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Blockchain Technology for Space Surveillance in Indian Airspace: A Comprehensive Academic Review

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Abstract

Space surveillance constitutes a critical domain for national security, aerospace management, and the sustainable use of orbital environments. As the volume of space objects—including active satellites, defunct spacecraft, and orbital debris—continues to grow, the integrity, security, and interoperability of surveillance data become paramount. This review examines the potential application of blockchain technology to space surveillance, with particular emphasis on the Indian airspace context. Drawing upon evidence from blockchain fundamentals, remote sensing data management, air traffic management, unmanned aerial vehicle (UAV) communications, and space traffic management (STM) architectures, this paper synthesizes current knowledge on how blockchain's properties of decentralization, immutability, transparency, and security can address persistent challenges in aerospace data governance. The review identifies applications including tamper-proof telemetry logging, decentralized multi-agency data sharing, smart contract-enabled automation, cybersecurity enhancement, and satellite lifecycle management. Challenges such as computational demands, latency constraints, integration complexity, and regulatory ambiguity are critically assessed. The paper concludes with future directions encompassing AI-blockchain convergence, quantum computing integration, and international collaboration frameworks.

Keywords: *Space Surveillance, Blockchain Technology, Data Integration, Decentralized Governance, Artificial Intelligence*

1. Introduction

1.1 The Imperative for Space Surveillance in India

Space surveillance is a multidimensional activity that involves detecting, tracking, identifying, and cataloging objects in Earth's orbit, as well as monitoring aerial threats within sovereign airspace. The orbital environment is currently experiencing unprecedented congestion. According to **Chen et al. (2013)**, the increasing number of on-orbit satellites and debris objects is creating a high-risk environment. A seminal example of this risk was the 2009 collision between Iridium 33 and Kosmos 2251, which produced over 2,000 pieces of trackable debris. This catastrophic event was largely attributed to "imprecise SSA [Space Situational Awareness] data, and inadequate methods of orbital updates or data sharing" **(Chen et al., 2013)**.

For a nation like India, which operates an expansive and growing constellation of satellites for communication, navigation, Earth observation, and defense, a robust space surveillance system is not merely a technical requirement but a pillar of national security. India's defense posture has already been enhanced through the deployment of advanced radar systems and surveillance architectures, such as the Israeli Phalcon AWACS and AESA radars, which significantly increase cross-border monitoring and communication interception capabilities **(Xie et al., 2019).** Protecting these assets requires high-integrity, high-availability, and auditable data flows to support operational decision-making.

1.2 Current Challenges in Aerospace Governance

The challenges currently facing space surveillance are multifaceted and systemic. Existing Space Traffic Management (STM) services are primarily centralized and designed for a limited number of specialized consumers. Consequently, these systems lack the scalability needed to handle the projected 10- to 100-fold increase in orbital population **(Blakeslee et al., 2020)**. Furthermore, the data sources for surveillance are highly heterogeneous, ranging from ground-based radars and optical telescopes to space-based sensors. Integrating this diverse information is essential for managing the complexity, dynamics, and uncertainties of modern space systems **(Aste et al., 2017)**.

Another persistent concern is the validation of satellite-derived data products against "ground truth" observations. Studies evaluating

satellite retrievals against in-situ networks highlight the need for traceable evaluation and governance of data versions **(Chen et al., 2013; Xie et al., 2019)**. Operational decisions depend on these data flows, yet maintaining multi-party trust remains a hurdle once data is exchanged between different organizations.

1.3 The Relevance of Blockchain Technology

Blockchain technology offers a new paradigm to address the core requirements of space surveillance: data integrity, multi-stakeholder trust, and decentralized coordination. Fundamentally, blockchain is a distributed ledger that uses a consensus protocol and cryptography to achieve trust transfer and security **(Robinson & Mazzucato, 2019)**.

Major space agencies have already signaled interest in this technology. NASA has expressed intentions to launch blockchain-based missions and to implement blockchain in internal operations **(Mazzucato & Robinson, 2018)**, while the European Space Agency (ESA) has emphasized the relevance of integrating blockchain into remote sensing to support automation through smart contracts without a central authority **(Silber & Price, 2016)**. In the context of "Web3," blockchain is seen as a direct response to problems of centralization and data control, emphasizing peer-to-peer coordination **(Üstündağ et al., 2023)**.

2. Background and Fundamentals

2.1 Core Properties of Blockchain Technology

Blockchain operates as a distributed ledger technology (DLT) that allows transactions to be recorded concurrently on thousands of servers via a peer-to-peer (P2P) topology **(Salah et al., 2019)**. Its foundational properties distinguish it from conventional centralized databases:

- **Decentralization:** By eliminating the reliance on a central authority, blockchain ensures that data is tamper-proof **(S & Valarmathi, 2025).** This decentralization mitigates single points of administrative control.
- **Immutability:** Once data is validated by most "miner" nodes, it becomes a permanent and verifiable part of the record **(Alkhudary & Gardiner, 2024).** This ensures the integrity and traceability of information.

- **Transparency:** Distributed ledgers can make previously hidden processes visible, providing new ways to hold parties accountable **(Babazade & Gurtov, 2022)**.
- **Security:** The chained data structure, combined with distribution across peers, ensures that any tampering with a block changes its hash value, making modifications immediately detectable **(Pierce et al., 2024).**
- Blockchain platforms are generally categorized as public (permissionless) or private (permissioned), with "consortium blockchains" offering an intermediate model where a preselected group maintains the ledger—a model highly suitable for multi-agency defense environments **(Robinson & Mazzucato, 2019; Shafay et al., 2021).**

2.2 Sensing and Monitoring in Space Surveillance

- Space surveillance integrates several sensing modalities to maintain awareness of the orbital environment:
- **Space-Based Sensing:** Instruments like the International Space Station Lightning Imaging Sensor (ISS LIS) provide real-time data with high timing accuracy (better than 2 ms) and horizontal location accuracy (~3 km), proving vital for operational forecasting **(Reegu et al., 2023; Blakeslee et al., 2020).**
- **Ground-Based Sensing:** This includes radar networks and optical telescopes, as well as VLF (Very Low Frequency) narrowband measurement systems, which serve as an inexpensive remote sensing technique for probing the ionosphere **(Biswas et al., 2023; Silber & Price, 2016).**
- **AI Integration:** Artificial Intelligence is increasingly used to support decision-making and enable automated detection and classification pipelines **(Nag et al., 2021).**
- The integration of these building blocks into a cohesive system requires a coordination layer that can handle heterogeneous sensors with differing error modes and provenance requirements **(Silber & Price, 2016).**

3. Blockchain Applications in Space Surveillance

3.1 Data Integrity and Tamper-Proof Telemetry Logs

The primary use of blockchain is to record diverse data types such as assets, obligations, and identity records while ensuring their reliability as an information infrastructure **(Aste et al., 2017)**. In

remote sensing, a multi-level blockchain architecture can improve data security by storing data in the Interplanetary File System (IPFS) and uploading hashes to the Ethereum chain for public verification **(Batista et al., 2021)**. This approach addresses the vulnerability of centralized cloud systems, which can lose all data if a central server is successfully attacked **(Batista et al., 2021)**. For space surveillance, this ensures that telemetry logs and orbital element sets are tamper-evident and auditable.

3.2 Decentralized Data Sharing Across Agencies

Space surveillance involves a multitude of stakeholders, including defense agencies (DRDO, IAF), civilian space organizations (ISRO), and international partners. Blockchain enables coordination without the need for a single trust anchor **(Aste et al., 2017)**. For example, the "System-Wide Information Management" (SWIM) concept in air traffic management aims to enhance secure data sharing between stakeholders; blockchain can augment this by providing cryptographic guarantees of data provenance **(Pierce et al., 2024)**. This enables "shared situational awareness," where contributors can rely on the distributed ledger rather than a single database administrator.

3.3 Smart Contracts for Automation

Smart contracts are self-executing code deployed on a blockchain that can automate workflows with transparency and trust **(Batista et al., 2021)**. In a surveillance context, these contracts could specify specific conjunction assessment thresholds to automatically trigger collision-avoidance notifications when proximity criteria are met. This principle is already being explored in UAV communications to enable automated agreements between drones and other entities **(S & Valarmathi, 2025)**.

3.4 Cybersecurity and GPS Protection

Blockchain's distributed nature eliminates single points of failure, enhancing the cybersecurity of command-and-control systems **(Mazzucato & Robinson, 2018)**. A notable application is the potential to secure GPS signals; in the event of GPS spoofing, a system could rely on a blockchain-based digital ledger instead of the jammed signal to maintain operational integrity **(Mazzucato & Robinson, 2018)**. This provides a layer of accountability for data exchanges and actions within aerospace pipelines.

3.5 Satellite Lifecycle Management

Borrowing from the drone registration paradigm, blockchain can assign unique, tamper-proof identifiers to space objects **(Babazade & Gurtov, 2022).** This enables real-time tracking and improved compliance throughout the satellite's lifecycle, from manufacturing to decommissioning. It also facilitates risk management in the spacecraft supply chain by sharing information across a secure, distributed network (Aste et al., 2017).

4. Strategic Importance for Indian Airspace

4.1 Enhancing Trust Between Agencies

The Indian space ecosystem involves ISRO (civilian), DRDO (defense research), the Indian Air Force, and an emerging private sector. Blockchain's distributed ledger can establish "trust and transparency among stakeholders" by recording and verifying all interactions **(S & Valarmathi, 2025)**. By utilizing a consortium model, India can ensure that data is shared securely among preselected agencies without requiring full public transparency.

4.2 Real-Time Hazard Coordination

The ability of space-based sensors to deliver operationally relevant data in near real-time, as shown by the ISS LIS, is critical for Indian aviation and defense **(Reegu et al., 2023)**. Blockchain-enabled coordination can streamline the dissemination of conjunction warnings and debris-tracking updates, even in communication-degraded environments, by leveraging Edge AI and auditable ledger operations **(Mazzucato & Robinson, 2018).**

4.3 Resilience and National Policy

Decentralization offers inherent resilience against cyberattacks because data is distributed across multiple nodes; the loss of one server does not compromise the entire system **(Batista et al., 2021).** This aligns with India's Digital India and Make in India initiatives. Mission-oriented policies can help space agencies create new markets while aligning technological development with national strategic objectives **(Robinson & Mazzucato, 2019).** Furthermore, for India, blockchain architectures must be designed as both technical and legal artifacts that govern the rights over surveillance data and intelligence **(S & Valarmathi, 2025).**

5. Challenges and Constraints

5.1 Computational Overhead and Latency

A significant hurdle is the computational demand of consensus mechanisms, such as proof-of-work, which can introduce delays in data processing **(Shafay et al., 2021).** In applications like collision avoidance, where timing accuracy is measured in milliseconds, these latencies represent a major constraint **(Reegu et al., 2023).** Current research indicates that performance and scalability remain unresolved when integrating blockchain with high-throughput AI systems **(Salah et al., 2019).**

5.2 Organizational and Technical Integration

Integrating blockchain into established aerospace infrastructure is not a simple "add-on" but requires substantial organizational transformation. NASA's experience with Model-Based Systems Engineering (MBSE) suggests that large agencies must undergo structured change management **(Pierce et al., 2024; Zou et al., 2023).** Additionally, the interoperability between blockchain platforms and legacy aerospace systems remains a significant technical challenge **(Salah et al., 2019; Alkhudary & Gardiner, 2024).**

5.3 Regulatory and Legal Ambiguity

In India, the legal framework for blockchain is still developing. Legal analyses of blockchain-adjacent technologies, such as NFTs, highlight the urgent need for clarity on ownership, rights management, and infringement **(Dua, 2022; S & Valarmathi, 2025).** This regulatory uncertainty creates hurdles for deploying blockchain in sensitive defense and surveillance contexts where data rights and accountability are paramount.

6. Global Context and Future Directions

6.1 Lessons from International Space Agencies

- **NASA:** NASA's Ames Research Center has proposed STM architectures with standardized open interfaces. While their primary focus has been on service-oriented architecture, the agency's shift toward public-private partnerships creates an innovation ecosystem conducive to blockchain experimentation (Mazzucato & Robinson, 2018).
- **ESA:** The European Space Agency has explicitly promoted the assimilation of blockchain for remote sensing and automation. Their participation in the European Blockchain Partnership aims to

develop resilient blockchain service infrastructures for the continent.

6.2 AI and Quantum Convergence

The convergence of blockchain and AI is a major research frontier. Blockchain can provide an auditable record of AI-generated threat assessments, increasing trust in automated systems **(Salah et al., 2019; Wihartiko et al., 2021).** However, the advent of quantum computing poses a threat to current cryptographic foundations, necessitating the development of quantum-resistant protocols **(Silber & Price, 2016).**

6.3 Toward International Collaboration

Since orbital objects traverse multiple jurisdictions, space surveillance is inherently international. Blockchain can serve as a secure, auditable mechanism for international data exchange without a single intermediary. Future frameworks for Space Traffic Management (STM) could incorporate blockchain verification layers into existing standards, such as those from the Consultative Committee for Space Data Systems (CCSDS).

7. Conclusion

Blockchain technology serves as a transformative coordination and trust layer, enhancing the security, integrity, and interoperability of space surveillance data. By leveraging decentralization, immutability, and smart contracts, surveillance systems can move away from vulnerable centralized models toward resilient, multi-stakeholder architectures.

For India, the path forward requires interdisciplinary research involving aerospace engineering, cryptography, and defense studies. Collaboration between ISRO, DRDO, and the Indian Air Force, modeled on NASA's evolving partnership frameworks, can accelerate development. While challenges in latency, computational cost, and regulation persist, the strategic benefits of blockchain for national security and the global governance of space are profound.

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