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Algorithmic Sovereignty in Orbit: Governing AI as Critical Space Infrastructure

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ABSTRACT

As space systems become increasingly autonomous, artificial intelligence is evolving from operational support software into a foundational infrastructure layer of orbital and deep-space activity. AI already mediates satellite coordination, mission autonomy, collision avoidance, resource allocation, and space situational awareness, yet governance frameworks remain largely hardware-centric, focusing on launch systems, debris mitigation, spectrum allocation, and liability regimes while largely overlooking the algorithmic layer increasingly shaping orbital decision-making.

This paper introduces the concept of algorithmic sovereignty in orbit and describes the growing influence of opaque, proprietary, and nationally embedded AI systems over shared space environments. As intelligent systems assume greater operational authority across governmental and commercial infrastructures, they introduce new forms of geopolitical asymmetry, escalation risk, accountability fragmentation, and governance instability.

Rather than treating AI merely as software embedded within spacecraft, the paper argues that intelligent systems should be understood as critical cognitive infrastructure for future space civilization. As cislunar operations, autonomous logistics, and deep-space architectures expand, algorithmic systems may increasingly shape how orbital environments are navigated, coordinated, secured, and politically governed.

The analysis examines emerging governance gaps in transparency, auditability, escalation dynamics, and normative fragmentation. It proposes a multi-layered governance framework integrating resilience standards, cooperative oversight mechanisms, and cross-border transparency protocols.

Ultimately, the paper argues that the long-term sustainability of space activity may depend not only on physical infrastructure but also on the governance architectures embedded in the intelligent systems increasingly operating beyond Earth.

PAPER

1 Introduction: The Invisible Infrastructure in Space

For most of the Space Age, discussions of governance, sovereignty, and infrastructure have focused on physical systems. Launch vehicles, satellites, communication networks, space stations, lunar habitats, and resource extraction architectures have traditionally been viewed as the primary building blocks of human activity beyond Earth. These tangible assets remain essential, yet they are increasingly accompanied by a less visible layer of infrastructure that is becoming equally important for the operation and coordination of space systems.

Artificial intelligence is rapidly emerging as that invisible infrastructure.

AI-enabled systems already support a wide range of activities, including satellite constellation management, collision avoidance, mission planning, autonomous navigation, Earth observation, resource allocation, and space situational awareness. As space operations become more complex and geographically distributed, intelligent systems are increasingly required to process information and support decision-making at speeds and scales beyond direct human oversight. The result is a gradual but significant shift in the role of artificial intelligence, from operational support tool to foundational infrastructure.

This transition has profound implications for future space governance. Existing legal and regulatory frameworks have largely evolved around physical objects and activities. International agreements address issues such as territorial claims, spectrum allocation, orbital debris, launch authorization, and liability for physical damage. However, comparatively little attention has been devoted to the algorithmic systems that increasingly mediate decisions within these environments.

The growing reliance on autonomous and semi-autonomous systems raises important questions. Who governs the algorithms that influence orbital operations? How can transparency and accountability be maintained when critical decisions are delegated to complex computational systems? What happens when competing national, commercial, or military actors deploy proprietary AI systems within shared orbital environments?

This paper argues that artificial intelligence should no longer be understood merely as software embedded within spacecraft or ground systems. Instead, it should be recognized as a form of critical cognitive infrastructure that increasingly shapes how activities beyond Earth are coordinated, managed, and governed. Building on the concept of algorithmic sovereignty in orbit, the paper examines emerging governance challenges and proposes a framework to ensure that the intelligent systems supporting future space civilization remain transparent, resilient, and accountable.

As humanity expands into cislunar space and beyond, the sustainability of space activity may depend not only on who controls physical infrastructure but also on who governs the invisible algorithmic layer increasingly operating above it.

2 From Operational Tool to Critical Infrastructure

Historically, artificial intelligence has been viewed primarily as an operational capability. Within the space sector, AI systems were initially developed to support specific tasks such as image classification, anomaly detection, predictive maintenance, mission planning, and autonomous navigation. In these applications, AI functioned as a specialized tool designed to improve efficiency, reduce human workload, and enhance mission performance.

Today, however, the role of artificial intelligence is expanding beyond individual operational functions. The increasing scale and complexity of space activity are creating conditions in which intelligent systems are becoming deeply embedded within the infrastructure of space operations themselves.

This trend is already evident across multiple domains. Satellite operators rely on machine learning systems to monitor constellation health and optimize resource allocation. Space traffic management increasingly depends upon automated systems capable of processing large volumes of orbital data in real time. Future lunar settlements may require AI-supported logistics networks to coordinate energy distribution, resource utilization, transportation, and life support systems. Autonomous spacecraft operating at significant distances from Earth will likewise require decision-making capabilities that reduce dependence on constant human intervention.

As these systems become interconnected, artificial intelligence begins to assume a new role. Rather than functioning as an isolated tool, it becomes part of the underlying architecture that enables complex activities to occur. Much as communication networks, power grids, and transportation systems do, AI increasingly performs essential coordination functions upon which other systems depend.

This transformation is particularly significant because infrastructure possesses characteristics that ordinary tools do not. Infrastructure creates dependencies. Failures can propagate across multiple systems. Decisions made within infrastructure influence large numbers of actors simultaneously. Governance, therefore, becomes a matter of public and strategic concern rather than merely technical design.

The concept of critical infrastructure has traditionally been applied to physical systems whose disruption would significantly impact society or national security. By this definition, many future AI-enabled space systems may qualify as critical infrastructure in their own right. A failure in an orbital traffic management algorithm, an autonomous resource allocation system supporting a lunar settlement, or an AI-driven command architecture coordinating multiple spacecraft could have consequences extending far beyond a single mission.

Recognizing this shift from operational tool to critical infrastructure represents an essential first step toward understanding the governance challenges that accompany increasingly autonomous space environments. Once artificial intelligence becomes embedded within the operational fabric of space activity, questions of oversight, accountability, and control become unavoidable.

3 The Challenge of Algorithmic Sovereignty

The growing integration of artificial intelligence into space operations raises a fundamental governance question: who exercises authority over the algorithmic systems that increasingly shape activities beyond Earth?

Traditionally, sovereignty has been associated with territory, jurisdiction, and political authority. States exercise sovereignty within defined geographical boundaries, while international agreements establish rules for activities occurring in shared domains such as the high seas, Antarctica, and outer space. The emergence of AI-enabled infrastructure complicates these established frameworks because algorithmic systems do not fit neatly within traditional concepts of territorial governance.

An autonomous orbital traffic management system may influence the operations of satellites belonging to multiple nations. A commercial AI platform coordinating lunar logistics could affect governmental, scientific, and private actors simultaneously. Future space settlements may rely upon intelligent systems that allocate resources, manage energy distribution, monitor environmental conditions, and support critical operational decisions. In such environments, algorithmic systems become active participants in governance processes rather than merely technical tools.

This development introduces the concept of algorithmic sovereignty. Rather than focusing exclusively on control over territory or physical infrastructure, algorithmic sovereignty concerns authority over the computational systems that influence decision-making within complex environments. The question is no longer simply who owns a satellite, a lunar habitat, or a communication network. It increasingly falls to those who design, control, audit, and govern the algorithms upon which these systems depend.

Several challenges emerge from this shift. First, many advanced AI systems operate as proprietary technologies controlled by private companies rather than public institutions. This raises concerns regarding transparency and accountability, particularly when algorithmic decisions affect multiple stakeholders. Second, the growing geopolitical competition over artificial intelligence may lead to divergent technological standards, governance approaches, and operational norms. Third, the complexity of machine learning systems can make it difficult to explain or verify specific decisions, creating challenges for oversight and dispute resolution.

These concerns become particularly significant in the context of outer space because the environment itself is inherently international. Orbital space, cislunar space, and future settlements beyond Earth will likely involve a mixture of governmental agencies, commercial enterprises, international partnerships, and scientific organizations. The absence of universally accepted frameworks for algorithmic governance could create regulatory gaps precisely when intelligent systems become increasingly central to operational decision-making.

The challenge of algorithmic sovereignty, therefore, extends beyond technical performance. It concerns legitimacy, accountability, trust, and the distribution of authority within emerging space societies. As humanity expands its presence beyond Earth, questions of governance may increasingly depend upon who controls the invisible computational systems that coordinate activity across the space domain.

4 Emerging Governance Gaps

If artificial intelligence is becoming a form of critical infrastructure for space operations, then existing governance frameworks must be evaluated not only for what they regulate, but also for what they overlook. While international space law and national regulatory regimes provide mechanisms for addressing physical activities in space, they remain comparatively underdeveloped for the governance of autonomous and algorithmic systems.

One of the most significant challenges concerns transparency. Many contemporary AI systems operate as highly complex models whose internal decision-making processes are difficult to interpret. In commercial contexts, these systems are often protected as proprietary technologies, limiting external scrutiny. As algorithmic systems assume greater responsibility for orbital operations, resource allocation, or autonomous mission management, stakeholders may find it increasingly difficult to understand how critical decisions are reached. A lack of transparency can undermine trust, complicate oversight, and make independent verification difficult.

A second governance gap involves accountability. Traditional legal frameworks generally assume that responsibility can be assigned to identifiable actors. Autonomous systems challenge this assumption. When an AI-enabled system contributes to an operational failure, collision event, or resource management error, determining responsibility may become considerably more complex. Questions arise regarding the respective roles of operators, developers, regulators, and organizations deploying these technologies.

A third concern relates to escalation risks. Intelligent systems operating within highly dynamic environments may interact in ways that produce unintended consequences. Competing algorithms developed by different organizations or nations could respond to one another in unpredictable ways, particularly in situations involving limited resources, contested orbital environments, or strategic competition. As reliance on automation increases, the possibility of rapid decision cycles occurring beyond immediate human oversight becomes a growing concern.

Finally, there is the challenge of normative fragmentation. Different nations, corporations, and institutions may adopt divergent standards regarding transparency, autonomy, human oversight, and acceptable operational behavior. In the absence of shared principles, the result may be a fragmented governance landscape in which incompatible approaches coexist within the same operational environment. Such fragmentation could increase uncertainty and complicate international cooperation.

Taken individually, each of these governance gaps presents a significant challenge. Taken together, they suggest that existing frameworks may be insufficient for a future in which artificial intelligence plays a central role in coordinating activities beyond Earth. Addressing these gaps will require governance approaches that balance innovation with accountability, operational efficiency with transparency, and autonomy with meaningful human oversight.

5 A Governance Framework for Orbital AI

Recognizing artificial intelligence as critical infrastructure for space activity requires a corresponding evolution in governance approaches. The objective is not to restrict innovation or limit the deployment of intelligent systems. On the contrary, future space operations will likely depend upon increasingly sophisticated forms of automation. The challenge, therefore, is to ensure that these systems remain trustworthy, accountable, and aligned with broader societal and operational objectives.

A governance framework for orbital AI should be built upon five foundational principles: transparency, auditability, human oversight, resilience, and international cooperation.

Transparency represents the first requirement. While proprietary interests and security concerns may limit full disclosure of algorithmic systems, stakeholders should possess sufficient visibility into the operational logic, objectives, and decision boundaries of systems performing critical functions. Transparency helps build trust and enables meaningful oversight in increasingly complex operational environments.

Closely related is the principle of auditability. Independent review mechanisms should be able to evaluate system performance, identify failures, and investigate incidents when they occur. As AI systems assume greater responsibility for mission-critical activities, the ability to reconstruct and assess algorithmic decision-making becomes increasingly important for accountability and learning.

Human oversight remains equally essential. While autonomous systems may operate with varying degrees of independence, ultimate responsibility for strategic decisions should remain with accountable human

institutions. Human oversight does not imply constant intervention, but rather the establishment of governance structures capable of supervising, reviewing, and, when necessary, overriding autonomous processes.

Resilience constitutes a fourth pillar of governance. Space systems operate in inherently challenging environments characterized by uncertainty, communication delays, and operational risks. Governance frameworks should therefore encourage redundancy, fail-safe mechanisms, and robust contingency planning. Resilient systems are not those that never fail, but those that can recover from failure without catastrophic consequences.

Finally, international cooperation will be essential. Space activities increasingly occur within shared operational environments that transcend national boundaries. Common standards, transparency protocols, and cooperative oversight mechanisms can help reduce uncertainty and promote trust among diverse stakeholders. While complete regulatory harmonization may be unrealistic, establishing shared principles for the governance of orbital AI would represent an important step toward long-term stability.

Together, these principles provide the foundation for a governance framework that balances innovation with responsibility. As artificial intelligence becomes more deeply embedded in the operational architecture of space activities, governance must evolve from an afterthought to an integral component of system design. The future of space infrastructure may depend not only on technological capability, but on the institutions and norms that guide its use.

6 Conclusion: Governing the Invisible Frontier

Humanity's expansion into space has traditionally been framed in terms of physical infrastructure. Discussions have focused on launch systems, spacecraft, habitats, communication networks, energy production, resource extraction, and transportation architectures. These elements will remain essential components of future space development. However, an equally important layer of infrastructure is emerging alongside them.

Artificial intelligence is increasingly becoming the invisible operating system of space activity.

As intelligent systems assume growing responsibility for coordination, navigation, resource management, situational awareness, and operational decision-making, they are evolving from specialized tools into critical infrastructure. This transformation introduces new governance challenges that existing legal and regulatory frameworks are only beginning to address.

The concept of algorithmic sovereignty in orbit highlights a fundamental reality of future space activity: control over physical infrastructure alone may no longer be sufficient. Authority over the algorithms that guide decisions, allocate resources, coordinate systems, and influence operational behavior may become equally important. Questions of transparency, accountability, resilience, and oversight are therefore not secondary concerns. They are becoming central elements of sustainable space governance.

This paper has argued that the governance of orbital AI should be approached proactively rather than reactively. The objective is not to constrain innovation, but to ensure that increasingly autonomous systems remain aligned with human values, institutional accountability, and the long-term interests of spacefaring societies. Establishing shared principles and governance mechanisms today may help avoid fragmentation, uncertainty, and instability tomorrow.

Throughout history, infrastructure has shaped the development of civilizations. Roads enabled trade, communication networks connected societies, and energy systems powered economic growth. In the coming decades, algorithmic systems may perform a similar role beyond Earth.

The next great challenge of space governance may therefore not be governing the visible frontier of spacecraft, habitats, and settlements, but the invisible frontier of intelligent systems increasingly operating behind them.

As humanity extends its presence into cislunar space and beyond, the future sustainability of space civilization may depend as much on governing algorithms as on building rockets.

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