjustments for each of the other scenarios. Starting with the most optimistic *Prosperous Frontier* scenario, assumptions were made about the number of missions (e.g., ones related to the number of satellite launches from the Moon, tourist loadings, Mars missions, number of bases) and the oxygen consumption per mission. Together, this yielded an estimate of the total oxygen demand. For the other four scenarios, adjustments were made to each of the assumptions based on the nature of the scenario. (Full details of the calculation methodology can be found in "A Prospective Market & Business Perspective on Lunar ISRU for Propellant Applications."[8]

Figure 7 shows the results of the calculations. As illustrated, the projected oxygen demand varies hugely from over 40 kt/year in the *Prosperous Frontier* scenario to a very small number in *The Dawn of Lunar Energy* scenario. This is perhaps to be expected, given the current high levels of uncertainty surrounding the future of lunar exploration and development.

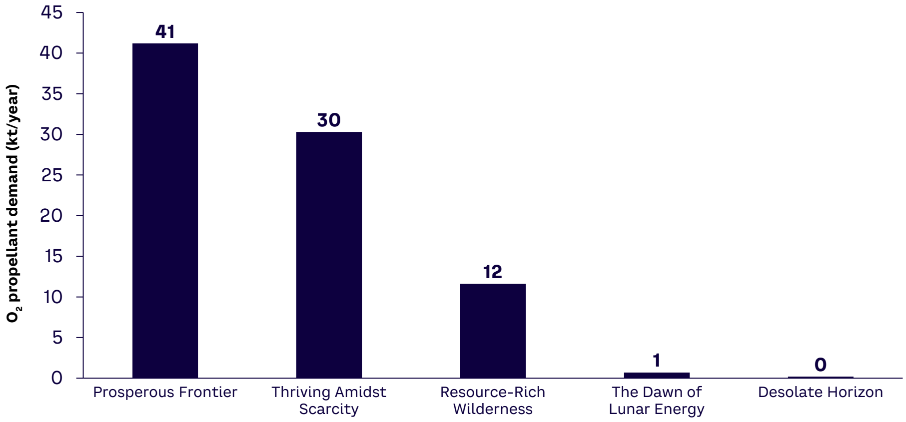

Figure 7. Projected 2050 time horizon oxygen demand for different scenarios (source: Arthur D. Little)

CONCLUSIONS & KEY TAKEAWAYS

Ultimately, the projected value of oxygen propellant demand is only of secondary interest. More valuable is that the study demonstrated a systematic, thorough, and transparent way of dealing with the future potential of lunar development, in a situation where there are still large uncertainties.

The main challenge for businesses seeking to invest in the future lunar economy is basing their business cases on reliable long-term market forecasts in a nascent ecosystem. Identifying the main drivers of the lunar ecosystem and their main divergence points allows stakeholders to better account for the high levels of uncertainty.

This approach also helps build a comprehensive, high-level vision of the future ecosystem and the associated value chains. Once businesses have built such a vision, they are better able to keep the main underlying drivers under watch and refine their vision as their level of uncertainty reduces. This helps them gain early insights into how different factors will affect different parts of the value chain, resulting in different outcomes. It also shows more clearly which factors are less scenario-dependent than others — in other words, factors that could be addressed by "no regret" actions.

Finally, the study confirms that building a sustainable, peaceful lunar economy is going to be heavily dependent on strong international collaboration; robust principles around key issues such as sustainability, security, and ethics; and bold decision-making by public space agencies and businesses working in partnership. If this can be achieved, the benefits could be huge.

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EURO2MOON is an industry association geared toward leveraging lunar resources to foster European leadership and collaboration in benefit of sustainability, both in space and on Earth. The association's vision is to position the European industry as a key contributor to the rising cislunar economy by creating a strong industrial ecosystem and developing an ambitious and sustainable in-situ resource utilization vision and implementation plan. Current members include space and non-space companies and research institutes, including Airbus Defence & Space, Air Liquide, ANRT, Arthur D. Little, CEA, ESRIC, ispace, OffWorld, OHB, Spartan Space, and Yokogawa.

3D PRINTING & THE FUTURE OF SPACE EXPLORATION

Author

Curt Hall

3D printing technology, also called "additive manufacturing," is designed to create physical objects from digital models by depositing layers of material (e.g., polymer resins, plastic, rubber, metal) on top of each other. Advancements in 3D printing have made it possible to rapidly manufacture parts and equipment for spacecraft and space infrastructure, helping to reduce spacecraft R&D and manufacturing costs on Earth.

Efforts are underway to advance 3D printing to support in-space manufacturing, a capability that will become increasingly important for the future of space travel because it will (1) reduce the need for costly, resource-intensive resupply missions to space stations and other off-world bases and (2) lead to the establishment of space-based manufacturing platforms (in-orbit, on the Moon, and on planets like Mars).

3D printing is also important to space exploration because of its ability to support reusability and sustainability efforts. This article examines the various uses of 3D printing in the space industry and its role in the future exploration of the cosmos, especially for long-duration missions.

3D PRINTING ON EARTH

Currently, the biggest use of 3D printing in the space industry is Earth-based manufacturing of spacecraft parts. The benefits from 3D printing include accelerated development (from prototype to manufactured component), reduced weight and part count, reduced complexity of parts, and lower development and manufacturing costs. National space agencies and commercial enterprises are using the technology in a range of applications.

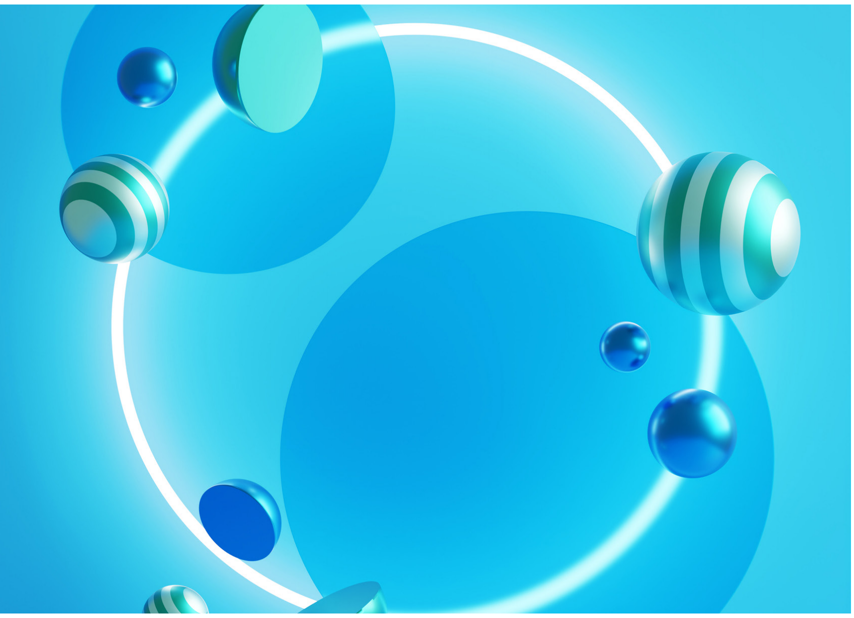
For example, SpaceX uses 3D printing to produce parts for its Falcon 9, Dragon, and Starship spacecraft. This includes engine chambers, injectors, nozzles, heat shields (for rocket boosters), and various spacecraft docking and cargo components.

Blue Origin pioneered the use of 3D printing in the space industry and uses the technology to manufacture engines and other parts for its New Shepard and New Glenn rockets. Blue Origin reportedly used 3D printing to speed the design of its BE-4 rocket engine, which uses liquefied natural gas. This allowed the company to replace parts that previously took a year or more to manufacture with 3D-printed parts that took only a few months to make.[1]

EFFORTS ARE UNDERWAY TO ADVANCE 3D PRINTING TO SUPPORT IN-SPACE MANUFACTURING, A CAPABILITY THAT WILL BECOME INCREASINGLY IMPORTANT FOR THE FUTURE OF SPACE

The European Space Agency (ESA) has used 3D printing to manufacture pure copper electromagnetic coils, which are important for electric motors and space operations, including satellite attitude control. The coils, produced using laser powder bed fusion 3D printing technology, demonstrate that this technology can support complex designs while increasing production efficiency.[2]

Some companies, including Relativity Space, seek to manufacture entire rockets and spacecraft using 3D printing. The company reportedly operates the world's largest 3D metal printer, which allows it to manufacture rockets faster and with fewer parts than other processes. For example, Relativity's Terran R is a medium-to-heavy lift rocket designed for rapid development and reusability. Current versions are built with aluminum alloys using a hybrid manufacturing approach. Eventually, the company hopes to build most of the rocket using 3D printing and is actively working to develop the necessary technology.



NASA engineers and academic researchers are 3D printing electronic components and circuits for space applications. An experiment conducted in April 2023 tested printed electronic circuits that were launched on a rocket that reached the edge of space.[3] The test involved humidity and electronic sensors that were 3D printed directly onto two attached panels and the payload door of the rocket, with the sensors transmitting data to ground control during the flight.

Printing sensors directly where required allows more efficient utilization of available surfaces within a spacecraft.[4] NASA is interested in advancing the technology to support 3D printing of electronics circuits and components in zero-gravity environments.

3D PRINTING IN SPACE

3D printing in space is an experimental technology that holds vast potential for revolutionizing space exploration by enabling astronauts to manufacture spare parts, tools, key components, and building materials on demand. It is also of significant interest to companies looking to establish in-space manufacturing facilities that could take advantage of the zero-gravity and vacuum environment of space for researching and manufacturing goods that cannot be manufactured on Earth.

3D PRINTING PLASTIC IN SPACE

NASA has been experimenting with 3D printing on the International Space Station (ISS) since 2014, collaborating with other space agencies, universities, and private companies like Redwire. This includes printing tools such as wrenches and ratchets and spacecraft parts like radiation shields. In these applications, the 3D printer (developed by Made In Space) is about the size of a desktop printer. It uses a fused filament fabrication process that feeds a continuous thread of plastic through a heated extruder onto a tray layer by layer to create a three-dimensional object.[5]

This and subsequent experiments were deemed successful because they indicated that microgravity had no significant engineering effect on the process, demonstrating that a 3D printer can function in space. This opens up the possibility that in-space 3D printing could not only help with the logistics of resupplying space stations in low Earth orbit (LEO), it could also prove useful for supporting long-distance space missions and the establishment of a permanent presence of the Moon and Mars.[6] Tests of various 3D printing techniques are continuing on the ISS.

3D PRINTING METAL IN SPACE

In February 2024, ESA delivered equipment to the ISS to test the feasibility of 3D printing small metal parts in space.[7] The goals of this project are to:

1. Understand how a metal 3D printer behaves in zero gravity.
2. Determine which types of metal shapes can be printed in space and their qualities.
3. Study how 3D metal printing in space may differ from printing metal parts on Earth.
4. Ascertain how crew members can work safely and efficiently with 3D metal printers within the confines of a spacecraft.

From a technical perspective, findings from this experiment could provide a better understanding of the functionality, performance, and operations of metal 3D printing in space. They could also assist with benchmarking the quality, strength, and characteristics of 3D-printed metal parts.

From a strategic perspective, 3D metal printing could prove essential when it comes to the feasibility of long-duration human missions, especially on the Moon and distant planets. In addition to reducing launch-load weights, 3D printers could be used to manufacture metal parts necessary for maintaining equipment and key components on-demand, including improvising custom tools for emergencies and other unforeseen situations. This is important because it would be impossible to predict every tool or spare part needed for a Mars mission or constructing a base on the Moon.

RECYCLING IN SPACE WITH 3D PRINTING

3D printing is playing an important role in developing recycling capabilities that could make long duration space missions more sustainable. In 2018, NASA installed integrated 3D printer and recycling hardware developed by Tethers Unlimited on the ISS.

In various experiments conducted in 2019, the ReFabricator demonstrated the ability to convert plastic waste (including from previously 3D printed plastic parts) into 3D printer feedstock that was successfully used to create new tools and parts. The experiment included using plastic that had been recycled multiple times to create parts that were returned to Earth for testing.[8]

3D PRINTING IN SPACE WITH LOCALLY SOURCED MATERIALS

One of the most ambitious 3D printing projects involves using the technology in concert with locally sourced materials (i.e., in-situ resource utilization) to create the infrastructure necessary to support planetary exploration. Developing such technology could prove essential: in theory, it could reduce the need to transport pre-built objects from Earth to the Moon or planets, making space exploration and long-term settlements more practical and sustainable.

NASA has been collaborating with ESA, various commercial enterprises, universities, and other organizations to explore the potential of using 3D printing in this capacity. Key to the effort is the development of 3D printing technology that uses lunar regolith as feedstock to print blocks (and other shapes) that can be used to construct bases on the Moon and Mars. (Regolith is the dust and crushed rock found on the surfaces of terrestrial planets, moons, and some asteroids. The term comes from the Greek words for "blanket" and "rock.")

3D PRINTING WITH REGOLITH

A number of projects and experiments have been conducted or are underway that combine 3D printing with regolith feedstock for space construction. The goal is to efficiently produce building materials that can be easily formed into structures able to withstand the harsh environments of space and extraterrestrial environments.

PROJECT MOONRISE

In 2021, scientists at the Technical University of Braunschweig, Germany, and Laser Zenntrum successfully 3D printed structures using lunar regolith simulant under zero-gravity conditions. Lunar regolith simulant is a synthetic feedstock composed of metal oxides and a binder that is designed to simulate lunar regolith. The project's goal was to reduce the cost of launching payloads into LEO.

Researchers mounted a customized laser onto a lunar rover specifically designed to facilitate 3D printing in space. By manipulating the rover's robotic arm, they were able to direct the laser to melt the lunar regolith simulant into precisely fabricated spherical shapes.[9]

These experiments were conducted on Earth using a large-scale research device called the Einstein-Elevator, a drop tower that allows experiments to be carried out under conditions of microgravity and a high repetition rate.[10] The laser, which weighs less than 3 kg, demonstrated its resilience in space-like conditions.

PROJECT OLYMPUS

This ambitious project seeks to revolutionize space-based construction systems and is a key project for NASA's upcoming Artemis mission, which aims to return humans to the Moon. Olympus focuses on creating robust structures for the Moon that will provide better thermal, radiation, and micrometeorite protection than traditional metal or inflatable habitats. Icon, a Texas-based company, is leading the R&D efforts. This includes developing a full-scale prototype off-world 3D printer that can use lunar and Martian resources as building materials. Icon is also developing technology for conducting 3D printing construction robotically on the lunar surface.

Icon plans to develop its 3D printing technology using both lunar regolith simulants and regolith samples brought back from Apollo missions to determine their mechanical behavior in simulated lunar gravity. Findings from these experiments should provide crucial knowledge and expertise for developing future lunar construction approaches for the broader space community, including critical infrastructure like landing pads, blast shields, and roads.

In 2022, NASA awarded Icon a US $57.2 million contract that runs through 2028.[11] It is meant to further Icon's commercial activities and other work it has collaborated on with NASA, including a 3D-printed, 1,700-square-foot simulated Martian habitat called Mars Dune Alpha, which NASA plans to use to conduct a series of analog missions simulating year-long stays on the surface of Mars.[12]

3D MICROWAVE PRINTER

In July 2023, NASA awarded Redwire Corporation $12.9 million to prototype 3D printing technology. Redwire has developed a 3D printer that employs a microwave emitter to heat and solidify regolith simulant into materials to construct landing pads, roads, foundations, and other infrastructure.[13] The project calls for making the technology scalable enough to meet various deployment needs, including on lunar rovers, vehicles, and robotic arms.

BIOPRINTING IN SPACE

Bioprinting is a revolutionary technology that employs 3D-printing-like techniques to combine cells, growth factors, and biomaterials into biomedical parts that closely mimic natural tissue. Although experimental, bioprinting is being used to create mini tissues and organs for studying diseases and pharmaceutical side effects. The technology is anticipated to advance to the point where it can create replacement tissues and organs from a patient's own cells.

Space agencies like NASA, biotech companies, and pharmaceutical firms are keenly interested in performing bioprinting in space because bioprinted materials in zero-gravity environments tend to retain their form and remain in a three-dimensional shape. This quality helps eliminate or reduce the need to use "scaffolds" and other supports typically required for bioprinting on Earth.[14] In space, tissues can grow in three dimensions without support, simplifying the fabrication process.[15]

In future space missions, bioprinting could make it possible to print food and medicine on demand, reducing payloads while providing resources for maintaining crew member health. In-space bioprinting could also aid in the development of new drugs and therapies and support breakthroughs in regenerative medicine and organ transplantation.[16]

Several 3D bioprinting experiments have been conducted on the ISS. In 2018, the Russian state space agency delivered a magnetic printer called Organ.Aut, which was developed by 3D Bioprinting Solutions to culture cartilage cells using magnetic fields.[17,18] Experiments conducted from 2018 through 2020 demonstrated this approach could create tissue constructs, helping to inspire additional research on producing artificial organs.

In July 2023, Redwire successfully bioprinted the first human knee meniscus in orbit (on the ISS). The meniscus was successfully returned to Earth for analysis. This project sets the stage for advanced treatments for patients with meniscal injuries on Earth and for crew members who experience musculoskeletal injuries on space missions. This is critical, since microgravity can cause cartilage degeneration that could affect the health and performance of astronauts on long-duration space missions and in lower-gravity environments like the Moon and Mars.

Sometime this year, Redwire is scheduled to experiment with bioprinting cardiac tissue on the ISS. This and subsequent experiments could lead to the ability to print complex, thick tissues that cannot be produced on Earth and the development of patches to be applied to the outside of damaged hearts.

CONCLUSION & FUTURE DEVELOPMENTS

3D printing has made a significant impact on the space industry by enabling on-demand manufacturing of spacecraft components and equipment within Earth-based facilities.

Use of 3D printing is destined to grow significantly over the next decade as space exploration becomes increasingly commercialized. As the technology evolves to meet commercial demands, it should become possible to print more complex parts and equipment, including entire (or nearly so) spacecraft, using robust, lightweight, heat-resistant materials (e.g., high entropy alloys, nano carbon reinforced composites, and non-oxide ceramics) developed through advances in materials science.

3D printing to recycle waste and print electronic circuits and components will also advance the technology and lead to increased use. Moreover, the integration of 3D printing technology with generative AI will enable engineers (and, eventually, astronauts) to rapidly design and print parts and equipment on Earth and in space.

It's quite possible that 3D printing's biggest impact on the space industry will come from its use of in-space manufacturing. By reducing reliance on costly resupply missions, 3D printing will pave the way for the sustainable exploration of space and extraterrestrial environments.

USE OF 3D PRINTING IS DESTINED TO GROW SIGNIFICANTLY OVER THE NEXT DECADE

Establishment of commercial space-based orbiting platforms using 3D printing techniques (including bioprinting) could also prove valuable. This would enable companies in industries like manufacturing, biotech, and pharmaceuticals to establish orbiting manufacturing facilities that leverage the benefits of zero-gravity environments for researching and manufacturing new products that would be complicated or impossible to develop on Earth.

Finally, the advancement of 3D printing technology capable of supporting in-situ resource utilization is crucial for the future of space exploration and . By using locally available materials to build 3D-printed infrastructure, this technology can significantly reduce the expense of transporting construction materials from Earth to space. Eventually, it could enable on-demand construction on the Moon's surface and Mars (a key goal of NASA's Artemis mission). This will support both human and robotic missions and lay the foundation for a sustainable human presence in the cosmos.

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