Emerging Digital Technologies on the Final Frontier – Distributed Ledger Technology Applications in Space Systems

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Abstract: Space systems have become key components in a wide variety of critical infrastructures and some would say that they are critical infrastructures in themselves. They provide data gathering, communications, navigation, positioning and timing services that enable an important variety of critical services affecting billions of users. Increasingly, distributed ledger technology has begun to be integrated into the functioning of space systems, both in support of their roles and also to enable new roles. This article traces the main applications, discusses the issues inherent in blockchain use for space systems and underscores the potential that the technology provides across the space sector.

Keywords: space systems, distributed ledger technology, resilience, decentralization, cybersecurity.

INTRODUCTION

Since its inception with the publication of the Bitcoin whitepaper in 2008, distributed ledger technology (DLT) or blockchain has developed significantly in capabilities, diversity of use and means of regulation. Its initial use case was in cryptocurrencies and the financial sector in general, underscoring the ideological commitments of its pseudonymous creator, Satoshi Nakamoto. However, various other applications have started being developed to take advantage of the features enabled by blockchain, such as decentralization, auditability, immutability, transparency, high levels of security and disintermediation (Nicolae, 2024), with attendant cost savings.

Potentially, the range of applications enabled by blockchain use is limitless, encompassing any area which can be reliably organized using ledgers and token transfers. Applications include logistics management (maintenance organization, origin control, supply chain management), identity management, credentials

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management, decentralized marketplaces, distributed autonomous organizations, rewards and other benefit systems (Nicolae, 2024). Increasingly, researchers have turned to the idea that blockchain use can occur within critical infrastructure (CI) systems beyond the financial sector, including the aviation sector, in energy and elsewhere (Vevera and Georgescu, 2024). Neither do the DLT-based systems have to be front-facing with the CI users, they can be a component of a wider system which the ultimate beneficiaries and users may not even know is there. Critical infrastructures are systems composed of assets, resources, facilities and organizations whose destruction or disruption would cause significant loss of human life, material damage and functionality loss, in addition to hits to confidence, because they produce critical goods and services (Georgescu and Cîrnu, 2019). Critical infrastructure operators are mostly private entities, and so they are driven to increase efficiency while, at the same time, being interested in maximizing resilience.

Blockchain technology offers both opportunities to lower costs, as well as to increase resilience and functionality, with the attendant generation of new risks, vulnerabilities and threats (Eniță, 2024).

As part of our research into the issue of digital emerging technologies' impact on critical infrastructures, this article proposes to analyze blockchain technology use within the space sector. Space is now a critical enabler for an immense variety of applications, from weather forecasting to financial market synchronization, and from disaster management to energy grid operations and global transport management. Space systems contribute through their capabilities in data gathering, remote sensing, communications, positioning and synchronization. These capabilities are expanding continuously, as new developments in miniaturization and the economics of launch and construction services change the landscape of the space economy (Botezatu, 2024). Blockchain technologies are also making inroads into the space economy, both in support of current functions, as well as in the role of enabler for new functions and business models. This article presents a key overview of the developments in the field, highlights unique challenges and formulates recommendations for future development.

DISTRIBUTED LEDGER TECHNOLOGY

Distributed ledger technology or blockchain is a digital emerging technology focused on the resolution of conflicts between distributed instances of the same database. It stands in contrast to centralized models of record keeping, where a central entity is trusted to guard the integrity of a database (or "ledger"), as well as validate any legitimate attempts to add to it while flagging fraud and other issues and providing the capabilities to perform audits and analyses (Nicolae, 2024). This high-level description covers everything from banks with accounts to logistics companies and from financial markets to universities issuingdegrees and certifications.

These entities act as middlemen in vital functions and require both time and adequate resources to function, while being themselves corruptible by dedicated agents or open to failures such as fraud and mismanagement. Blockchain aims to solve these issues by making numerous instances of these ledgers kept with independent nodes and creating digital processes for changes to the ledger to be accepted by all of the participants in order for the change to take place, with the process being recorded through the transmission of a dedicated utility token (which may or may not be financialized on secondary markets). This process is automatic, runs independently of human action, provides transparency, traceability and auditability of the process itself (though not necessarily of the contents of the change) and lacks a true central clearing authority that could be suborned, corrupted or which could make mistakes. Figure 1 highlights the main differences between a normal centralized clearing process and a blockchain-based one.

Ideally, the blockchain process is safer, faster, cheaper, more transparent and with potentially

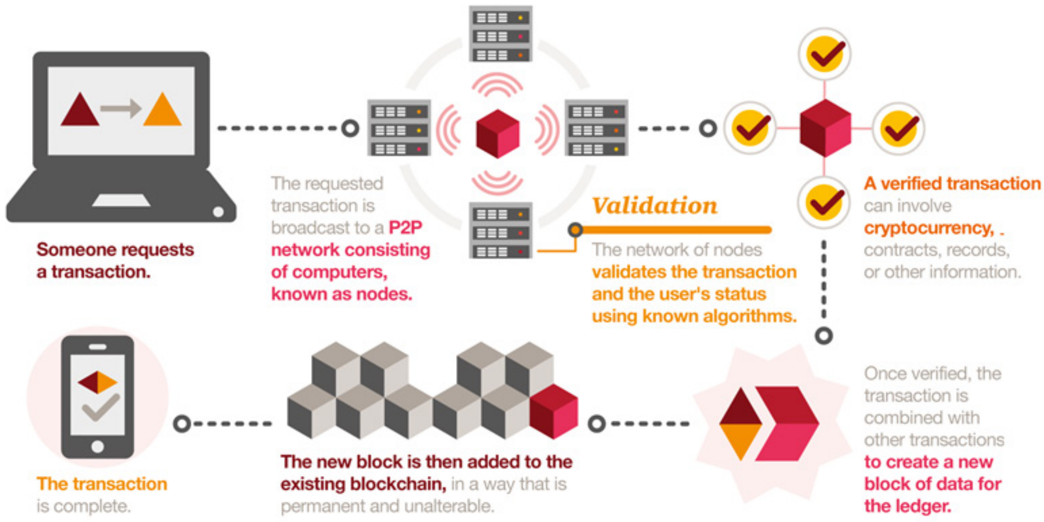

Figure 1. *Explanation for distributed ledger technology processes (source: PwC, 2016)*

numerous other side-benefits resulting from the lack of an intermediary such as added personal data protection. The creator of Bitcoin and the first generation of blockchain products, which were the cryptocurrencies, envisioned decentralized financial systems operating independently of banks and immune to state abuses. The technology did not deliver the full anonymity and fully-formed parallel (libertarian) economies that its founders envisioned, but it rapidly expanded into numerous other fields with new capabilities such as smart contracts while states decided how best to regulate its use, especially in the contentious monetary and financial sectors. While the validation process was initially made up of computationally intensive algorithms that consumed a lot of energy (proof of work) and which required high validation numbers from the nodes, later blockchain examples adopted models such as proof-of-stake (based on random validation of staking nodes for financialized tokens – used increasingly by smart contract blockchains like Ethereum) and proof-of-authority (fewer nodes handled by known trusted entities, such as public institutions – used primarily by government-backed blockchains like the ones running on the European Blockchain Services Infrastructure for government services) (Baboi, 2023). This diversification of blockchains on the market, each with advantages such as lower energy consumption and disadvantages such as a more centralized nature, reflects the growing diversity of users and services running on distributed ledger architectures.

BLOCKCHAIN APPLICATIONS IN SPACE

Now that DLT applications are no longer confined to cryptocurrencies and the financial sector, there is a race to identify new fields and processes amenable to transformation through blockchain. Georgescu and Cîrnu (2019) have discussed the use of blockchain within industrial control systems and other general critical infrastructure applications such as predictive maintenance, logistics, supply chain management, the enforcement of trade secrets and privacy, access to control to systems and user privileges. The new legitimacy for blockchain applications, founded on greater regulation and on mass application, is encouraging an effervescence of new applications, also in the space sector. Some applications specifically address security issues, also in cybersecurity, while it should be noted that Vacusta and Nica (2023) emphasize that blockchain applications that are industry-specific are often running on semi-centralized blockchain networks with a lower number of nodes and which are more prone to brute force attacks that can subvert or sabotage them. In general, DLT applications have been shown to be vulnerable to hacks (in addition to errors in their functioning), depending on the specific architecture, the resources and know-how of attackers and the mode of functioning for the DLT systems.

To provide a clearer framework for understanding distributed ledger technology (DLT) applications in space, we propose a taxonomy that distinguishes between three categories: "Blockchain in Space," "Blockchain for Space," and "Space for Blockchain."

- Blockchain in Space refers to blockchain networks deployed aboard satellites or within space systems themselves, such as the use of smart contracts for inter-satellite communication or satellite-supported data validation (e.g., SpaceChain, OneSafe, 2025).
- Blockchain for Space describes terrestrial blockchain applications aimed at improving space-related operations — such as satellite supply chain tracking, launch insurance, and licensing (Wainscott-Sargent, 2019; IBM, 2019).
- Space for Blockchain refers to using space infrastructure to support broader blockchain networks on Earth, like satellite-enabled crypto wallets or decentralized data storage services (e.g., Blockstream, SpaceBelt). This categorization helps differentiate the intent, architecture, and stakeholder involvement across a growing ecosystem of blockchain-space convergence.

Extensions of current working models in the space sector

Current blockchain applications can be expanded into the space sector, especially when they are process or system-agnostic. For instance, Wainscott-Sargent (2019) emphasizes the use of blockchain in the supply chain management for the production of satellites, as well as the use of smart contracts for governing launches or insurance. The trust, decentralization and transparency of blockchain networks are useful across the entire value chain for the space economy, from the procurement, building, testing, validation, launch and operation of the satellites, to their actual use by clients through the contracting of various services. Of particular and novel importance is the use of blockchain in monitoring space operations and in space governance such as the licensing of satellite launch and operation. Blockchain serves as a valuable tool for the management of suppliers and validating any changes made to the supply chain or manufacturing process. IBM (2019) has described an entire space economic process that uses blockchain peer-to-peer networks to bring together various participants (manufacturers, operators, regulatory entities) within defined channels where smart contracts can be created to manage various assets (data structures related to satellite parts etc.). Figure 2 describes the envisioned ecosystem.

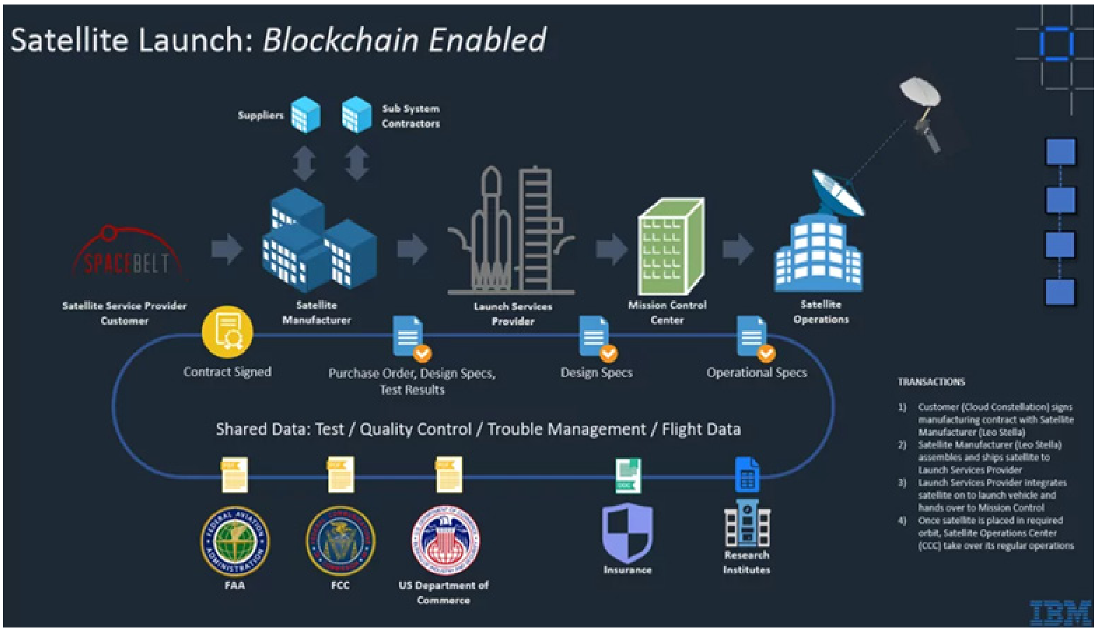

Figure 2. *Blockchain-enabled space entities network (source: IBM, 2019)*

The possibility of data centers not relying on terrestrial communication networks and moving to blockchain-secured satellite networks is also a significant possibility, especially for industries that work with many data sources on remote sites, such as the oil and gas or mining industry, but also for government applications.

DLT capabilities are also being explored by NASA as sources of cybersecurity for inter-satellite communications by employing "zero trust cybersecurity principles by scrutinizing every transaction in the system, examining user credentials and permissions for requested operations, and further inhibiting malicious actors from attacking system resources." (Jones, 2023). Additional controls are needed in the context of the proliferation of constellation plans, especially using nanosatellite architectures, which enable economies of scale in satellite production and launch, making inter-satellite communication just as important as the communication between satellites and ground stations and ground control centers. NASA is already utilizing the Cardano ecosystem for smart contracts which will enable a wide variety of applications in the future (OneSafe, 2025).

New applications

Blockchain can enable satellites to become "smart emancipated devices" (Wainscott-Sargent, 2019), using telecom capabilities to communicate blockchain data and involving satellites in the execution of smart contracts. Satellites then become key assets for blockchain applications on the ground, providing services especially in places lacking in ground infrastructure by verifying data and running smart contracts without human intervention. This is also useful when ground infrastructure or ground control centers are compromised or unavailable. Applications include cadaster services, financial services and various governmental services in places without fixed physical communications infrastructure, such as least developed and developing countries. The core attributes of blockchain such as immutability, transparency and decentralization enable such applications, as well as the sharing of constellation specific data between satellites, enabling autonomous constellation management (WIPO, 2025).

Satellite constellations also provide a "global distribution network that is persistent and sovereignty agnostic" for running various applications (Wainscott-Sargent, 2019). Satellite services provider Blockstream specifically wants to support blockchain validation services for a whole host of users on its satellites systems, starting with a network of transponders on satellites in geosynchronous orbits (https://blockstream.com/satellite/). Over time, they can also enable users to send any form of data through their network in a completely anonymized fashion and pay for it in cryptocurrency. Relevant developments in this sense also include Blockchain-based Privacy Protection Protocol with Smart Contracts (BPPSC) (SimpleSwap, 2024). Other companies plan on satellite support for their proprietary blockchain services. Singapore-based SpaceChain has launched satellites with blockchain-enabled payloads enabling the functioning of a private network that currently offers a cryptocurrency wallet service for users on Earth, enabling cryptofinance without reliance on fixed (and state-controlled) Internet infrastructure (https://www.spacechain.com/).

It is using software-defined satellites to provide an open-source environment for other developers to build blockchain-apps to run on their proprietary network (Decent Cybersecurity, 2024). Moreover, the decentralized nature of blockchain networks enables the formation of constellations based on shared protocols with orbital hardware provided by multiple different entities. This partnership format is totally different from what is the current practice, where constellations are solely managed and built by a single organization, maybe with different suppliers. In this way, instead of one entity building a 100-satellite constellation, which is a significant financial effort, one can build a constellation with five entities, each launching 20 compatible satellites running shared protocols. This solves certain scalability issues, as well as the limits of centralized control structures, also for maintenance.

Blockchain capabilities can also find a role in the management of computing and other resources for deep-space missions that are otherwise reliant on "human in the loop" systems because of the distance from Earth. Edge computing is another similar application that can benefit from blockchain systems, along with data security, with companies such as Cloud Constellations offering "global connectivity directly to the enterprise and secure data storage in orbit, with a roadmap to analytics and edge computing from IBM, as part of its SpaceBelt Data Security as a Service (DSaaS) portfolio" with a constellation of ten low-Earth orbit satellites (Wainscott-Sargent, 2019). The use of blockchain technology can boost sensing and communications, by optimizing the use of bandwidth, improving the quality of communications (through "redefining waveform design within integrated communication and sensing parameters") (SimpleSwap, 2024). Mital et al. (2018) and Mital et al. (2021) have proven the usefulness of blockchain in the exploitation of multi-sensor architectures for satellite networks, addressing "issues of constellation flight architecture, management of computational operation, autonomous observation, time-critical event planning of ground and space autonomous operation of satellite systems". In particular, DLT enables the finetuning by system administrators of access to system services by muti-tiered user databases, which will become especially important when certain channels will be reserved for hybrid AI-blockchain applications enabling the secure transfer of machine learning parameters while maintaining data access privileges (Mital et al., 2018, Jones, 2023). The end result will be the prevention of single points of failure in the systems through decentralized architectures, auditability, data integrity and immutability, and greater security of software updates, which add up to improved cybersecurity outcomes (Decent Cybersecurity, 2024).

J.P. Morgan, as a representative of the financial and banking industry, is also exploring space-based financial services through its Kynexys service, having performed the first "bank-led tokenized value transfer in space" (J.P. Morgan, 2021). It contracted Gomspace to deploy a Consensys Quorum blockchain on one of its low Earth orbit satellites, using it to first perform a transaction between ground and space and then between two different satellites without any human intervention, paving the way for automation of constellation management and of resource allocation through the use of blockchain, starting with peer-to-peer DvP (data versus payment) services (J.P. Morgan, 2021). Another such service, called GEODNET, improves access to geolocation and timing data using blockchain-based space services (https://geodnet.com/product).

The European Space Agency (ESA) is also seeking to implement blockchain in space as part of its Space 4.0 strategic initiative. It has launched competitions for "Kick-Start activities" seeking business applications for blockchain in space. Areas of interest include the automatic processing of Earth Observation data to execute smart contracts on satellite-based DLT services in fields such as insurance or the automatic upload of geolocation data and validation of consignments and handovers for DLT-enabled trustless logistics (ESA, 2019). Prior finalized projects include the SpaceChain Wallet (ESA, 2020a) and the Datarella and Weaver Labs and Oracle Orbital Technologies prototype for Track & Trust logistics systems using a LoRa Mesh multi-hub communication protocols for low-power, long-range wireless communication and an Ethereum based DLT solution (ESA, 2020b). In the smart contracts for insurance area, funded and completed projects include EO claim ledger by Riscognition that automatically processes Sentinel 1 and 2 remote sensing data to initiate insurance payouts for a wide variety of customers (especially in agriculture) (ESA, 2020c). A dedicated agriculture and DLT application is the ongoing EZ Labs SmartAgriSat for precision agriculture project funded in 2023 (EZ Lab, 2023). An application which leveraged both DLT and IoT technologies was Safeblock, which uses sensors in smart buildings and smart cities to evaluate safety norms and compliance with GNSS authentication at source and inscribed results on the Safeblock blockchain service (ESA, 2020d). As a last example, in the blockchain for space category, we find the partnership between Thales Alenia Space and 3IPK, a Slovakian startup, to develop a solution for ESA to ensure the traceability and integrity of Earth Observation data using unique digital signatures and blockchain (Thales Alenia Space, 2023).

Technical limitations of consensus mechanisms in space

The deployment of blockchain technologies in space must contend with a variety of technical constraints that significantly impact consensus mechanisms. Notably, latency is a primary challenge due to the long distances between satellites and ground stations or among satellites themselves, making real-time validation through traditional consensus models like proof-of-work or proof-of-stake impractical. Bandwidth limitations also pose a problem, especially for nanosatellite constellations, where communication resources are severely constrained. Furthermore, space radiation can affect both hardware reliability and data integrity, which are critical to maintaining secure and accurate ledgers in space environments. As discussed by Baboi (2023), even terrestrial consensus mechanisms are vulnerable to attacks if not properly tuned; these vulnerabilities are exacerbated in the harsh conditions of space. Mitigating these issues may require lightweight consensus mechanisms such as proof-of-authority or hybrid models optimized for delay-tolerant networking (DTN) architectures.

Trends in space DLT applications

Blockchain applications within the space sector are likely to follow similar adoption patterns as in other fields. Firstly, there will be easy adoption (from a technical standpoint, not necessarily regulatory) within business and financial processes which are immediately amenable to disintermediation (payments, identity checks, privileged access check, maintenance, component tracing). There is an interesting use case for blockchain in product control for respecting restrictions on the export of dual-use technologies, especially in aerospace (the ITAR regime), where there is a concern regarding the illicit transfer of advanced materials, avionics and other components to rogue and sanctioned states. These facile blockchain applications can either be unilaterally adopted (such as payment options and identity control), or they may require adoption within an entire ecosystem of users (maintenance and logistics) which becomes a coordination problem that is difficult to resolve outside of state intervention. A useful analogy is with the International Air Transport Association (IATA). IATA's efforts on promoting blockchain use (including through an ecosystem of apps running on its own IATAcoin) are instructive with regards to the difficulties and possibilities of blockchain adoption in aerospace ecosystems, as opposed to targeted applications (Vevera and Georgescu, 2024). IATA (2018) presents the Travel Grid platform, a general view of IATA's vision in translating business models from other sectors into aviation (figure 3), using IATA's central role in the industry as a factor in coordinating adoption.

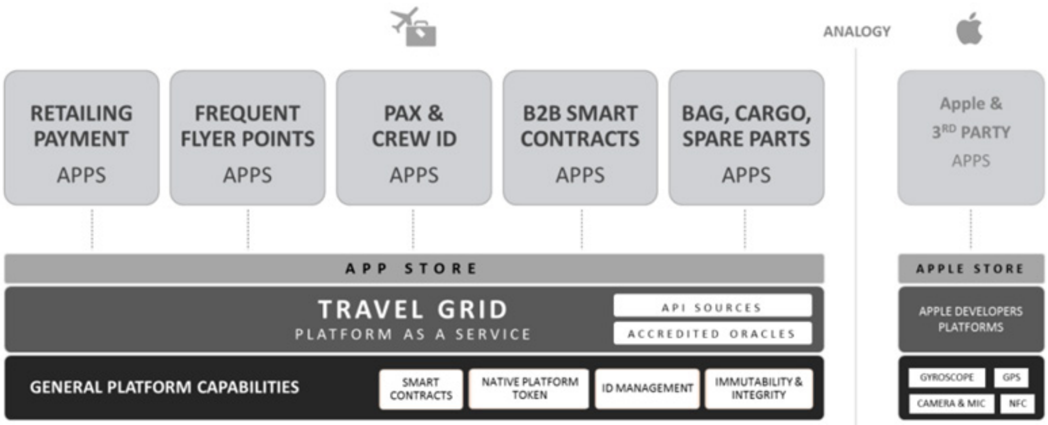

Figure 3. *The Travel Grid platform of IATA (source: IATA, 2018)*

Poleshkina (2021) also emphasizes the role of blockchain in ground operations in the aviation sector, which are a useful parallel to space operations as well, since their specific operations bear a strong resemblance to aviation – cargo handling, fueling, spacecraft assembly, checks for leaks and other damage in reusable craft, verification of certificates in equipment and components etc.

Secondly, entrepreneurs and scientists will begin to think outside the box with regard to blockchain use in the space sector to enable new capabilities, use cases and business models. We have already presented ongoing research on constellation management through blockchain control mechanisms, as well as the role of satellites in supporting new blockchain services in general, with lower reliance on fixed ground infrastructure which may be restricted or subverted. The intersection between blockchain and Artificial Intelligence, or blockchain and quantum computing, is also likely to enable new space services and working models. The key dichotomy here is between back-office and front-office blockchain applications within space systems, referring to the possible interaction between end-users and blockchain systems. We are likely to see increased regulation efforts from states to address illegitimate uses of these systems and new cybersecurity vulnerabilities and threats.

As adoption increases, these developments will necessitate robust models for coordination and oversight, particularly in multi-actor ecosystems. As satellite constellations grow in scale and complexity, particularly with participation from multiple stakeholders, interoperability becomes a fundamental concern. The decentralized and trustless nature of DLT makes it well-suited for international and commercial collaboration, but effective governance models are required. These should specify shared standards for consensus mechanisms, identity management, smart contract execution, and dispute resolution. Multi-actor constellations—where different entities contribute to compatible satellites require a federated governance structure, potentially anchored in neutral institutions or smart contract-based DAOs. Vevera and Georgescu (2024) offer lessons from aviation blockchain ecosystems, while initiatives like SpaceChain and Blockstream highlight early examples of federated space-based DLT networks. Further research should explore DLT standards under the umbrella of international frameworks, such as those promoted by the ITU or ISO.

CONCLUSIONS

We have reiterated the argument of the systemic importance of space infrastructures to a wide variety of terrestrial applications in energy, transport and more. The rapid technological development in this field concerns not just the miniaturization of systems or the use of better sensors, batteries, propulsion or shielding, but also the implementation of emerging digital technologies to reduce costs, increase efficiency and unlock new capabilities. One such emerging technology is distributed ledger technology, which can not only streamline and disintermediate key processes in logistics, payments, access control and others, but can also generate new applications such as better options for constellation management, less reliance on expensive and extensive ground infrastructure and, potentially, revolutionary new applications. We have systematized the current thinking regarding blockchain use in the space sector and used our findings to anticipate future trends, including through reference to the related aviation/aerospace sector. Future research in this field needs to push the envelope of the technical possibilities of blockchain implementation in space and must also start to address security concerns both with regards to individual systems, infrastructures and processes, as well as at the systemic level. Such research will be of use to policymakers in deciding whether and how to regulate blockchain use in the space sector.

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