Blockchain Enabled Space Traffic Awareness (BESTA)

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ABSTRACT

Today, satellite launches, on-orbit operations, and deorbiting by space faring countries is manual-intensive and safe. However, projected increases in both number of space faring nations, and volume of space traffic, will strain these processes and operations, and require increased stakeholder coordination and automation. Stakeholder coordination requires situational awareness of the current orbit and position of satellites, launch paths through the atmosphere, and deorbit paths at end of life. Today, situational awareness of orbits is expressed in the USSTRATCOM (U.S. Strategic Command) space catalog, where objects are screened and potentially updated at least daily.

Maturation of current launch, orbit, and deorbit lifecycle processes and operations into STM (Space Traffic Management) requires not only USSTRATCOM orbital data in the current space catalog, but also orbital data from commercial launch and payload companies, academic and lab observations, and all space faring nations. Recently, U.S. Dept. of Commerce is tasked under Space Policy Directive – 3 to provide a catalog to incorporate SSA (Space Situational Awareness) data from not only traditional sources, but also commercial companies, and SpOC (Space Operation Center) data from other nations. Today, this data is provided in siloed services with independent access rules. Beyond orbital data, launch paths through the atmosphere, and deorbit paths must be included.

STM situational awareness must be useful for space operations in a tactical timeline, versus a post-mortem autopsy, and must remain current and relevant during expected and unexpected circumstances. STM situational awareness also must be extensible to include new data types and sources, with transparent access for all stakeholders to access data once written. This expanded definition of situational awareness tracks assets from ground to space and back is challenged by the need for data collection and sharing among a diverse and increasing number of stakeholders. The classic approach is to create a new repository, owned and operated by a single stakeholder. Yet, as number of data types and stakeholders increase, confidence decreases in the single owner and operator.

BESTA (Blockchain Enabled Space Traffic Awareness) is proposed as both an extension to the current catalog, and as an alternative to the single owner / operator model. Blockchain technology is uniquely suited to enable reading and writing among all STM stakeholders, by increasing the confidence in data that is cryptographically attributed to the originator, where that data cannot be counterfeited, changed, or destroyed. Blockchain provides the opportunity to streamline stakeholder relationships, shortening timelines for capturing data, and provides a secure foundation for increased automation. BESTA is an extension of ongoing MITRE permissioned blockchain research and prototypes, including capturing orbital element sets from space sensors. BESTA is based on open source technology, and proposed as an internationally governed effort, usable by all stakeholders.

BESTA provides SSA, based on space object position data input from space sensors owned and operated by contributing nations and commercial interests. SSA data is recorded on the BESTA blockchain which is resilient to attacks and tamper evident via native blockchain cryptographic functions. Contributing nations own and operate BESTA blockchain nodes providing a large diversity of operating and political environments, ensuring that BESTA will continue to operate in the event of loss of nodes or malicious nodes. All BESTA nodes operate in a peer-to-peer manner, which prevents any node from imposing their will upon other nodes.

BESTA is informed with SSA position data from contributing countries and commercial interests. In addition, BESTA supports international governance bodies by securely recording critical shared agreements that support STM

implemented as processes and blockchain smart contracts (e.g. conjunction alerts). Further, BESTA captures the governing agreements by pairing blockchain technology with decentralized file systems to securely store documents such as policy and regulation, protected against tampering and deletion.

BESTA assumes an architectural context, managed by the governing body to prioritize activities to reach shared agreements. Once agreements are reached, the documents and shared agreements are recorded in the blockchain and decentralized file system. The corpus of recorded agreements informs the larger architecture and completes the cycle of innovation.

1. BACKGROUND

Satellite launches, on-orbit operations, and deorbiting is manual-intensive and safe, and requires stakeholder SSA (Space Situational Awareness), coordination, and automation. However, projected increases in both number of space faring nations, and volume of space traffic, will strain these processes and operations, and require increased stakeholder coordination and automation.

Stakeholder coordination requires situational awareness of the current orbit and position of satellites, launch paths through the atmosphere, and deorbit paths at end of life. Today, much of space situational awareness of orbits is expressed in the USSTRATCOM (U.S. Strategic Command) space catalog [1], where objects are screened and potentially updated at least daily. Recently, SPD-3 (U.S. Space Policy Directive – 3) [2] directs the DoC (U.S. Dept. of Commerce) to provide a catalog that incorporates SSA data from not only traditional sources, but also commercial companies (e.g. LEO-Labs, AGI), and SpOC (Space Operation Centers) data from other nations (e.g. Germany, France, Australia).

SPD-3 directs U.S. Government to:

- Provide basic SSA data and basic STM (Space Traffic Management) services to the public (Sec. 4.d Goals)
- Improve SSA data interoperability and enable greater SSA data sharing (Sec. 4.e Goals)
- Improve SSA coverage and accuracy (Sec. 5.a.i Guidelines)
- Establish an Open Architecture SSA Data Repository (Sec. 5.a.ii Guidelines)

There are additional space situational efforts such as APOSOS (Asia-Pacific Ground-Based Optical Space Object Observation System) organized by China, ISON (International Scientific Optical Network) organized by Russia, as well as commercial and academic sensors. Today, the SSA data above is provided as disparate siloed services with independent access rules.

Maturation of current launch, orbit, and deorbit lifecycle processes and operations into STM requires not only DoC orbital data in the current space catalog, but also orbital data from APOSOS, ISON, commercial launch and payload companies, academic and lab observations, and all space faring nations. Today, this data is provided in siloed services with independent access rules. Beyond orbital data, launch paths through the atmosphere, and deorbit paths must be included.

SSA for STM must be useful for space operations in a tactical timeline, versus a post-mortem autopsy, and must remain current and relevant during expected and unexpected circumstances. STM situational awareness must also be extensible to include new data types and sources, with access for all stakeholders to data once written. This expanded definition of situational awareness tracks assets from ground to space and back is challenged by the need for data collection and sharing among a diverse and increasing number of stakeholders. This paper focuses on timely information sharing among diverse stakeholders to support STM.

The international space faring community will benefit by sharing SSA from the above sources and more. Sharing SSA information among competitive nations and commercial interests requires transparency, identifying which party is contributing what data (identity, and data provenance), and trust in the safe keeping of SSA data (data integrity, availability, resilience to accident and attack). Sharing SSA information among competitive nations and commercial interests requires a mutually beneficial mission (STM and flight/orbit safety) and transparent structure of data protection to incentivize cooperation. The FAA (U.S. Federal Aviation Administration) overcame the competitive concerns among commercial airlines though a clearly defined structure of data protection in the ASIAS

(Aviation Safety Information Analysis and Sharing) program [3], and this effort can inform improvements to SSA and STM.

BESTA (Blockchain Enabled Space Traffic Awareness) is proposed as both an extension to the current catalog, and as an alternative to the (multiple) single owner / operator model. Blockchain technology is uniquely suited to enable reading and writing among all STM stakeholders, by increasing the confidence in data that is cryptographically attributed to the originator, where that data cannot be counterfeited, changed, or destroyed. Blockchain provides the opportunity to streamline stakeholder relationships, shortening timelines for capturing data, and provides a secure foundation for increased automation.

2. DIFFUSED AND CENTRALIZED MISSION INFORMATION SHARING

Missions are multi-stakeholder endeavors which span enterprise stakeholders and end user persons. These missions deliver benefits for the stakeholders and individual persons and require cooperation and coordination among stakeholders to achieve success.

Examples of multi-stakeholder missions include:

- Cryptocurrencies
- Food safety and other supply chains
- Logistics and shipping
- Sensing
- Financial and banking

Cooperation and coordination are largely achieved by stakeholders exchanging data across their enterprise and organizational boundaries, often in diffused (all-to-all), centralized (all-to-one), or feudal (islands of centralization) information sharing approaches. A government, commercial, or other enterprise typically has their own identity and credential regime, and funds, owns and operates its own computing and data resources. Each stakeholder is responsible to maintain their data inside their own enterprise, including their version of situational awareness of the entire mission, sharing as needed with other mission stakeholders to execute their contribution to mission execution.

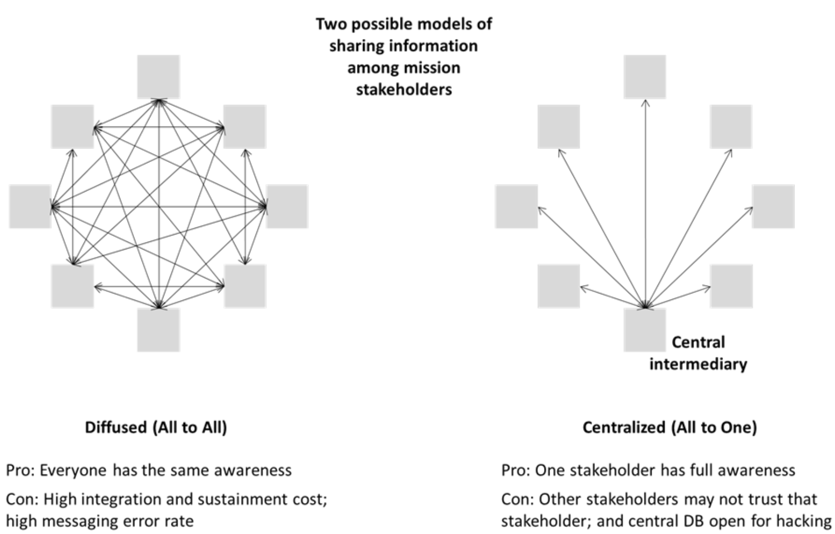

Fig. 1. Possible Information Sharing Models

Two types of mission stakeholder information sharing are diffuse and centralized, see Fig. 1. Each pose significant challenges to free flow of sharing mission information. The diffuse model requires each stakeholder to negotiate with all the other stakeholders to bridge bi-lateral security and data sharing protocols. Each new stakeholder is required to integrate with all other stakeholders and requires existing stakeholders to integrate with the newcomer.

This results in significant integration and sustainment cost, as well as numerous points of failure for exchanging information, due to political, technical, accidental, and malicious attack causes.

One approach for information sharing within a mission is to create a new centralized repository, owned and operated by a single stakeholder who functions as a centralized intermediary, and whose data is collected from all or a subset of stakeholders, and later used by all mission stakeholders. One example of a centralized intermediary is the USSTRATCOM publication of the www.space-track.org space object catalog [4]. The data is centrally collected from sensors (e.g. government and commercial) and published as a centralized resource.

The obvious benefit of the centralized information sharing model is a simplified data exchange where each stakeholder accesses one space catalog. However, as the criticality and number of data types and stakeholders increase, so does distrust of the single owner and operator among the stakeholder community.

Stakeholder distrust of shared information can arise in each of the diffused, centralized, or feudal information sharing models. The diffused sharing model can drop messages (e.g. accident or attack) and prevent each stakeholder's internal mission worldview from accurately reflecting reality. When stakeholder's internal worldviews are not in sync with reality, distrust increases (e.g. do I have all the critical data?) and cooperation is slowed or inhibited. The centralized sharing model attempts to correct the synchronization problem (e.g. one source of data) but in turn introduces distrust due to one stakeholder holding all the data (e.g. possibility of agenda driven data), since there may be no assurance of integrity and availability (e.g. lack of cryptographic proof). The feudal sharing model combines aspects of both centralized and diffuse and inherits the data sharing problems of both.

An alternative is to decentralize the mission using blockchain technology [5].

3. DECENTRALIZED MISSION INFORMATION SHARING

Missions can improve the sharing of information and mission outcomes, by requiring stakeholders to post information sharing transactions to a shared mission blockchain. The mission blockchain is conceptually external to all stakeholders, while being shared by all stakeholders. This is a disruptive change from legacy information sharing models, whether diffuse, centralized, or feudal. These legacy information sharing models require each stakeholder to generate and maintain their own internal copy of needed mission data in their enterprise. Independent copies of mission data introduce risk of data misalignment among stakeholders.

In contrast, a decentralized information sharing model externalizes mission data to the blockchain, which is comprised of independent nodes, each of which contain a redundant copy of all the data posted to the blockchain, see Fig. 2. Stakeholders operate blockchain nodes in their enterprise environments in accordance with mission governance decisions. Ideally, blockchain nodes will operate in sufficiently diverse operating environments to provide resiliency to attack. Regardless of node allocation to operating environments, nodes must maintain P2P (Peer-to-Peer) network connection with each other to validate transactions and perform consensus on blocks of transactions.

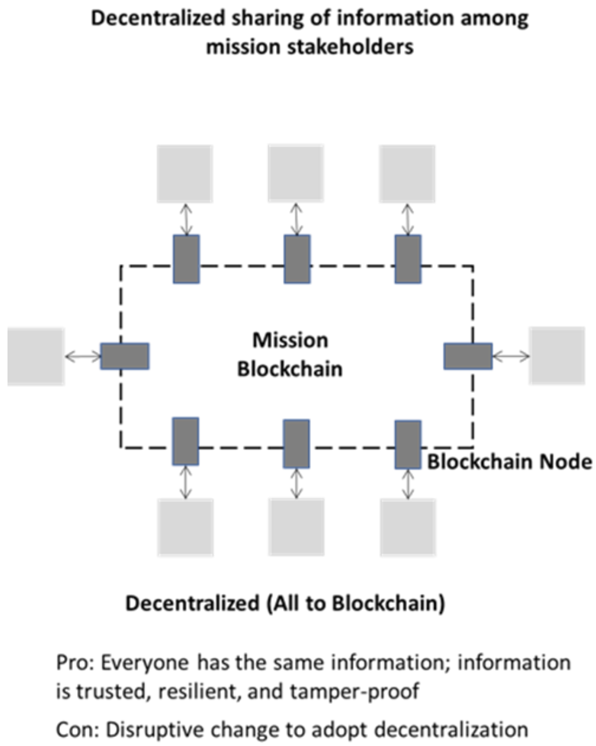

Fig. 2. Decentralized Information Sharing Model

Using blockchain, all stakeholders post and read transactions, simplifying information exchange and maximizing data transparency. The blockchain uses multiple nodes for redundancy, where posted transactions are replicated across blockchain nodes, and data consistency is assured by the consensus algorithm. Each stakeholder reads each other's blockchain transactions, improving situational awareness, self-synchronization, and outcomes. Each stakeholder bears the responsibility to update their own enterprise data capabilities to incorporate blockchain as the mission authoritative source for shared information.

Stakeholders individually have confidence in the blockchain data, even if they would not necessarily trust each other bilaterally without the blockchain. Some blockchain descriptions use the term "trustless" although this is confusing. A better description is that stakeholders who may not otherwise trust each other, can trust the blockchain and share specific agreed types of mission data for the mutual benefit of stakeholders engaged in a common mission.

Blockchain was first used to implement cryptocurrency such as Bitcoin [6], which records amounts of digital value (BTC) assigned to users via their public Bitcoin addresses. Blockchain later evolved to support commercial activities, such as the Walmart food safety blockchain network, where the blockchain records food supply chain events (e.g. harvest, process, retail sale) as blockchain transactions. Both cases can be described as missions with many users or stakeholders, where effective information sharing can improve mission outcomes (e.g. indisputable ledger of Bitcoin ownership, rapid response to tainted food).

Cryptocurrencies are implemented with public blockchains, frequently with thousands of nodes, operated by crypto mining companies and individuals alike. Public blockchains use a consensus mechanism that is competitive, energy intensive, and can survive sizeable attacks up to nearly half of the nodes being malicious. Commercial and government missions frequently use permissioned blockchains, with a hundred or less nodes, controlling which nodes are permitted to join, participate, and leave. Permissioned blockchains which use the voting-based byzantine fault tolerant consensus mechanism, is significantly faster and less energy intensive, and can survive attacks up to almost a third of the nodes being malicious.

4. BESTA ARCHITECTURE

BESTA is proposed as an open source, internationally funded, built, governed, and operated permissioned blockchain to record SSA of space objects, and other critical data to enable international cooperation in the STM mission.

BESTA captures the catalog of SSA space objects position data, recorded from independent sensors, curated feeds (e.g. DoC, Russia, China), commercial, and academic sources, see Fig. 3. BESTA is also proposed to record SSA data such as intents to maneuver, as well as critical international governance shared agreements that support STM such as architecture, policy and regulation documents. Blockchain technology provides trust in SSA data and shared agreement documents by using cryptographically hashed documents, added to blockchain transactions which are signed by the originator (proof of origin), and cannot be counterfeited, changed, or destroyed (proof of integrity). BESTA is owned and operated by international stakeholders providing diversity of operating and geopolitical environments, ensuring that BESTA will continue to operate in the event of accidents or attacks. Blockchain technology enables use of increased automation (e.g. smart contracts) to process data as it is recorded as a transaction.

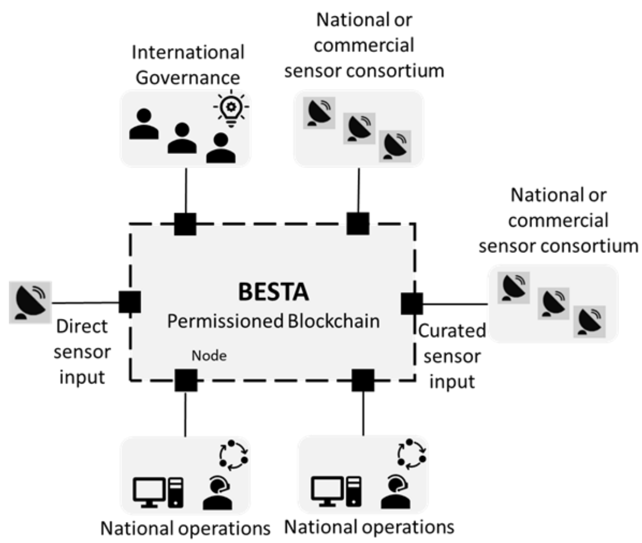

Fig. 3. BESTA Architecture

BESTA assumes a technical and architectural context managed by the BESTA international governing body, to prioritize activities to develop and operate the blockchain, record SSA data, and record shared agreements including smart contracts (e.g. support conjunction alerts). Once agreements are reached, the document hashes and shared agreements are recorded in the blockchain, and the files stored in appropriate repositories. The corpus of recorded agreements informs the larger architecture and cycles of innovation. BESTA concepts are an extension of ongoing MITRE research SNARE (Sensor Network Autonomous Resilient Extensible) which uses permissioned blockchain to record orbital element sets from space sensors, discussed next.

SNARE (Sensor Network Autonomous Resilient Extensible) is a prior MITRE architectural and operational concept that uses permissioned blockchain for a space-based sensor network which is sensor agnostic, extensible, and enables the use of traditional and non-traditional sensor data to achieve greater observational capacity and information gain. The SNARE concept enables storage and processing of any position state measurement. Initially, state will be constrained to space object positional data (e.g. state vector/covariance or TLE (Two Line Element set)). One goal is to increase custody of objects, which refers to the ability to unambiguously detect and track the position of an object to a specified degree of certainty.

SNARE is decentralized and enables sensors associated with SNARE nodes to independently collect space object position state data and share data with each other via the blockchain. Ideally, sensors in SNARE can perform complex sensor data collection as an autonomous and decentralized swarm, providing greater information gain than a centrally tasked federation of sensors. SNARE seeks to maximize overall information gain, while minimizing resource loading to individual sensors, using techniques like coordinated search, autonomous tip and cue, and uncertainty resolution. SNARE uses algorithms and blockchain technology, to provide sensors the ability to coordinate and self-synchronize (e.g. tip and cue) by sharing the position state written to the blockchain. Both the blockchain and the algorithms execute on each SNARE node.

Algorithms, presently under development, include logic to inform each sensor of opportunities to track objects (subject to physical and time-sensitive constraints of the sensor), and to resolve conflicting position data. These algorithms are partitioned into complementary local and global functions. The global function maximizes overall information gain with minimal cost, for the whole SNARE network swarm. The local function maximizes information gain with minimal cost, for that sensor. Both algorithms are summarized next.

GVF (Global Value Function):

- Evaluates each sensor score for their network contribution
- Evaluates each value/time for total gain over all combinations
- Highest information gain is accepted
- Creates rank ordered scale of space objects for all sensors capable of observation
- Seeks to maximize yield and minimize cost where
    - Yield is number of objects at specific accuracy measurement
    - Cost is duty cycle requirements and regrets for any given object

LVF (Local Value Function):

- Each sensor calculates collection value of each object using LVF:
    - Can I see it? When? How well? What else am I doing at that time?
- Seeks to maximize yield and minimize cost where:
    - Yield is a function of (priority, revisit, quality, accuracy, phenomenology, etc.)
    - Cost is a function of (duty cycle, regrets, etc.)

Each SNARE node consists of sensor integration, algorithms, blockchain, and communications software. All the blockchain and algorithm code is identical between nodes, as is typical in a blockchain network, while the sensor-specific integration code is unique (e.g. comm protocols, scheduler peculiarities, specific tasking requirement data), where per-sensor customization may be required. Further the LVF cost/yield is calculated based on the specific sensor to which the node is assigned (e.g. speed of motors to move sensor direction). In SNARE, all full blockchain nodes have a complete set of position data, which provides resilience to accidents and attacks, as is the case for typical blockchains. Additionally, there may be additional custom integration software in each node, between the sensor and the SNARE node, to accommodate for legacy communication protocols and other sensor unique features. SNARE uses a permissioned blockchain with a byzantine fault tolerant consensus algorithm, which requires a majority of the validator nodes to agree on the transactions processed by the network. The blockchain is implemented with redundant nodes which provides data resilience against up to one-third damaged or malicious nodes, with greater data resiliency than centralized approaches.

SNARE presently only uses space sensors directly connected to the blockchain. BESTA extends SNARE to an international context, includes additional types of SSA data, as well as critical shared agreements that support STM such as architecture, policy and regulation documents.

5. BESTA DATA

BESTA provides increased confidence in the data written and read by international stakeholders including space position data, intent to maneuver, smart contracts, shared agreements, and more, see Fig. 4. Each data transaction is cryptographically attributed to the sender and recorded as a tamper-evident transaction on the BESTA blockchain. Attribution combined with data integrity creates an internationally trusted set of data [7].

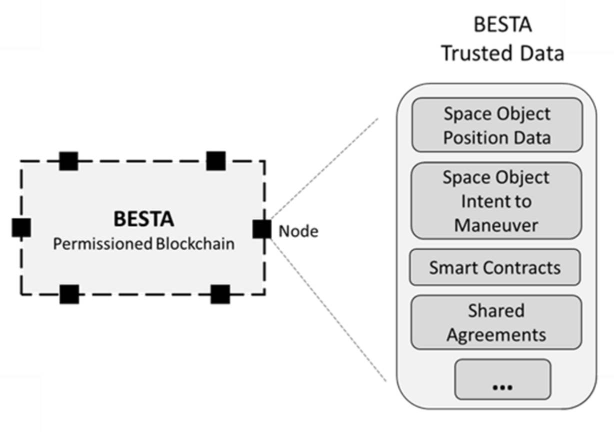

Fig. 4. BESTA Trusted Data

Space object position data is recorded from independent sensors, as well as curated data from sensor consortiums operated by nations, commercial, and academic interests. Space object position data is used by international governance, nations, commercial, academic, and independent interests, for building their space situational awareness. Attribution is transparent and enables stakeholders to build their situational awareness according to their data quality and provenance criteria. Transparency also enables national operators to alert sensors and sensor consortiums if their data appears to be missing or in error. Space object intent to move is also shared, enabling advanced planning by stakeholders to conduct their own subsequent defensive maneuvers.

Smart contracts are modules of code, deployed to each blockchain node, which execute on behalf of select transactions. Smart contracts enable portions of a mission business process to be executed, and can be complemented with off-chain mission processes.

Shared agreements between stakeholders are implemented as versions of documents, enforced by operations and governance. Documents can be a variety of formats and stored in repositories as appropriate. A cryptographic link to the document can be established by storing a hash of the document in a blockchain transaction, which can be subsequently used when needed to verify the authenticity of the document. The corpus of recorded shared agreements informs the mission architecture and cycles of innovation.

6. BESTA GOVERNANCE

Development, operation, and sustainment of BESTA as part of international SSA and STM requires an international governance body to enforce the agreed direction and tempo. The decisions of the governing body should be informed by an architecture that enables technical interoperability of all technology required for international space cooperation, including but not limited to BESTA, see Fig. 5. The goal of governance and BESTA is to build a layer of trusted and transparent data which informs SSA and ultimately improves the performance of STM. All data recorded in BESTA can be seen by any stakeholder and verified as authentic, which enhances international trust in the data in the blockchain.

MITRE is proposing ISRA (International Space Reference Architecture) as a starting point for such an architecture (separate paper). Intent of ISRA is to support international interoperability. Each spacefaring nation can contribute and cooperate in this architecture, which also drives the development and operation of BESTA.

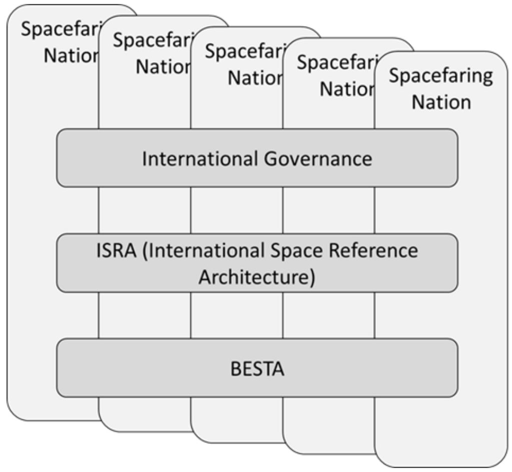

Fig. 5. BESTA Governance

ISRA is an open architecture that serves as a foundation for generating shared agreements which support and enable space flight safety, SSA, STM, and other related space activities. ISRA is an internationally governed and interdisciplinary concept that sets the foundation for standards and conventions that multilaterally span technical, engineering, operational, and policy domains.

ISRA intends to solve unique challenges of an international space mission, supporting decentralized stakeholder relationships. The theme is to forge international agreements on language, policy, and technical points as needed, generate shared agreements and record them as hashed versions in BESTA and full versions in file repositories. Open decentralized file repositories assure everyone has equal access to the shared agreements as needed, with ability to verify authenticity in BESTA by comparing hashes to pertinent blockchain transactions. In addition to formal shared agreements – best practices, behavioral norms, and TTPs (Tactics, Techniques, and Procedures) can be recorded in BESTA as well.

The result is a foundation on which rules of engagement can be generated, persisted, and used to enable safe international space travel in an era of rapidly increased use of space. Rules of engagement can include operational aspects such as proximity definitions, and governance such as transparency, accountability, and forensic approaches. Further, governance must listen to international community feedback and prioritize development needs, which drives iterative improvement of BESTA and ISRA as continuous cycles of innovation. Feedback can also drive risk analysis which further informs governance.

7. BESTA OPERATION

BESTA operation creates two flows of internationally trusted data: (1) SSA, and; (2) documented shared agreements, both of which inform and enable STM, see Fig. 6.

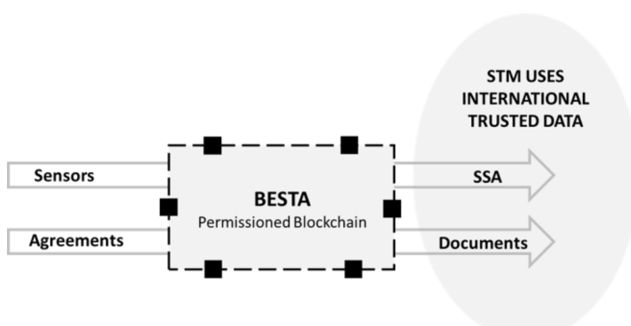

Fig. 6. BESTA Operational Data

SSA trusted data is the result of cumulative sensor data and intents to maneuver, recorded as blockchain transactions submitted, validated, and recorded in BESTA. Space object position data is recorded from independently reporting sensors, as well as curated data from sensor consortiums operated by nations, commercial, and academic interests. Space position data can be copied from BESTA as transactions are written (transactions committed from block consensus), to national and international data lakes and space operations centers, and build their situational awareness according to their data quality criteria.

Documents are the result of forging shared agreements between stakeholders, implemented as versions of documents. Documents can be a variety of formats and a cryptographic link to the document can be established by storing a hash of the document in a blockchain transaction. The hash can be subsequently used when needed to verify the authenticity of the document. The corpus of recorded shared agreements informs the mission architecture and cycles of innovation.

The documents help establish rules of engagement within ISRA, and SSA informs STM (e.g. conjunction alerts). Other domains can interface with BESTA, such as national air space controllers who are responsible for relevant air space to support launches. The cryptographically secure historical record within BESTA can support forensic investigations after incidents to improve practices and evolve shared agreement documents.

8. CONCLUSION

As of publishing this paper, Starlink is planning to launch thousands of broadband satellites [8]. Amazon is planning its own constellation with over three thousand satellites [9]. And the race for commercializing and exploring space is just beginning. The international space mission is too complex for any single owner of SSA data, and BESTA is proposed to support decentralizing the space mission. BESTA and decentralization is intended to enhance information sharing by creating a highly available, secure, trusted data layer of SSA and agreement data which every nation and every person on the globe can access and use to make space safer, even while more congested.

BESTA is a decentralized, open source, internationally funded, built, governed, and operated catalog of SSA space objects position data, recorded from independent sensors, curated feeds (e.g. U.S., Russia, China), commercial, and academic sources. BESTA provides data for international stakeholders including space position data, smart contracts, shared agreements, and more. Data is cryptographically attributed to the sender and recorded as a transaction in the BESTA blockchain. In addition, BESTA blockchain cryptographically prevents tampering and node redundancy prevents loss of data. Attribution combined with data integrity creates an internationally trusted set of data. Development, operation, and sustainment of BESTA requires an international governance body to enforce the agreed direction and tempo. The decisions of the governing body should be informed by an architecture such as ISRA, that enables technical interoperability of all technology required for international space cooperation, including but not limited to BESTA. BESTA operation creates two flows of internationally trusted data: space situational awareness and documented shared agreements, both of which inform and enable STM.

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