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Space Economy Session - A focus on space sustainable operations and the role of governments l to stimulate sustainable economic development for both in space and on Earth.

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LEVERAGING A CIRCULAR ECONOMY FOR SPACE SUSTAINABILITY: GOVERNMENT ROLES AND ECONOMIC IMPACTS

Abstract

The accumulation of space debris presents a critical challenge to the sustainability of orbital operations and the long-term utility of space as a vital resource. Based on MITRE economic studies of space sustainability, this paper proposes a framework based on the principles of a circular economy to address the issue of space debris, focusing on the repurposing and reuse of materials from decommissioned satellites and spent launch vehicles. The proposed framework outlines a holistic approach that includes regulatory reforms, technological innovations, and economic incentives to facilitate the removal and recycling of space debris.

The pivotal role of governments in stimulating sustainable economic development in space through funded research and development (RD), specific programs, incentives, and regulatory actions targeting private sector space initiatives is analyzed.

The paper argues for the necessity of an international cooperative model that harmonizes policies and integrates economic motivations towards space sustainability. This approach involves a detailed examination of the cost-benefit analysis of implementing a circular economy model in space, highlighting the potential for material recapture to emerge as a profitable sector within the space industry, thereby contributing to economic growth both in space and on Earth.

Technological advancements in debris-tracking, robotic capture mechanisms, and on-orbit servicing and manufacturing are discussed as essential enablers for the material reclamation process. The paper delves

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into the socio-economic impacts, including job creation, skill development, and the fostering of international collaborations that facilitate technology transfer and capacity building.

Environmental and sustainability considerations form a core component of the analysis, with the paper assessing how a circular space economy can mitigate risks to future missions and contribute to the long-term sustainability of space operations. The presentation concludes with actionable recommendations for policymakers, industry leaders, and stakeholders, offering a vision for a future where space operations are characterized by efficiency, sustainability, and economic viability. This paper contributes valuable insights and practical solutions to the discourse at the International Astronautical Congress, addressing the urgent need for sustainable orbital operations and the significant role governments play in achieving this goal through economic and regulatory means. Presenting a transformative model that aligns the circular economy principles with the unique challenges of space logistics paves the way for new business opportunities and sustainable utilization of space resources, ensuring the preservation of the near-Earth environment for future generations.

Introduction

The increasing accumulation of space debris presents a critical and growing challenge to the sustainability of orbital operations and the development of the space economy. As commercial activity in space intensifies and the number of operational satellites multiplies, the threat of collisions due to debris becomes more severe. This condition, in turn, jeopardizes the long-term utility of space, potentially hindering economic growth and access to the space environment. In response, a circular economy model offers an innovative solution, focusing on reusing, recycling, and repurposing materials in space.

This paper outlines the role of governments in enabling a circular space economy through policies, regulations, and economic incentives. Drawing on MITRE's economic studies of space sustainability, the paper explores how the application of circular economy principles can foster a sustainable space industry. In particular, it argues for government-backed initiatives, technological advancements, and international cooperation as essential factors in transforming the current space debris problem into an economically viable and sustainable sector.

Hypothesis

This paper hypothesizes that integrating a circular economy in space, underpinned by strategic government intervention, will mitigate space debris and establish a nascent industry with significant economic potential. Governments must provide the infrastructure, funding, and policy framework to encourage private sector innovation and investment in space sustainability technologies. This approach will enable space debris recycling and repurposing to emerge as a cornerstone of space operations, driving economic growth and sustainability.

Background Discussion

The concept of a circular economy in space builds on well-established principles from terrestrial industries. A circular economy emphasizes the continuous use of resources through recycling and reprocessing rather than following a linear model—where materials are used once and discarded. In space, this could mean refurbishing decommissioned satellites, transforming debris

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into fuel or building materials, and reducing the need for new launches.

Paul Krugman's theory of **dynamic scale economies**, for which he was awarded the Nobel Prize, provides an important lens through which to view the potential impact of first-movers in the circular space economy. Krugman's theory suggests that early entrants in a new market can gain long-term advantages by accumulating knowledge and expertise. Much like a river carving a canyon, these first movers shape the landscape in ways that benefit them over time, making it increasingly difficult for late entrants to compete.

In the context of space, companies and governments that invest early in debris recycling technologies and infrastructure will entrench their positions. They will reduce operational costs and create new standards and practices that others will have to follow. This entrenchment gives them a significant competitive advantage, as they can dictate the market entry terms, set sustainability benchmarks, and secure long-term profitability.

Key Takeaways

· **First-mover advantage and Entrenchment**

Krugman's theory highlights the significance of being a first mover in emerging industries. In the space economy, early leaders in the development of circular economy technologies will establish long-lasting advantages by shaping market standards, driving innovation, and accumulating invaluable operational knowledge. As these companies build the infrastructure for debris recycling and in-space manufacturing, they dominate key orbits, making it challenging for new entrants to compete on the same level. This advantage will be particularly pronounced in high-demand areas like geostationary and low-Earth orbits, where space debris is already a significant concern.

· **Government's Role in Supporting the Circular Space Economy**

Governments have a vital role in nurturing the circular space economy. This role includes funding R&D initiatives, creating incentives for private companies to adopt sustainable practices, and establishing regulatory frameworks that promote responsible space operations. Governments can also drive international cooperation, ensuring that space debris mitigation becomes a global priority and that all nations can access sustainable space practices. Policies such as launch taxes, subsidies for recycling initiatives, and grants for debris removal technologies will be critical in fostering this new sector.

· **Economic and Environmental Impacts**

Shifting to a circular space economy will have profound economic and environmental implications. By developing in-space recycling and debris removal technologies, companies can reduce the costs of space operations while mitigating the environmental risks associated with space debris. The economic potential of this new sector is significant—by repurposing materials that would otherwise be waste, companies can open up new revenue streams and create a more resilient and sustainable space economy. Environmentally, these practices will reduce the risk of collisions and contribute to the long-term sustainability of space activities.

Foundational Economic Simulation Setup (Groesbeck)

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Our goal is to understand how the different policies and technologies could promote long-term space sustainability. The model has the following goals:

· The model reflects a market with both for-profit satellite operators and government authorities

· The model reflects the "tragedy of the commons," i.e., actions that are profitable to individual actors may present externalities that result in a reduction in total welfare

· The model incorporates harmful feedback effects, namely the fact that debris from satellite collisions could go on to create further collisions and further debris

· The model incorporates heterogeneity in the orbital regime: this spatial differentiation highlights how economic value, in situ resources, and carrying capacity may vary between different categories of Earth orbit.

The following are set aside at present:

· Precise orbital elements are abstracted into broad neighborhoods called orbital "bins." Inspired by "gravity models" in international trade, we represent each bin as a location with a bilateral "distance" to each other bin as well as an average "distance" for travel within the bin

· Variation in satellite sizes and reliance of a satellite on other satellites to form a constellation for operation

· Cislunar and interplanetary missions

For simplicity, we abstract the wide variety of manmade objects in space into three broad categories:

- Operational satellites, which are maneuverable and able to provide services/profits
- "Dead" objects, consisting of non-operational satellites and spent upper-stage rocket bodies
- "Shrapnel," consisting of satellite and rocket body parts from a collision or explosion

The distinction between "Operational" and "Dead" is somewhat stylized, ignoring the possibility that a satellite may have a damaged instrument, reduced power output, etc., and remain capable of completing its mission under diminished capacity or conduct collision avoidance and disposal maneuvers. The distinction between "Dead" and "Shrapnel" has two purposes:

1. This is to reflect the fact that planning rendezvous missions with individual bolts and paint chips for recycling or disposal will likely be infeasible.

2. To roughly distinguish between the *number* and *mass* of debris objects.

3. This reflects that a collision between an operational satellite and small debris is more likely to cause the satellite to fail rather than disintegrate.

The state of the world consists of a set of arrays:

- The number of operational satellites with (row) years remaining in orbital bin number (column)
- The number of non-operational but intact (salvage-worthy) satellites (and rocket bodies) with (row) years remaining before exiting to a lower bin or Earth's atmosphere
- The number of pieces of small debris
- The profit of each of the surviving satellites for each satellite, organized by age x bin combination

The following is the sequence of events which occurs during each calendar year:

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1. Entrepreneurs are drawn; each entrepreneur has a desired orbit for a satellite and an annual profit derived from the satellite for each year it remains functional.
    1. Entrepreneurs calculate the *current* annual risk of collision for their desired orbit and the expected discounted future profit.
    2. Those with sufficient anticipated profit enter the market by paying an up-front cost to launch their satellites.
    3. Depending on technology/regulations, a launch may also result in a rocket body added to the Dead Satellite count.
2. Collisions are calculated
    1. The number of collisions between a type and a type satellite is drawn from the Poisson distribution with mean. Objects are removed from type T and moved to either DEAD or SHRAP (see table).
    2. The lost satellites are distributed among the age brackets
    3. The lost satellites are distributed among the 3rd dimension (the stack of profits)
3. Satellite operators who did not lose their satellites to a collision collect their profits.
    1. Profits are added to the global welfare count.
4. The surviving satellites increase have their remaining years reduced by 1 in; those starting at 0 years remaining are added to.
    1. Dead satellites may decay into lower orbits

For the rest of the paper, we will present a series of technologies

1. A one-sentence description of how we portray a given policy as an element in the simulation

2. Graphs and summaries for the simulation results

3. An in-depth view of the state of the policy or technology:

a. Detailed concept of operations (including who's paying for it)

b. Current projects and interested organizations

c. Obstacles, legal jurisdiction (for policies), or technological maturity (for technologies)

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Baseline Scenario

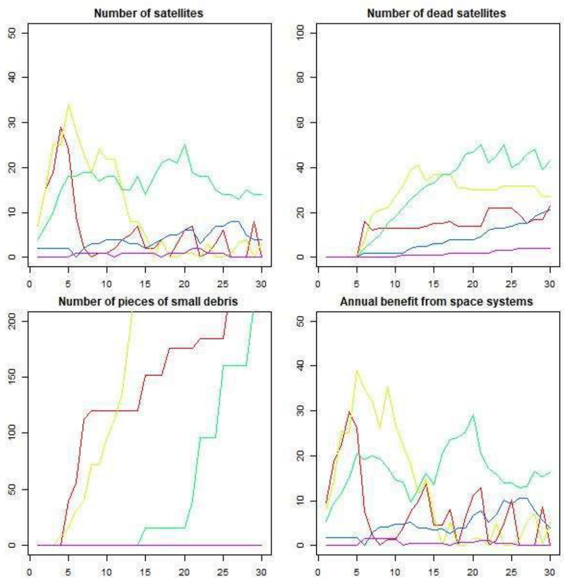

Figure 1-1: Baseline Simulation

Our baseline simulation shows that the number of active satellites and their value rapidly approaches a carrying capacity and then plateaus or even collapses. This is due to the rising number of dead satellites and shrapnel which kill active satellites and deter new satellite owners from launching. The latter effect is an imperfect mechanism for promoting sustainability: prospective satellite operators consider whether or not their satellite is more profitable than their launch cost, but ignore the fact that an additional satellite in an orbit reduces the expected remaining lifespan of all other satellites in that orbit, i.e. "the tragedy of the commons".

Policy: Graveyard and De-Orbiting Regulations

Simulated scenario: Satellite operators are ordered to remove satellites that have not been prematurely rendered inoperable to either a graveyard orbit or de-orbiting. We include this as an up-front cost, reflecting the additional fuel reserve resulting in a heavier satellite and thus requiring a heavier-lift launch vehicle compared to a satellite with the same function and planned service life with no EOL provision. This gives us more granularity in scaling the cost for the differences in delta-v requirements between orbits. Alternatively, we could represent this policy as reducing lifespan due to the disposal burn reserve coming from the same fuel tank as routine orbit adjustments.

This will be an effective policy when the space environment is already sustainable and steady, but it will not address dead satellites and shrapnel.

Technology + Business Case Example: Refurbishing and Recycling Dead Satellites - CisLunar Industries

Simulated scenario: When entrepreneurs receive their business opportunities in Step 1, they can either pay the standard launch cost *or* an amount to eliminate a dead satellite in their desired bin (or an adjacent bin) to produce a new satellite *in situ*. The cost is smaller than a new launch but scales up with travel, i.e., in large orbit bins or when debris comes from an adjacent bin.

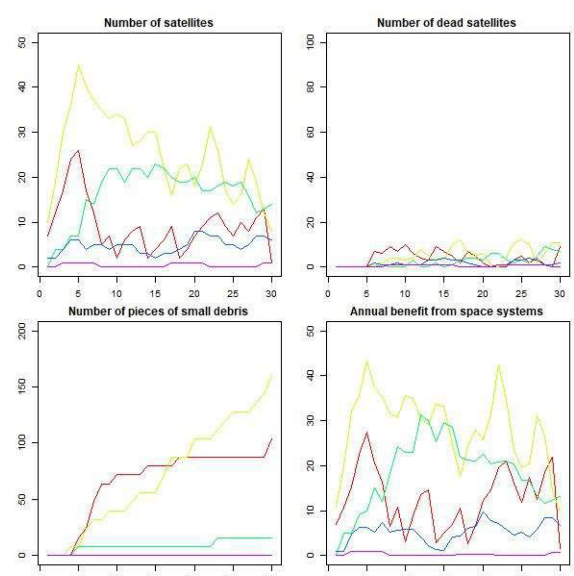

Figure 1-2: Simulation with in-orbit recycling of large debris

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Our simulation shows that satellite recycling could be ideal for valuable orbits with many valuable business opportunities, many dead satellites, and limited shrapnel. A secondary use will be restoring dead satellites that have been perforated by shrapnel. Note that shrapnel continues to accumulate in high orbits with limited aerodynamic drag due to collisions among live satellites and dead satellites awaiting recycling.

Technology: Collecting and De-Orbiting Space Debris

Simulation: Active debris removal is an expensive proposition, requiring a round trip mission to a crowded orbit. The cost could be significantly reduced by recycling dead satellites into solid metal propellant, which we represent by a discount in transport costs in exchange for reducing the dead satellite count by 1.

The United States Space Force supported one study of the circularization of the space economy through an Orbital Prime Direct to Phase II SBIR called "Propulsion Ecosystem Based on Recycled Metal Propellant." CisLunar Industries USA Inc. primed the 15-month contract and brought in partners Astroscale US, Sierra Space, and Plasma Controls at Colorado State University. Neumann Space of Australia was a key supplier of the program. Omnetix LLC performed some analyses.

The Metal Propellant Ecosystem (MPE) is an integrated concept of operations to provide capabilities that address key challenges for space customers, specifically Mobility (Dynamic Space Operations) and Space Domain Management (e.g., Space Domain Awareness, Space Traffic Management, etc.). In the investigated concept of operations, the partners would work together to create an ecosystem that would provide the benefits of an in-space closed-loop resupply system. Specifically, refueling of prepared spacecraft would be provided by removing and recycling harmful space debris into solid metal propellants that could be used for station-keeping and active debris removal missions. The MPE involves capturing, transporting, and transferring resident space objects or space debris. The objects would then be salvaged, dismantled, melted, and processed into solid metal propellant rods. The processing would take place on salvage platforms in space, and the rods would be transferred into swappable propellant cartridges and distributed to end users for use in metal-propellant thrusters. These metal propellant thrusters could be installed on spacecraft for station keeping and additional mobility. In short, the MPE turns space debris into delta-v.

The investigation defined the elements of the ecosystem, described target markets, quantified market demand and growth, analyzed the competitive landscape, and mapped a path to commercialization of this capability through the development and integration of relevant technologies. Multiple prototypes of hardware for producing metal propellants were designed and built, and thrusters were run in a vacuum chamber using the solid metal propellant produced. Data on thruster performance were collected and used to model station-keeping and active debris removal operations.

Competitive Advantages: Addressable Markets are in hundreds of millions of dollars (US), and adoption of electric propulsion is projected to accelerate. While government funding will support technology development in the short term, the analysis conducted as part of this program shows that delta-v achieved through MPE has dramatically lower costs than other

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propellant architectures. There are three compounding reasons for this:

1. Aluminum is orders of magnitude cheaper than other propellants.
2. Space-sourced aluminum does not have launch cost.
3. Aluminum produces more delta-v per kilogram of mass than some popular propellants.

The analysis estimates that to deliver the same amount of delta-v to a customer in GEO, a provider of hydrazine would have to spend many times the amount of money that a provider of recycled metal propellant would have to spend. This opportunity for a stunning reduction in the cost of refueling could represent a turning point in space mobility. It is also estimated that recycling only two defunct GEO satellites could meet the entire annual need for station-keeping delta-v in GEO. Similarly, estimates for volumes of space station waste metal suggest that recycling that metal could meet more than half the need for the same station's station-keeping delta-v. The solid metal propellant is shelf stable, is easy to transfer relative to liquids and gases, and is not susceptible to slosh that can obscure tank-volume measurements and complicate operations. Finally, diversifying fuel options, including one sourced in space, supports a robust supply chain. Beyond these first-order competitive advantages, the MPE is the only solution that addresses a separate problem in its solution. By contributing to space debris cleanup, the MPE is simultaneously contributing to Dynamic Space Operations and mitigating increases in the need for Dynamic Space Operations by making Space Domain Management easier. The Space Foundry® that performs the recycling operation is the missing link that closes the loop on the circular MPE capability. This in-space metal-processing capability can mitigate space debris and manufacture propellant in space. The opportunities for efficiency, cost reduction, sustainability, and optionality could change how commercial and government markets view the constraints on mobility and spacecraft life. Because of these various competitive advantages, the system's critical components are more than capable of supporting an active commercial market that would benefit from the resourcefulness of the MPE.

The MPE addresses a broad combination of high-demand capabilities in a single integrated solution, including Space Domain Management and Dynamic Space Operations. The MPE has a growing market in which to compete and many competitive advantages over other propellant options for station keeping and transportation. Although several technologies must develop in parallel to achieve full commercialization of MPE, there are risk-mitigating revenue opportunities for the partner companies developing the technologies. Intermediate technology demonstrations also require only portions of the ecosystem to function at a given time. The MPE solution is valuable and can differentiate itself in the market for its unique and varied contributions to a robust in-space economy.

The role of government in supporting this aspect of an in-space circular economy may, in part, be aptly reflected in Alexander Hamilton's 1791 "Report on Manufactures," in which he posited that even the most marketable of technologies in a free market may reasonably need government support in their development due to slow adoption by industry. He attributes slow adoption to "the strong influence of habit; the spirit of imitation; the fear of want of success in untried enterprises;" and the competitive support foreign governments provide to accelerate the progress of their own citizens' untried enterprises. Another role of government might be to support the investment in research and development required

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to field a capability that may result in a competitive advantage over other nations. The government must also advance policy alongside the technology so that its application, risks, and commercial opportunities may be appropriately measured. Among four risks to commercialization noted in the report—technological, timing, policy, and funding—at least three of the four may be mitigated by government action.

Policy: Neighborhood-Level Interventions

Neighborhood-level interventions introduce a tailored approach to space sustainability, focusing on specific orbital regimes such as Geostationary Orbit (GEO) and Low-Earth Orbit (LEO). These orbits present distinct challenges, ranging from the overcrowding of LEO due to mega-constellations to the high-value, high-risk operations in GEO. By applying space sustainability measures at the neighborhood level, governments and regulatory bodies can address the unique needs of each orbital regime, allowing for more effective management of space debris and resource allocation.

Introducing new countries into the circular space economy is akin to new companies entering an emerging market. These new entrants face the challenge of establishing themselves in an environment already shaped by existing players. In this context, space sustainability measures, such as debris mitigation policies or capacity-building programs, can help level the playing field for emerging space nations, allowing them to contribute to the global space economy while adhering to established norms and practices.

This approach ties into capacity-building efforts, where new space-faring nations can be supported by transferring knowledge, technology, and regulatory frameworks. By fostering normative development in space governance,neighborhood-level interventions can bridge established space powers and newer entrants, ensuring that all parties adhere to sustainable practices. This will be particularly important as space infrastructure expands, with new players contributing to the growth of space-based economies while navigating the risks of overcrowding and debris conjunctions.

As orbital regions become more congested, especially in LEO, the timing of entry and the margins required to operate in space increase. This could potentially trigger the need for new policies, such as a launch tax or stricter debris removal requirements, to manage the growing number of actors in space. However, such measures could inadvertently create barriers to entry, particularly for newer or less-resourced countries or companies, leading to what can be termed the "empty punch bowl" phenomenon, where only the most established players can afford to remain competitive.

Simulated Scenario

In this simulation, two of the earlier proposed space sustainability measures are combined, each applied to specific orbital bins where they are most effective. In GEO, where high-value satellites operate with longer lifespans and fewer debris risks, policies may focus on post-mission disposal and de-orbiting of defunct satellites. In LEO, where the risk of collision is higher due to the sheer number of objects, interventions would prioritize active debris removal and stricter regulations on satellite constellations.

By tailoring interventions to the characteristics of each orbit, governments can ensure that sustainability efforts are welfare-maximizing, providing the greatest benefit with the least disruption to economic activities. This neighborhood-level approach also simplifies international coordination, allowing countries and organizations to focus on specific orbital

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regimes rather than simultaneously attempting to regulate the entire space domain.

Application

Neighborhood-level interventions offer a more practical approach to space sustainability. Rather than attempting to implement one-size-fits-all regulations across all orbits, policymakers can tailor solutions to the specific needs of LEO, GEO, or other orbital regimes. This approach can lead to more effective cooperative governance as nations focus on shared interests in specific orbital areas, increasing the chances of reaching a quorum on space sustainability measures.

By applying these policies more localized, the complexity of international negotiations is reduced, allowing for quicker adoption of new regulations and technologies. This incremental approach fosters cooperation and allows for the gradual scaling of sustainability measures, ensuring that they can be adapted as the space environment evolves.

Conclusions

The circular space economy represents a transformative shift in addressing the pressing challenge of space debris while fostering sustainable economic growth in both space and on Earth. This paper has presented a compelling case for the role of governments in this emerging sector, emphasizing the need for robust regulatory frameworks, financial incentives, and technological innovations to drive the development of sustainable space operations. The key takeaway from this research is that the principles of a circular economy—focused on reuse, recycling, and resource repurposing—are not only applicable to space logistics but essential for maintaining the long-term viability of space as a critical asset.

As illustrated throughout the paper, the accumulation of space debris has become a significant threat to orbital operations. Without meaningful intervention, the continued growth of this debris could lead to cascading failures, rendering vital orbits unusable. As both regulators and market facilitators, governments are uniquely positioned to lead the transition towards a circular economy in space. By leveraging their ability to provide incentives, fund research and development, and promote international cooperation, governments can ensure that space operations evolve in a way that is both economically viable and environmentally sustainable.

Paul Krugman's theory of dynamic scale economies, for which he won the Nobel Prize, is highly relevant to this discussion. Krugman's insights into how early entrants in a market can secure long-term advantages through accumulated knowledge, expertise, and infrastructure are directly applicable to the circular space economy. The early adoption of space debris recycling technologies by governments and private sector innovators will allow these actors to shape the market and entrench their positions in ways beneficial for open competition, sustainability, and industry-wide standards. As with terrestrial markets, first-movers in space will carve pathways that late entrants must follow, creating economic opportunities and long-term competitive advantages for those who act now.

This emerging market is not just about mitigating the environmental risks posed by space debris—it also presents significant economic opportunities. As highlighted by Lee Steinke's work at CisLunar Industries, recycling defunct satellites and other space debris into usable materials such as propellant is an example of how space waste can be transformed into a resource.

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By embracing these technologies, the space industry can reduce operational costs, extend the lifespan of spacecraft, and create a more resilient supply chain. Moreover, developing a circular economy in space will drive job creation, foster new skills, and promote international collaborations that enhance technological transfer and capacity building.

From an environmental perspective, the transition to a circular space economy offers a clear pathway to mitigating the risks of Kessler syndrome and preserving critical orbital environments for future generations. Integrating recycling technologies, such as those outlined in the Metal Propellant Ecosystem (MPE), provides a dual benefit by reducing debris and supporting space mobility operations. These efforts contribute to environmental stewardship in space and reduce costs associated with launching new materials from Earth, thereby decreasing the environmental impact of space missions.

The future of space operations lies in harnessing the principles of a circular economy to address the growing problem of space debris. Governments have a pivotal role in this transformation, and their support is critical for developing policies, technologies, and economic models that will shape the future of space. By fostering collaboration between public and private sectors, promoting innovation through R&D funding, and encouraging the adoption of sustainable practices, governments can ensure that tomorrow's space economy is both economically vibrant and environmentally sustainable.

This paper has laid the groundwork for understanding a circular space economy's economic, environmental, and technological benefits. As the space industry continues to evolve, the lessons learned from terrestrial circular economies can be adapted and applied to space, creating a new frontier of sustainable economic development. Through strategic government intervention and the active participation of the private sector, the circular economy model can become a cornerstone of space sustainability, ensuring that space remains a shared resource that benefits all of humanity for generations to come.

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