

Towards Cloud Native Ground Segment Data Systems

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Abstract

Cloud computing is a technology capable of modernizing and enhancing the functionality and scalability of mission operations and ground data systems, putting new capabilities within easy reach of users and organisations. However, the adoption of fully cloud-native solutions poses several technical and managerial challenges. This paper presents an overview of the current vision of ESOC toward adoption of cloud computing paradigms and describes the activities preparing and promoting a step-by-step migration of systems and services in the ESA Ground Segment to the cloud.

The current ESOC ground segment approach is based around on-premises infrastructure, hosting siloed and uncoordinated independent data systems, containing heterogeneous data storage and access, which impacts scalability and coherency. Meanwhile, modern IT systems typically exploit dynamic applications, pay-as-you-use services, managed database solutions, and secure and collaborative access features that are achieved using a cloud-native approach. The main opportunities for ESOC of cloud native ground segment therefore include benefits such as scalability, flexibility, cost-efficiency, security, and data accessibility, but also pose challenges such as complexity, integration, and operational overhead.

Therefore, ESOC is currently executing several technology activities that aim to develop and demonstrate important aspects for cloud-based data system solutions that are scalable for both large and small missions, based on next generation monitoring and control (M&C) software. The activities are exploring the key concepts and opportunities that derive from the cloud-native approach, concepts such as microservice architecture, existing cloud computing solutions and capability, ESOC's A2I Roadmap, cloud-native storage approaches, data as an enabler, data democratization, distributed operations, and commercial space systems.

A key aspect of this paper are related ESA activities that provide inputs and synergies, such as MICROCONTROL, EGOS-MG, MCS-CC, SIMULUS-NG, and Zero Trust Architecture. Therefore, a key element and first step is to focus on implementing selected cloud-native systems, that can work alongside traditional, legacy systems where possible, to start moving toward a decentralized, accessible, flexible, and scalable Ground Segment.

The paper concludes with a summary of the findings and the outlook for the next steps.

Keywords: Cloud Computing, Ground Segment, Data Systems.

1. Introduction

In recent years, cloud computing has emerged as a transformative technology, offering significant advancements in the way organizations manage and process data. Its relevance to mission operations and ground data systems cannot be overstated, as it provides the scalability, flexibility, and efficiency needed to handle the increasing complexity and volume of data in modern space missions. The European Space Operations Centre (ESOC) recognizes the potential of cloud computing to revolutionize its ground segment data systems and is actively exploring ways to integrate cloud-native solutions into its operations.

The current approach at ESOC relies heavily on on-premises infrastructure, which hosts a variety of independent and uncoordinated data systems. These systems often operate in silos, leading to challenges in data storage, access, and overall system scalability. The heterogeneity of these systems further complicates efforts to achieve a cohesive and efficient data management strategy. As a result, there is a pressing need to transition to a more unified and dynamic approach that leverages the capabilities of cloud computing.

The vision for adopting cloud computing paradigms at ESOC is driven by the desire to enhance the functionality and scalability of mission operations. By embracing cloud-native solutions, ESOC aims to provide users and organizations with new capabilities that were previously out of reach. This includes the ability to deploy dynamic applications, utilize pay-as-you-use services, implement managed database solutions, and ensure secure and collaborative access to data.

However, the journey towards a fully cloud-native ground segment is not without its challenges. Both technical and managerial hurdles must be overcome to achieve a successful migration. Technical challenges include the complexity of integrating cloud-native solutions with existing systems, ensuring data security and compliance, and managing the operational overhead associated with cloud-based infrastructure. On the managerial side, promoting and executing the migration requires careful planning, coordination, and buy-in from various stakeholders.

To address these challenges, ESOC is currently undertaking several technology activities aimed at developing and demonstrating cloud-based data system solutions. These activities focus on key concepts and opportunities that arise from the cloud-native approach, such as microservice architecture, existing cloud computing solutions, and ESOC's A2I Roadmap [1]. Additionally, related ESA activities, including MICROCONTROL, EGOS-MG, MCS-CC, SIMULUS-NG, and Zero Trust Architecture, provide valuable inputs and synergies that support the transition to cloud-native systems.

The purpose of this paper is to present an overview of ESOC's vision for adopting cloud computing paradigms and to describe the activities that are preparing and promoting a step-by-step migration of systems and services in the ESA Ground Segment to the cloud. By focusing on implementing selected cloud-native systems alongside traditional, legacy systems, ESOC aims to move towards a decentralized, accessible, flexible, and scalable ground segment. The paper concludes with a summary of the findings and an outlook for the next steps in this transformative journey.

2. Current ESOC Ground Segment Approach

ESOC currently relies on an on-premises infrastructure to support its ground segment data systems. This infrastructure is characterized by a collection of independent and uncoordinated data systems, each operating in its own silo. These systems have been developed over time to meet specific mission requirements, resulting in a heterogeneous environment with varying data storage and access mechanisms.

One of the primary challenges with this approach is the lack of scalability. As the volume and complexity of data continue to grow, the existing infrastructure struggles to keep up with the demands of modern space missions. The siloed nature of the data systems further exacerbates this issue, as it hinders the ability to efficiently share and access data across different missions and departments. This fragmentation leads to inefficiencies and limits the potential for collaboration and innovation.

Another significant challenge is the heterogeneity of the data storage and access mechanisms. Different systems use different technologies and formats for storing and accessing data, making it difficult to achieve a cohesive and integrated data management strategy. This lack of standardization not only complicates data sharing but also increases the operational overhead required to maintain and support the various systems.

The current on-premises infrastructure also poses limitations in terms of flexibility and adaptability. Traditional data systems are often rigid and difficult to modify, making it challenging to quickly adapt to changing mission requirements or to incorporate new technologies and capabilities. This rigidity can impede the ability to respond to emerging opportunities and to leverage advancements in data processing and analysis.

Despite these challenges, the existing infrastructure has been instrumental in supporting ESOC's mission operations over the years. It has provided a reliable and secure environment for managing mission-critical data and has enabled the successful execution of numerous space missions. However, as the demands on the ground segment continue to evolve, there is a clear need to transition to a more dynamic and scalable approach that can better support the future needs of ESOC and its missions.

Over the past 20 years one important role, that ESOC has taken on very successfully, is to support the European space industry. However, the current ground segment systems are large, complex, and monolithic, making them difficult to tune for different mission profiles. The adoption of cloud-native solutions offers a significant advantage in this regard. Cloud-native systems are inherently more modular, allowing for greater flexibility and scalability. This modularity makes them more appealing to ESA industry partners, as they can be tailored to specific mission requirements with ease. Additionally, cloud-native systems are easier to deploy on cloud infrastructure, which is particularly beneficial for smaller industry players who may not have the resources to invest in extensive datacentres. By transitioning to cloud-native solutions, ESOC can continue to support the industry effectively, fostering innovation and collaboration while ensuring that mission operations remain efficient and adaptable.

3. Desired Cloud-Native Approach

The vision for adopting a cloud-native approach at the ESOC is driven by the need to enhance the functionality, scalability, and efficiency of mission operations and ground data systems [2]. By embracing cloud-native solutions, ESOC aims to provide users and organizations with new capabilities that were previously out of reach. This includes the ability to deploy dynamic applications, utilize pay-as-you-use services, implement managed database solutions, and ensure secure and collaborative access to data.

One of the primary goals of the cloud-native approach is to achieve scalability. Cloud computing offers the ability to scale resources up or down based on demand, which is particularly beneficial for handling the varying workloads associated with space missions. This scalability ensures that ESOC can efficiently manage large volumes of data and accommodate the needs of both large and small missions.

Flexibility is another key benefit of the cloud-native approach. Traditional on-premises systems are often rigid and difficult to modify, making it challenging to adapt to changing mission requirements or to incorporate new technologies. In contrast, cloud-native solutions offer a high degree of flexibility, allowing ESOC to quickly deploy and update applications, integrate new services, and respond to emerging opportunities.

Cost-efficiency is also a significant advantage of the cloud-native approach. By leveraging pay-as-you-use services, ESOC can optimize its resource usage and reduce operational costs. This model allows ESOC to only pay for the resources it actually uses, rather than investing in and maintaining expensive on-premises infrastructure. Additionally, managed database solutions provided by cloud service providers can further reduce the operational overhead associated with data management.

Security is a critical consideration in the adoption of cloud-native solutions. Cloud service providers offer robust security measures, including encryption, access controls, and compliance with industry standards. These measures help ensure the confidentiality, integrity, and availability of mission-critical data. Furthermore, the cloud-native approach enables secure and collaborative access to data, facilitating collaboration among different teams and departments within ESOC.

Data accessibility is another important aspect of the cloud-native approach. By centralizing data storage and providing standardized access mechanisms, ESOC can improve data sharing and collaboration across missions and departments. This democratization of data access enables more efficient and informed decision-making, as well as the development of innovative solutions based on shared data.

However, the journey towards a fully cloud-native ground segment is not without its challenges. Technical challenges include the complexity of integrating cloud-native solutions with existing systems, ensuring data security and compliance, and managing the operational overhead associated with cloud-based infrastructure. Managerial challenges involve promoting and executing the migration, which requires careful planning, coordination, and buy-in from various stakeholders.

To address these challenges, ESOC is currently undertaking several technology activities aimed at developing and demonstrating cloud-based data system solutions. These activities focus on key concepts and opportunities that arise from the cloud-native approach, such as microservice architecture, existing cloud computing solutions, and ESOC's A2I Roadmap. Additionally, related ESA activities, including MICROCONTROL, EGOS-MG, MCS-CC, SIMULUS-NG, and Zero Trust Architecture, provide valuable inputs and synergies that support the transition to cloud-native systems.

4. Technical and Managerial Challenges

The journey towards a fully cloud-native ground segment at ESOC is fraught with both technical and managerial challenges. These challenges must be carefully addressed to ensure a successful migration and to fully leverage the benefits of cloud computing.

One of the primary technical challenges is the complexity of integrating cloud-native solutions with existing systems. The current on-premises infrastructure at ESOC hosts a variety of independent but interlinked data systems, each with its own unique architecture and data management practices. Migrating these systems to the cloud requires a thorough understanding of their intricacies and the development of strategies to ensure seamless integration. This includes addressing issues related to data interoperability, compatibility with cloud platforms, and the potential need for re-architecting certain components.

Data security and compliance are also significant technical challenges. Cloud environments introduce new security considerations, such as data encryption, access controls, and compliance with industry standards and regulations. Ensuring the confidentiality, integrity, and availability of mission-critical data in the cloud is paramount.

This requires the implementation of robust security measures and continuous monitoring to detect and mitigate potential threats.

Managing the operational overhead associated with cloud-based infrastructure is another technical challenge. Cloud-native solutions often involve the use of microservices, containerization, and orchestration tools, which can introduce additional complexity in terms of deployment, monitoring, and maintenance. Ensuring the reliability and performance of these systems requires specialized skills and expertise, as well as the adoption of best practices for cloud operations.

On the managerial side, promoting and executing the migration to cloud-native solutions requires careful planning, coordination, and buy-in from various stakeholders. One of the key managerial challenges is the need to align the migration strategy with the overall goals and objectives of ESOC. This involves defining a clear vision for the cloud-native ground segment, setting realistic milestones, and ensuring that all stakeholders are on board with the plan.

Change management is another critical managerial challenge. The transition to cloud-native solutions represents a significant shift in the way ESOC operates, and it is essential to manage this change effectively. This includes addressing concerns and resistance from staff, providing training and support to help them adapt to new technologies and processes, and fostering a culture of innovation and continuous improvement.

Resource allocation and budgeting are also important managerial considerations. Migrating to cloud-native solutions requires investment in new technologies, tools, and training. It is essential to allocate resources effectively and to ensure that the migration is cost-efficient. This involves careful budgeting, monitoring of expenses, and the identification of potential cost-saving opportunities.

Financial Operations (FinOps) is a critical aspect of managing cloud-native solutions. FinOps involves the practice of bringing financial accountability to the variable spend model of cloud computing, enabling organizations to make informed decisions about their cloud investments. One of the primary challenges in FinOps is the need to balance cost optimization with performance and scalability requirements. This requires continuous monitoring and analysis of cloud usage and costs to identify opportunities for savings without compromising on the quality of service.

Another challenge is the complexity of cloud billing and pricing models. Cloud service providers offer a wide range of pricing options, including pay-as-you-go, reserved instances, and spot instances. Understanding and selecting the most cost-effective pricing model for each workload can be challenging, especially in a dynamic and rapidly changing environment. Effective FinOps practices involve regular reviews of cloud spending, forecasting future costs, and adjusting usage patterns to take advantage of the most cost-efficient options.

Collaboration between finance, operations, and engineering teams is essential for successful FinOps implementation. This requires establishing clear communication channels, setting shared goals and metrics, and fostering a culture of financial accountability. By working together, these teams can ensure that cloud spending aligns with organizational objectives and that resources are used efficiently.

The adoption of FinOps tools and platforms can help automate and streamline the management of cloud costs. These tools provide visibility into cloud spending, enable cost allocation and chargeback, and offer insights and recommendations for cost optimization. However, selecting and implementing the right FinOps tools can be challenging, and organizations must ensure that these tools integrate seamlessly with their existing systems and processes. [3][4]

Finally, collaboration and communication are crucial for the success of the migration. The transition to cloud-native solutions involves multiple departments and teams within ESOC, each with its own responsibilities and expertise. Effective collaboration and communication are essential to ensure that all stakeholders are aligned and that the migration progresses smoothly. This includes regular updates, feedback loops, and the establishment of cross-functional teams to address specific challenges.

5. Technology Activities and Synergies

ESOC is actively engaged in several technology activities aimed at developing and demonstrating cloud-based data system solutions. These activities are designed to explore the key concepts and opportunities that arise from the cloud-native approach, and to address the technical and managerial challenges associated with the migration to cloud-native solutions.

One of the focuses of our technology activities is the development of a microservice architecture. This approach involves breaking down complex applications into smaller, independent services that can be developed, deployed, and scaled independently. By adopting a microservice architecture, ESOC aims to improve the flexibility, scalability, and maintainability of its ground segment data systems. This approach also facilitates the integration of new

technologies and services, enabling ESOC to quickly adapt to changing mission requirements and to leverage advancements in data processing and analysis.

A key area of focus is the exploration of existing cloud computing solutions and capabilities. ESOC is evaluating various cloud platforms and services to identify the most suitable options for its ground segment data systems. This includes assessing the performance, security, and cost-efficiency of different cloud providers, as well as exploring the potential for hybrid cloud solutions that combine on-premises and cloud-based infrastructure. By leveraging the capabilities of cloud computing, ESOC aims to enhance the functionality and scalability of its mission operations.

ESOC's A2I (Automation and Artificial Intelligence) Roadmap is another important aspect of its technology activities. This roadmap outlines the steps and milestones for integrating automation and AI technologies into ESOC's ground segment data systems. The goal is to improve the efficiency and effectiveness of mission operations by automating routine tasks, enhancing data analysis capabilities, and enabling more informed decision-making. The A2I Roadmap also includes initiatives to develop and demonstrate AI-based solutions for mission planning, anomaly detection, and predictive maintenance.

In addition to these activities, ESOC is also exploring cloud-native storage approaches. This involves evaluating different storage solutions that are optimized for cloud environments, such as object storage, distributed file systems, and managed database services. The aim is to improve data accessibility, scalability, and cost-efficiency, while ensuring the security and integrity of mission-critical data. By adopting cloud-native storage solutions, ESOC can better manage the growing volume and complexity of data associated with modern space missions.

Data democratization is a key concept being explored. This involves making data more accessible and usable for a wider range of users and applications. By centralizing data storage and providing standardized access mechanisms, we aim to facilitate data sharing and collaboration across missions and departments. This democratization of data access enables more efficient and informed decision-making, as well as the development of innovative solutions based on shared data.

ESOC is also investigating the potential for distributed operations. This approach involves decentralizing mission operations and enabling remote access to data and services. By leveraging cloud-based infrastructure, ESOC can support distributed teams and operations, improving flexibility and resilience. This is particularly important for supporting international collaborations and for ensuring continuity of operations in the event of disruptions to on-premises infrastructure.

The AIMA (AI-ready Multi-mission and Multi-asset Archiving) project is part of a set of projects developing future cloud-native architecture for the Ground Segment with a focus on supporting the increasing use of AI processing tools and frameworks. AIMA aims to provide a common data foundation solution as a service for ESA Ground Segments. This involves decoupling data storage from the systems that generate operational data, enabling access to this data for advanced applications, including AI-based ones. AIMA's goal is to increase data processing efficiency, promote external data reuse, provide common access, serve as disaster recovery storage, reduce risk, ensure long-term data preservation, and avoid vendor lock-in. AIMA focuses on the storage aspect of the future Ground Segment Architecture.

The Cloud Native Ground Segment (CNGS) project is another related activity that focuses on developing future cloud-native architecture for the Ground Segment with a focus on supporting the increasing use of AI processing tools and frameworks. The main objective of CNGS is to develop an out-of-the-box, cloud-based data system solution that is scalable for both large and small missions, including small-sats and cubesats. The project aims to address the need for scalable and cost-effective IT capabilities for mission operations, which typically follow a burst pattern driven by spacecraft passes or mission phases. The goal is to create a single multi-mission solution that can cover the entire mission spectrum, from cubesats to large institutional missions. To achieve this, the project develops cloud-based systems that can be shared among industry and ESA, lowering development and maintenance costs while increasing performance, security, reliability, and accessibility. CNGS focuses on the processing aspect of the future Ground Segment Architecture.

The Zero Trust Architecture initiative is another important related activity. This initiative focuses on enhancing the security of ESA's IT infrastructure by adopting a zero-trust approach. This approach assumes that threats can exist both inside and outside the network and requires strict verification for every access request. The principles and technologies developed through the Zero Trust Architecture initiative are directly applicable to ESOC's efforts to ensure the security of cloud-native solutions.

One of the key related activities is the MICROCONTROL project. This project focuses on developing microservice-based control systems for space missions. By leveraging microservice architecture, MICROCONTROL aims to enhance the flexibility, scalability, and maintainability of control systems. The insights and technologies developed through MICROCONTROL are directly applicable to ESOC's efforts to implement cloud-native solutions.

Another important initiative is the EGOS-MG (European Ground Operations System - Monitoring and Control) project. EGOS-MG is a next-generation monitoring and control system that aims to provide a unified and scalable platform for ground segment operations. The project emphasizes the use of cloud-native technologies and microservices to achieve its goals. The synergies between EGOS-MG and ESOC's cloud-native initiatives are significant, as both efforts share common objectives and technical approaches.

The MCS-CC (Mission Control System - Common Core) project is another related activity that provides valuable inputs to ESOC's cloud-native efforts. MCS-CC aims to develop a common core for mission control systems, enabling the reuse of components and reducing development costs. The project leverages cloud-native technologies to achieve its goals, and the lessons learned from MCS-CC are directly applicable to ESOC's migration to cloud-native solutions.

SIMULUS-NG (Next Generation Simulation Infrastructure) is a project focused on developing advanced simulation capabilities for space missions. The project aims to create a scalable and flexible simulation infrastructure that can support a wide range of mission scenarios. By leveraging cloud-native technologies, SIMULUS-NG aims to enhance the performance and scalability of simulation systems. The synergies between SIMULUS-NG and ESOC's cloud-native initiatives are significant, as both efforts aim to improve the scalability and flexibility of mission operations.

6. Implementation of Cloud-Native Systems

The implementation of cloud-native systems at ESOC is a critical step towards achieving a decentralized, accessible, flexible, and scalable ground segment. This section outlines the key strategies and steps involved in implementing cloud-native systems, as well as the challenges and considerations that must be addressed to ensure a successful transition.

Key Strategies for Implementation

One of the primary strategies for implementing cloud-native systems is to adopt an incremental migration approach [4]. This involves gradually transitioning components and services to the cloud, rather than attempting a complete overhaul all at once. By taking a step-by-step approach, we can minimize disruption to ongoing operations, identify and address issues early, and build confidence in the new systems. This incremental migration can be achieved by initially focusing on non-critical systems and services and gradually expanding to include mission-critical components.

Implementing hybrid cloud solutions is another key strategy for the transition to cloud-native systems. A hybrid cloud approach combines on-premises infrastructure with cloud-based services, allowing ESOC to leverage the benefits of both environments. This approach provides flexibility in managing workloads, enables seamless integration with existing systems, and allows for a phased migration to the cloud. Hybrid cloud solutions also offer the advantage of maintaining control over sensitive data while taking advantage of the scalability and cost-efficiency of cloud services.

Adopting a microservice architecture is essential for the implementation of cloud-native systems. This approach involves breaking down complex applications into smaller, independent services that can be developed, deployed, and scaled independently. Microservices enable greater flexibility, scalability, and maintainability, and facilitate the integration of new technologies and services. Implementing a microservice architecture, can improve the agility and responsiveness of the ground segment data systems.

Automation and orchestration are critical components of cloud-native systems. Automation involves the use of tools and scripts to perform routine tasks, such as provisioning resources, deploying applications, and managing configurations. Orchestration involves coordinating and managing the interactions between different services and components. Implementing automation and orchestration, can improve the efficiency and reliability of infrastructure operations, reduce the risk of human error, and ensure consistent and repeatable processes.

Ensuring the security and compliance of cloud-native systems is paramount. This involves implementing robust security measures, such as data encryption, access controls, and continuous monitoring, to protect mission-critical data. Compliance with industry standards and regulations is also essential to ensure the confidentiality, integrity, and availability of data. By adopting a zero-trust security model, ESOC can enhance the security of its cloud-native systems and mitigate potential threats.

Challenges and Considerations

One of the primary challenges in implementing cloud-native systems is the integration with existing legacy systems [5]. Many of ESOC's current systems are based on on-premises infrastructure and may not be fully

compatible with cloud-native technologies. Addressing this challenge requires a thorough understanding of the existing systems, the development of integration strategies, and the use of middleware and APIs to facilitate communication between legacy and cloud-native components. This process can be complex and time-consuming, as it involves ensuring data interoperability, compatibility with cloud platforms, and potentially re-architecting certain components to fit the new environment.

Managing the costs associated with cloud-native systems is a critical consideration. While cloud computing offers cost-efficiency through pay-as-you-use pricing models, it is essential to monitor and control cloud spending to avoid unexpected expenses. Implementing FinOps practices, such as continuous monitoring of cloud usage, optimizing resource allocation, and leveraging cost-saving opportunities, can help ESOC manage its cloud costs effectively. This involves regular reviews of cloud spending, forecasting future costs, and adjusting usage patterns to take advantage of the most cost-efficient options.

Ensuring the performance and reliability of cloud-native systems is essential for mission-critical operations. This involves implementing robust monitoring and alerting mechanisms, conducting regular performance testing, and adopting best practices for cloud operations. By continuously monitoring and optimizing the performance of cloud-native systems, we can ensure that our ground segment data systems meet the required service levels and performance standards. This includes addressing issues related to latency, availability, and scalability to ensure that the systems can handle the demands of modern space missions.

Managing the organizational change associated with the transition to cloud-native systems is another important consideration. This involves addressing concerns and resistance from users, providing clear communication and guidance, and fostering a culture of innovation and continuous improvement. Effective change management ensures that all stakeholders are aligned with the migration strategy and that the transition is smooth and successful. This includes engaging with staff at all levels, providing training and support, and promoting the benefits of cloud-native systems to build buy-in and support for the migration.

Effective collaboration and communication are crucial for the success of the migration to cloud-native systems. The transition involves multiple departments and teams within ESOC, each with its own responsibilities and expertise. Establishing clear communication channels, setting shared goals and metrics, and fostering a culture of collaboration are essential. Regular updates, feedback loops, and the establishment of cross-functional teams can help address specific challenges and ensure that the migration is coordinated effectively.

Steps Towards Implementation

The first step in implementing cloud-native systems is to conduct a thorough assessment of the existing infrastructure, systems, and processes. This involves identifying the components and services that are suitable for migration, evaluating the technical and managerial challenges, and developing a detailed migration plan. The assessment includes an analysis of the current state of the ground segment data systems, including their architecture, performance, and security. It should also identify any dependencies and potential risks associated with the migration. The planning phase involves defining the goals, milestones, and timelines for the migration, as well as the resources and support required. This step is crucial for setting a clear direction and ensuring that all stakeholders are aligned with the migration strategy.

Implementing proof of concepts is an important step in validating the feasibility and benefits of cloud-native systems. The proof of concepts involve selecting a specific components or services for migration, implementing the cloud-native solutions, and evaluating their performance, scalability, and security. This step allows us to test the new systems in a controlled environment and to identify any issues or challenges that may arise. The insights gained from the proof of concepts help refine the migration strategy and build confidence in the new systems. It also provides an opportunity to demonstrate the benefits of cloud-native solutions to stakeholders and to gain their support for the migration.

Following the proof of concepts, the next step is to begin the incremental migration of components and services to the cloud. This involves prioritizing the migration of non-critical systems, gradually expanding to include mission-critical components, and continuously monitoring and optimizing the performance of the cloud-native systems. The incremental migration approach allows ESOC to minimize disruption to ongoing operations and address issues early in the process. It also provides opportunities for continuous learning and improvement, ensuring that the migration is smooth and successful. By taking a step-by-step approach, we can build confidence in the new systems and ensure that they meet the required performance and security standards.

The implementation of cloud-native systems is an ongoing process that requires continuous improvement and optimization. This involves regularly reviewing and updating the migration strategy, monitoring the performance and security of the cloud-native systems, and identifying opportunities for further optimization and innovation. Continuous improvement ensures that the systems remain agile, scalable, and efficient, and that they can adapt to

changing mission requirements and technological advancements. By fostering a culture of continuous improvement, ESOC can ensure that its ground segment data systems remain at the forefront of innovation and that they continue to deliver value to mission operations.

These steps provide a structured approach to implementing cloud-native systems at ESOC. By conducting a thorough assessment and planning, validating the feasibility through a proof of concept, adopting an incremental migration approach, and continuously improving the systems, ESOC can achieve a successful transition to cloud-native ground segment data systems. Each step addresses specific challenges and considerations, ensuring that the migration is smooth, efficient, and aligned with ESOC's overall goals and objectives.

7. Conclusion and Outlook

The adoption of cloud-native ground segment data systems at ESOC would represent a transformative shift in the way mission operations and data management are conducted. By leveraging the capabilities of cloud computing, we aim to enhance the functionality, scalability, flexibility, cost-efficiency, security, and data accessibility of our ground segment data systems. This paper has presented an overview of ESOC's vision for adopting cloud computing paradigms, described the current challenges with the on-premises infrastructure, outlined the desired cloud-native approach, and detailed the technical and managerial challenges associated with the migration.

The implementation of cloud-native systems involves adopting key strategies such as incremental migration, hybrid cloud solutions, microservice architecture, automation and orchestration, and ensuring security and compliance. Addressing the challenges and considerations associated with the migration, including integration with legacy systems, training, cost management, performance and reliability, change management, security and compliance, collaboration and communication, and resource allocation and budgeting, is essential to ensure a successful transition.

ESOC's technology activities, including the development of microservice architecture, exploration of existing cloud computing solutions, implementation of the A2I Roadmap, adoption of cloud-native storage approaches, data democratization, distributed operations, and integration of commercial space systems, are focused on developing and demonstrating cloud-based data system solutions that are scalable, flexible, and cost-efficient. These activities are supported by several related ESA initiatives, such as MICROCONTROL, EGOS-MG, MCS-CC, SIMULUS-NG, Zero Trust Architecture, AIMA, and CNGS, which provide valuable inputs and synergies to ESOC's cloud-native efforts.

The steps towards implementation, including assessment and planning, proof of concepts, incremental migration, and continuous improvement, provide a structured approach to achieving a successful transition to cloud-native ground segment data systems. By following these steps, we can ensure that the migration is smooth, efficient, and aligned with its overall goals and objectives.

Looking ahead, the adoption of cloud-native ground segment data systems offers significant opportunities to enhance mission operations and data management capabilities. The benefits of cloud computing, including scalability, flexibility, cost-efficiency, security, and data accessibility, will enable us to better support the increasing complexity and volume of data associated with modern space missions. The transition to cloud-native systems will also facilitate collaboration and innovation, allowing ESOC to leverage advancements in data processing and analysis, automation, and AI technologies.

However, the journey towards a fully cloud-native ground segment is not without its challenges. Both technical and managerial hurdles must be overcome to achieve a successful migration. Continuous monitoring, optimization, and improvement of the cloud-native systems are essential to ensure that they meet the required performance and security standards. Effective change management, skill development, and collaboration are also crucial for building a workforce that is capable of managing and optimizing cloud-native systems effectively.

In conclusion, the adoption of cloud-native ground segment data systems at ESOC represents a significant step towards modernizing and enhancing mission operations and data management. By leveraging the capabilities of cloud computing and addressing the associated challenges, we can achieve a decentralized, accessible, flexible, and scalable ground segment that meets the demands of modern space missions. The outlook for the next steps in this transformative journey is promising, with continued efforts to develop and demonstrate cloud-based solutions, foster collaboration and innovation, and ensure the successful implementation of cloud-native systems.

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