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Integrating Digital Twins in Space Operations: Challenges and Solutions

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Abstract

This study presents Korea Aerospace Research Institute's approach and results from interviews with each subsystem engineers to understand their needs and challenges. Based on this feedback, we have been developing a user-friendly interface to support the monitoring and automation of operational subsystems such as Satellite Operation Subsystem, Mission Planning Subsystem, and Flight Dynamics Subsystem and ground infrastructure subsystems such as Antenna and Network. The platform facilitates rapid dissemination of issues across subsystems, improving risk management and operational efficiency. The integration of digital twin platforms in space operations offers a comprehensive solution that addresses the specific needs of each subsystem engineer as well as operation manager, enhances mission efficiency, and increases the reliability and safety of space systems. The collaborative approach in design and implementation ensures that the technology aligns with the operational requirements and constraints of space missions, paving the way for more advanced and automated future missions.

Keywords: Digital Twins, Space Operations, UXUI Design

Nomenclature None

Acronyms/Abbreviations

Digital Twin (DT), Flight Dynamics Subsystem (FDS), Korea Aerospace Research Institute (KARI), MPS (Mission Planning Subsystem), SOS (Satellite Operations System), User Interface (UI), User eXperience (UX)

1. Introduction

The growing complexity of space operations and the increasing demand for mission reliability have driven the space industry to adopt cutting-edge digital technologies. Among them, Digital Twin (DT) platforms have emerged as a transformative solution that bridges physical systems and their digital counterparts, enabling real-time monitoring, simulation, and predictive analysis across satellite and ground segments. Originally developed for industrial manufacturing and automotive applications, DT technology is now making significant inroads into aerospace and space mission operations, offering a pathway toward smarter, more autonomous, and risk-resilient mission architectures.

In the space domain, digital twins enable operators to create high-fidelity virtual replicas of both space-based and terrestrial subsystems. These replicas are continuously updated with live data, allowing for state-aware decision-making, early fault detection, and automated control adjustments. Notably, their application extends beyond spacecraft modeling to include mission planning, ground infrastructure management, and cross-system coordination. As emphasized in recent studies [1,2], digital twins have demonstrated their value in optimizing anomaly response times, reducing operational burden, and enhancing situational awareness in mission-critical settings.

This paper introduces the Korea Aerospace Research Institute (KARI)'s effort to integrate a digital twin platform tailored to the operational requirements of national satellite missions. The platform development was rooted in a bottom-up approach: we conducted in-depth interviews with subsystem engineers—including Satellite Operation Subsystem (SOS), Mission Planning Subsystem (MPS), Flight Dynamics Subsystem (FDS), and ground infrastructure teams (antenna and network)—to identify pain points, user needs, and automation opportunities. These insights formed the foundation of a unified, user-friendly digital twin interface designed to facilitate real-time monitoring, rapid issue dissemination, and cross-domain situational coordination.

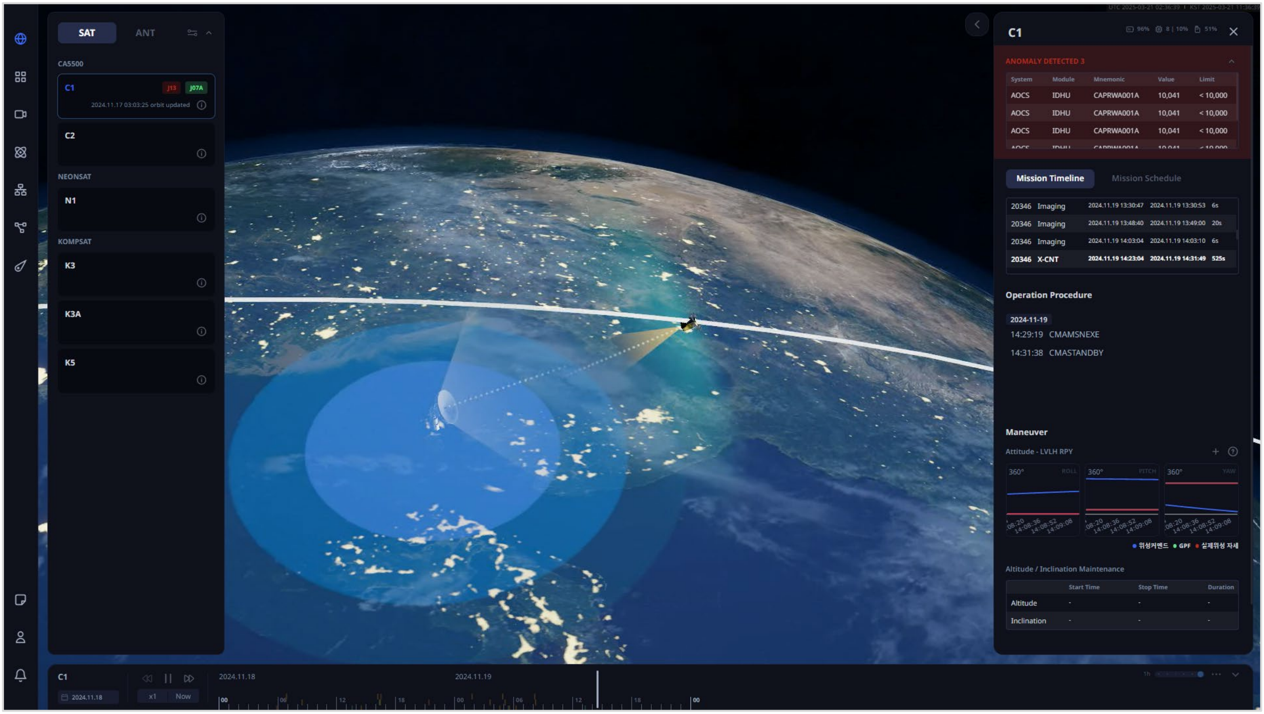

Figure 1 Concept image of KARI's digital twin platform

The KARI digital twin platform was engineered not as a standalone simulator but as an integrated operational assistant. It acts as a collaborative tool bridging siloed teams and processes, thereby improving operational transparency and enabling more agile mission execution. The system also emphasizes usability and automation, reflecting the real-world constraints and decision-making workflows of Korean satellite operations. Importantly, the platform not only supports individual subsystem views but also enhances horizontal integration across different mission-critical domains—laying the groundwork for smart risk management and future mission autonomy.

However, implementing digital twin technology in space operations is not without challenges. Our development process encountered a range of issues, including model fidelity limitations, real-time data integration bottlenecks, lack of common interface standards, and difficulty translating user needs into dynamic digital logic. These challenges required iterative resolution through interdisciplinary collaboration, incremental validation cycles, and close engagement with end-users.

Through this work, we aim to contribute to the global effort of digital transformation in space mission operations, offering not only a case study but also a replicable model for integrating digital intelligence into the fabric of mission control and management systems.

2. User Experience in Space Operations

2.1 Challenges

In the context of national satellite missions, daily operations involve a wide range of subsystems, each responsible for highly specialized tasks—from flight dynamics and mission planning to ground infrastructure and anomaly resolution. While these functions are technically interconnected, the operational workflow remains fragmented, with each team relying on dedicated tools, data formats, and communication protocols. This siloed environment leads to inefficiencies in coordination, limited situational awareness, and delayed anomaly responses.

Fragmentation Across Subsystems

Subsystems such as SOS, MPS, and FDS typically function in independent operational domains, each with its own interface, data logs, and team-specific interpretation of events. Although mission success relies on cooperation between these units, cross-functional integration is largely manual, depending on informal communication or post-event analysis. As a result, early detection of cascading failures or inter-subsystem risks is often missed until after symptoms have manifested.

Communication Bottlenecks and Latency

Communication between subsystem engineers and operation managers primarily occurs through scheduled meetings, email updates, or periodic reports. In fast-changing situations—such as orbit adjustments, unexpected telemetry patterns, or ground station failures—these asynchronous channels introduce critical delays in risk propagation and decision-making. Engineers often lack real-time visibility into changes made by others, leading to duplicated efforts or incompatible control actions.

Lack of Real-Time Contextual Awareness

Operators frequently face limitations in accessing holistic, real-time views of satellite health and system interdependencies. While telemetry streams are available, the interpretation of anomalies is left to individual expertise, making diagnosis heavily reliant on human memory and pattern recognition. The absence of unified dashboards or shared situational models prevents stakeholders from quickly grasping the broader context of a malfunction or event.

Operational Stress and Error Vulnerability

Under time pressure, especially during satellite emergencies or rapid maneuver planning, the current workflow places significant cognitive load on engineers. They must mentally integrate fragmented data sources, interpret logs across systems, and manually relay findings to other teams. This process not only increases workload but also introduces a higher probability of human error—particularly in time-sensitive scenarios.

Based on the user research conducted at KARI, the meta-level keywords representing user needs can be summarized as follows:

Rank	*Keyword*
1	Integrated systems
2	Intuitive 3D objects
3	Efficient state and situational sharing
4	Visualized analysis and simulation
5	User-friendly UX/UI
6	Anomaly response and guidance features

Figure 2 Meta Keyword Cloud (written in Korean)

2.2 User research (interviews and workshop)

To ensure the digital twin platform met the real-world operational demands of satellite management, we adopted a user-centred design approach grounded in qualitative research. Recognizing that subsystem engineers possess domain-specific knowledge and are the primary actors in mission-critical workflows, our research focused on capturing their challenges, priorities, and expectations. This process involved structured interviews and cross-disciplinary workshops conducted with key stakeholders across KARI's satellite operations division.

Research Objectives and Approach

The primary goals of the user research phase were to:

- Identify bottlenecks and pain points in current operations
- Capture user expectations for digital augmentation
- Understand mental models and decision-making patterns
- Derive functional and interface-level requirements

We conducted in-depth, semi-structured interviews with engineers from core operational teams, including SOS, MPS, FDS, and ground infrastructure teams managing antennas and network systems. These interviews were complemented by co-creation workshops, where engineers collaborated to map workflows, simulate typical scenarios, and sketch ideal system behaviours.

Interview Methodology

To gain a deeper understanding of the operational context and user-specific requirements, the research team conducted an environmental assessment of the current space operations workflow at KARI. This assessment involved reviewing existing tools, communication processes, and subsystem interdependencies to ensure that the subsequent user research would be aligned with actual operational practices.

A key element of the user research involved conducting one-on-one, in-depth interviews with eight key personnel from different operational subsystems, including SOS, MPS, FDS, and ground infrastructure teams. These interviews aimed to capture a comprehensive view of the challenges and needs experienced by those working directly with the systems.

During each interview, participants were introduced to the current subsystem screens in use in the operations room, allowing them to interact with the actual tools they use in real-time. This hands-on approach provided invaluable insights into the real-world applicability of the tools and allowed the participants to reflect on the specific functionality and features they felt were lacking or could be improved. Each interview lasted approximately two hours, ensuring sufficient time for participants to provide detailed feedback on their roles, pain points, and expectations for a future digital twin platform.

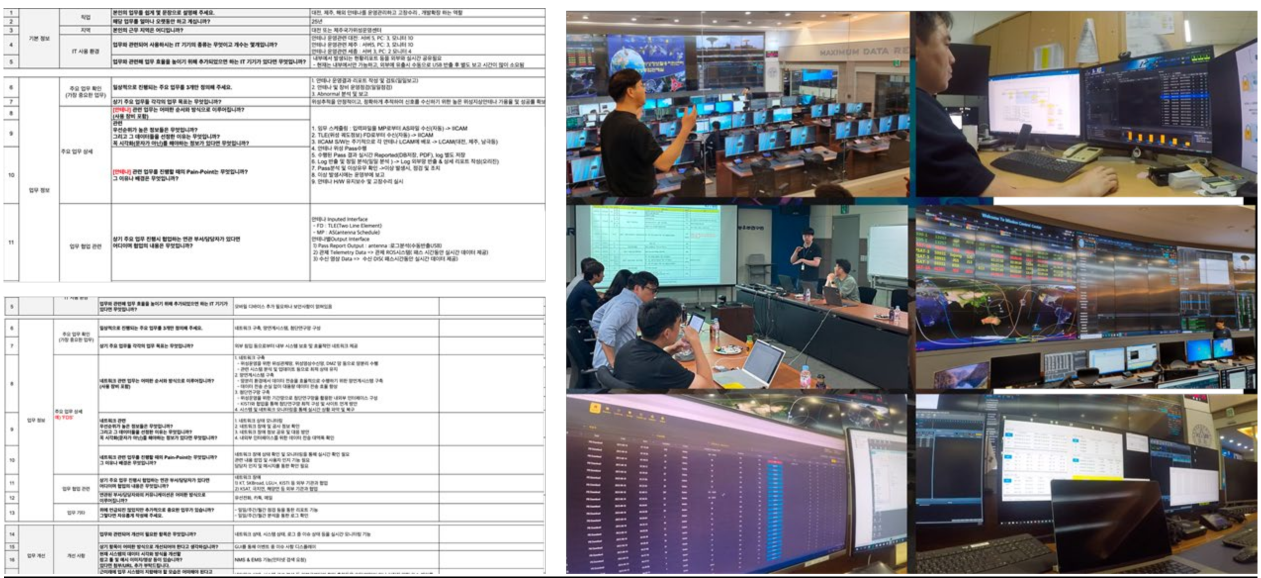

Figure 3 Discovery step with pre-survey and in-depth interviews

The interview protocol was semi-structured, covering the following key areas:

- Role and responsibilities within the operational framework
- Goals and motivations for day-to-day operations
- Pain points experienced in current workflows and tool usage
- Communication and collaboration difficulties between subsystems
- Unmet needs and expectations for future systems

These in-depth discussions provided a rich understanding of the operational bottlenecks and also clarified the specific requirements for a unified digital platform. The insights gained from the interviews were directly applied to guide the design of the co-design workshop, where subsystem engineers participated in collaborative activities to further refine their needs and envision the ideal system.

Workshop Activities

Following the individual interviews, a collaborative workshop was held to validate the initial findings and foster cross-functional dialogue. The workshop brought together all participating subsystem engineers in a shared discussion format, allowing for real-time exchange of ideas and collective refinement of the project direction.

The workshop was structured around four key activities:

- Review of Interview Findings
- Discussion of the Project Roadmap
- Idea Generation (Ideation)
- Prioritization of Ideas

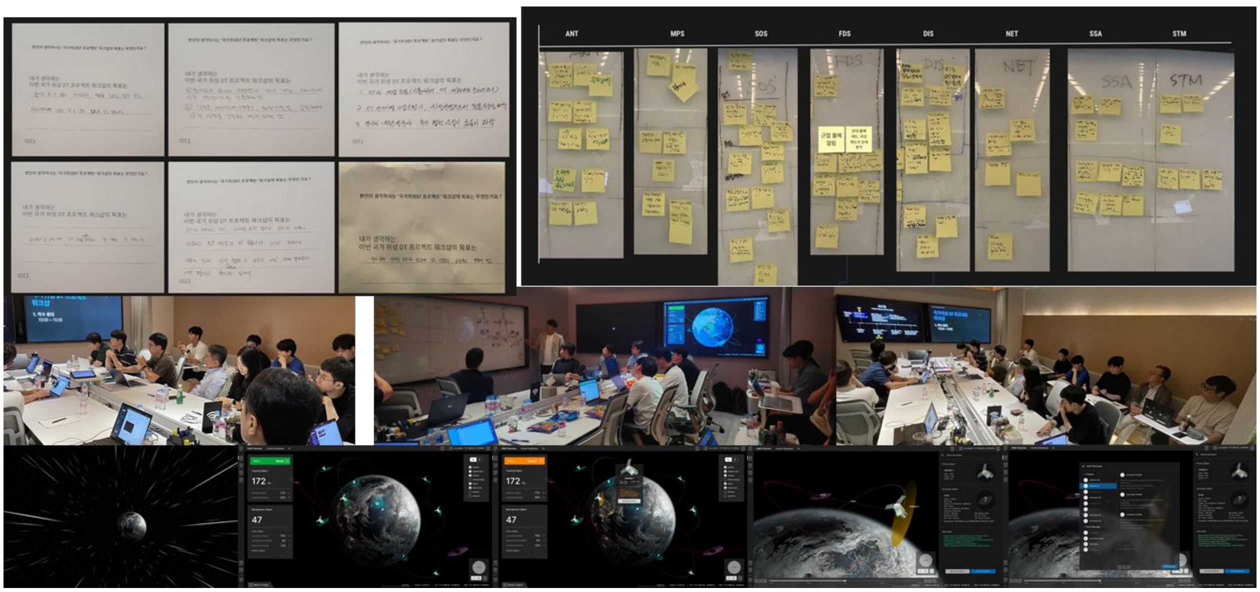

Figure 4 Workshop step with discussion and ideation

The open and inclusive format of the session encouraged the sharing of feedback across subsystem boundaries, enabling participants to hear how their own tools and workflows were perceived by others. This cross-pollination of perspectives was particularly valuable in identifying coordination blind spots and integration opportunities that would not have surfaced in isolated interviews.

Moreover, the workshop played a key role in shaping the strategic direction of the project. By discussing the interdependencies between subsystems from a holistic perspective, participants helped define how the digital twin platform could serve as a collaborative operational layer, rather than merely a tool for individual subsystems. This collective alignment became a foundational input for the mock-up and prototype phases that followed.

Insights and Meta-Level Needs

The user research revealed consistent themes that point to systemic issues and unmet needs across space operations at KARI. These insights have been translated into five actionable user requirements, each mapped to a corresponding design strategy within the digital twin platform:

- High Demand for Shared Information Across Subsystems
- Frequent Cross-Team Collaboration and Data Exchange
- Need for Visual Representation of Spatial and Temporal Behavior
- Lack of Consistency Across Subsystem Interfaces and Tools
- Workforce Adaptation and Knowledge Transfer Requirements

These five insights serve as the foundation for the mock-up and prototype designs presented in the next section, where we align these needs with visual interfaces and user interaction flows tailored to space mission operations.

2.3 Design Strategies

The outcomes of the interviews and workshop activities provided not only a detailed view into operational pain points but also a valuable foundation for establishing the strategic direction and interaction model of the proposed digital twin platform. Following table outlines the core design principles that emerged from user feedback, followed by the UX/UI goals, ideation patterns, system architecture, and the resulting development roadmap.

Focus Area	Key Strategy	Explanation
Project Direction	Real operations-based	Designed based on actual operator workflows observed during user research
	Scalable	Supports future expansion for managing multiple satellites simultaneously
	Integrated	Aims to bring fragmented subsystems and processes into a unified platform
	Predictive	Enables forecasting of future system behaviour using historical and real-time data
	Decision-aid	Assists operators by providing insights and contextual recommendations
	Unification of fragmented workflows	Streamlines communication and task handoffs across subsystem teams
UXUI Goals	Unified platform	Central interface integrates all functions while maintaining cohesion
	Role-based views	Allows customization based on user role and operational needs
	Visual context	Emphasizes graphical representation for clarity and situational awareness
	Intuitive interaction	Ensures ease of use and minimizes learning curve in high-pressure environments
Idea Grouping	Grouped by domain and function	Ideas clustered by key areas (satellite, antenna, network, data) and grouped into core DT functions
Structure	Three-layer model	Each DT includes visualization, analysis, and simulation modules
Road map	Phased rollout	Stepwise development approach supports testing, usability, and scalability

2.4 Mock-up & Prototype

To translate user insights and strategic design directions into tangible outcomes, we developed a series of mock-ups and interactive prototypes. These visual artifacts served two primary purposes:

(1) to validate the conceptual design with subsystem engineers, and

(2) to explore UX/UI solutions for key digital twin functions across the satellite operation lifecycle.

Mock-up Design Principles

Initial mock-ups were structured around the three functional modules identified during the ideation phase—status visualization, result analysis, and predictive simulation. Each screen was designed with the following principles in mind:

- Management object–centred layout: Rather than subsystem-focused views, screens were organized around key operational objects such as satellites, antennas, or mission plans.
- 3D visualization anchors: A central 3D scene represented the spatial context of assets, enabling intuitive situational awareness.
- Role-based widgets: Widgets and panels were dynamically customized based on the user's operational role (e.g., flight dynamics engineer vs. system operator).
- State-linked interaction: Clicking or selecting objects revealed historical status trends, current telemetry, or predictive metrics.

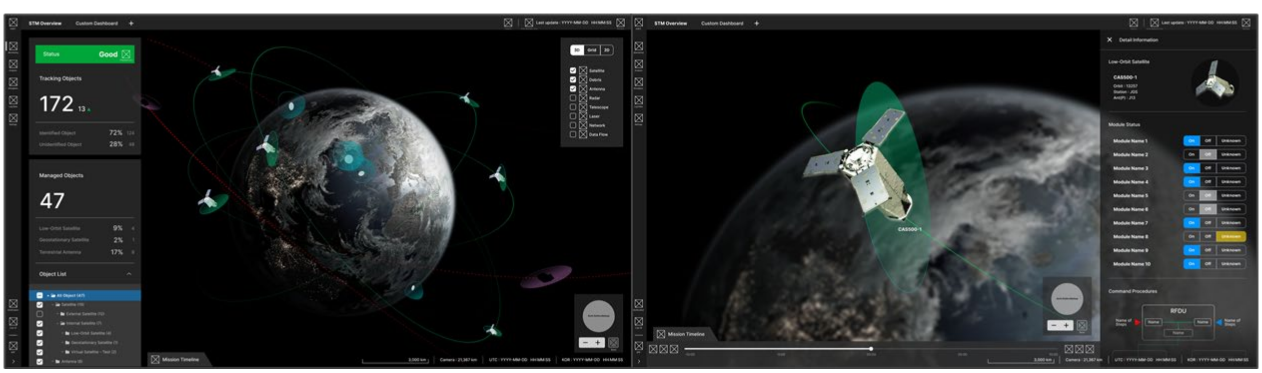

Figure 5 Mock-up version of KARI DT platform

Prototyping and Feedback Loop

Using interactive tools such as Figma and Unity-based WebGL scenes, clickable prototypes were created for user evaluation. These prototypes allowed engineers to explore simulated operational scenarios and navigate subsystem states using digital twins.

Three primary prototype flows were developed:

- Satellite overview with orbit visualization and health status indicators
- Antenna status panel with signal coverage animation and failure logs
- Anomaly scenario simulation showing risk propagation between subsystems

User feedback sessions were conducted in small groups, during which participants interacted with the prototypes and provided real-time comments on usability, clarity, and usefulness. Key feedback included:

- Strong preference for minimally styled dashboards with alert-focused design
- Requests for more traceable interaction paths (e.g., what caused a status change?)
- Need for seamless toggling between real-time and playback modes

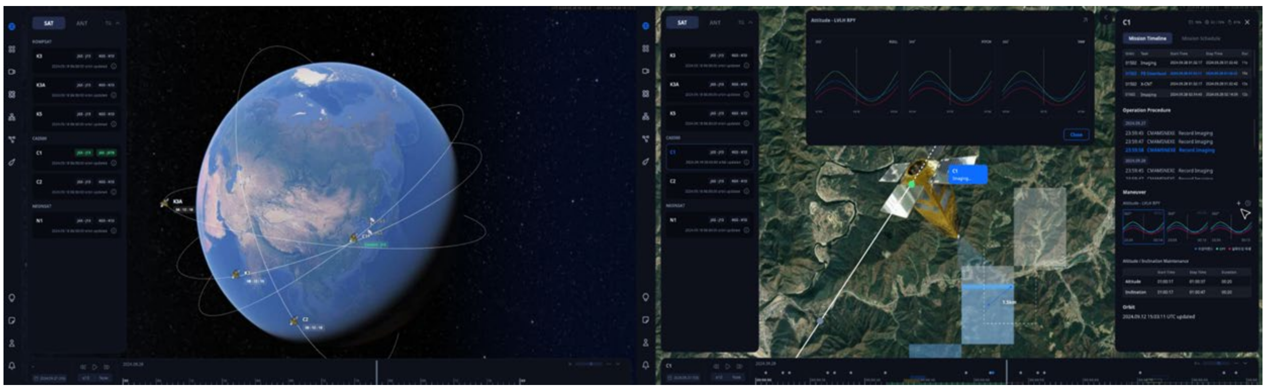

Figure 6 Updated version during feedback loop

Iteration and Refinement

Based on feedback, successive iterations incorporated:

- Improved layout consistency across subsystems
- Tooltips and explanation layers for complex visualizations
- Enhanced time navigation for viewing past-to-future transitions

This iterative, feedback-driven approach ensured that the resulting interface was not only functional but also intuitive, visually coherent, and aligned with the mental models of space operations personnel. As of this writing, KARI is actively engaged in the iteration and refinement phase of the project. Ongoing feedback cycles with subsystem engineers are being used to further enhance the usability, system integration, and overall alignment of the prototype with live operational workflows. The platform remains under active development, with progressive validation steps planned for future deployment phases.

3. Digital Twins in Space Operations

3.1 Architecture

The digital twin platform developed at KARI is structured as a multi-layered architecture, designed to mirror the complexity and interdependence of real-world space operations. Rather than treating each subsystem in isolation, the platform introduces a unified digital representation framework that integrates hardware, data, and mission logic through hierarchical and functional layering.

Hierarchical Structure

To support both micro-level detail and macro-level oversight, the platform is organized across three hierarchical levels:

(1) Object Level
Each physical asset (e.g., satellite, antenna) is represented as a standalone digital object. These objects carry their own telemetry streams, status indicators, and configuration metadata.
(2) Subsystem Level
Objects are grouped by operational function into subsystems (e.g., SOS, Ground Station Network), enabling visualization and simulation at the system level rather than per device.
(3) Mission Level
Subsystems are contextualized within the broader mission framework, allowing for mission-wide analysis, planning validation, and risk visualization.

This layered hierarchy allows operators to drill down from high-level mission views into detailed asset behavior, and conversely to aggregate localized events into mission-level implications.

Three-Layer Digital Twin Structure

Each digital twin instance—whether representing a satellite, ground component, or network segment—is composed of three functional layers:

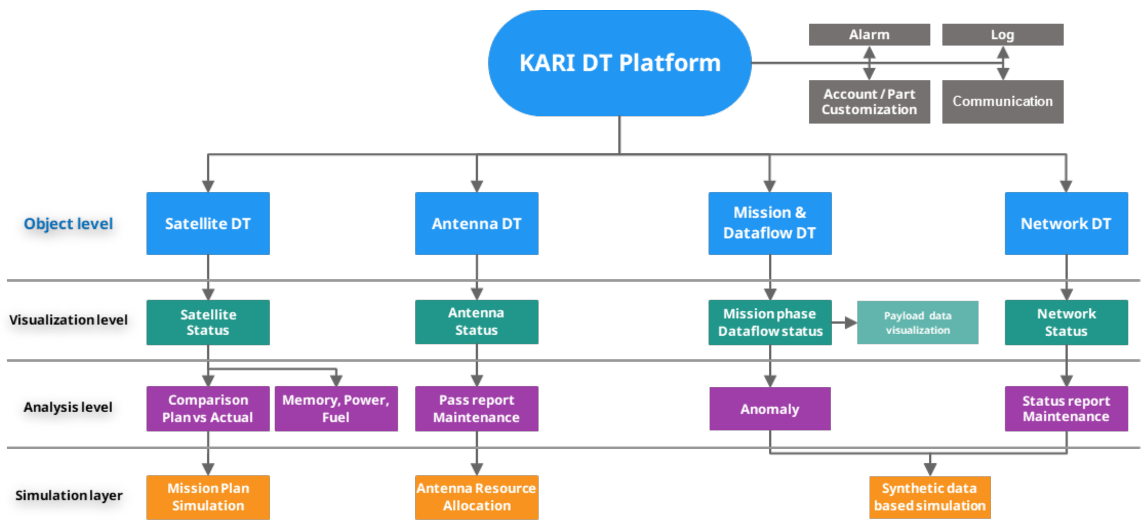

Figure 7 KARI DT platform structure

(1) Visualization Layer
Presents real-time and historical state information through 2D and 3D graphical interfaces. Users can view satellite orbit trajectories, antenna beam paths, network status, and subsystem interconnections. Visual cues indicate anomalies, critical states, or predicted risks.
(2) Analysis Layer
Supports diagnostic analysis and event correlation by integrating telemetry, logs, and operational metadata. Includes chart panels, trend visualizations, and time-synchronized data replay. This layer is essential for post-event review and real-time interpretation.
(3) Simulation Layer
Enables predictive operations by simulating future scenarios based on current conditions or operator-defined inputs. Simulations may include orbit maneuvers, subsystem failure propagation, and antenna scheduling under adverse conditions.

Each layer is modular and interoperable, allowing different engineering teams to extend or adapt functionality without disrupting the overall architecture.

Real-Time and Asynchronous Data Handling

To support the demands of live satellite operations, the architecture incorporates a dual-mode data interface as

- Real-time mode: continuously ingests and visualizes streaming telemetry and events.
- Replay mode: reconstructs past operation states from logged data for anomaly investigation or training purposes.

The system synchronizes data streams using unified time stamps and supports multi-speed timeline navigation, enabling seamless transition between historical review and predictive forecasting.

3.2 GUI

The graphical user interface (GUI) of the KARI DT platform was designed to support both situational awareness and actionable decision-making across various operational roles. It integrates 3D spatial visualization with modular UI components, allowing engineers to monitor, analyze, and simulate system behavior in a cohesive environment.

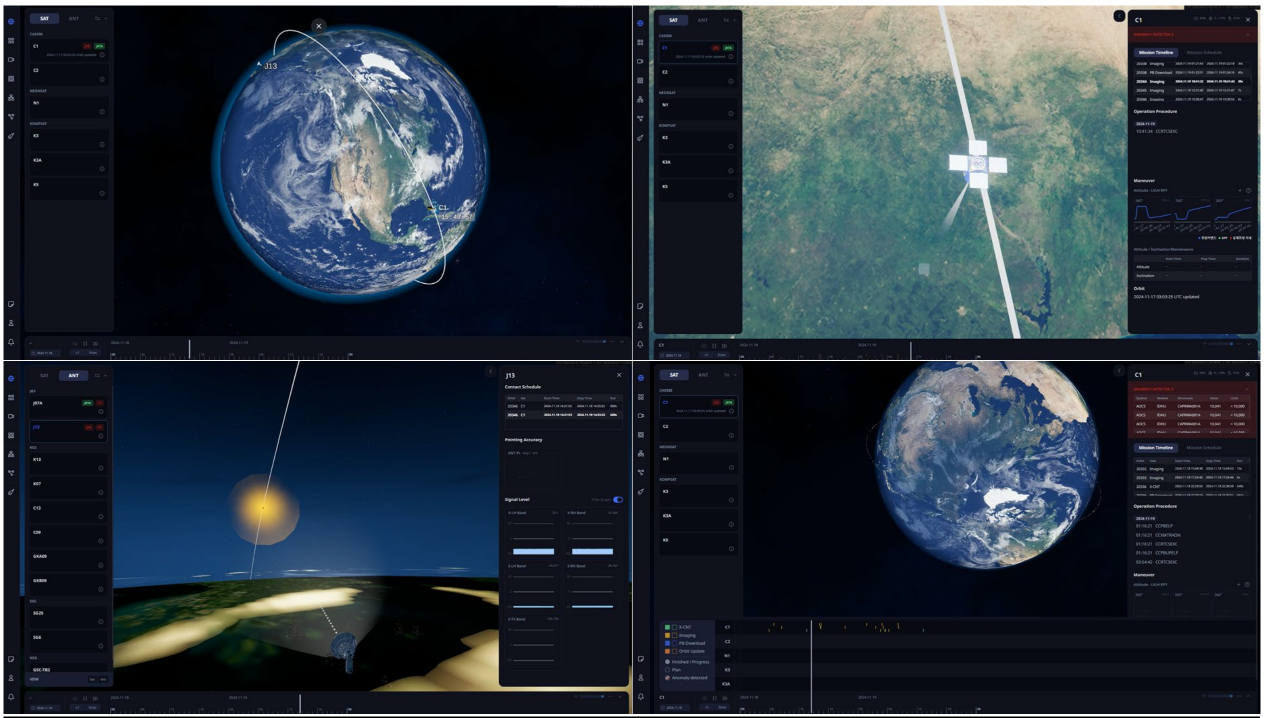

Figure 8 Current GUI version of KARI DT platform

4. Conclusions

This paper presented KARI's effort to design a digital twin platform for national satellite operations, based on real user needs gathered through field interviews and workshops. The resulting system adopts a layered architecture—comprising visualization, analysis, and simulation functions—and supports hierarchical management from individual assets to mission-level coordination.

By combining 3D visualization, real-time data integration, and workflow-aligned UX/UI, the platform improves situational awareness and supports decision-making across subsystems. As of now, the project is in the iteration and refinement stage, with ongoing feedback from engineers shaping future features.

This work provides a practical reference for applying digital twins in space operations and highlights the value of user-cantered design in complex mission environments.

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