The Optimization of Data Management in Low Earth Orbit (LEO) Through Data Storage and Edge Computing Services

Shareef Al Romaithi, PhD. [1], Basel Altawil [2]

[1] MADARI SPACE ; salromaithi@madari.ae
[2] Khalifa university , KUSTIL ; basel.altawil@ku.ac.ae
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Abstract: The commercialization of low Earth orbit (LEO) has resulted in an exponential growth of data generated in space. This growth is primarily driven by the increase of remote sensing applications, such as Earth observation (EO) satellites, which present a significant challenge for data storage and transmissions. This paper studies the challenges and opportunities of data management in space while focusing on the increase of congestion at ground stations and costs associated with downstream data.

Recently, there has been a significant surge in the deployment of satellites. The majority of these satellites generate data related to EO operations, which have increased the demand for data storage, processing, and transmission. Traditional data management relies on ground stations that are experiencing unprecedented congestion levels, leading to delays, data losses, and increased operational costs.

This research paper aims to explore innovative solutions to tackle these problems through the integration of advanced technologies capable of storing and processing data in LEO. Managing data in space could reduce the volume of data transmitted to Earth by allowing scientists and satellite operators to transmit processed and relevant data only. Importantly, real-time data analysis and decision-making for most Earth observation (EO) satellite missions can be achieved by processing data in LEO. Accomplishing these steps can be critical for time-sensitive operations, such as responses to natural disasters.

Data storage capabilities in LEO is viewed as a cost-effective alternative to conventional transmission methods. By utilizing such capabilities, satellite operators could optimize their communication process through the transmission of processed and vital data to ground stations. This approach reduces the frequency and volume of data transmissions, lowering operational costs and minimizing data congestion at ground stations.

By decreasing the dependency of satellite operators on ground stations and the volume of data transmissions, the proposed services can result in substantial cost savings and enhanced operational processes. In addition to the economic benefits, this paper highlights the technologies proposed to successfully operate data storage and edge computing systems capable of withstanding the harsh environment in space.

The exponential increase of data generated in LEO necessitates innovative solutions to optimize future operations and enable sustainable growth in near-Earth space. The ability to provide data storage and edge computing services in LEO presents viable solutions to address challenges associated with congestions at ground stations, increased transmission costs, and delays in obtaining critical data. This research underscores the importance of developing space-based data management solutions that would provide the necessary infrastructure to sustain the commercialization of LEO.

Keywords: LEO, satellite data, EO, data centers, remote sensing, data transmission, ground stations, real-time analysis, time-sensitive operations

1. Introduction

The space industry has undergone a significant evolution over the past several decades, marked by rapid commercialization and technological advancements, particularly in LEO. This evolution has been driven by a surge in remote sensing applications such as Earth Observation (EO) satellites, which have become major contributors to the industry's economic activity. In 2023, the commercial satellite sector alone generated revenues totaling $285 billion, accounting for 71% of the global space industry's economic activity (Jewett, 2024). Projections indicate that by 2032, an average of 2,800 satellite launches per year will occur, leading to a total of 28,700 satellites in Earth's orbit, representing a market value of $588 billion (Euroconsult, 2023)[1].

This proliferation of satellites has led to an exponential increase in data generated in space, presenting significant challenges for traditional ground-based data management systems. These systems struggle with congestion, resulting in delays, data losses, and rising operational costs. As the volume of data surges, with satellites producing petabytes of information daily, including EO, scientific research, and communication signals, the necessity for efficient data management becomes paramount (Mohney, 2020[2]; Myśliwiec, 2023[3]).

In response to these challenges, this paper explores innovative solutions focused on optimizing data management directly in LEO. By leveraging advanced technologies, such as edge computing, satellite operators can process data in real-time, significantly reducing the need to transmit large volumes of unprocessed information to Earth. This capability is especially crucial for time-sensitive missions, such as disaster response, where rapid decision-making is essential.

Storing and processing data in LEO offers numerous benefits, including the utilization of free solar power, efficient cooling in the vacuum of space, and protection from Earth-bound risks, such as natural disasters. These advantages not only reduce reliance on ground stations but also minimize transmission frequency, thereby enhancing operational efficiency and reducing costs.

Furthermore, the United Arab Emirates (UAE) plays a pivotal role in supporting the space sector, with forward-thinking policies and initiatives from the UAE Space Agency aimed at fostering innovation and commercial ventures in LEO. As a leading space hub, the UAE provides an ideal environment for developing space-based data management infrastructure, aligning with the nation's broader goals of becoming a global leader in space exploration and technology.

This research underscores the importance of space-based data management solutions in sustaining the rapid growth of LEO activities and highlights the solutions required to enable this future.

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[1] "Four Tons of Satellites to Be Launched Daily by 2032, Demand Concentrates by a Handful of Players - Euroconsult Group, Merged with SpaceTec Partners to Form Novaspace."

[2] "Terabytes From Space: Satellite Imaging Is Filling Data Centers | Data Center Frontier."

[3] "Enhancing Earth Observation Capabilities - Satellite Data Applications and Implications - Blog | CloudFerro."

2. Problem Statement

The rapid increase in satellite launches, coupled with advancements in satellite technologies, has led to an unprecedented surge in the volume of data generated in space (Mohney, 202)[4]. The data output has already surpassed petabyte levels on a daily basis. This exponential growth presents significant challenges in terms of transmitting space-based data from space to Earth. Satellite operators face growing challenges in efficiently transmitting this data, leading to rising operational costs and potential bottlenecks at ground stations (Rotoiti, 2021)[5].

3. Purpose Statement

This research aims to explore and propose solutions to the challenges posed by the exponential growth in space-generated data, particularly in terms of storage, processing, and transmission. This research aims to examine the current limitations of ground-based infrastructure in handling petabyte-scale data output and to highlight the potential of a space-based data center as a viable alternative. By focusing on the innovations currently being developed by MADARI Space, this research seeks to provide insights into how these technologies can support the growing demands of the space industry.

4. Literature Review

The rapid and exponential increase in satellite numbers in orbit generates vast amounts of data. To sustain the forecasted growth of satellite operations, innovative solutions, such as space-based data centers, will be essential to efficiently process, store, and transmit this massive data volume while ensuring operational efficiency**.**

4.1. Satellite Operations

Currently, there are 9,900 active satellites, with 84% operating in LEO, 12% in geostationary Earth orbit (GEO), and 3% in medium Earth orbit (MEO) (Nano Avionics, 2024[6]). These numbers are projected to grow rapidly as the commercialization of space accelerates, driven by increasing demand for services, such as communication, EO, and satellite-based internet. The rise of private sector involvement and the deployment of mega-constellations, particularly in LEO, will further boost the number of satellites in orbit, significantly expanding the industry and the volume of data being produced (Oni,

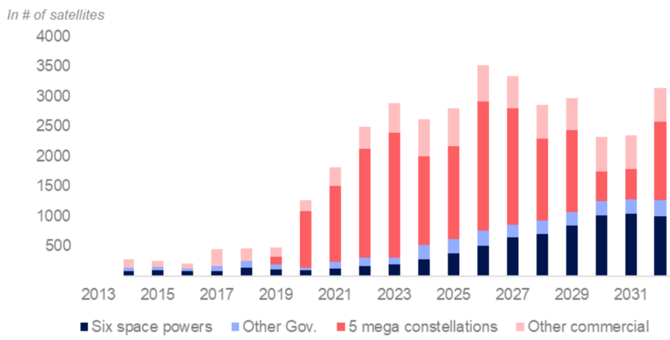

Figure 1 Annual Satellite Launch Forecast, Note. Adapted from "Four tons of satellites to be launched daily by 2032, demand concentrates by a handful of players," by Euroconsult, 2023. Copyright 2023.

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4 "Terabytes From Space: Satellite Imaging Is Filling Data Centers | Data Center Frontier."

5 Rotoiti (2021). Brief: Downlink bandwidth constraints and solutions. Retrieved from https://rotoiti.space/wp-content/uploads/2021/06/210624-Brief-Downlink-Bandwidth-Constraints-and-Solutions-1.pdf

6 Ieva, "How Many Satellites Are in Space?"

2023[7]). This commercial expansion is demonstrated by the rising number of annual satellite launches into Earth's orbit, as depicted in Figure 1.

Oni reports that EO data makes up approximately 86% of the total data generated by space applications. EO datasets currently total 807 petabytes (PB) and are growing at a rapid pace, with an increase of over 100 PB per year (Wilkinson et al., 2024[8]). According to Figure 2, EO satellites will generate over two exabytes (EB) by 2032, reflecting a compound annual growth rate (CAGR) of 11%.

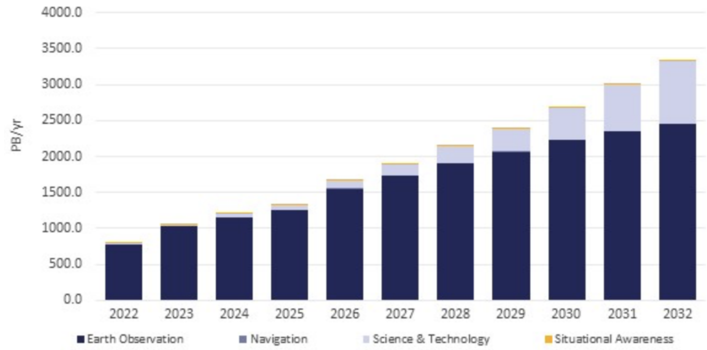

Figure 2 Satellite and Space Applications Data Traffic by Segment , Note. Adapted from "The implications of increasing Earth observation data," by D. Oni, 2023. Copyright 2023.

For example, Maxar Technologies, a Colorado-based company, holds an extensive library of over 110 PBs of space-based data and is adding more than 80 TBs of new data each day (Mohney, 2020). Other EO companies also collect similar volumes of data, contributing to the growing global repository of space-generated data. Table 1 provides a list of EO companies and their space-based data collection activities.

Company / Satellite	Data Collection
Planet	40 TBs per day
Copernicus	12 TBs per day
Capella Space	72 - 360 TBs per day
ICEYE	5 - 12 TBs per day
Umbra Labs	5 - 12 TBs per day

Table 1 Space-Based Data by EO Companies , Note. This table provides the approximate amount of space-based data generated by each company or satellite constellation, providing a snapshot of the scale of data collection activities within the EO industry. A range of figures are provided for constellation satellites, with both low and high-end estimates subject to the operational status of the planned constellation size.

4.2. Ground Stations

Ground stations are essential, serving as the key link for satellites to transmit their data to Earth after the collection process in orbit (Rotoiti, 2021). To downlink data, satellites must

[7] Oni, "The Implications of Increasing Earth Observation Data."

[8] "Measuring Greenhouse Gas Emissions in Data Centres."

be within range of ground stations. The average satellite pass over a given ground station is 10 minutes, encompassing the acquisition of signal (AOS), data downlink opportunity (DDO), and end of signal (EOS) (Carvalho, 2019). Ground stations have limited throughput, and satellites may wait for hours and, in some cases, days before downlinking their data (Rotoiti, 2021). In addition to high latency, satellite operators may be restricted to certain ground stations due to jurisdiction limitations (Rotoiti, 2021).

Given these constraints, ground stations are forced to prioritize certain satellites, as they lack the capacity to process data from all satellites simultaneously (Rotoiti, 2021). Moreover, the enormous volume of data generated in space, combined with the limited window for DDO, creates a significant bottleneck. The demand for downlink capacity far exceeds the available resources, underscoring the widening gap between the rapid pace of data collection in space and the constraints of ground-based processing infrastructure (Rotoiti, 2021).

The cost of data transmissions varies significantly and depends on multiple variables, such as the satellite's orbit, availability of ground station networks, the duration of DDO, bandwidth requirements, and volume of data. According to a quotation from a European-based ground station, the cost of transferring one TB is $45,000.

4.3. Sustainability

Storing the global EO dataset of 807 PB in terrestrial data centers produces a staggering 4,101 metric tons of carbon dioxide (CO2) emissions annually, underscoring the significant environmental impact of data storage at this scale and highlighting the urgent need for more sustainable solutions (Wilkinson et al., 2024). Terrestrial data centers are already facing the challenge of storing an ever-increasing amount of terrestrial data, which is projected to reach 181 zettabytes (ZB) by 2025 (Duarte, 2024). This growing demand places additional strain on existing infrastructure, exacerbating energy consumption and carbon emissions (Duarte, 2024[9]).

Terrestrial data centers are estimated to consume 90 billion kilowatt-hours (kWh), accounting for 3% of the world's electricity (Hill, 2024). Additionally, CO2 emissions generated by terrestrial data centers exceed the aviation and shipping sectors, as demonstrated in Figure 3 (Lavi, 2024).

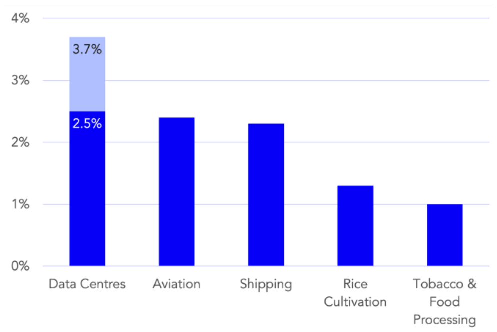

Figure 3 CO2 Emissions Generated by Sector, Note. Adapted from "Measuring greenhouse gas emissions in data centers: the environmental impact of cloud computing," by H. Lavi, 2022. Copyright 2022.

4.4. Space Data Centers

As the limitations of terrestrial data centers become increasingly apparent, the concept of space-based data centers is emerging as a viable solution. Space data centers aim to

[9] "Amount of Data Created Daily (2024)."

address the growing demands of data storage and processing by leveraging the unique advantages of space environments, such as sustainable solar energy (Tomaswick, 2024). Instead of transmitting raw data directly to Earth, satellites would relay it to space-based data centers. These centers would process the data in orbit, transmitting only the required data to ground stations on Earth, thereby optimizing transmission efficiency and reducing the volume of data sent to Earth (Putol, 2024).

Hence, edge and fog computing services would ultimately reduce latency and bandwidth costs, optimizing overall operations by enabling efficient data processing and transmission (Uppal, 2024[10]). This is critical for real-time decision-making requirements, where immediate access to processed data can significantly impact mission outcomes (Uppal, 2024). Space data centers can be scaled by deploying a constellation of satellites, supporting additional processing and storage capacity as demand increases (Uppal, 2024). This modular approach enables operators to seamlessly add resources without the physical and environmental constraints of terrestrial data centers.

5. Proposed Solution: MADARI's Vision for Future Data Management in LEO

In addressing the myriad challenges of space operations, the potential benefits of deploying sophisticated solutions that offer both high computing power and extensive storage capabilities are too significant to overlook[11]. MADARI represents a unique convergence of technological innovations born from a wealth of knowledge and experience accumulated in the region. This system is designed to harness the intrinsic advantages of space to provide high-efficiency computing paired with robust data storage solutions. Below, we detail key aspects of this ambitious initiative, which aims to transform how data is managed in LEO. While MADARI is not the ultimate remedy for all existing space data management challenges, it adopts a forward-thinking approach with the potential to profoundly influence global space-based data operations.

5.1. Power Efficiency, Thermal Management, and Security Measures in Space

5.1.1. Power Generation and Sustainability

In the realm of space operations, power is a critical resource that can be sustainably harnessed through solar energy. Unlike terrestrial data centers that often rely on conventional power sources, contributing to a significant carbon footprint, space-based platforms like MADARI utilize solar panels to generate electricity. This "free" and sustainable solar power alleviates the substantial energy load that data centers impose on Earth's power grids, enhancing the overall sustainability of data operations.

5.1.2. Thermal Management in Space

One of the intrinsic challenges of operating servers, whether for storage or high-computing tasks, is managing the heat they generate. On Earth, this typically requires energy-intensive cooling systems that not only increase operational costs but also reduce the system's overall efficiency. In contrast, MADARI leverages the cold vacuum of space to passively radiate heat away from its systems. While thermal management in space is not without its challenges, the technology MADARI employs is designed to effectively dissipate heat without the need for additional energy consumption, thus enhancing the efficiency and operational longevity of the hardware.

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[10] Tomaswick and Today, “Could We Put Data Centers in Space?”

[11] Rogenmoser and Benini, “Trikarenos.”

5.1.3. Enhanced Security Measures

Security is paramount in data management, particularly when handling sensitive information. MADARI's placement in the isolated expanse of space inherently enhances data security. By storing data away from any physical access, the risk of unauthorized data leakage is reduced. This isolation limits data exposure to strictly controlled transmissions, virtually eliminating the possibility of physical tampering. As such, MADARI not only promises enhanced operational security but also ensures that data integrity is maintained across its lifecycle in space.

5.2. Immediate On-board Data Processing and Enhanced Satellite Capabilities

5.2.1. High-Capacity Computing and Storage

MADARI is pioneering the advancement of high-capacity storage and computing capabilities directly in space. This strategic initiative addresses a critical bottleneck in space operations: the transmission of vast quantities of raw data to Earth. By processing data on-board, MADARI significantly reduces the strain on ground-based communication networks, which are currently overwhelmed by the petabytes of data generated by modern satellite operations as reviewed in the literature.

MADARI is set to revolutionize data management in orbit by providing necessary hardware solutions to other vendors interested in implementing immediate on-board data processing. This capability allows for real-time decision-making based on data analyzed directly in space, thereby enhancing the responsiveness and utility of satellite missions. Furthermore, MADARI could serve as a mid-point satellite for storage and processing, offering older satellites new capabilities that were previously unattainable due to their design limitations.

By integrating advanced artificial intelligence (AI) and machine learning (ML) algorithms, MADARI is setting a new standard in satellite functionalities. This technology enables satellites to process data and make informed decisions directly in orbit before downlinking it to Earth. The application of AI and ML augments the effectiveness of current satellite missions and paves the way for a broad spectrum of new applications. For example, enhanced Earth observation strategies, which can provide precise and timely data, can be achieved swiftly and accurately based on real-time analysis. By leveraging these cutting-edge technologies, MADARI effectively creates a paradigm shift in how satellite operations are conducted, offering substantial improvements in both the scope and the efficiency of space-based data processing.

5.2.2. Reducing Satellite Power and Hardware Constraints

Traditional satellite designs often allocate a considerable portion of their power budget to support the transmission of data to Earth, which also intensifies the wear on their limited-lifetime hardware components. MADARI's approach not only conserves satellite power but also extends the operational lifespan of these systems by reducing the frequency and volume of data transmissions. This conservation of resources is crucial for maximizing the efficiency and longevity of satellites.

5.3. Technological Innovations in Radiation Hardening and Thermal Management

5.3.1. Mastering Radiation-Hardened Electronics

MADARI's research and development trajectory is heavily focused on mastering the development of radiation-hardened electronics, a critical component for ensuring the longevity and reliability of space-based systems. In the harsh environment of LEO, where high levels of cosmic and solar radiation pose a significant threat to electronic integrity, MADARI's advancements in this area are pivotal. By enhancing the radiation tolerance of electronic components, MADARI aims to extend the operational lifespan and functionality of space servers.

5.3.2. Integrated Thermal Management Systems

In conjunction with its efforts on radiation hardening, MADARI is innovating in thermal management by developing systems that combine both passive and active cooling technologies. This integrated approach is essential for managing the heat generated by high-performance computing tasks aboard space-based platforms. While passive cooling leverages the ambient space environment to dissipate heat, active cooling is employed for more demanding applications, ensuring optimal performance even under sustained high loads. Additionally, incorporating highly efficient semiconductor chips that produce minimal heat and require less power further enhances the systems' thermal efficiency and operational sustainability.

5.4. Comparative Analysis: LEO Data Centers vs. Ground-Based Data Centers

While the concept of LEO data centers like MADARI presents transformative possibilities for space-based operations, there are inherent challenges when compared to traditional ground-based data centers. Understanding these differences is crucial for developing effective strategies to mitigate potential drawbacks and enhance the viability of space data centers.

5.4.1. Latency and Processing Speed

One of the primary concerns with space-based data centers is the latency in data transmission and processing speed compared to their terrestrial counterparts[12]. To address this, MADARI is actively exploring potential paths in research and development focused on integrating optical communication systems. These systems promise significantly faster data transmission rates than current radio frequency (RF) communications, reducing latency to levels that rival or even surpass ground-based infrastructure. This advancement could revolutionize how quickly data is sent and received from space, enabling near real-time data processing and significantly boosting the responsiveness of satellite operations.

5.4.2. Risk and Security

Security in data transmission and storage is paramount, particularly for applications involving sensitive or critical information[13]. Space-based systems face unique challenges in this regard, including the risk of data interception and the need for robust encryption protocols. MADARI is committed to the continuous development of high-end encryption protocols to ensure that data transmitted to, from, and between satellites is securely encrypted. This ongoing focus on enhancing data security protocols is designed to protect

[12] "Delay Is Not an Option | Proceedings of the 17th ACM Workshop on Hot Topics in Networks."

[13] Moltz, *The Politics of Space Security*.

against evolving threats and ensure the integrity and confidentiality of the data handled by MADARI.

5.4.3. Cost Considerations

Initially, the cost of deploying and maintaining space-based data centers is significantly higher than for ground-based centers, primarily due to the expenses associated with launch and the sophisticated technology required for operations in harsh space environments. However, MADARI projects that these costs will decrease substantially as the technology is refined and mass production is initiated. Demonstrating the long-term viability and cost-effectiveness of space-based operations through successful technological demonstrations will be key to attracting investments and scaling up production, ultimately making space data centers a more economically feasible option.

6. The Role of the UAE in Supporting Space-based Data Centers

6.1. Strategic Commitment to Space Technologies

The UAE has established itself as a leader in space technology, recognizing the sector's potential to drive national development and innovation. Through strategic investments in EO satellites and space exploration, the UAE has bolstered its infrastructure and policy framework, creating a fertile ground for cutting-edge projects like MADARI[14].

6.2. Supporting Local Startups and Innovation

The UAE's support for local startups and entrepreneurs in the space sector is vital in cultivating a culture of innovation. This ecosystem not only fosters the development of new technologies but also directly supports initiatives like MADARI. By providing the necessary resources and regulatory backing, the UAE enables these projects to thrive and advance the frontier of space technology.

6.3. Business Opportunities in the Space Sector

Leveraging its strategic geographic and economic position, the UAE serves as a hub for space-related activities, offering significant business opportunities[15]. This environment is crucial for the development and implementation of innovative projects such as MADARI, which benefits from the country’s investment-friendly climate and its commitment to technological advancements.

6.4. Pioneering Space Law and Policies

The UAE's proactive approach to crafting space law and policies ensures the sustainable and responsible development of space technologies[16]. These frameworks are instrumental in supporting projects like MADARI, providing guidelines that foster innovation while ensuring compliance with international standards.

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[14] “Tests in Orbit: A Nationwide Challenge in the UAE to Engage University Students, and a Region, in Space Station Microgravity Research | ASCEND.”

[15] “Investigating Factors Influencing Career Choice of Emirati Women in the Satellite and Space Industry in the UAE.”

[16] Abashidze, Solntsev, and Mirzaee, “The United Arab Emirates Approach towards International Space Law.”

7. MADARI's Current Capabilities

Supported by the UAE's robust space sector framework, MADARI has made remarkable strides in space technologies by integrating a high-capacity data storage system capable of handling 8 terabytes and a cutting-edge computing platform designed for AI and real-time data processing. This system features an advanced microcontroller that performs up to 20 trillion operations per second (TOPS), significantly optimizing space missions. MADARI's latest projects have the capability to integrate high-definition cameras with adjustable fields of view ranging from 33 to 220 degrees, offering unprecedented capabilities in environmental monitoring and debris observation in LEO. This technological ensemble serves as a critical platform for testing its capability in data management and as a technology demonstrator, continuously refining its performance and expanding its capabilities.

8. Conclusion

This paper has systematically explored the emerging paradigm of space-based data management, particularly focusing on LEO operations, which are poised to redefine the traditional methodologies used in data handling across the global space industry. Through a detailed examination of the current challenges associated with satellite data management—such as data congestion, high operational costs, and latency issues inherent in ground-based systems—this research highlights the transformative potential of integrating advanced technologies like MADARI to address these issues.

MADARI, as a pioneering initiative, demonstrates how leveraging cutting-edge technologies and innovative solutions, such as high-capacity storage, advanced computing capabilities, and robust security measures, can significantly enhance the efficiency and reliability of space-based operations. By processing and storing data in LEO, MADARI not only minimizes the dependency on terrestrial infrastructure but also paves the way for real-time data processing capabilities that are crucial for critical missions, including disaster response and environmental monitoring.

Furthermore, the role of the UAE in cultivating a conducive environment for the advancement of space technologies has been instrumental. The UAE's strategic commitment to supporting the space sector through progressive policies, substantial investments, and fostering international collaborations has significantly contributed to positioning MADARI at the forefront of this technological frontier.

In conclusion, as the space industry continues to expand and the volume of data generated in orbit grows exponentially, the development of space-based data centers like MADARI will be crucial in ensuring the sustainability and effectiveness of global space operations. The ongoing research and development efforts aimed at overcoming the technical challenges and economic barriers associated with space data management are expected to yield substantial benefits, not only for the space sector but for the broader realm of global data infrastructure. This evolution marks as a significant step towards a future where space-based data centers are a standard component of the world's data management ecosystem, pushing the boundaries of what is possible in space technologies and data management.

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