DADOS: Decentralized Autonomous Disaster Observation System

Edilson Filho, Marc Saideh, Laurent Vercouter, Jarbas Silveira, *Member, IEEE*, César Marcon, and Walter dos Santos

***Abstract*—Monitoring climate and natural disasters depends on international satellite collaboration, but current activation processes are slow and complex. DADOS (Decentralized Autonomous Disaster Observation System) enhances emergency mapping by integrating multiagent systems and blockchain to automate satellite tasking, data acquisition, processing, and dissemination. Using data from 71 satellites, NASA's natural events database, and activation records from ESA and the International Charter, experiments showed DADOS can increase coverage capacity by up to 270 times, with autonomous agents making decisions in approximately 555 ms.**

***Index Terms*—Automated decision-making, decentralized systems, disaster response, multiagent systems (MAS), satellites.**

Nomenclature

Acronyms	*Description*
AI	Artificial Intelligence.
AOI	Area Of Interest.
API	Application Programming Interface.
AU	Authorized User.
CC	Control Center.
CCSDS	Consultative Committee for Space Data Systems.
DAO	Decentralized Autonomous Organization.
DRM	Disaster Response Management.
ECO	Emergency On-Call Officer.
EONET	Earth Observatory Natural Event Tracker.
GSaaS	Ground Stations as a Service.
GS	Ground Station.
IC-SMD	International Charter Space and Major Disasters.
IPFS	Inter Planetary File System.
LEO	Low Earth Orbit.
MAS	Multiagent System.
PM	Project Manager.
RAAN	Right Ascension of the Ascending Node.
RPC	Remote Procedure Call.
SEM	Satellite-based Emergency Mapping.
STM	Space Traffic Management.
TASC	Task Allocation and Satellite Coordination.
TLE	Two-Line Element.
VPNs	Virtual Private Networks.

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Edilson Filho is with the Department of Teleinformatics Engineering, Federal University of Ceara, Fortaleza 60355-636, Brazil, and also with INSA Rouen Normandie, Normandie Univ, LITIS UR 4108, 76000 Rouen, France (e-mail: jose.silvafilho@insa-rouen.fr).

Marc Saideh and Laurent Vercouter are with INSA Rouen Normandie, Normandie Univ, LITIS UR 4108, 76000 Rouen, France (e-mail: marc.saideh@insa-rouen.fr; laurent.vercouter@insa-rouen.fr).

Jarbas Silveira is with the Department of Teleinformatics Engineering, Federal University of Ceara, Fortaleza 60355-636, Brazil (e-mail: jarbas@lesc.ufc.br).

César Marcon is with the Pontifical Catholic University of Rio Grande do Sul (PUCRS), Porto Alegre - RS 90619-900, Brazil.

Walter dos Santos is with the Small Satellites Division—National Institute for Space Research (INPE), São Paulo 12227-010, Brazil.

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I. Introduction

The response to natural disasters involves a vast and growing collaborative network of operators and satellites of different sizes and orbits, which makes control and communication among the involved parties more difficult. As the number of satellites in orbit and the diversity of their operators increase, DRM protocols become increasingly complex, with the involvement of new actors and the need to integrate new satellite payload capabilities and ensure reliability among participants and data. In addition, the rising frequency of natural disasters, driven by climate change, demands faster and more coordinated responses. The IC-SMD [1] or *Copernicus Program* [2] [3] represents one of the key examples of global collaboration in the use of satellites for SEM. However, current SEM-based solutions face significant delays due to centralized operations, data verification processes, political factors, and lack of automation, all of which hinder the effective delivery of aid to society [4]. In some cases, the collaborative network can take more than 10 days to be activated, which, in the event of natural disasters, may significantly impact delays in humanitarian aid and the evacuation of high-risk areas. A secure and automated solution could extend the time for logistics, rescue operations, and save lives.

A. Motivation, Contribution, and Organization

This work presents a solution to securely and reliably automate SEM satellite activations. The main contributions are 1) a secure and decentralized activation methodology, 2) reduced response time for delivering critical data, and 3) integration guidelines for existing systems. The rest of this article is organized as follows. Section II provides background. Section III outlines methodology. Section IV provides Results. Section V

TABLE I
CHARTER ACTIVATION WORKFLOW

Step	Description
1-Activation request	An *Authorized User* (AU), such as civil protection agencies or the United Nations, submits a formal request including disaster type, location, time, and specific needs.
2-Assessment and approval	The *Emergency On-Call Officer* (ECO) evaluates the request based on activation criteria and feasibility. If approved, coordination with Charter members begins.
3-Acquisition planning	A designated space agency (Project Manager - PM) plans satellite usage based on orbital paths, sensor capabilities, and weather conditions.
4-Satellite tasking	Satellites are operated by their respective agencies (e.g., European Space Agency, Indian Space Research Organisation, China National Space Administration). Commands are issued from mission control centers for data acquisition.
5-Data acquisition and processing	Images are collected and downlinked to ground stations, then processed (e.g., orthorectification) into usable geospatial products.
6-Product distribution	Final products are delivered to requesters and shared with international partners. This process can occur within hours of activation.

discusses limitations and implementation strategies and deployment challenges and proposes strategies to improve real-world applicability. Finally, Section VI concludes this article. Nomenclature presents a list of the main acronyms and abbreviations used throughout this work.

II. BACKGROUND

This section begins with a foundational overview of DRM, with particular emphasis on the approach adopted by IC-SMD. Subsequently, we present related works that propose solutions to optimize the control of satellite constellations for Earth observation, along with key concepts essential for understanding our proposal, such as decentralized systems, and multiagent systems.

A. Disaster Response Management

In recent years, DRM using satellite solutions has been enriched by a series of technological solutions and combinations [5], [6]. One of the greatest highlights of the initiative is IC-SMD [1]. It includes dozens of space agencies and institutes around the globe monitoring the Earth 24/7 [7]. However, implementing these solutions is sometimes unfeasible due to their complexity. The main steps, as defined by the IC-SMD, have been compiled and are presented in Table I.

Accordingly, the following stages typically require human intervention:

1) Activation Request and Assessment: The first step is the activation request by AU. An ECO will confirm whether the activation is both useful and feasible.

2) Acquisition Planning: The PM conducts a manual assessment to determine:

a) The type and severity of the disaster;
b) The most appropriate sensor technology (e.g., radar, optical, multispectral);
c) The availability and visibility of suitable satellites;
d) AOI definition is *manually* delineated using maps, geographic coordinates, and field reports;
e) Priority evaluation, such that in scenarios involving multiple concurrent disasters, human decision-makers are responsible for determining the relative urgency and prioritization of satellite tasking.

3) Satellite Tasking: Satellite operators prepare telecommands to be sent to a GS. These telecommands are scheduled in the GS activity list to be transmitted to the target satellite once the communication link between them is established.

4) Product Validation: Raw satellite data are processed into interpretable geospatial products that are reviewed and validated by geoinformation specialists prior to dissemination.

Fig. 1 presents a product generated by the scientists and collaborators of the IC-SMD network. The representation delineates an oil spill near the Equator in March 2025.

It is important to note that the activation process is inherently bureaucratic, designed to ensure both security and reliability. It involves formal communication initiated by the activation requester, a registered system user with valid credentials, followed by an assessment of available satellites, coordination between multiple institutions, and the execution of additional procedural protocols. This process is inherently slow, with a minimum response time of 24 hours. According to the European Commission for Humanitarian Aid [8], the first 24 hours following a natural disaster are critical for saving lives. Nevertheless, implementing an automated solution to improve satellite coverage through activation extends beyond merely identifying potential observation and monitoring targets. It necessitates a sophisticated decision-making framework and a high degree of trust among participating agents. Moreover, the 260 operational satellites are distributed across 35 constellations, each managed by different institutions.[1] Consequently, automating the transmission of telecommands to these satellites constitutes a challenge that intersects both the domains of security and safety.

Based on IC-SMD data from the last 24 months, Fig. 2 displays the monthly activation count, revealing a significant rise in 2024 when compared to 2023.

The speed and efficiency analysis of the SEM activation shows that different partners require varying amounts of time to activate their satellites. We can identify the activated main satellite networks using open data from the IC-SMD platform. Unfortunately, not all networks provide all the necessary details to reproduce the time consumption from the natural event occurrence to the activation of the satellite network. Therefore, based on Fig. 3, we will use the open data from Copernicus [3] to conduct our studies and experiments. Although only 34.9% (44 of 126) of the available data from the last 24 months represents Copernicus data, it is sufficient for our experiments, mainly due to the richness of the data obtained.

In the DADOS system, digital twins represent physical entities such as satellites, ground stations, and natural events. These agents process real-time data, simulate scenarios where the activation of the SEM is necessary or not, and communicate the results to the network and authorities. Combining digital

[1] [Online]. Available: https://disasterscharter.org/about-the-charter

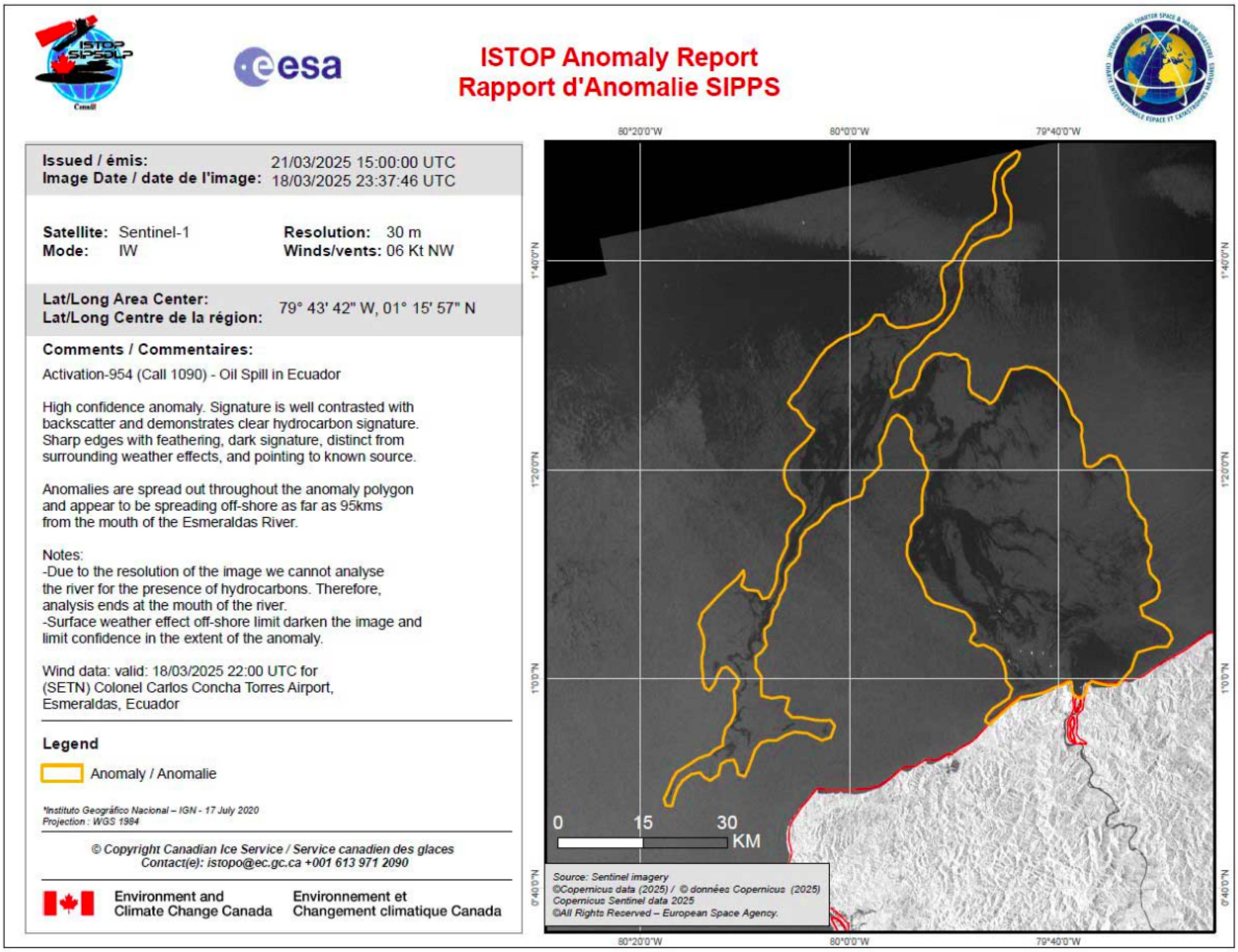

Fig. 1. Image, also referred to as a product, is a real example of the information sent to users who request data from IC-SMD. On the right side of the image, a satellite photo displays the delineation of an oil spill at sea. In the lower right corner, a highlighted text box contains information about the image source, in this case, the Sentinel Constellation, and the copyright notice. On the left side of the figure, technical information is presented, including the time of image capture, position, satellite name, mode, resolution, and wind direction. In the upper left-center, comments and notes from the technical staff responsible for the report are provided. Lastly, the figure includes a legend for the markings on the satellite image, as well as contact information for the organization that produced the report. For improved viewing, we recommend accessing the source website. *Source:* https://disasterscharter.org/activations/oil-spill-in-Ecuador-activation-954-

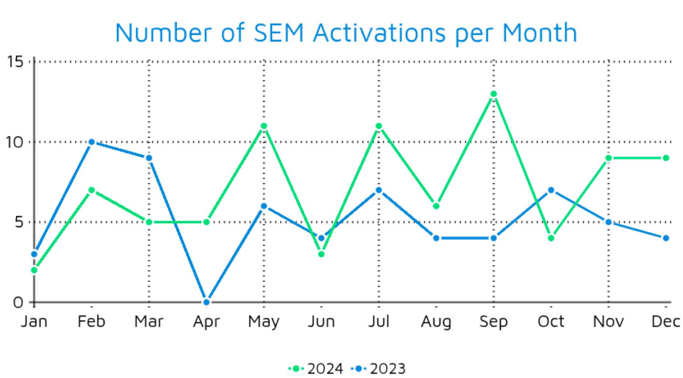

Fig. 2. Comparison of activations between 2023 and 2024. For better visualization, the number of activations for the year 2023, by respective month, were as follows: [3, 10, 9, 0, 6, 4, 7, 4, 4, 7, 5, 4]. For the year 2024, the figures were: [2, 7, 5, 5, 11, 3, 11, 6, 13, 4, 9, 9]. Source: IC-SMD, with a graph made by the author.

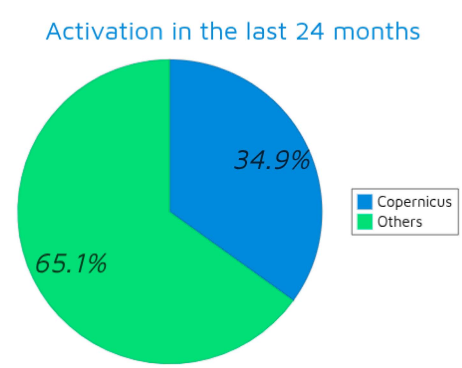

Fig. 3. Activation in the last 24 months, 2023-2024 (IC-SMD x Copernicus). Note that during the period, more than one-third of the activations were carried out by just one of the thirty-five satellite constellations partnered with IC-SMD. Source: International Charter Space and Major Disasters, with a graph made by the author.

twins with a multiagent system and decentralized processing via blockchain enables the creation of a highly responsive and intelligent network. In this network, decisions are made based on real-time data and predictive models, improving the efficiency and accuracy of, for example, the autonomous management of a satellite network and its resources. A detailed explanation of

TABLE II
SUMMARY OF RELATED WORK

Work	Title	Key contributions
[9]	Satellite-based approaches in the detection and monitoring of selected hydrometeorological disasters	It focuses on the role of Earth observation satellite systems in managing hydrometeorological disasters, mainly tropical cyclones such as Idai and Kenneth
[10]	On the use of satellite remote sensing to detect floods and droughts at large scales	The work explores the use of satellite remote sensing for monitoring and managing floods and droughts, emphasizing its efficacy; also, case studies are presented to illustrate its successful application in real-world contexts, highlighting its potential to enhance disaster preparedness and response strategies
[11]	Autonomous task planning method for a multi-satellite system based on a hybrid genetic algorithm	Introduces a hybrid genetic algorithm that combines traditional genetic algorithms with other optimization methods, designed to improve the efficiency and effectiveness of task planning for multi-satellite systems
[12]	Task allocation strategies for cooperative task planning of multi-autonomous satellite constellation	Presents key approaches to efficiently allocate tasks among a constellation of autonomous satellites working together, for example: *Distributed Decision-Making* and *Cooperative Task Planning*
[13]	A new multi-satellite autonomous mission allocation and planning method	It proposes a new multi-dimensional and multi-agent clusters collaboration model for dynamic task allocation to satellites, incorporating decision-making processes and task pre-processing
[14]	Online scheduling of distributed Earth observation satellite system under rigid communication constraints	The paper discusses the online scheduling of urgent tasks in a distributed satellite system using stochastic methods while adhering to strict communication and Earth observation time windows
[15]	A distributed cooperative dynamic task planning algorithm for multiple satellites based on multi-agent hybrid learning	Presents a distributed cooperative dynamic task planning algorithm for multiple satellites, utilizing multi-agent hybrid learning to optimize task allocation and enhance the efficiency of satellite systems
[16]	A cooperative autonomous scheduling approach for multiple earth observation satellites with intensive missions	Introduces a cooperative autonomous scheduling approach for numerous Earth observation satellites. It is designed to enhance mission efficiency and optimize resource allocation for high-demand observational tasks through effective collaboration among satellites
[17]	Intelligent mission planning for autonomous distributed satellite systems	Presents an intelligent mission planning framework for autonomous distributed satellite systems, focusing on enhancing operational efficiency and adaptability through advanced algorithms and real-time decision-making capabilities
[18]	Multi-satellite mission planning using a self-adaptive multi-agent system	A self-adaptive multi-agent system for multi-satellite mission planning is proposed to enhance coordination and flexibility during mission execution. Agents dynamically adjust their strategies in response to environmental changes and evolving task requirements
[19]	Optimal mission scheduling for hybrid synthetic aperture radar satellite constellation based on weighting factors	Application of genetic algorithm techniques to optimize image acquisition of areas of interest. The objective is to reduce the need for multiple passes over the same location to capture images of the target.
[20]	Multiple super-agile satellite collaborative mission planning for area target imaging	Presents an optimal mission scheduling strategy for hybrid synthetic aperture radar satellite constellations, leveraging weighting factors to enhance scheduling efficiency and improve the overall effectiveness of satellite operations
[21]	Automating and decentralizing satellite-based emergency mapping	Show a collaborative mission planning framework for multiple super-agile satellites focused on area target imaging, optimizing coordination and resource utilization to enhance imaging performance and responsiveness to dynamic environmental conditions
[22]	Orbit decentralized autonomous organization using blockchain-based consensus mechanisms	Proposes an orbit-decentralized autonomous organization that utilizes blockchain-based consensus mechanisms to enhance satellite coordination and decision-making, promoting efficiency and reliability in space operations
[23]	Decentralized and neutral consensus mechanisms in space conjunction assessment and mitigation: Space DAO STM	Introduces a decentralized and neutral consensus mechanism within the Space DAO framework for assessing and mitigating space conjunctions. It enables real-time decision-making among satellite operators, promoting collaboration and improving safety in space operations

how DADOS works and the experimental methodology used to test it is provided in the DADOS and Methodology Section.

B. Related Work

In recent years, DRM using satellite solutions has been enriched by a series of technological solutions and combinations. For example, IC-SMD [1] brings together dozens of space agencies and institutes around the globe, with more than 260 satellites in 35 constellations monitoring the Earth 24/7 [7]. Even with so many resources, coordinating the potential of these assets is challenging, as it is a manual and time-consuming process. Table II presents some of the primary studies in recent years aimed at providing support for automating or intelligently coordinating satellites to cover natural disasters.

The state of the art presents current efforts to improve the efficiency of satellite data collection through the automation of satellite management. In [9], [10], [11], [12], [13], [14], various solutions are presented for automating satellite flight planning through task sharing (monitoring defined areas of the Earth's surface). While these efforts offer unique contributions, the work in [9], [10] focuses on monitoring hydrological disasters, with limited presentations of the solution's scalability to other scenarios. Task-sharing models for sharing satellite resources are introduced in [11], [12], [13], [14]. However, in-depth reliability, security, and fault tolerance issues are not adequately explored, and the solutions present a limited collaborative landscape. The works [15], [16], [17], [19], [20] utilize decision-making processes for automation, creating cooperative networks for flight plan and mission sharing. The limitation still lies in the scalability and fault tolerance of the solutions; at the same time, they do not show how the execution and implementation of the solution impact current satellite systems and processes.

The use of blockchain and the concept of decentralization to coordinate satellite management has attracted the attention of the industry and space agencies, as seen in the case of the European Space Agency's Nebula Public Library[2] project [24]. In this way, the authors in [21], [22], and [23] discussed and implemented the blockchain concepts to create a DAO for satellite management [25]. In [21], the authors outline key architectural elements essential for functional systems, including the use of oracles for off-chain data processing, the considerable cost of on-chain data storage, and the adoption of IPFS [26] for decentralized storage to mitigate these expenses while enhancing data security through encrypted fragmentation and distribution. A brief section also outlines how DAO should handle trust management. Despite the merits of the work, some points were not addressed, such as the experimental implementation of the project and the consumption of computational resources, including processing time, energy, or memory usage. In [22], high-level concepts are presented on how decentralized and autonomous orbit organizations would work using a consensus algorithm. While the topic is interesting, the paper falls short in several areas, such as the feasibility of using smart contracts and the presentation of a satellite model (especially since satellites are different and have various sensors, actuators, and attitude controls). In [23], the authors present a consensus mechanism model for space traffic management in an environment where some entities dominate space situational awareness. The paper provides a mathematical formalization for consensus management and some governance elements, but it lacks the presentation of experimental implementation and the results of such experiments.

In addition to academic approaches aimed at providing task automation solutions for satellites, some commercial solutions are also observed in professional practice. For instance, as described in [27] and [28], automated rescheduling of satellite tasks in response to operational changes is implemented. These commercial solutions often employ the concept of GSaaS, in which a distributed infrastructure of commercial ground stations is made available on a pay-per-use basis [29] and [30]. While this model can be attractive for small-scale space applications, the high cost per minute of usage may render it financially unfeasible for larger projects such as telecommunications, Earth observation, or defense operations [31].

1) Gap in Literature: Although the literature highlights various research efforts, most works focus on formalizing concepts and raising concerns rather than offering practical solutions. Multiagent systems show promise for task-sharing in satellite networks but lack clarity regarding computational costs, security issues, and how they align with standard technologies such as CCSDS protocols.[3] Some examples of these protocols are 1) [32], a service designed to enable the transfer of data between space agencies and institutions through cross-support infrastructure, such as tracking antennas or ground stations; 2) [33], a protocol that defines a standard format for data packets used in space communications; 3) [34], a protocol used for short-distance communication between devices in LEO; and 4) [35], a protocol that allows different space agencies or partners to operate antennas and ground stations from other agencies remotely. It standardizes tracking, telemetry, and command operations, enabling real-time control of space devices from partner stations.

While creating autonomous networks, blockchain-based solutions often assume ideal trust conditions, overlooking potential vulnerabilities such as those in smart contract layers. It is by addressing this gap that DADOS emerges as an attractive solution. Aiming to present the key fundamentals of these two technologies and how they are associated with DADOS, the sections on decentralized systems and multiagent systems provide a summary of the content.

C. Decentralized Systems

Decentralized systems consist of a network of devices where control and data processing are not centralized in a single entity but distributed across various devices [36]. This architecture eliminates the need for a central authority, enhancing the system's resilience, security, and efficiency. Each participant can operate independently, and decisions or transactions are carried out through consensus using specific algorithms. The use of decentralized technology in our project supports the development of a robust, secure, and transparent framework to automate the decision-making process, authenticate participating entities, and distribute stored telecommand commands for satellites. By using smart contracts combined with an API[4] that enables integration with artificial intelligence modules, the project also includes scalability capabilities for the solution [37].

Blockchain is an example of decentralized system technology and perhaps has popularized the concept the most. It allows transactions and data to be recorded in a distributed, immutable, and transparent ledger, where each node in the network holds an updated copy of the identical records. Security is ensured through consensus mechanisms and cryptographic techniques. The relationship between blockchain and decentralized systems is fundamental, as blockchain provides the framework for decentralization to occur reliably without relying on a central authority to validate transactions or manage data.

D. Multiagent Systems

An MAS is an advanced computational paradigm in which multiple autonomous entities, known as *agents*, interact within a shared environment to address complex problems in a distributed and decentralized manner. These agents may represent physical systems, computational devices, or virtual entities, each characterized by specific goals, domain knowledge, and operational capabilities [38]. Within a MAS, agents engage in either cooperative or competitive behaviors, communicating through

[2]The knowledge bank of ESA's R&D programs.

[3]The CCSDS protocols are a set of internationally recognized communication and data handling standards designed to ensure interoperability and efficient data exchange between space missions and ground systems worldwide.

[4]Developed especially for the project.

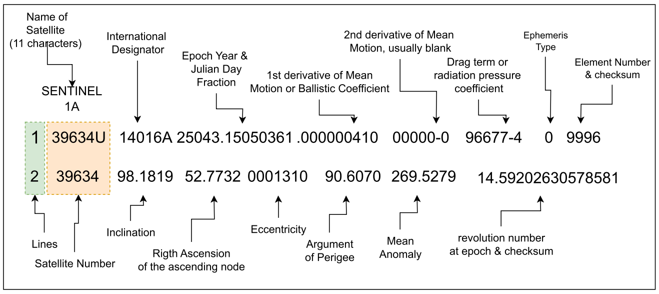

Fig. 4. Sentinel 1 A TLE Datas. Feb 12 10:31:56, 2025.

well-defined protocols to pursue both individual and collective objectives. This decentralized structure enables high levels of adaptability, scalability, and robustness, particularly in dynamic and heterogeneous environments [39].

A key feature of MAS lies in its decision-making mechanisms, which are inherently context-aware and multicriteria. Agents can factor in a diverse range of variables, including their own goals, the current state of the environment, the behavior and intentions of other agents, available resources, system constraints, and the projected consequences of alternative actions, thus enabling dynamic, flexible, and adaptive responses to evolving scenarios. In the context of the DADOS solution, the creation of agents is grounded in the concept of *digital twins* of satellites. A digital twin is defined as a continuously updated, real-time virtual replica of a physical system that accurately reflects its operational state, behavior, and performance characteristics.

Trust in decision-making is essential and can vary in complexity and security levels [40]. During the authentication process, DADOS focuses on the decision to trust information from another agent (satellite). This agent possesses a valid identity on the blockchain, and the process verifies through smart contracts whether the requesting entity (observation target) has a valid record in the decentralized database. The innovative manner in which the DADOS solution integrates and implements these technologies is presented in the DADOS and Methodology section.

E. TLE Data

The TLE sets are standardized data formats that describe the orbital parameters of Earth-orbiting objects [41]. These datasets, maintained by organizations such as NORAD (Satellite Number), provide the necessary information to compute satellite positions and velocities at given times. See an example in Fig. 4.

Our solution modeling uses the orbital parameters combined with Keplerian equations and a perturbation model to allow orbit forecasting.

III. DADOS AND METHODOLOGY

DADOS is a method and system for automated decision-making aimed at activating satellites across different constellations. It seeks to provide a secure mechanism for task sharing to enable more efficient Earth monitoring, particularly in the event of natural disasters. Specifically, the DADOS solution contributes to the state of the art in the following aspects:

1) Automation and Collaboration in Task Execution: The solution provides a foundational framework enabling tasks and decisions to be conducted automatically while maintaining reliability and privacy, concurrently ensuring compatibility with current and traditional communication protocols.
2) Compatibility with Traditional Methods: The DADOS does not interfere with the communication between the CC and the satellite; it merely provides complete automation to enable the CC to send telecommands to the satellite using its traditional resources, means, and protocols.
3) Mapping of key elements for the creation of satellite digital twins for decision-making in multiagent systems.
4) A solution with loosely coupled submodules, meaning that users can interchange techniques used for decision-making, satellite identity management, and image or signal recognition, while the DADOS system remains operational.

This section presents how the *DADOS* project works. The main modules and diagrams describe how the experiments were carried out and which data sources were used during the work. The experimental results are discussed in Results.

A. DADOS: An Overview

DADOS implements decentralized processing and decision-making concepts to provide a fast, autonomous, and reliable response for activating SEM satellites. DADOS operates directly as an autonomous and intelligent support system for agencies and institutions that partner with DRM.

1) *Automation and Collaboration in Task Execution:* DADOS, in both *supervised* and *unsupervised* operation modes, provides an automated decision-making process that takes into account the characteristics, capabilities, and contextual information of the satellites and GS that are part of the network. In *supervised* mode, it functions as an assistant, providing operators (as described in Table I) with suggestions on which satellites can be activated and which commands can be transmitted. The *unsupervised* mode fully automates all steps, from activation to the development of the final product (see Fig. 1).
2) *Compatibility with Traditional Methods:* DADOS was conceived to ensure seamless integration with existing legacy infrastructures. The framework strictly adheres to established security policies and standardized communication protocols governing interactions among CC, GS, and satellites. Consequently, the transmission of telecommands, whether via proprietary or partner ground stations, remains fully compliant with pre-existing interinstitutional agreements and operational regulations. Some considerations regarding real-world adoption are presented in the limitations and implementation strategies section.

1) Operating in an Integrated Manner: The decentralized network solution of DADOS is designed to accommodate an arbitrary number of participating institutions. For conceptual

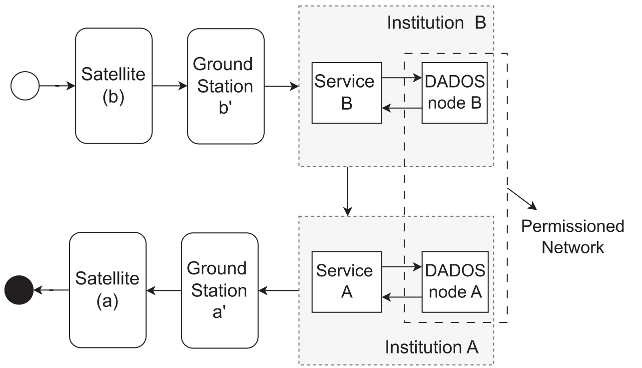

Fig. 5. Illustrates the data flow and interaction within the DADOS framework between two institutions.

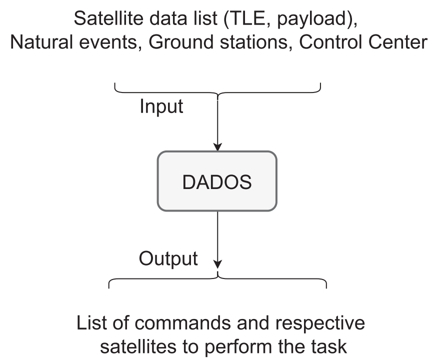

Fig. 6. Abstract representation of a DADOS node as a black box. The input to the node comprises heterogeneous data streams originating from satellites, ground stations, and control centers. In addition, the node may optionally incorporate data related to natural events, provided such information is sourced from verified and trusted external systems.

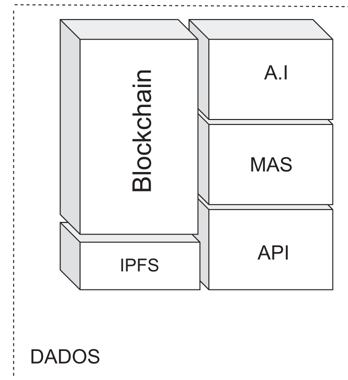

Fig. 7. Block diagram of DADOS illustrates its five primary submodules. Blockchain facilitates decentralization, unique identity management, and smart contracts. IPFS provides distributed and encrypted storage for parameterizable telecommands. The API represents a suite of services for DADOS's internal and external communication. MAS embodies the decision-making capabilities within a multiagent framework. Finally, AI encompasses a collection of techniques for orbit prediction, pattern recognition, and machine learning.

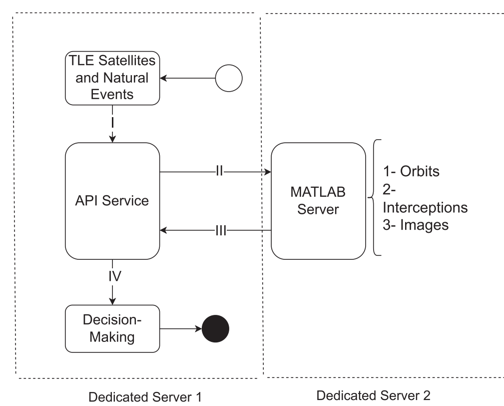

Fig. 8. Development of the simulations relied on dedicated servers performing distinct functions. On Server 1, data processing for TLE and natural events, as well as the decision-making process, were orchestrated by API services. On Server 2, only the execution of orbit prediction models, target interceptions, and image generation took place.

clarity and analytical tractability, this study restricts its scope to the interaction between two representative institutions. Fig. 5 presents a high-level overview of the DADOS operational workflow. The process begins with satellite b transmitting the collected payload data to GS b', which subsequently forwards the data to Institution $\mathcal{B}$. Within Institution $\mathcal{B}$, two core components are instantiated and actively engaged: $Service_B$ and $Node_B$.

$Service_B$ is responsible for delivering the decrypted payload and its associated metadata to $Node_B$. Upon receipt, $Node_B$ executes the necessary data processing routines and, based on defined optimization criteria, identifies the most suitable satellite for task execution. This analysis also determines the institution responsible for operating the selected satellite. Following this, $Service_A$, corresponding to Institution $\mathcal{A}$, receives the tasking message and coordinates with $Node_A$ to validate the authenticity, integrity, and trustworthiness of the received data. Once successfully verified, the appropriate telecommand is generated, encapsulated, and encrypted for secure transmission to satellite a via ground station a'.

2) DADOS as a Closed Box: The proposed solution constructs digital twins of satellites using real-time TLE data, along with other relevant satellite information as described in Section III-D1. These digital twins constitute the basis for the creation of autonomous agents capable of interacting within a multiagent system. Throughout this work, the term agent will be used to refer to the satellite's digital twin, for the sake of clarity and conciseness.

The primary objective of these interactions is to enable cooperative behavior that enhances the detection and monitoring of natural events and disasters. The simplified view of Fig. 6 shows that DADOS receives satellite data, such as TLE and payloads such as images, signals, and sensor data, along with the satellite mission details and its set of sensors, as well as other data such as natural disaster information from open sources such as EONET [42] (this is optional), and information from ground stations. After processing, the output is a list of satellite commands that will be activated.

B. Components of the DADOS Model

The DADOS solution is entirely instantiated and operated within the ground segment. As depicted in Fig. 9, the DADOS infrastructure is deployed across computational nodes that interface with the servers of ground stations, control centers, and

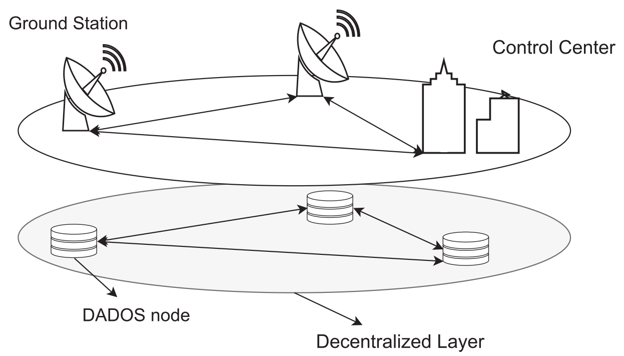

Fig. 9. Highlighting the decentralization layer, supported by the blockchain nodes installed in ground stations and control centers.

tracking facilities. This communication is established following conventional security protocols, including the use of digital certificates, firewall configurations, and VPNs.

Fig. 7 illustrates the constituent components that establish DADOS as a modular framework. The API module functions as the singular interface for external system interaction. This API encompasses scripts facilitating communication with the Blockchain, IPFS, AI, and MAS modules.

The API module is also responsible for its functions, such as processing the received data and encapsulating telecommands for communication protocols, such as the CCSDS cross-service [32], and consultation and authentication of the entities belonging to the system, such as agencies, satellites, and ground stations. The AI module consists of several functions, with the main ones being: 1) Prediction of future orbit and 2) Data recognition.[5] These functions are used as inputs for the decision-making process.

The ground station, an entity outside of DADOS, participates in the system as a data source for DADOS and as a recipient of DADOS data. The API module is a set of methods and functions implemented in the decentralized processing units of DADOS. It is responsible for unpacking the data received from the GS and sending it to the *smart contracts* within the blockchain module. Note that the API module communicates with all the modules of the method, providing compatibility between communications. The blockchain module consists of the *smart contracts* and the blockchain node. The AI module performs disaster recognition calculations; it is fed by information stored in the blockchain (such as historical data on natural disasters and events) and data from the digital twins of the satellites and ground stations. The AI module creates the digital twins and uses this entire set of information to send, via API, to the decision-making module. The MAS module is responsible for the decision-making process. A more detailed explanation of the decision-making process and what it entails is presented in the Additional Details. After the decision-making process, the API module sends the decision result to the blockchain and receives the necessary data and information. During SEM network activation, it sends the telemetry commands to the designated stations and the properly packaged data following the protocols used by the network participants.

To quickly dive into how the communication process between the API (Dedicated Server 1) and the AI module (Dedicated Server 2) is carried out, we present in Fig. 8 one of the elements of the AI module: orbit prediction (using the next 24 hours), possible target interceptions (and their duration), and the generation of simulation images used in this article.

C. Decentralized Infrastructure and Blockchain

The infrastructure is based on a permissioned blockchain architecture [43]. In this context, for a node to join the network and actively participate in the DADOS system, its inclusion must be approved by the existing nodes through a consensus mechanism. Any instances of abuse, anomalies, or suspicious behavior are subject to automated detection mechanisms, and the respective node may be excluded [44] from the network to preserve the integrity and security of the system. Additional details regarding the DADOS system's security considerations are presented in the section security considerations.

The permissioned network mechanism not only provides enhanced security and fault tolerance but also ensures higher service availability. In the event that one or more partner nodes go offline, the network autonomously redistributes the workload and reorganizes itself to maintain operational continuity. Hyperledger Besu [45] was selected for the development of the DADOS proof-of-concept due to its inherent facility in establishing permissioned networks, coupled with its expansive developer community and comprehensive documentation. Future implementations may incorporate alternative blockchain platforms without detriment to the fundamental tenets of the proposed solution.

Fig. 9 presents the structures incorporating this decentralization layer. Note that the ground station and the control center are structures that receive the DADOS nodes, enabling the decentralization of DADOS. The model is a decentralized and permissioned network where the inclusion of a new node (ground station or control center) is signed by all current entities by consensus.

1) Data Ownership and Security: In the context of storing, sharing, and managing sensitive data within DAO and other decentralized applications, such as the DADOS system, IPFS, as referenced in the related work section, represents a compelling technological approach. Its integration with blockchain technology is consistently presented in the academic literature as a secure and trustworthy framework for data exchange, particularly in scenarios requiring elevated levels of confidentiality, integrity, and resilience [46], [47] [48], [49]. Within this framework, one of the most critical and sensitive components managed within the automation framework of our proposed solution is the set of *parameterizable telecommands*, which underpin the execution of the TASC process [50], [51], [52].

D. Multiagent Systems

This section presents how DADOS implements decision-making based on multiagent systems. We begin by defining the

[5] Since we did not have access to the satellites' footprint, this module remained deactivated throughout the entire simulation.

agent through the mapping of its constituent elements, which characterize the agent and consequently the decision-making process. Finally, we describe the overall decision-making workflow within the system.

1) Mapping Elements for Agent Creation: The mapping of the elements constituting an agent in our model begins with the creation of a digital twin of the satellite, constructed based on the received data. This process ensures that the agent maintains accurate copies of the satellite's key characteristics, notably orbital predictions, battery level, and attitude. The system also incorporates data on natural events, which are obtained through reliable data sources and/or derived from pattern recognition, machine learning, or other artificial intelligence techniques. In our experiments, however, we utilized exclusively data from verified and trusted sources.

Satellite Modeling: Let S*sat* be the set of satellites, and $s \in$ S*sat* be a specific satellite, which

1) E_s: Battery level of satellite s;
2) M_s: Free disk memory of satellite s;
3) θ_s: Set of sensors available on satellite s;
4) θ_j: Set of sensors required for task j;
5) $\mathcal{T}_s$: Information about the orbit of satellite s by TLE, which includes
   a) Norad: Satellite catalog number.
   b) i: Inclination (degrees).
   c) Ω: RAAN (degrees).
   d) e: Eccentricity.
   e) ω: Argument of Perigee (degrees).
   f) M: Mean Anomaly (degrees).
   g) n: Mean Motion (revolutions per day).
   h) T: Epoch Time.
   i) $\dot{n}$: First Time Derivative of the Mean Motion.
   j) $\ddot{n}$: Second Time Derivative of Mean Motion
   k) B^*: BSTAR drag term, i.e., accounts for atmospheric drag effects, impacting long-term orbit prediction.
   l) rev: Revolution number at epoch.
6) Owner$_s$: Owner of satellite s;
7) $\mathbf{v}_s$: Velocity of satellite s.

Natural Event Modeling:

$$\Gamma \leftarrow \{\gamma_1, \gamma_2, \ldots, \gamma_n\} \quad \text{Set of possible natural events} \tag{1}$$

$$\gamma_i \leftarrow \{\text{type, name, lat, lon, extent, time}\} \quad \forall \gamma_i \in \Gamma. \tag{2}$$

Constraints: The following constraints ensure that the DADOS operates correctly, considering available E_s, suitable sensors $\theta(s, j)$ for data collection, future orbit O_s that intercepts the target γ_i, and trusted agents.

1) *Future Interception:* Satellite s must intercept at least once the γ_i (within the h hours, we use 24 hours).

$$O(s, \gamma, h) \geq 1 \quad \forall s \in S_{\text{sat}} \quad \forall \gamma \in \Gamma.$$

2) *Sensor Availability Constraint:* Satellite s must have the required sensors to complete task j. The set of sensors on satellite s must intersect with the required sensors for task j.

$$\theta_s \cap \theta_j \neq \emptyset \quad \forall s \in S_{\text{sat}}, j \in \mathcal{J}.$$

3) *Trust Constraint:* Satellite s must be verified as a trusted agent within the system.

$$\Omega(A_i) = \text{True} \quad \forall s \in S_{\text{sat}}, \quad j \in \mathcal{J}.$$

4) *Decision Constraint:* The decision function $D(j, s)$ must be boolean, indicating whether satellite s accepts task j or not.

$$D(j, s) \in \{\text{False, True}\} \quad \forall j \in \mathcal{J}, \quad s \in S_{\text{sat}}.$$

5) *Energy Constraint:* Each satellite must have enough energy to perform the task. The battery level must be sufficient to complete the task j without going below the minimum energy threshold.

$$E_s - C_j \cdot D(j, s) \geq E_{\text{min}} \quad \forall s \in S_{\text{sat}}, \quad j \in \mathcal{J}.$$

6) *Global Energy Constraint:* The system must ensure that after completing all assigned tasks, every satellite has enough energy for its operations.

$$E_s - \sum_{j \in \mathcal{J}} C_j \cdot D(j, s) \geq E_{\text{min}} \quad \forall s \in S_{\text{sat}}.$$

2) Decision-Making Process: The decision-making is based on direct testimonies and self-declarations[6] from the agents. These are captured via smart contracts and stored on the blockchain and IPFS (along with each satellite's own identity). Each set of agents is instantiated in parallel across blockchain nodes until one of the nodes writes the result of its calculations to the blockchain. The result is then propagated throughout the network, and the corresponding telecommands (when applicable) are sent to the satellites. Fig. 10 represents a two-layered diagram: The agent's action, which summarizes *what it saw* and *what it heard* from system interaction, and the decision layer, which considers the elements mapped in our developed model. The outcome will be the agent's decision to collaborate or not with data collection on the designated target.

In the decision-making module titled *"Confirm that I trust this agent?"*, two activities take place: 1) the verification of credentials to ensure that the agent is indeed a legitimate element of the system, and 2) the assessment of its reputation,[7] which aggregates information from past interactions, including instances in which the agent provided *false-positive* information. That is, the agent indicated the presence of a target in a given location, which was later disproven by another agent.

Considering that the state of the art in decision-making for multiagent systems is continuously evolving, DADOS is designed with the flexibility to adapt and incorporate new, more advantageous models as they emerge. This versatility is a valuable feature, allowing DADOS to be customized and continuously improved over time in response to advancements in the field. (See Fig. 7, where the MAS is a submodule of the DADOS

[6]Direct testimonies refer to first-hand information an agent gathers through its interactions, while self-declarations are statements an agent makes about its capabilities, intentions, or attributes.

[7]In a multiagent system, an agent's reputation refers to the trustworthiness it has earned based on its past behavior and interactions, influencing future decision-making.

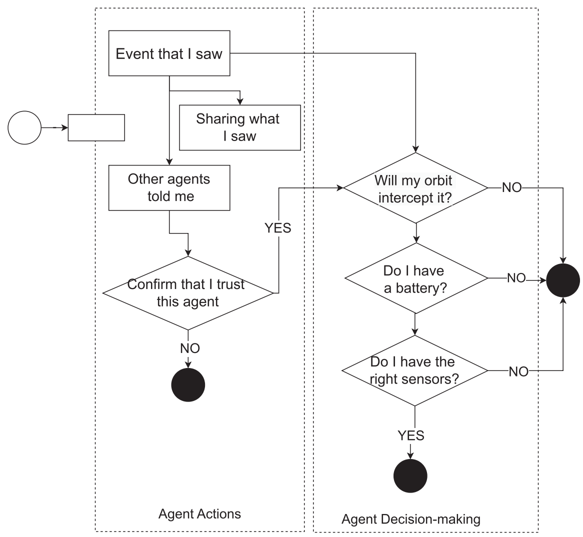

Fig. 10. DADOS decision-making process occurs in two stages: 1) the actions of the agent (the satellite's digital twin) that observes events and shares its information with other agents, 2) listens to other agents talk about what they have seen (e.g., location and type of event) and the subsequent verification of whether the agent can trust the other agents who have spoken to him. In 2), a structured decision-making process is based on a series of questions that guide the agent in determining whether or not to collect data on the target.

system, already designed to be modified or updated when necessary.)

E. Additional Details

1) Within the AI Module: Several submodules are found. For example, we can mention: 1) The query of telecommands that relate the digital agent, real satellite, and the actions it should take after the decision-making process; 2) the function of encapsulating the telecommand in standard protocols, such as the CCSDS cross-service and others, maintaining a level of security and confidentiality by using blockchain to store these predetermined telecommands; 3) the selection of the GS that will deliver the packets.

2) Security Considerations: In addition to a reliable decision-making process and data privacy measures, the DADOS system incorporates an additional layer of protection against external threats. The use of a private and permissioned blockchain network enhances the security and traceability of each participant (i.e., CC and GS), while simultaneously offering increased protection against potential intrusions. In particular, a permissioned blockchain network is made up of computational nodes, referred to as blockchain nodes, which can serve various functions. These include listening nodes that monitor network activity and promote transparency; validating nodes that authenticate and record transactions; and RPC nodes, which serve as communication gateways between the blockchain and external applications such as the DADOS API, AI module, and IPFS.

Within this architecture, the RPC node is considered the most exposed to malicious actors, as it represents the primary interface between the blockchain and external systems. However, both academic literature [53] and professional practice provide robust defense mechanisms for securing such nodes. The implementation of firewall rules, digital certificates, and strict IP *whitelisting*[8] that define which entities may interact with the network are integral components of this security layer. Furthermore, the use of load balancing and IP *whitelisting* for authorized access to the DADOS infrastructure strengthens system resilience, making it highly resistant to attacks such as the 51% attack [54] or consensus disruption.

F. Experiments

The experience for testing the solution was divided into three stages: Scheme, Data Extraction, and Simulations. Special attention was given to making the databases and codes used to evaluate our solution available to the scientific community, enabling the reproducibility of our experiments.

1) Scheme: The experimental procedure begins with the acquisition of data from public sources, either through direct requests or extraction mechanisms. Once obtained, the data is transmitted to the DADOS system, which initiates the processing phase. Upon completion, two parallel workflows are triggered. The left-hand path, known as the agent path, involves transmitting the parameters required to configure each agent to their respective agent entity, which then instantiates the agent accordingly. In parallel, the right-hand path, known as the prediction path, involves the generation of satellite trajectories for the next 24 hours.[9] For each satellite, DADOS stores the predicted trajectory data, including latitude and longitude, in an array indexed by satellite name.

This trajectory information is then utilized in a conference module, where the position of each natural event is cross-referenced with the predicted coverage of each satellite. Satellites determined to be capable of observing a given event are notified via their corresponding agents, which interface directly with the system's coordination module.

Fig. 11 illustrates the overall experimental workflow. The Data Request Service is highlighted in green as the entry point. Modules related to the DADOS simulation algorithms are colored red, while testing and analysis scripts for agent interactions are colored blue. The External Environment component illustrates how agents interact and share information. These interactions are used as input for the Coverage Prediction module, which evaluates whether a satellite is positioned to monitor a natural phenomenon.

The *External Environment* module puts all the trajectories of natural events and satellites (the agent) in contact (in the same environment). In this module, the agent checks whether it has captured any events using its position and the coverage area of its sensor. If an event is captured, it reports the characteristics of the event to all the other agents, i.e., its name and the latitude and longitude captured.

2) Data Extraction: We used open data from reliable sources to work with actual data in our experiment. For natural event

[8]Term used in information security to refer to a list of trusted entities that have been preauthorized to access a system, resource, or network.

[9]This time window was selected based on the orbital characteristics of CubeSats in Low Earth Orbit (LEO), which typically complete multiple revolutions around Earth in 24 hours. This parameter is configurable within the system.

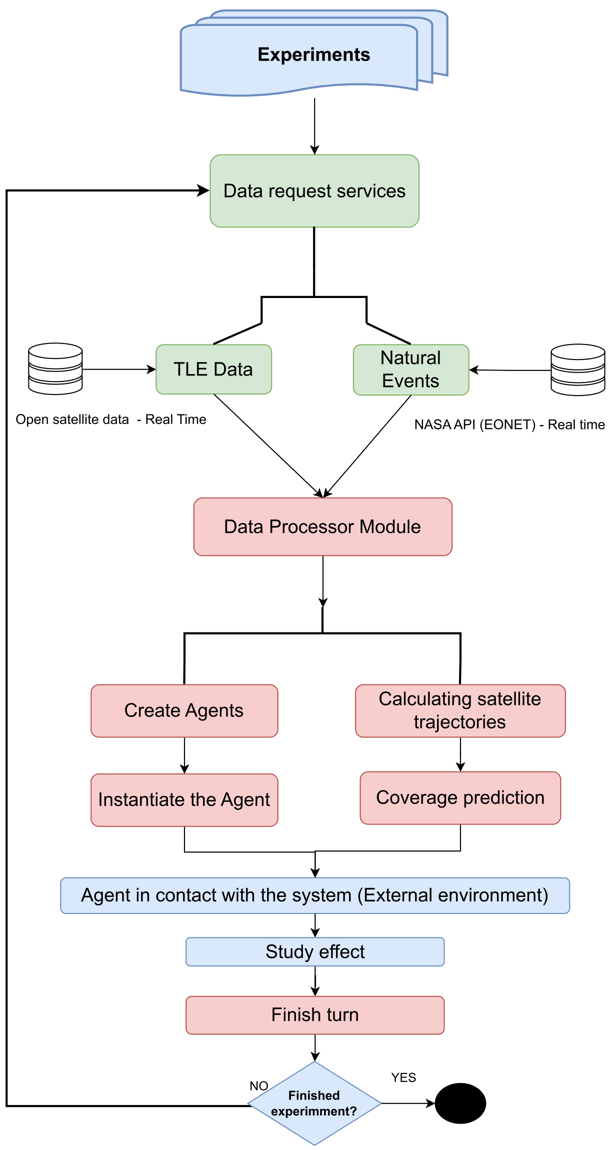

Fig. 11. Experimental flow. For the experiment, real data with the satellites' positions was used to cross-check with data from natural events in the period. The result compares the observations and potential observations of whether the activation was automated.

data (already categorized by event type), we used EONET [42] public API. To obtain TLE data for the satellites, we used open satellite tracking sources such as N2YO[10] and SatNogs.[11] The digital twins of the satellites, comprising attributes such as sensors, resolutions, and other technical specifications, used in the simulation were modeled based on publicly available information from satellites listed on the IC-SMD website [55].

DADOS was designed to be configurable. Thus, the project's *config.ini* file can contain additional data sources, including potential future scenarios where data is received directly from ground stations or control centers. In [31], the authors had already developed a framework capable of decentralizing uplink/downlink using ground stations.

[10][Online]. Available: https://www.n2yo.com/
[11][Online]. Available: https://network.satnogs.org/

TABLE III
TECHNICAL CONFIGURATIONS

Type	Detail
Number of servers	3
Operations System (servers)	Ubuntu 22 LTS
RAM	16 Gb
Languages used	Python, Bash, MATLAB, and Solidity
Toolbox	Satellite Communications Matlab
Blockchain and Number of Nodes	Hyperledger Besu v24.1 and 4 nodes
Open Sources used	EONET, Copernicus, IC-SMD, N2YO

3) Simulations: Two scenarios were the focus of our experiment: 1) Using only Copernicus satellites (not limited to Sentinel 1 A/B and 2 A/B), and 2) Satellites registered in the IC-SMD (see Fig. 12). This approach allowed us to analyze DADOS's performance when operating with a single satellite constellation (consisting of nine satellites) and when handling 17 constellations (a total of 71 satellites). The comparison between the figures highlights the coverage potential when DADOS is expanded to automate IC-SMD partners.

Table III shows the technical configurations of the experiments.

IV. Results

This section presents the results of the experiments for the two scenarios mentioned in the simulations. The first part of the results presents the tests for Automating the Activation of the Sentinel Constellation. In addition to the four satellites from IC-SMD (Sentinel 1 A/B and Sentinel 2 A/B), we include the other five satellites from the Sentinel constellation. In this scenario, all satellites belong to the same institution, so the identity verification on the blockchain network for the agents has been deactivated. The trust process is done through a simple query to a *whitelisting* with a 256 hash of their identity. For the scenario of automated activation for multiconstellations, we used the assignment of a unique ID (sha256 format) for each satellite. We did not assign some satellites an identity, so the agents performed checks to determine whether the agent providing information during interactions was trustworthy. We conclude with the analysis of the Blockchain layer and the potential of the solution.

A. Automating the Activation of the Sentinel Constellation

In the intraconstellation automation scenario, verifying the authenticity of each agent's identity was bypassed. The result was a faster decision-making process. We highlight that the decision-making process considered the diagram in Fig. 10. In Figs. 13 and 14, we present a comparison of the coverage time between the solitary acquisition of each agent and the potential coverage in the case of the C.A (certainly, only the agents deciding to collaborate with the coverage). Fig. 13 illustrates the observation capabilities related to *Cyclone Taliah*. The blue curve depicts the cyclone's potential coverage, with its points indicating the projected times of data acquisition. Conversely, the purple line represents a solitary satellite's observation, showing two actual data collections performed within the initial 24

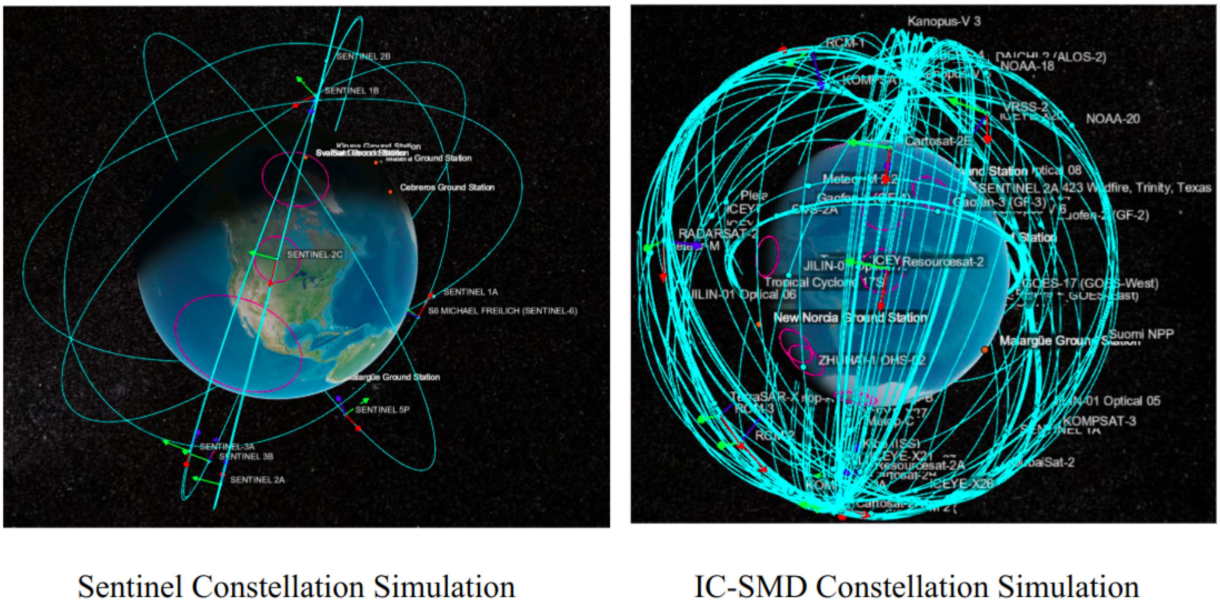

Fig. 12. View of the simulation of the two analyzed scenarios: Intraconstellation and multiconstellation activation.

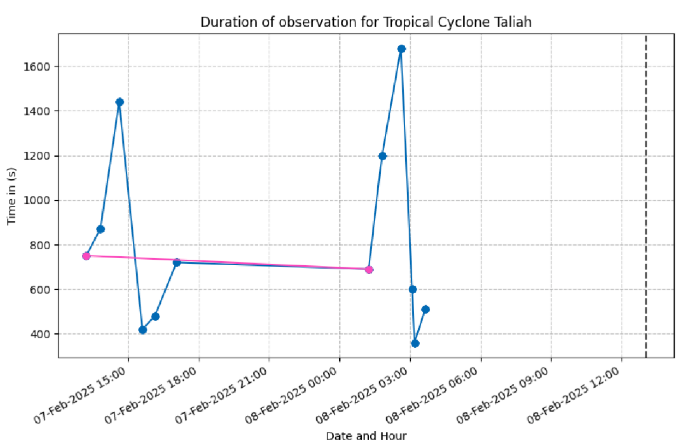

Fig. 13. Comparison between the observation time in the first 24 hours of tropical cyclone Taliah, made both by the first satellite to be able to capture data and by the other satellites (constellation) in the automated activation scenario.

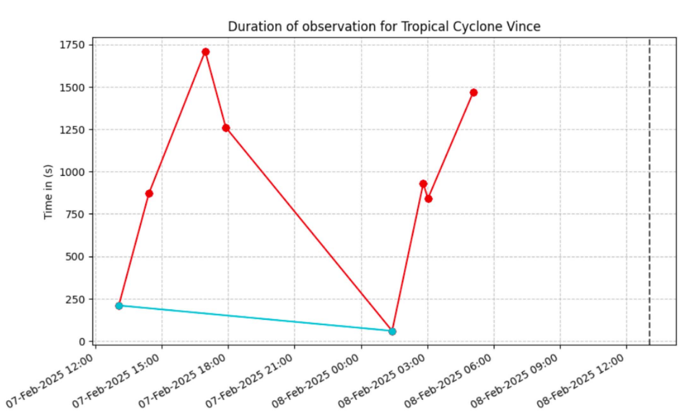

Fig. 14. Comparison between the observation time in the first 24 hours of tropical cyclone Vince, made both by the first satellite to be able to capture data and by the other satellites (constellation) in the automated activation scenario.

TABLE IV
COVERAGE SOLITARY AND MULTICONSTELLATION ACTIVATED

Event	**S.O(s)**	**C.A(s)**	**Gain**	**Who has activated?**
Cyclone Zelia	1290	349950	270 ×	No one
Cyclone Vince	1880	373440	206.5 ×	No one
Cyclone 16P	1350	442350	326 ×	No one
Cyclone Taliah	2250	406050	179 ×	No one

hours from the first acquisition (indicated by the dashed line). The points on both curves collectively denote the number and timing of data collections.

Conversely, in Fig. 14, *Cyclone Vince* is depicted with two data collections marked by the blue curve. The potential for data collection through automated activation is represented by the red curve, showing eight possible collections that could be performed within the first 24 hours.

B. Automated Activation for Multiconstellations

The automation of multiconstellations considerably increased the system's complexity. However, considering data from 71 satellites, the system demonstrated resilience in responding to the simulations, which we will discuss next.

1) Coverage Gain Analysis: Table IV presents the event name, the observation time in seconds for solitary observation (S.O), the observation time in seconds with the activated constellation (C.A), the gain indicating how many times the C.A time is greater than the S.O time, and whether any satellite was officially activated and by whom (Copernicus or IC-SMD). We emphasize that the activation of both the Sentinel constellation and IC-SMD is carried out through official requests by authorized members, following a minimum lead time of 24 hours.[12] The dataset produced by the experiments is available in [56]. In Table IV,

[12] With a few specific exceptions, when it can occur within a few hours.

TABLE V
DIFFERENT SCENARIOS FOR TRUSTING ANOTHER AGENT

Type	**AVG Time (ms)**
Without checking the identity of another agent	0.01
Checking locally (same server)	9.85
Checking with the remote server queries	555.98

the *Who has activated*, the possible options would be some of the satellites or partner constellations of the IC-SDM.

The simulations conducted, although based on real data regarding satellite positions, sensor specifications, and angles of incidence, as well as the location and type of natural events, did not account for the quality of the data obtained through activation/coverage. This limitation arose due to financial and technical constraints that prevented a more realistic simulation—one that would, for example, consider weather conditions, error rates in GS-satellite communication, and other technical and operational factors. Nevertheless, the results presented are valuable at this stage of DADOS development, as they yield outcomes of such magnitude that, even if the listed factors were to reduce the final performance by an order of magnitude, the solution would still demonstrate a significant advantage over traditional approaches.

2) Decision-Making Time: The measurement of the time taken for agents to make their decisions based on trust in other agents was analyzed in three stages: 1) Without checking the identity of other agents, i.e., complete trust; 2) Checking the agent's identity (whether they are an authenticated member of the system) with locally performed queries, and 3) Checking the agent's identity with queries to servers located in geographically distant locations. Table V presents the average decision time. The detailed presentation of the time taken by each satellite that agreed to collaborate is shown in Figs. 15 and 16, respectively. These two figures represent all satellites that participated in the decision-making process regarding whether or not to collaborate on data collection for the targets selected in Figs. 13 and 14. Note that the time difference between each decision process accounts for the chain of computations involved, such as whether the orbit will intercept the target within the next 24 hours, the suitability of the satellite constellation, battery level verification, and so forth. Satellites that took less time to make a decision likely encountered a negative flow, as presented in Fig. 10, leading to a faster response since other decision-making verifications were bypassed.

To illustrate (See Fig. 17) the experiment of distributing the DADOS service, we instantiated the blockchain and the smart contract on a server in Brasília, the capital of Brazil, while the application running the multiagent system was instantiated in the city of Rouen, Normandy, France. The experiment aimed to analyze the time impact on the agents' decision-making process.

A comparison between the results presented in Figs. 15 and 16 reveals that the impact of querying within the distributed node architecture of the DADOS solution results in approximately 60 times greater time consumption than local queries. Nevertheless, despite the presence of 71 satellites and the various communication links connecting the two servers, the time required remains

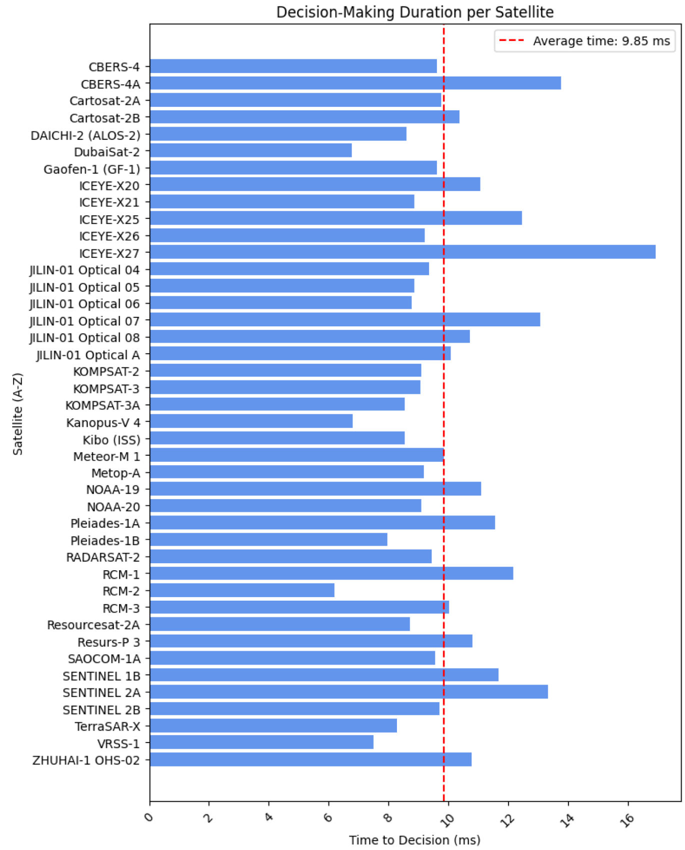

Fig. 15. Duration of decision-making time with trust among agents governed by local queries (on the same server) to verify the authenticity of agent identities during system interactions. In this case, the queries are performed via a smart contract on the Blockchain, ensuring that identity management and security are decentralized.

in milliseconds, thereby demonstrating the robustness of the proposed solution.

An additional noteworthy aspect of this scenario is that a query directed to a geographically distant server would occur when a ground station has not instantiated the blockchain node locally or when the node is unavailable at the time of the query. In such cases, DADOS employs a load-balancing service to route the query to an alternative available node, ensuring system reliability and operational continuity.

An interesting observation can be made when comparing the Brazilian satellites CBERS-4 and CBERS-4 A, where an inversion in consumption is observed. This occurs because, for the charts, we chose to present the list of satellites in alphabetical order; however, the processing did not take this ordering into account, particularly regarding the registration of satellites on the Blockchain.

In this case, during each decision-making process, agents search for the satellite's existence in the list of registered agents (satellites) by using its NORAD (Satellite number, see Fig. 4). The position of the record, given the volume of blocks created (one block every two seconds), impacts the search time.

3) Simulation of the Multiagent System: We used the Mesa library [57] to create and model the multiagent system. As illustrated in Fig. 10, we modeled the satellite and the system

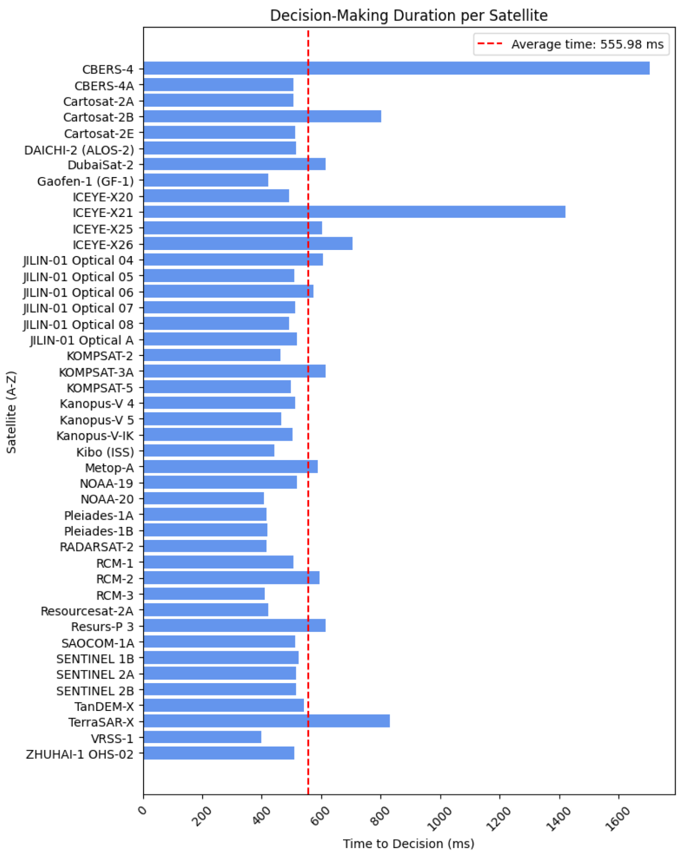

Fig. 16. Duration of decision-making time with trust among agents governed by geographically distributed queries (on distant servers) to verify the authenticity of agent identities during system interactions. In this case, the queries are performed via a smart contract on the blockchain, ensuring that identity management and security are decentralized.

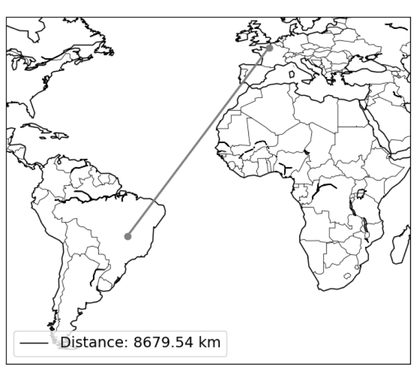

Fig. 17. For the server distribution experiment, a server was deployed in Brasília, Brazil, where the Blockchain (4 nodes) and smart contracts were instantiated. The other two servers were deployed in Rouen, France, where the digital twin applications and multiagent systems were executed.

for their interactions. One key parameter we focused on is the *grid*, representing the virtual space where agents can move and act.

The discretization of the Earth's surface could be configured with various widths, heights, and step counts. Given our modeling approach, we observed that using a width of 360 and a height of 180 with a single step was sufficient to accelerate the simulation without impacting the decision-making accuracy.

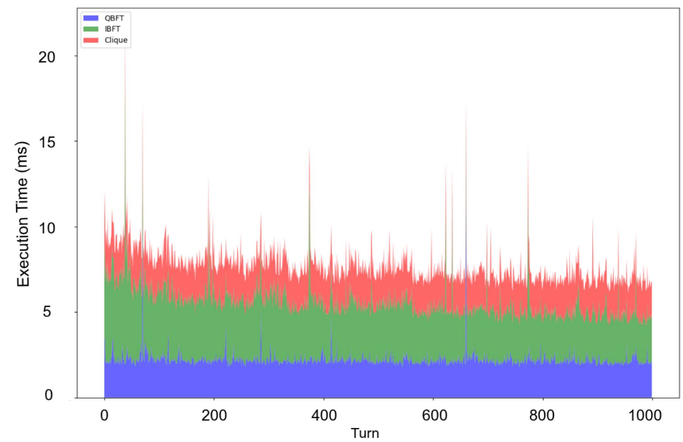

Fig. 18. Comparison of processing time for 1000 transactions across each consensus algorithm. In red, indicating higher time consumption, is the CLIQUE algorithm. In green is IBFT, inspired by the Byzantine fault tolerance algorithm, and finally, in blue, QBFT, an adaptation of the IBFT algorithm designed to simplify the logic of messages exchanged between validators, reducing communication overhead, and ideal for permissioned networks, such as in the case of DADOS.

C. *Blockchain Layer*

The blockchain used was Hyperledger Besu [45] due to its compatibility with the most extensive public blockchain network currently available, Ethereum [58]. This choice demonstrates DADOS's compatibility and interoperability capability should the solution be deployed on a public network. As a permissioned network using Besu, some consensus algorithms can be used.

The authors conducted a previous performance study comparing these three consensus algorithms and presented in [59], with results illustrated in Fig. 18.

Based on the network's configuration and requirements, *Quorum Business Fault Tolerance*[13] (QBFT) is the most suitable option. We recommend using a permissioned network, where, for instance, the gas[14] fees can be set to zero, eliminating costs for the consortium members formed by the solution's partners.

1) Processing and Storage: All DADOS processing takes place on the ground segment, ensuring that satellites, which have severe computational and power constraints [60], are not burdened with these calculations, being tasked only with receiving telecommands. As a result, DADOS remains entirely transparent for the satellites and constellations.

Regarding storage, the machine used has a 100 GB hard drive. The system can easily monitor the database's growth, as each empty block occupies 840 bytes (including all block data and metadata) and can reach up to 1.40 MB with a single recorded transaction containing a 32-byte payload. Database pruning techniques can be applied to remove empty blocks and reorganize the network when needed.

[13]The QBFT consensus algorithm is an enterprise-grade, proof-of-authority protocol recommended for private blockchain networks, where a pre-selected set of approved accounts (validators) take turns proposing and validating blocks, ensuring immediate finality and Byzantine fault tolerance (ability to function correctly even if up to one-third of validators are malicious or fail).

[14]Gas in Ethereum is the unit that measures the computational effort required to execute transactions or smart contracts, with fees paid in Ether to compensate network validators.

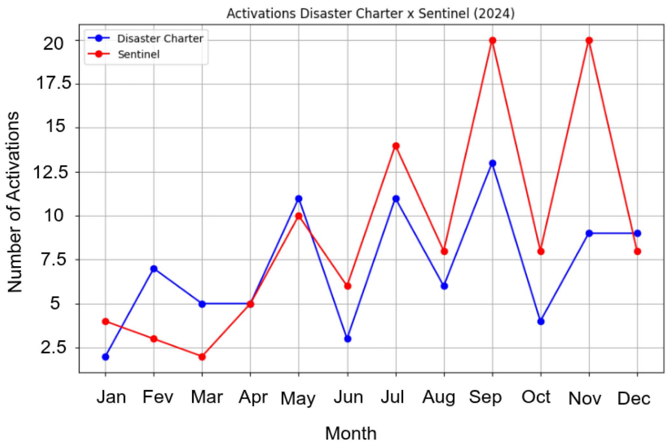

Fig. 19. Comparison of the activations that occurred in 2024. In red are the activations registered on the Copernicus website, and in blue are those registered on the International Charter website. Despite the IC-SMD having dozens of additional satellites (available potential), the highest number of activations is found in the curve referring to Sentinel, likely due to the number of steps and/or the autonomy each team has to control their satellites manually.

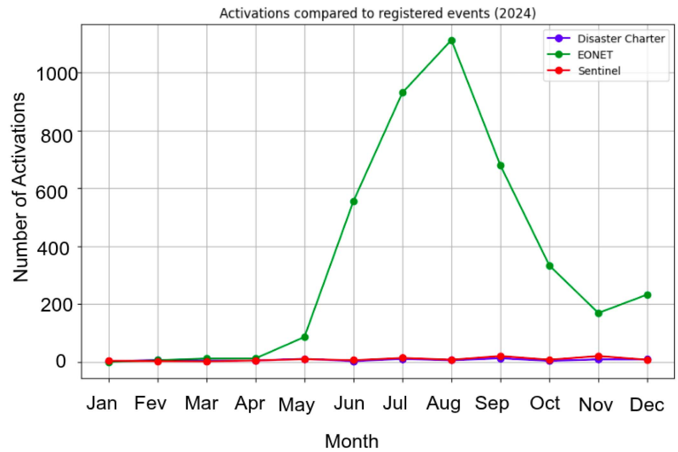

Fig. 20. The green curve, prominently displayed, represents all the natural events recorded in the EONET database, in contrast with the activations carried out during the same period, highlighting the monitoring gap, especially from April 2024 onward.

D. Potential of Solution

The solution's potential can be explored by examining the data available to feed and test our model. Using the EONET database to get the events or natural disasters captured by satellites during January 2025 [61]. In total, 103 observation targets were recorded, including wildfires, icebergs, and tropical cyclones. When analyzing the activation data of the Disaster Charter, we found only two activations, while Copernicus had five activations. If an automation process were applied to the decision-making for event coverage, based on the 103 events recorded in EONET and the possible interactions with the Sentinel constellation, there would be a potential of approximately 3500 possible interactions between Sentinel satellites and the events.

We can also explore the solution's potential by comparing activations with event records over a specific period. For example, we first analyze the number of Disaster Charter activations with the Sentinel satellites' activations in 2024 (see Fig. 19). We notice that, in general, there are more activations from the Sentinel constellation than from the Disaster Charter, with some Disaster Charter activations likely including data from Sentinel satellites that were activated through their partnership with the Disaster Charter. Analyzing why Sentinel has more activations is beyond the scope of this work, as the activation processes for the Sentinel constellation differ when done by Copernicus compared to when requested by the Disaster Charter. On the other hand, when comparing the overall activation numbers of the Disaster Charter and the Sentinel Constellation with the events recorded in the EONET database (see Fig. 20), we can notice a significant difference in uncovered targets, revealing untapped potential.

Even though the EONET database may contain targets that might not be of interest or generate an activation, such as icebergs and their monitoring, this can be addressed in the decision-making process of the system's satellite agents. An important fact is that some satellites from the Sentinel constellation make orbits that cover the Earth's poles, which could help capture data on icebergs, for instance, to provide warnings and alerts to ships in the region.

V. Limitations and Implementation Strategies

This section provides a critical reflection on aspects of an expanded technical discussion, outlining strategies to address and mitigate the identified challenges. In addition, it offers relevant insights that, while nontechnical, are important for implementing the solution in a real-world, collaborative environment.

A. Institutional Interoperability

The DADOS infrastructure design prioritizes minimal impact on existing systems, ensuring that the critical communication process between the CC and the satellite via the GS can be preserved using conventional infrastructures. This means that whether CCSDS protocols or other methods are employed, they can be maintained, as the final output of DADOS consists of the telecommands and the target satellite. Consequently, a human or automated operator can use the DADOS output to send these telecommands to a partner or proprietary GS for satellite transmission.

1) Integrating DADOS With Legacy Systems: Connecting DADOS to traditional and legacy infrastructures requires technical adaptations and, potentially, the development of new functionalities on the side of participating institutions. Fig. 5 illustrates that DADOS receives input data from a module referred to as $Service$, which is pre-processed and prepared for ingestion, comprising both the payload collected by the satellite and the associated metadata.

The metadata includes geospatial coordinates such as latitude, longitude, and altitude, as well as the data acquisition timestamps. In addition, technical details related to the onboard sensors responsible for the collection, such as calibration parameters and sensor specifications, are also provided. These inputs enable

DADOS to perform downstream processing and task inference with a high degree of contextual awareness and interoperability.

B. Geopolitics and Solution Adoption

Adopting the DADOS solution requires adjustments and adaptations to current processes, as well as agreements and decisions that will have technical and political consequences. We highlight some important points to consider:

1) *Revision of Agreements:* Participating institutions involved in joint Earth monitoring initiatives will need to review and adapt their existing agreements to facilitate the adoption of the automated processes proposed by DADOS.
2) *Update of Security Rules:* Implementing the DADOS infrastructure necessitates establishing a permissioned network of interconnected servers. The rules for a server (or node) to join this network must adhere to traditional cybersecurity guidelines, some of which have already been discussed throughout this work.
3) *New Routines:* With the adoption of new techniques, new procedures will be executed. This means that situations and procedures will need to be thoroughly mapped and documented, and involved teams will require training. Incidents, maintenance, and updates must be meticulously defined and observed.
4) *Mapping Non-Pre-emptible Tasks:* A crucial element in the decision-making process for agents representing satellites involves assessing their capacity to undertake novel tasks. This assessment specifically pertains to their ability to reallocate resources and modify existing flight plans to acquire data from newly designated targets. Consequently, this necessitates identifying whether a routinely scheduled task, currently being executed by a satellite at a specific orbital position, can be preempted by a new task subsequently processed by the DADOS system.

VI. Conclusion

The adoption of blockchain and decentralized technologies has garnered significant interest from space agencies globally. A prominent example is the white paper published by the European Space Agency in 2019, which identifies strategic areas for the application of blockchain in Earth observation systems [62]. The DADOS framework not only addresses the challenges and opportunities outlined in that document but also extends its scope by incorporating blockchain technologies with autonomous decision-making mechanisms grounded in MAS architectures.

DADOS is an integrated system designed to automate the activation of Earth observation satellites, operating either under human supervision or in a fully autonomous mode. It has demonstrated the potential to enhance target coverage efficiency while ensuring operational integrity through a secure, distributed infrastructure. The decision-making process is driven by data and executed autonomously by agent-based components within the system. Although the experimental validation employed real-world datasets—such as TLE sets and records of natural events obtained from open sources—the operational scenarios simulated the interactions among the system's principal entities: satellites, CC, and GS.

In real-world operational scenarios, several factors may significantly affect the timing and efficiency of decision-making, satellite activation, and data collection. These include network communication delays, the physical distance between CC and GS (which host the DADOS nodes), atmospheric conditions, communication quality, security policies, and the use of advanced pattern recognition techniques for detecting targets in imagery and signal data.

The simulation results are instrumental in validating critical aspects of the DADOS architecture, such as *real-time decision-making* based on *dynamic inputs* from satellite digital twins; *scalability* (for decision-making), demonstrated through simulated multiconstellation deployments; and system performance metrics, including *latency*, evaluated by deploying DADOS nodes across two geographically distant sites, Brazil and France, using nondedicated communication links. DADOS employs the concept of digital twins to instantiate autonomous, intelligent agents capable of responding dynamically to environmental changes. These agents interact cooperatively to determine whether to share computational resources and coordinate satellite activities with the shared objective of monitoring a target. In practical terms, this means satellites can autonomously exchange data and adjust orbital resources or acquisition plans to optimize Earth observation missions.

The experimental campaign used real satellite positional data from active Earth observation constellations and integrated real-world event data to validate the system's proof of concept. Involving 71 satellites across 14 different constellations, the simulation assessed DADOS's performance by comparing its simulated activations with the actual ones that occurred during the observed period. The dataset produced from these simulations has been made publicly available for research purposes.

Furthermore, the deliberate placement of test servers over a direct distance exceeding 8679 km (with actual data routes likely longer due to HTTP network paths) yielded an average decision-making latency of 555 ms per agent, underscoring the system's robustness and efficiency.

The next planned steps involve developing a governance and information security study related to DADOS, as well as conducting experiments using weather balloons and CubeSats to expand the scope of current research. In addition, the automation of final products (see Fig. 1) will be addressed in future publications.

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José Edilson Silva Filho is currently working toward the joint Ph.D. degree in computer science with the Institut National des Sciences Appliquées de Rouen (INSA Rouen), Rouen, France, and in teleinformatics engineering with the Federal University of Ceará, Fortaleza, Brazil.

His research interests include blockchain, intelligent systems, and data science, with interests in space applications, cybersecurity, IoT, and multiagent systems.

Marc Saideh received the bachelor’s degree in computer science from the Université de Poitiers, Poitiers, France, in 2020, and the master’s degree in distributed artificial intelligence from Université Paris Cité, Paris, France, in 2022. He is currently working toward the Ph.D. degree in computer science with INSA Rouen Normandie, Rouen, France.

He conducts his research for doctoral studies within the LITIS Laboratory. His doctoral work focuses on trust management and authentication decision-making in multiagent systems and the Internet of Things. His research interest focuses on developing adaptive, context-aware mechanisms that enhance security while balancing efficiency in dynamic IoT environments.

Laurent Vercouter received the Ph.D. degree in computer science from Ecole Nationale Supérieure des Mines de St-Etienne, in 2000.

He was an Assistant Professor with the Ecole Nationale Supérieure des Mines of Saint-Etienne. He is currently a Full Professor in computer science with INSA Rouen Normandie and with the LITIS Laboratory, Rouen, France, since 2011. He has led or participated in several international and national projects in his research fields and has authored or coauthored more than 100 papers on his works. Since 2024, he is Scientific Advisor on Artificial Intelligence for the French Ministry of Higher Education and Research. His research interests include the domain of multiagent systems with a specific focus on decentralized trust management systems, multiagent reinforcement learning, and socio-technical systems.

Jarbas Aryel Nunes da Silveira (Member, IEEE) received the Ph.D. degree in computer engineering from the Federal University of Ceará (UFC), Fortaleza, Brazil, in 2005.

He is currently an Associate Professor with the Department of Teleinformatics Engineering, UFC, Fortaleza, Brazil. His research interests include fault-tolerant embedded systems, radiation-hardened electronics for space applications, microelectronics design, and hardware-software co-design.

César Marcon received the Ph.D. degree in computer science from the Federal University of Rio Grande do Sul (UFRGS), Porto Alegre, Brazil, in 2005.

Since 1995, he has been a Professor with the Polytechnique School of Pontifical Catholic University of Rio Grande do Sul (PUCRS), Porto Alegre, Brazil. He has authored or coauthored more than 200 papers in prestigious journals and conference proceedings. He is an advisor to M.Sc. and Ph.D. students with the Graduate Program in Computer Science, PUCRS. He is a distinguished Brazilian Researcher.

Prof. Marcon was the recipient of a CNPq PQ grant. He is an ACM and an SBC member.

Walter Dos Santos received the B.Sc. degree in electronic engineering, the M.Sc. degree in computer engineering, and the D.Sc. degree in computer science from Instituto Tecnológico de Aeronáutica, São José dos Campos, Brazil, in 1987, 1992, and 2008, respectively.

He is currently with the National Institute for Space Research (INPE), São Paulo, Brazil. His research interests include model-driven systems engineering, on-board computing, satellite-based services, and multiagent systems.

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