On the Development of Digital Twins for Spacecraft Operations: European Space Operation Centre (ESOC) Perspectives

Federico Antonello, Jean Schuetz

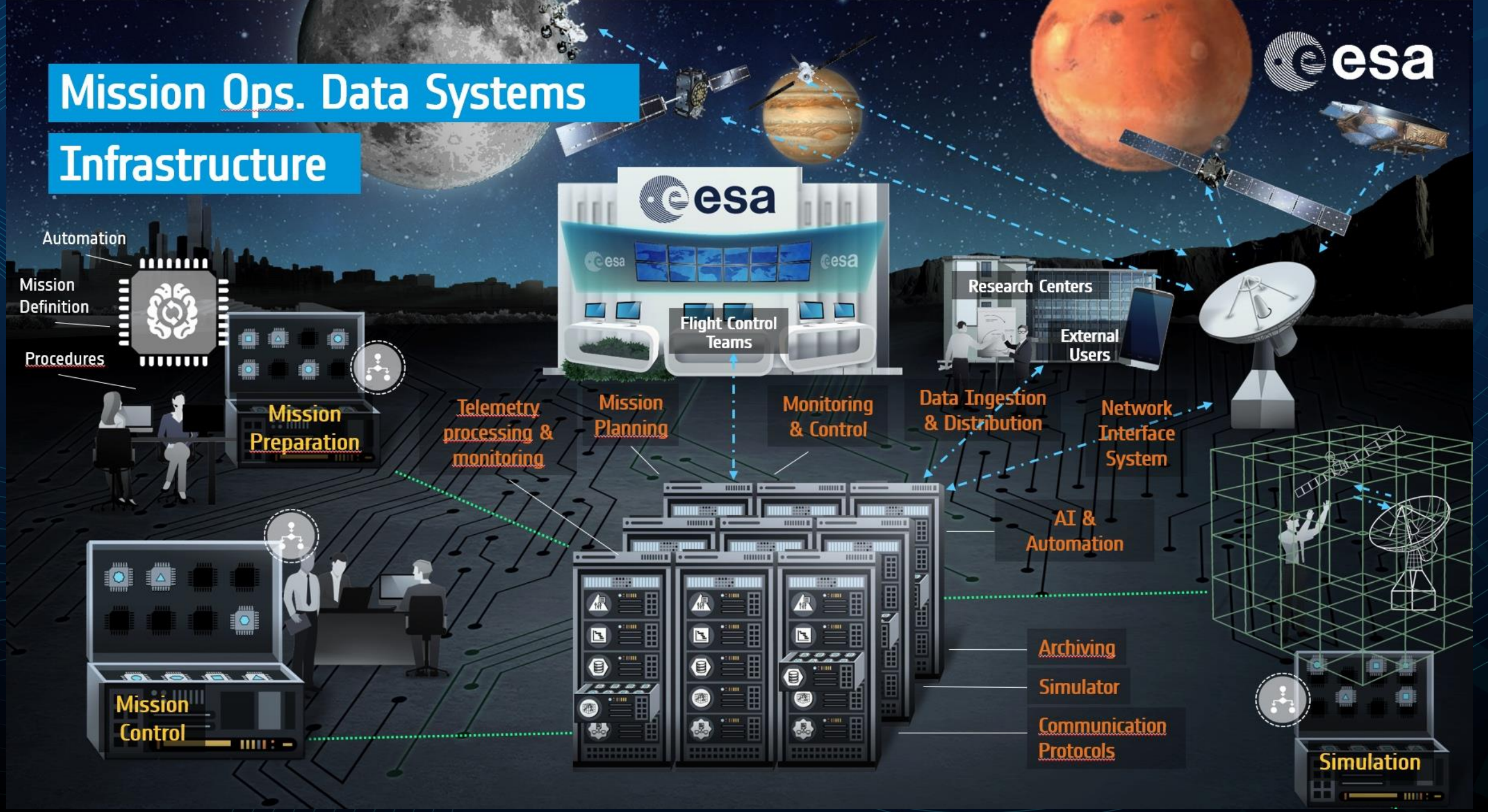
System and Applications Engineering Division
Engineering and Innovation Department, Directorate of Operations, European Space Agency

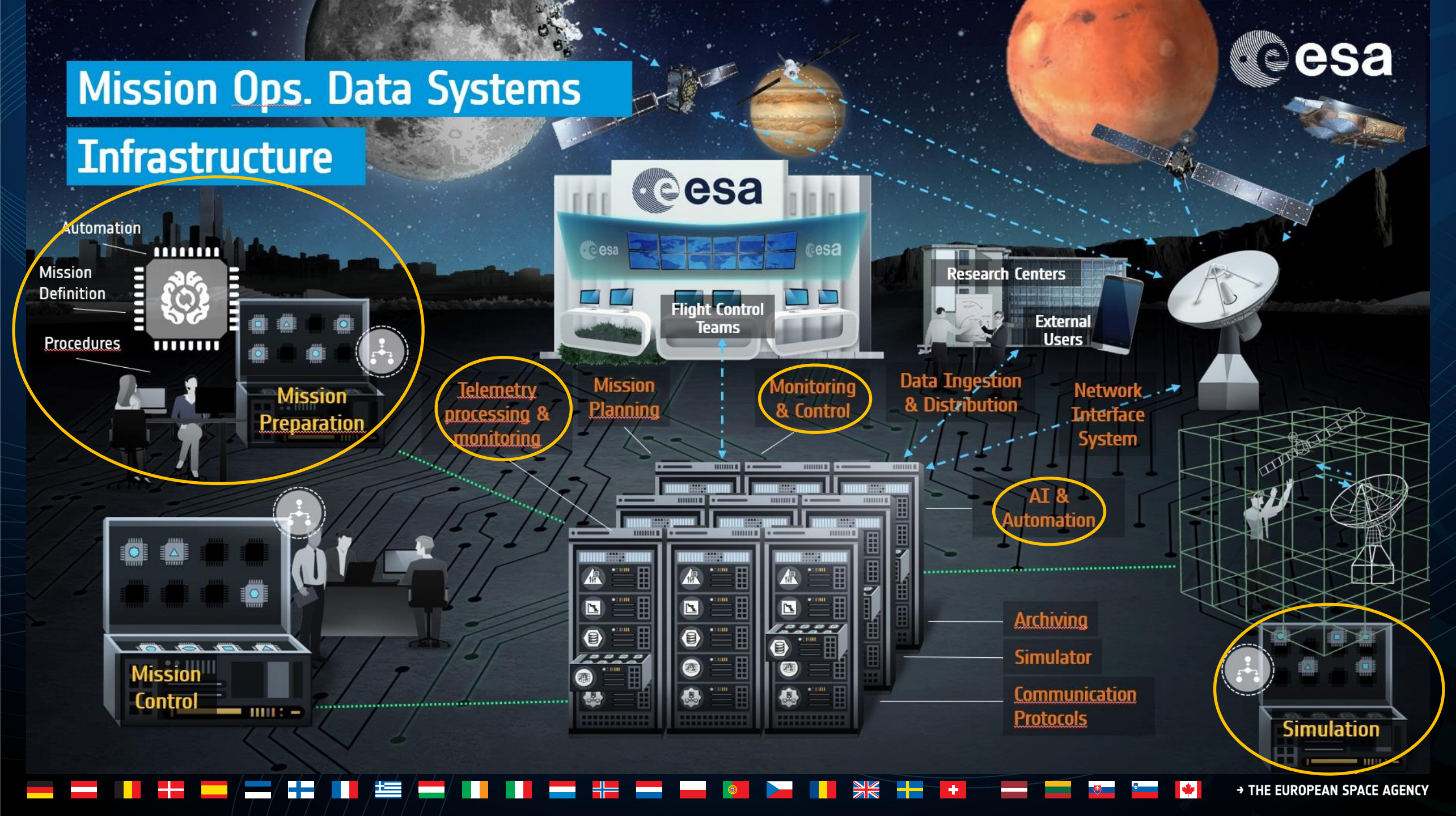
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The blueprint

- The enabler: Digital Twins and AI-enhanced simulation and modeling are shaping existing and new operational capabilities
- The Core: Human-centric design transforming needs and pain points, into tangible impact
- The Execution: Rapid prototyping (PoCs & MVPs) driven by quantitative KPIs
- The Vision: Long-term roadmapping and strategy to scale sustainably and avoid siloed tools

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Mission Ops. Data Systems
Infrastructure
esa
Automation
Mission Definition
Procedures
Mission Preparation
Flight Control Teams
Research Centers
External Users
Telemetry processing & monitoring
Mission Planning
Monitoring & Control
Data Ingestion & Distribution
Network Interface System
AI & Automation
Archiving
Simulator
Communication Protocols
Mission Control
Simulation
→ THE EUROPEAN SPACE AGENCY


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Current status and pain Points

Mission Preparation

Procedure generation is a key task involving multiple engineers for years

Procedure writing is a tedious task performed with siloed authoring tools

Knowledge base is scattered and info hidden in many docs

No direct connection between procedures and simulators

Operational Simulators

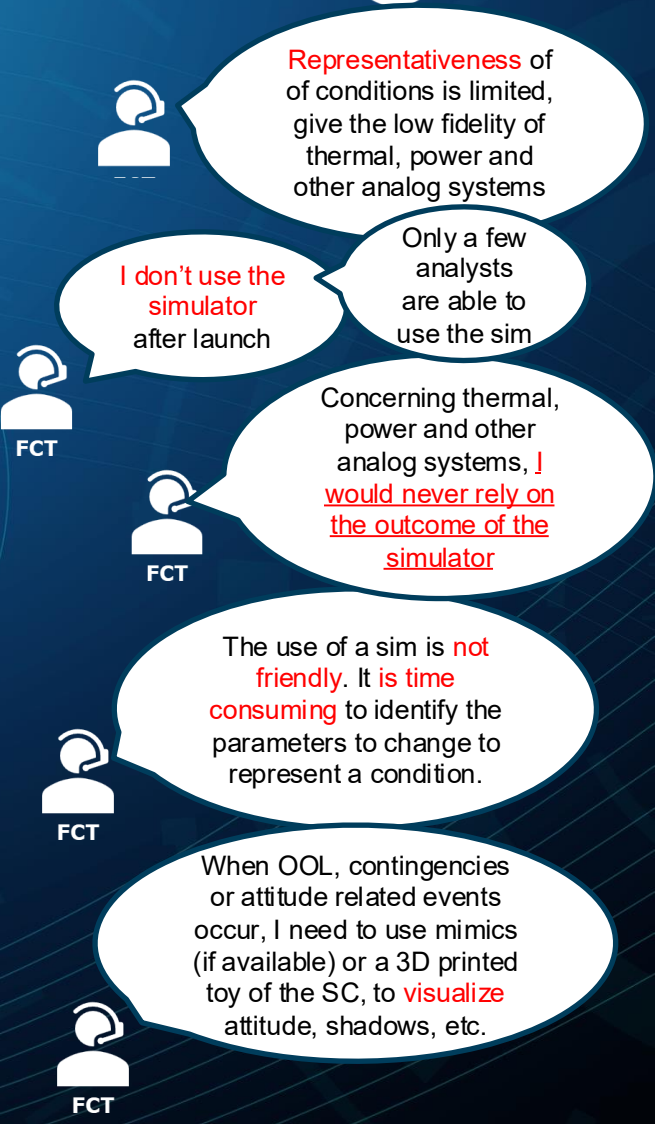
Time-consuming configuration and validation of simulations for mission preparation

Manual config and validation of Break-points. Sim seldomly used to approximate flying SC

Limited and 2D visualization with supported tools

Limited and inaccurate forecasting capabilities

Improving the processes can potentially **save hundreds of hours**/year for each engineer and **enable new capabilities** (e.g., live simulation, PHM, RUL, etc.)



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Vision: Digital twins and Smart Simulation and Preparation Suite

Procedure Preparation, Representative scenarios simulation, validation and planning

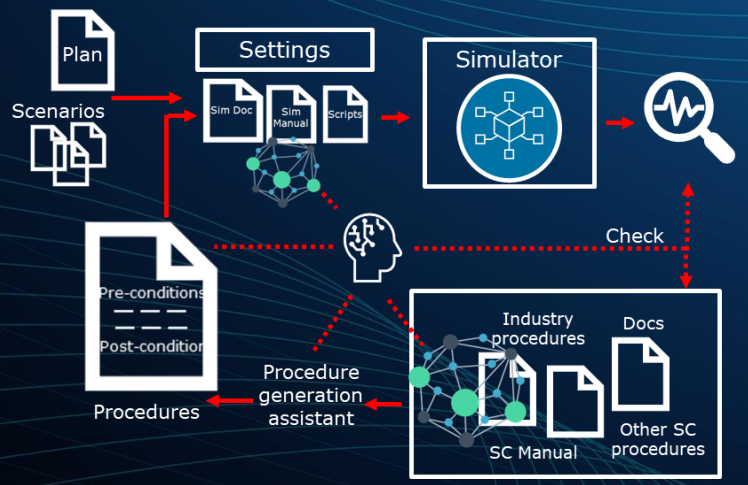
Situational Awareness

Enhanced representation, simulation and visualization

Prognostics and Health Management

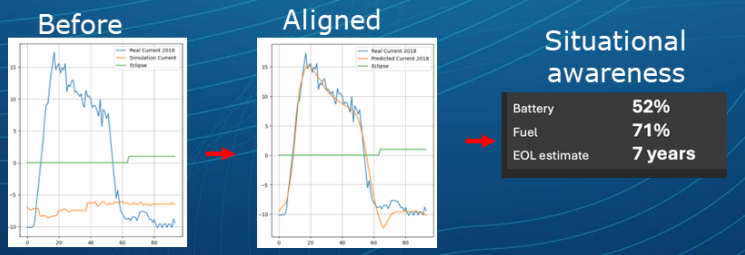
Remaining Useful Life Assessment

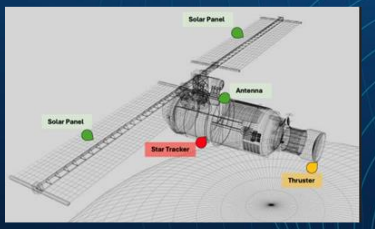
Integration with AI-enhanced preparation tools for seamless validation

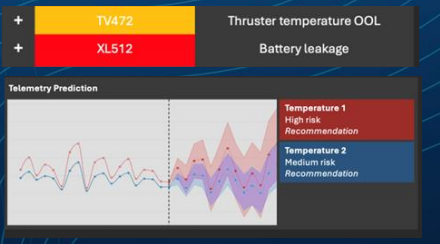


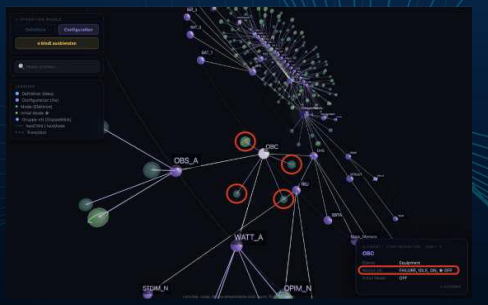
In operations, allows for validation of procedures and planning with real operating conditions

Simulations High fidelity Alignment

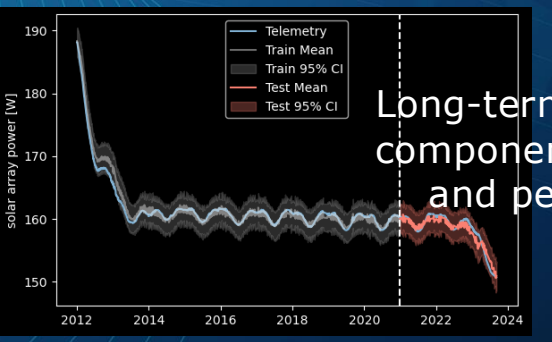




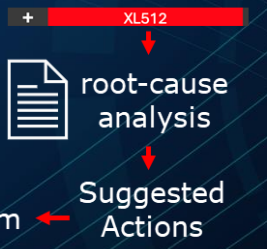




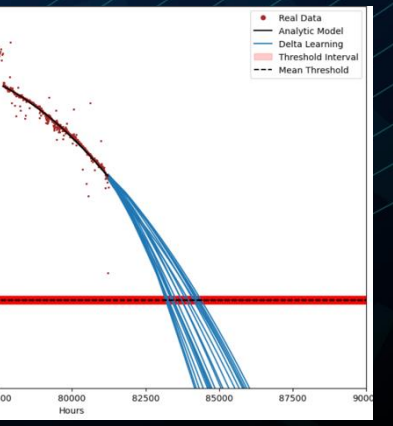
Navigable and interactive knowledge base representing the digital spacecraft



Long-term prediction of component degradation and performances



Assessment of component Remaining useful life



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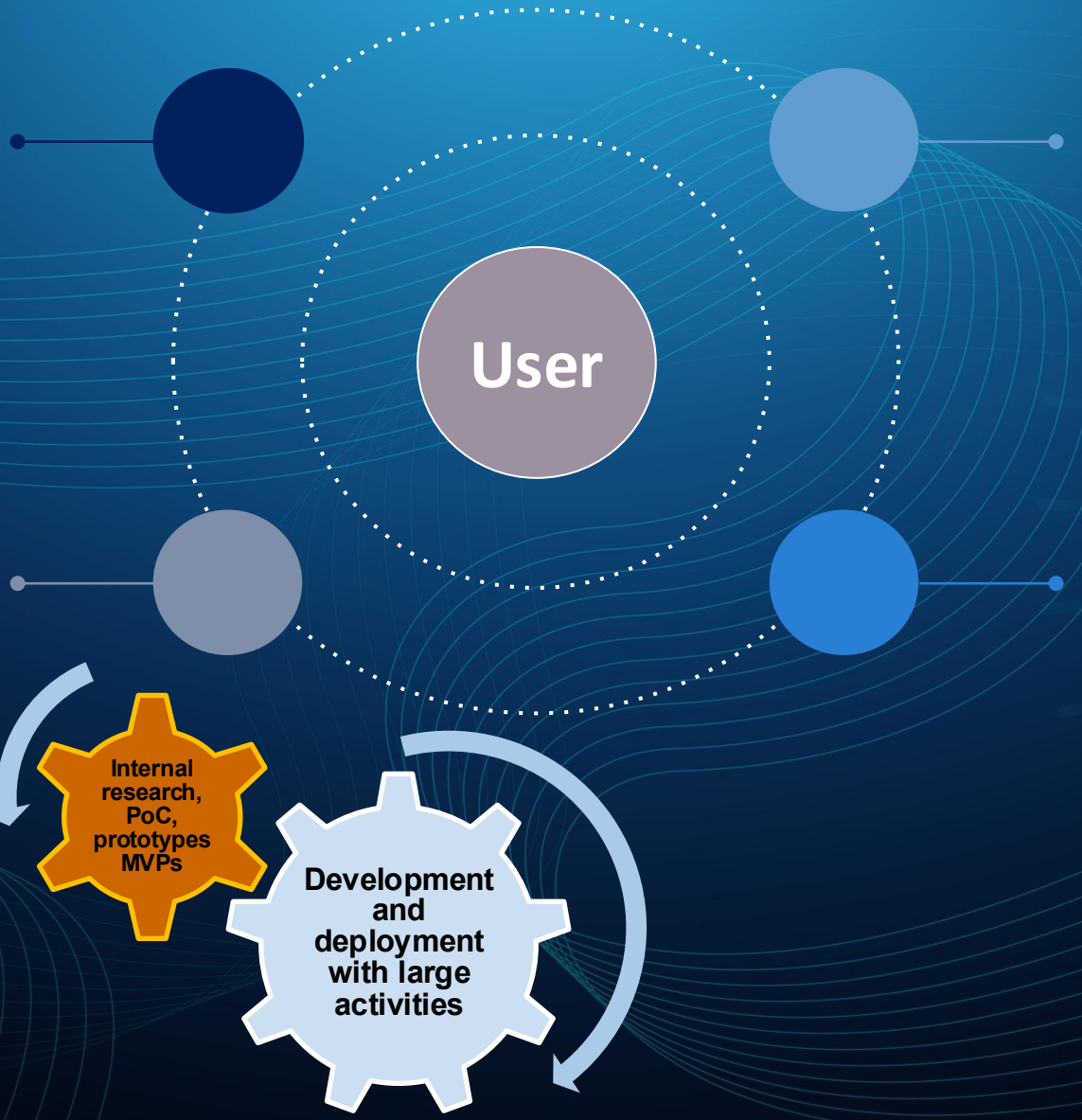
Approach: User Centric Development

User Needs

Develop a list of user needs to guide design work.

User Pain Points

Empathise with the user to identify improvement opportunities for current system.



UI and Prototypes

Fast prototyping and MVPs and continuous feedback from users

Impact and enable

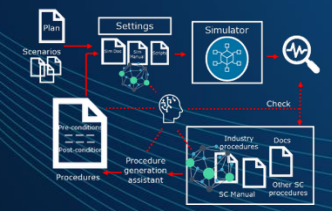
Identify concrete impacts and enabling capabilities to support the development and validation.

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Development strategy

DT Architecture, Data Management, MBSE, digital continuity, …

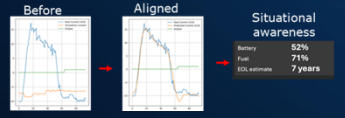
- Data management
- Ontology
- Digital Continuity



- Assisted procedures generation
- Assisted scenarios setting

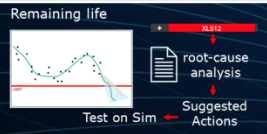
Assisted development, debugging, reporting and maintenance

Align simulator with S/C operational and health conditions



- SC-simulators aligner & configuration
- Surrogate models
- Enhanced fidelity
- Status-aware procedure validation
- Security testbed

Analytic, health monitoring and control, Prognostics



- Status and Anomalies Assessment
- Prognostics (trends, resources, …)
- Remaining Life Assessment
- Diagnostics (Root-cause, …)
- Planning
- Optimization and Decision Making

Advanced representation and immersive visualization



- XR visualizer
- Immersive visualization of insights

Identification of key capabilities to be developed

Identification of key architectural needs to ensure effectiveness and scalability

Development of fast prototypes and PoC proving impact and enabling capabilities

Development within large industrial activities

Constant synchronization and coordination with stakeholders. WG was established in RATIOSIM

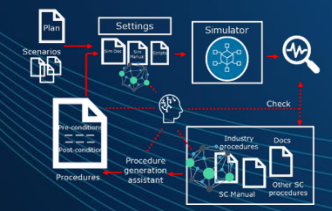
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Concrete Capabilities and Roadmap

DT Architecture, Data Management, MBSE, digital continuity, …

- Data management
- Ontology
- Digital Continuity

Contribution | Contribution | Contribution | Contribution | Contribution | Contribution



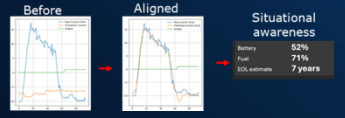
- Assisted procedures generation
- Assisted scenarios setting

PoC | Generalizability | Mission Adoption | Improvement | Mission Adoption

Assisted development, debugging, reporting and maintenance

PoC | Systematic approach | Generalizability

Align simulator with S/C operational and health conditions



- SC-simulators aligner & configuration
- Surrogate models
- Enhanced fidelity
- Status-aware procedure validation
- Security testbed

PoC | Systematic scalable framework | Advanced data assimilation | Mission Adoption | Mission Adoption

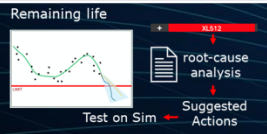
Systematic approach | Generalizability | New model | New model | New model | New model

PoC | Systematic approach | Generalizability | New model | New model | New model | New model

PoC | Systematic approach | Generalizability | Mission Adoption

PoC | Systematic approach | Generalizability

Analytic, health monitoring and control, Prognostics



- Status and Anomalies Assessment
- Prognostics (trends, resources, …)
- Remaining Life Assessment
- Diagnostics (Root-cause, …)

PoC | Systematic scalable framework | Generalizability | New model | Mission Adoption

- Planning
- Optimization and Decision Making

PoC

Advanced representation and immersive visualization



- XR visualizer
- Immersive visualization of insights

PoC | Systematic scalable framework | Generalizability

Activity
AiMsys
ExploDTwin
OPOS
PilotDT
UoM (old)
GenMSE
AI4DT
DT4Sec
Suite Analyt
DT debris
SW/FD/…
DT4Visual
Synthetic D
DTcontinuity

Vision Timeline

Feature	Enhanced Visualization	Health Monitoring	Predictions	Planning
	3D, XR and user experience-centred tools	Enhanced anomaly assessment, root-cause, patterns, etc.	Embed high-fidelity sim and intelligent models to predict SC long term behaviour	Use the predictions on SC status to inform planning

Feature	Preparation	Preparation	Operations	Operations
	Procedure Generation	Assisted Setting	Automated Alignment	Planning
	Assist procedures generation, related info retrieval and their validation in the sim	Assisted identification and setting of sim param. to simulate a condition	Process TM info to assess the SC status and automatically set simulator parameter	Use the info on SC status to inform planning

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In this presentation: Success Stories, Prototypes, MVPs

- Digital Twin (DT) Spacecraft Generalities
  - Concept
  - PilotDT
  - Other Examples
- DT-Based Prognostics and Health Management
  - RUL estimators
  - AiSTRA
- AI-enhanced mission preparation
  - OPOS

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What is a Digital Twin (DT)?

How a DT supports Operations?

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Vision: Digital Twin Spacecraft (DTSC) in Operations

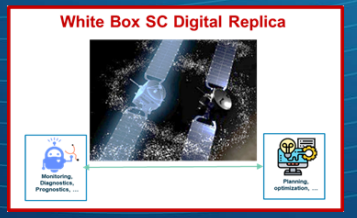
Data, Models, Tools, Infrastructure → Digital Twin SC



SC to DT

Flying SC





DT to SC

DTSC architecture and digital continuity

Definition:

- *A Digital Twin Spacecraft **DTSC in operations** is defined as a **dynamic** and **self-evolving** digital/virtual framework that represents the SC exact **state** (and the associated **uncertainty**) at any given point in time. Provides enhanced situational awareness by embedding models/simulators calibration, data assimilation as well as keeping and structuring the historical data.*
- *It is also an **enabler** for **automation**, **AI** applications and **decision-making**. A DTSC embeds models, simulators and AI and allows real-time **bi-directional data exchange***
- *A DTSC is also defined through the associated **tools** (DT toolkit or services), such as tools for **failure detection, diagnosis, prognosis**, real-time **predictions**, operations **optimization**, and surrogate modeling.*
- *A DTSC allows digital continuity among mission phases, and among missions, via holistic semantic, data aggregation tools and MBSE methods. This facilitate, optimize, and automate mission preparation processes*

Key Aspects:

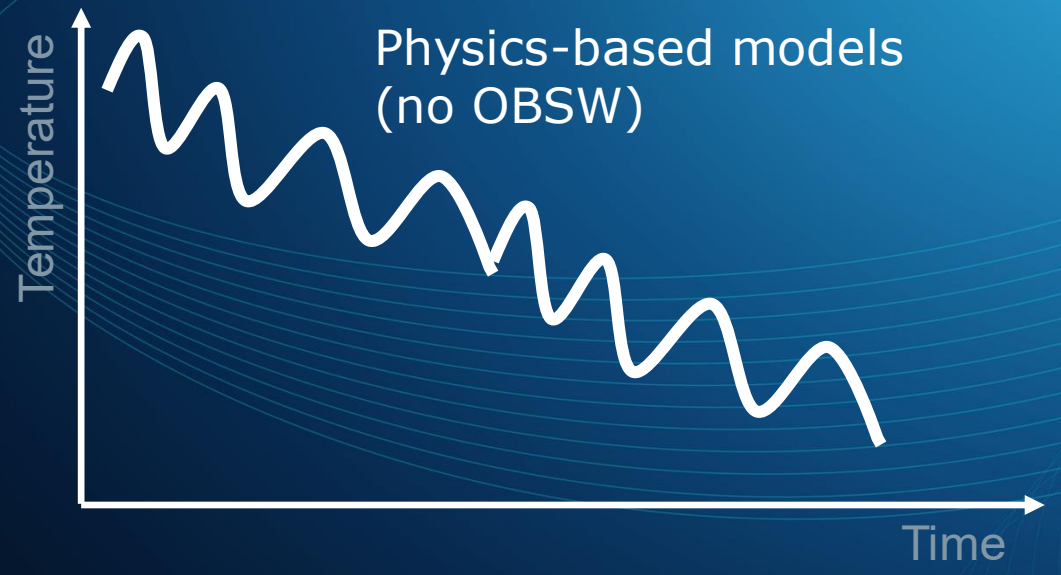
- Synchronization and Calibration
- Data management and digital continuity
- Bidirectionality of Data, information and decision making
- Capability of diagnostics and prognostics to enhance decision making capabilities and health management
- Operator in-the-loop → DT is an assistant

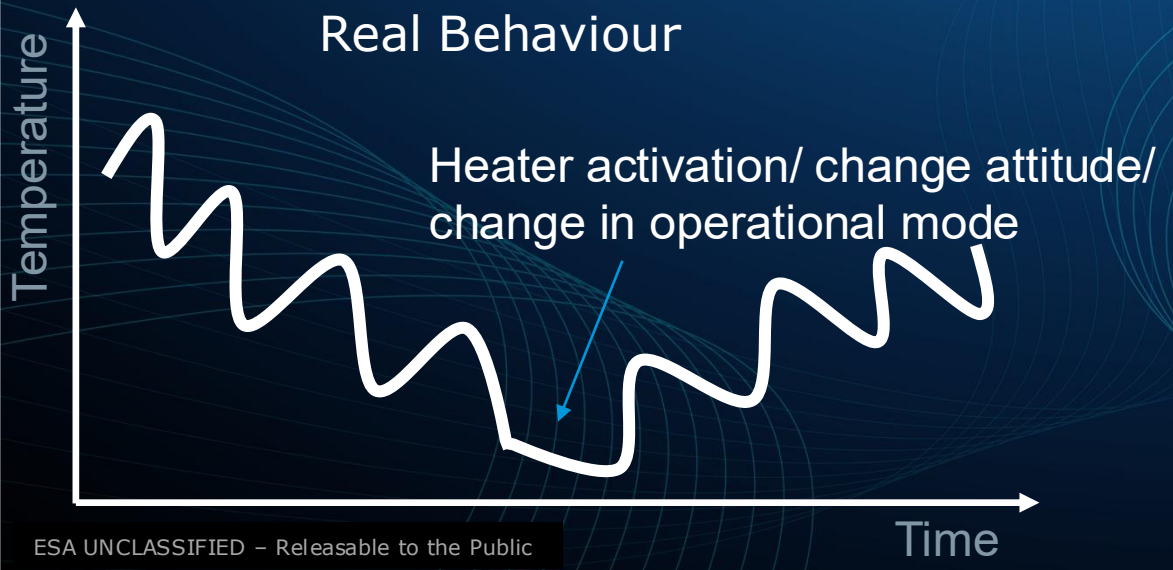
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Challenges and needs for advanced simulations and operational simulators

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Physics-based models vs OBSW response





Spacecraft behaviour depends on physical lows and the response/control actuated by the on-board software

Examples:

- Temperature: activation of heaters depends on OBSW response to scenarios (measured Temp vs limits)
- Attitude depends on operational necessities (RW etc to keep pointing to target)
- Functioning of systems and components depend on operational modes and operations planning

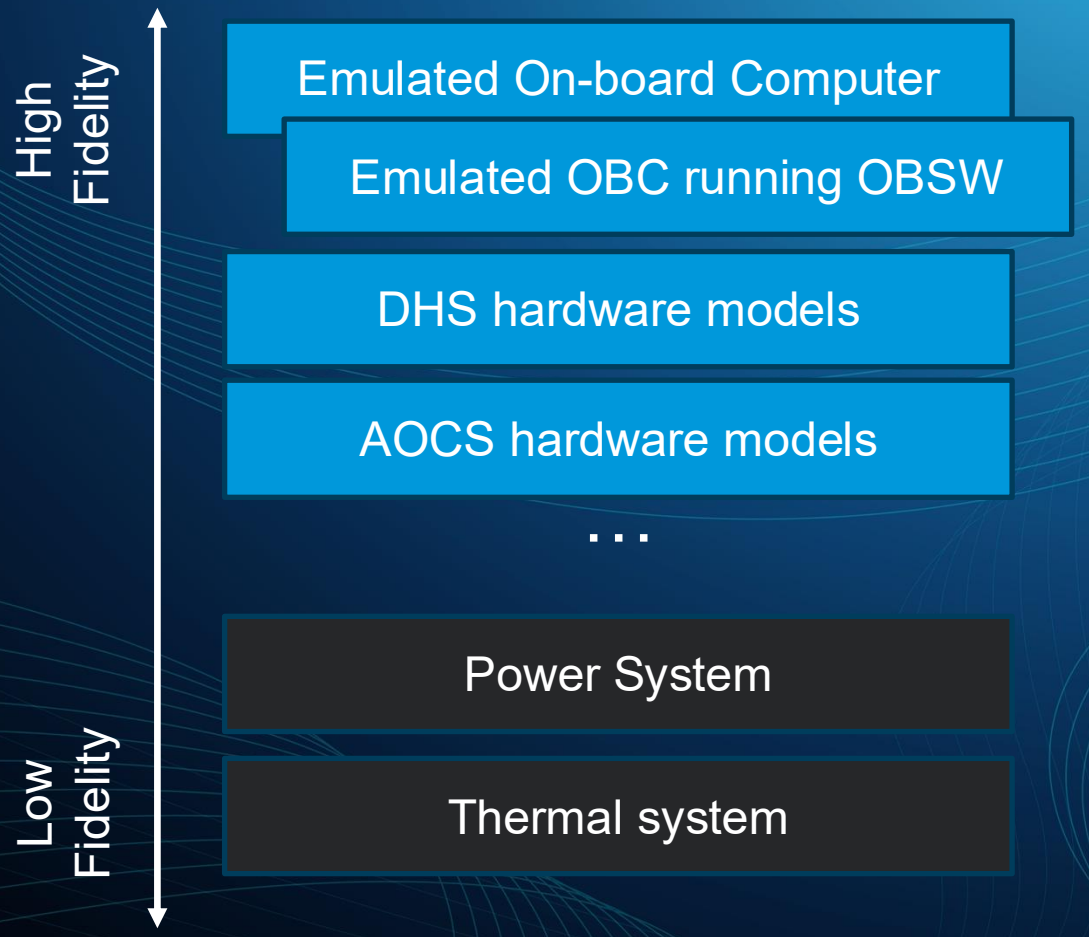
To properly model a SC, is essential to consider hardware, software, environments and the governing physics lows

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Opportunity: Use of Operational Simulator

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Operational Simulators

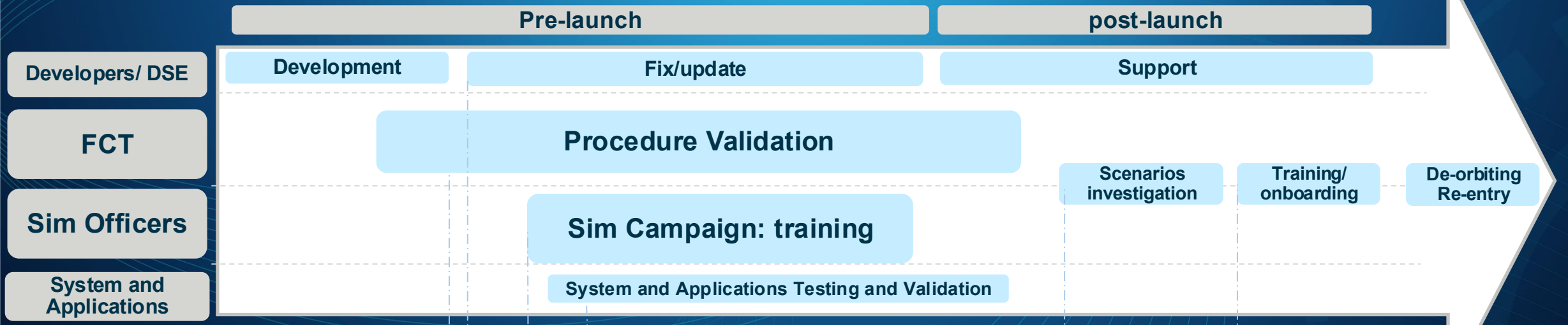


Operational Simulator characteristics:

- OBC is emulated and runs the exact same OBSW running in the SC
- Simulator OBSW responses to conditions and TC is extremely accurate
- Domains/sub-systems simulated with good fidelity: DHS, AOCS
- Domain simulated with low fidelity: Power, thermal, ….

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Current Simulators Lifecycle and Usage



- Setting of conditions for procedure validation
- Set up simulator to represent scenarios
- Post-launch: test/val procedures and investigate scenarios

- Test on ‘representative’ environment
- Use preconfigured breakpoints

- Continuous training and onboarding

- Definition of scenarios for training and set-up of sim.
- Breakpoints setting
- Requires expertise and experimenting

- new/unexpected/delta scenarios
- Troubleshooting

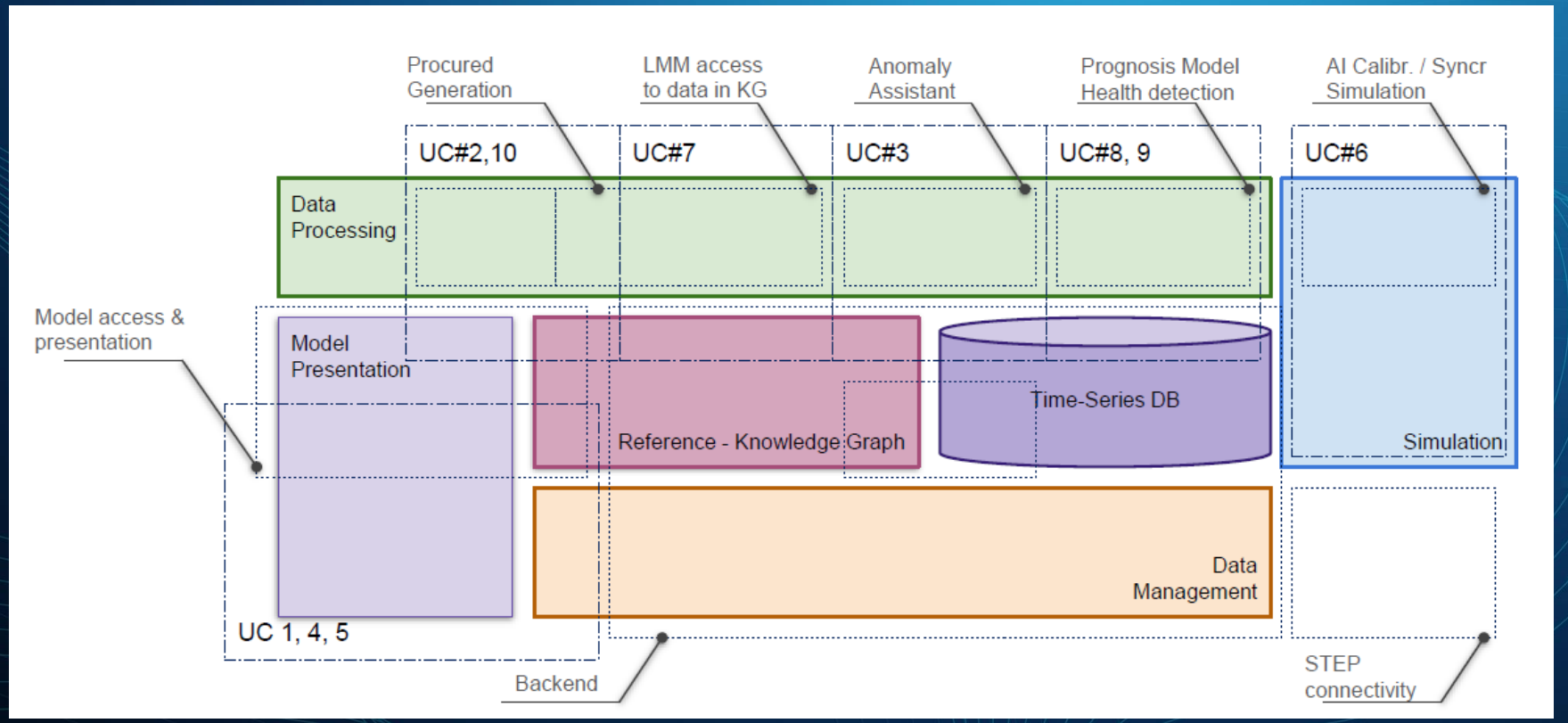
- Update and solve issues
- Generate Breakpoints at Sim Releases
- Generate breakpoints if asked

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DT related activities, applications and successful prototypes/MVPs/tools

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Pilot Digital Twin: foundation activity



Central backend and data modeling to support the concrete use cases

Use cases definition with **clear business** value for both ESA and industries

Applications span from simulation to AIT, operations, mission preparations

Introduction of **novel approach** combining modelling, semantics, ontologies and AI, LLM

Architecture to support all UCs and applications

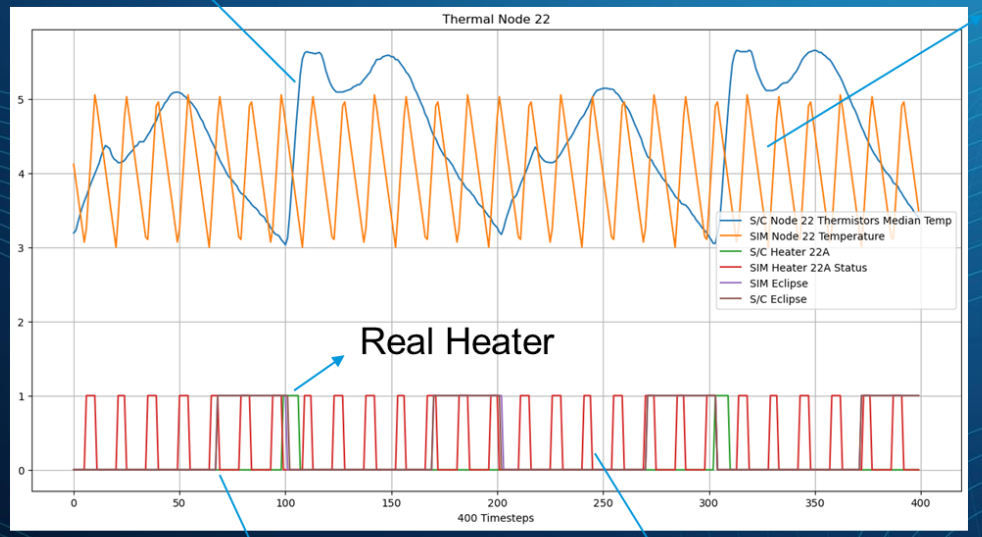
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PoC: More representative simulations

Real Temperature

Simulator's Temperature

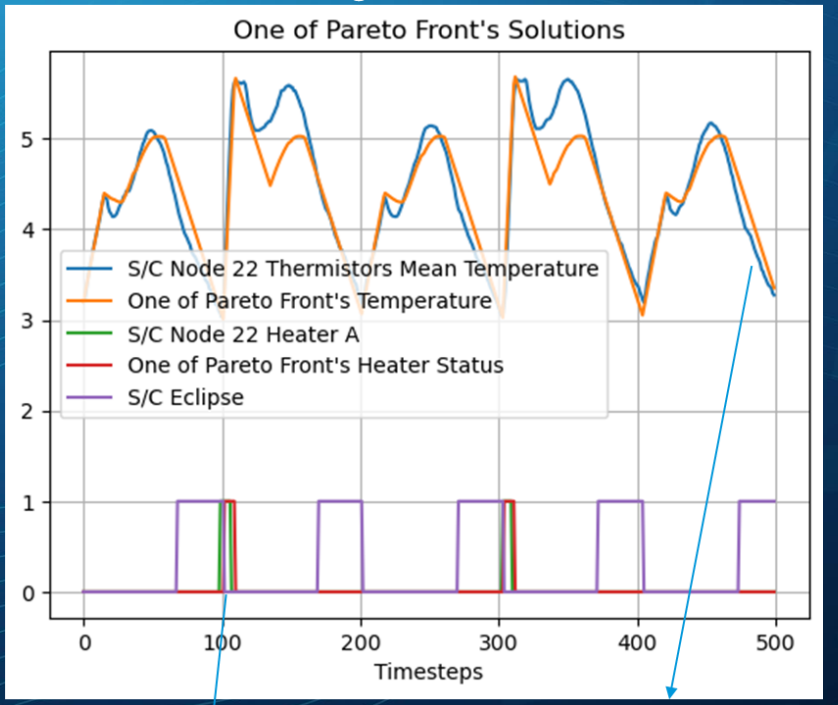
Before Changes and Calibration



Eclipse (Synchronized times)

Simulator Heater

After Changes and Calibration

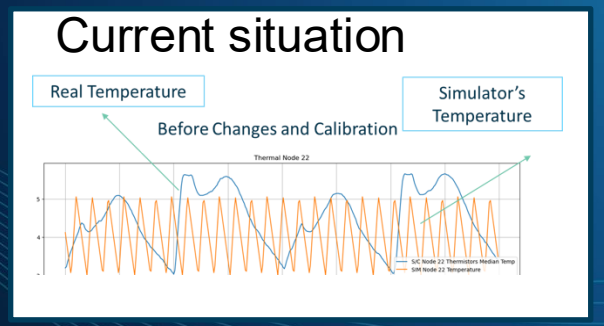


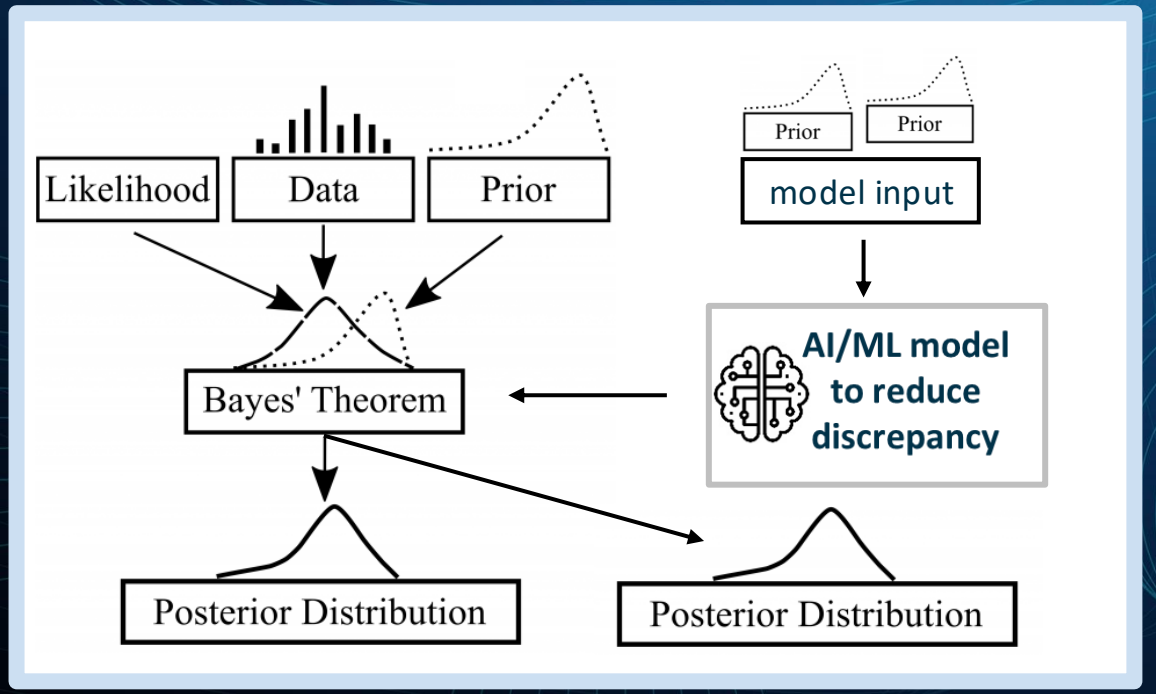
Heater Similar Behaviour

Impact: Enables the use of operational simulators to validate in-flight scenarios on various domains, provides predictive capabilities and reduces validation time

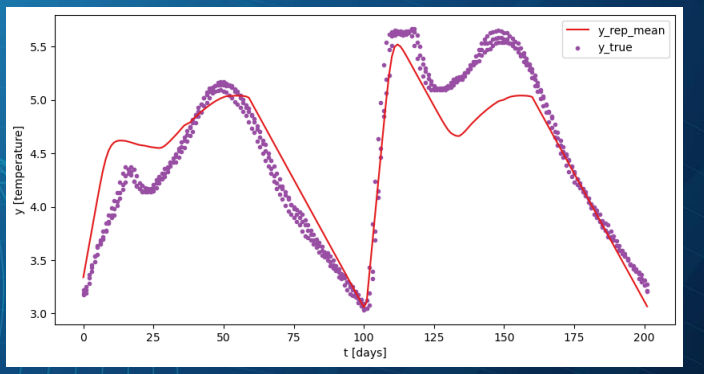
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Stochastic Calibration and model discrepancy reduction for more representativeness simulations

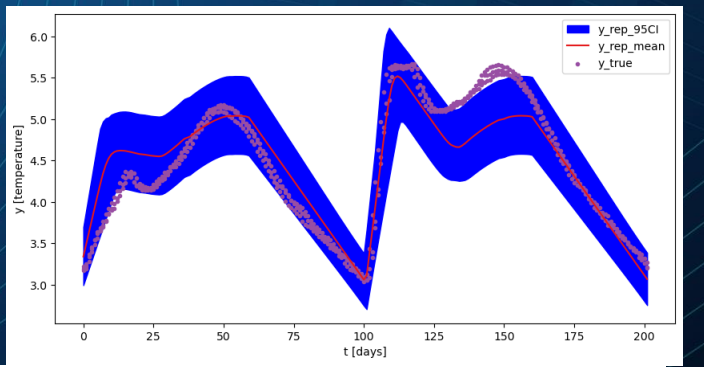




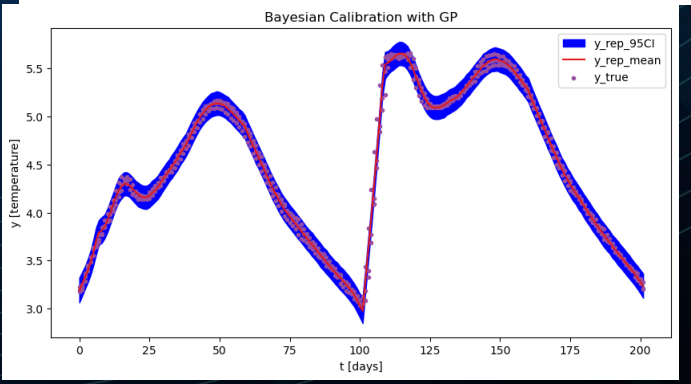
Evolutionary Optimization



Stochastic Optimization

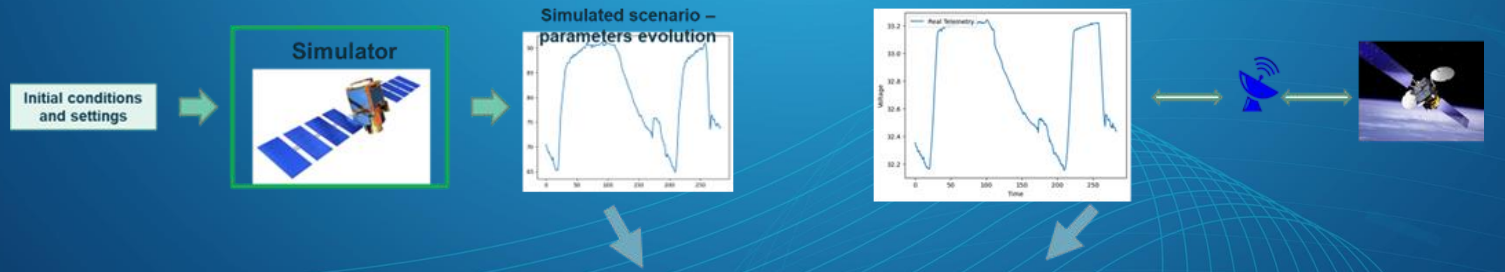


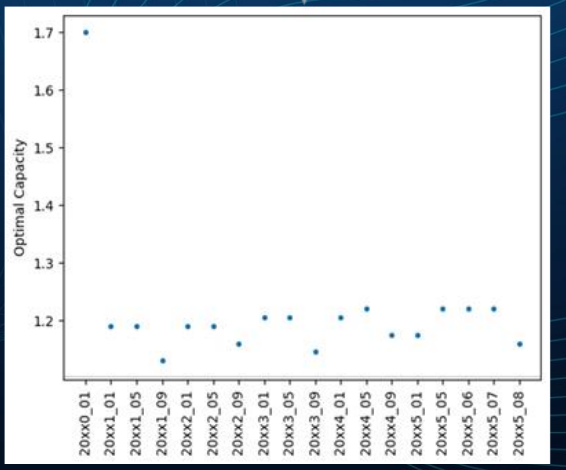
Stochastic Optimization and discrepancy reduction



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Digital state update to enhance situational awareness



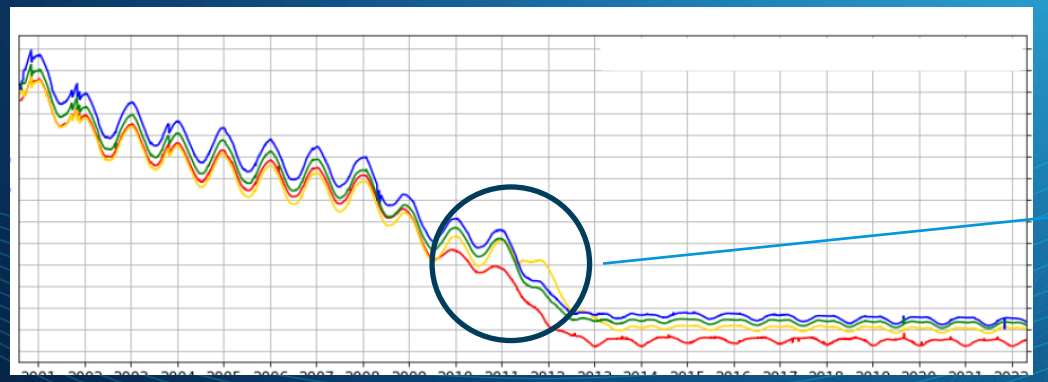


Impact: Supports health management and enables independent analysis on SC status

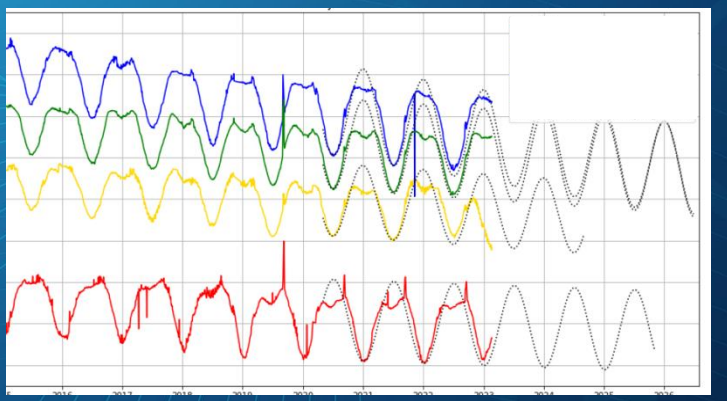
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Solar Arrays Power Production under degradation

Monitoring data



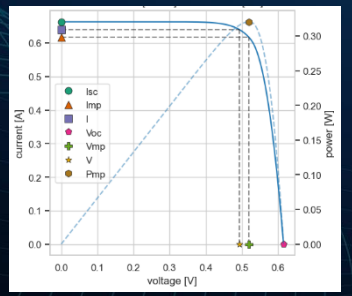
Equivalent predictive model



Both data-driven and physics-based models cannot predict the drops in Power production

SOLUTION

Physics-based model



+

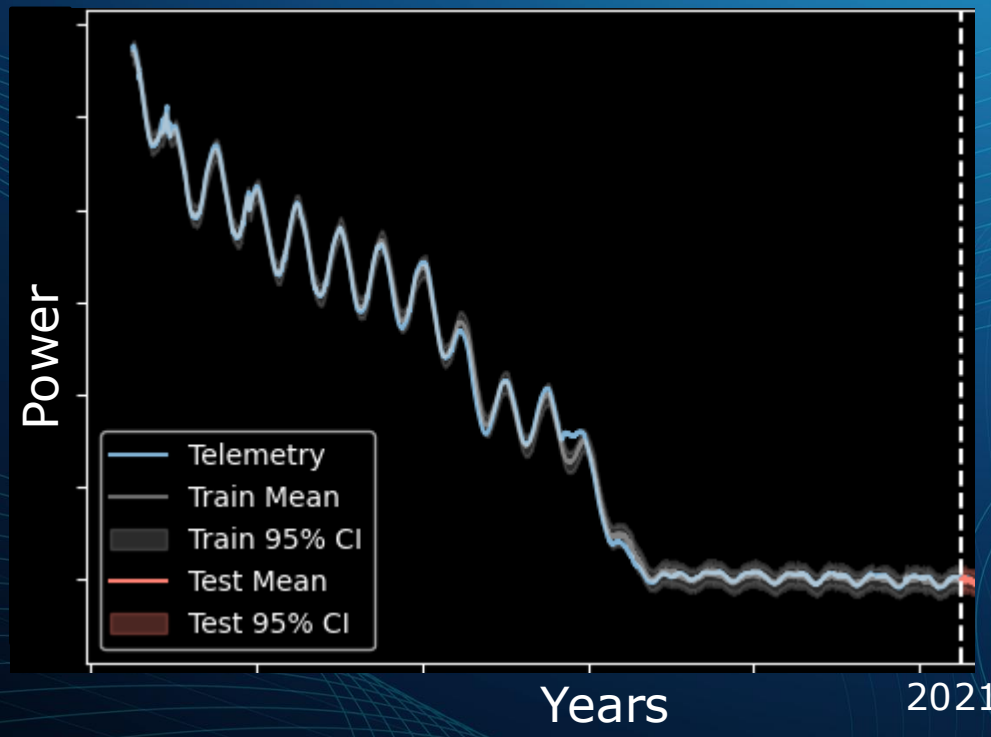
Optimization algorithm

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AI/ML model to reduce discrepancy

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Solar Arrays Power Production under degradation

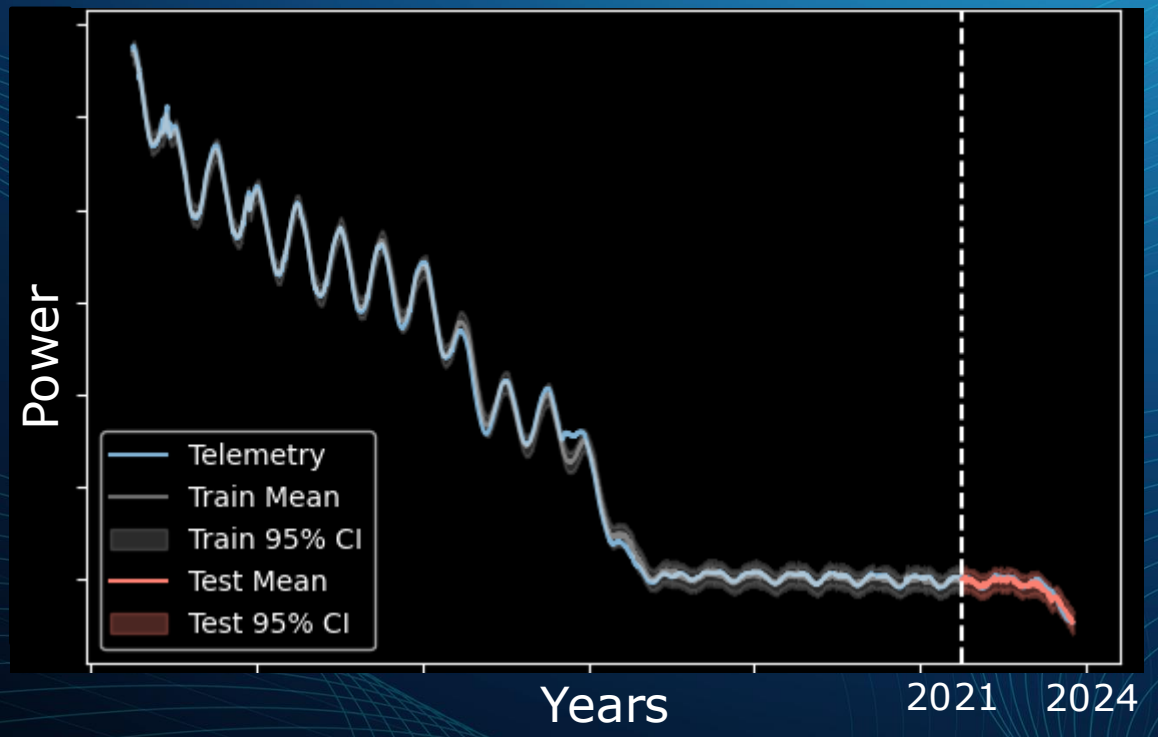


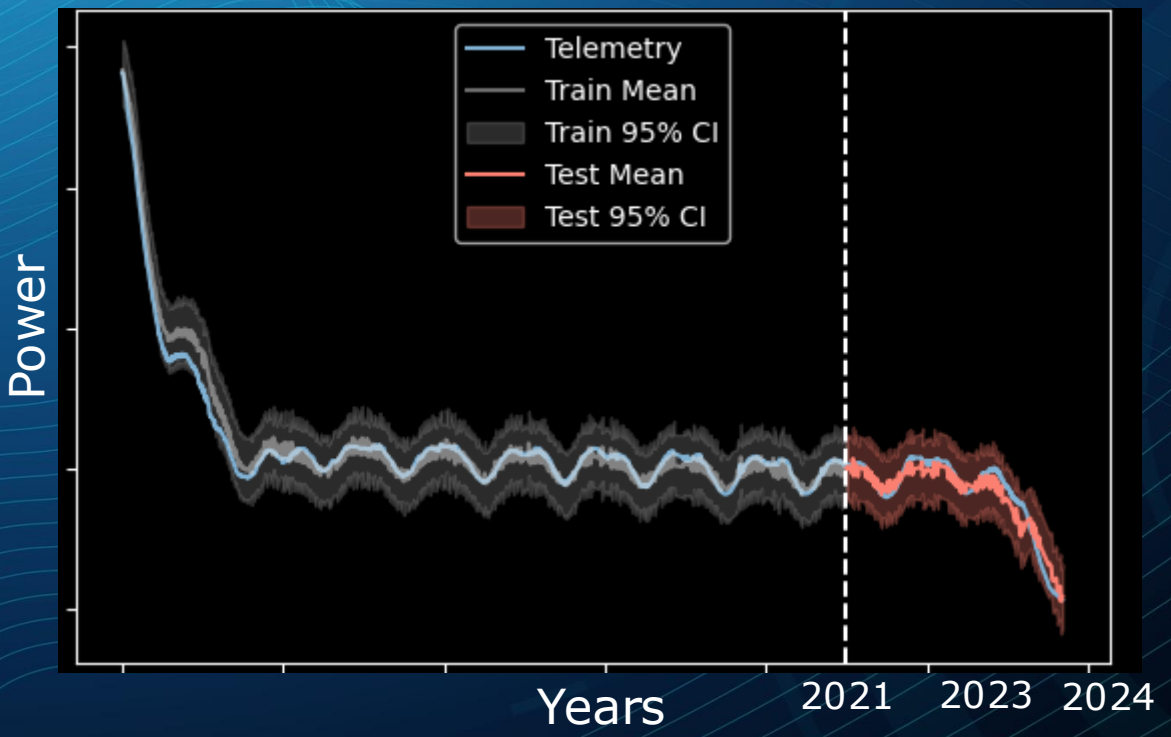
- The model fits well the data used for the training.

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Solar Arrays Power Production under degradation

Impact: 1) Enables predictive analytics to validate support planning.
2) Extends mission lifecycle; 3) operations optimization and enhanced scientific return





- The model fits well the data used for the training.
- **The model predicts the further drop that occurs 2 years later**.

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Predicting Remaining Life of Components

Critical components

Data

Processing

Model

Health Indicator

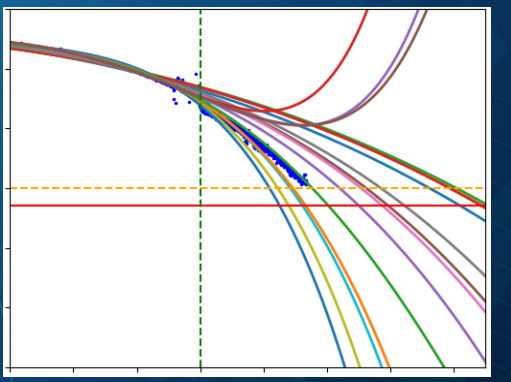
LIMIT

Estimation

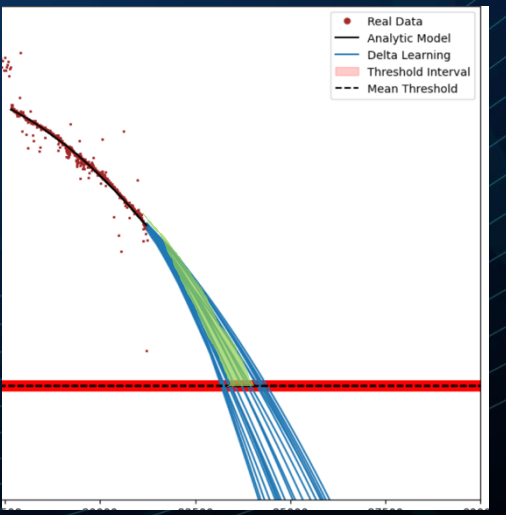
Prediction

LIMIT

Previous approach



DT-Based GAM ensemble

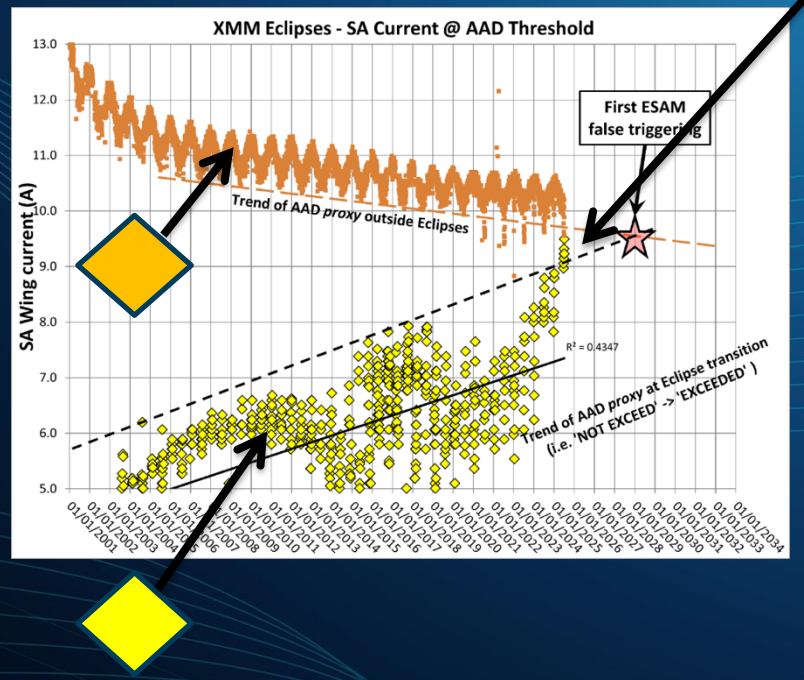


Hours of Ops

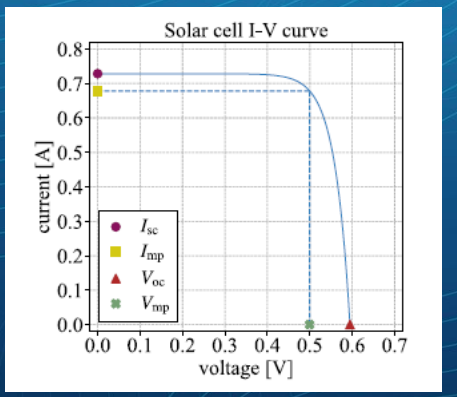
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Modelling Degradation of Spacecraft Sensors

PROBLEM: Unexpected surge in degradation and no TM of sensor A



2-Step solution:

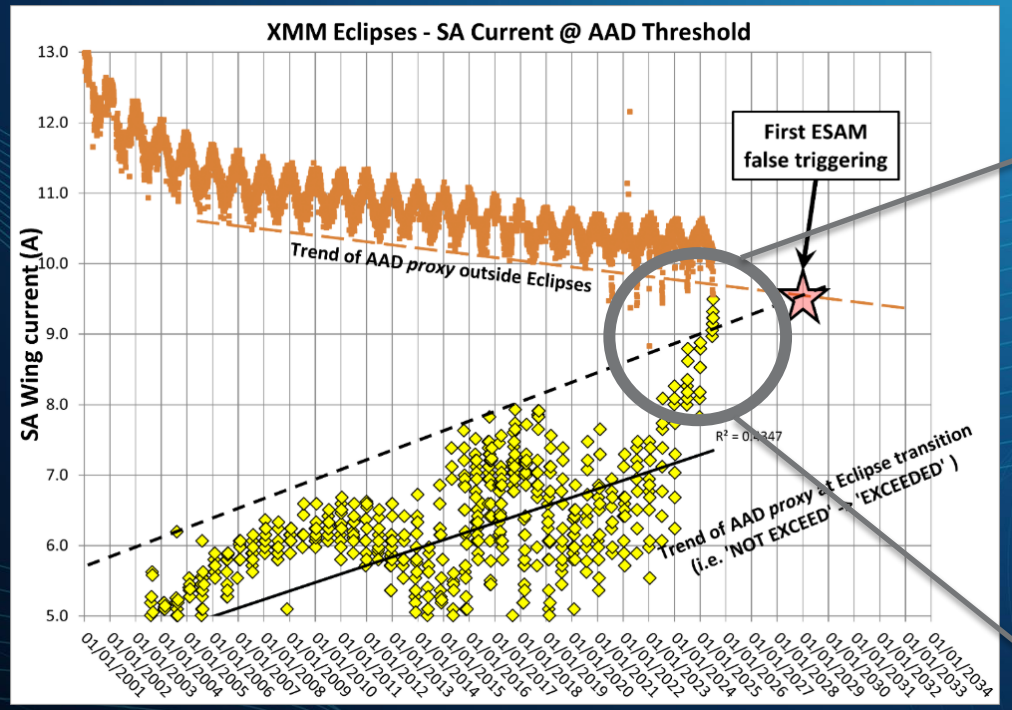


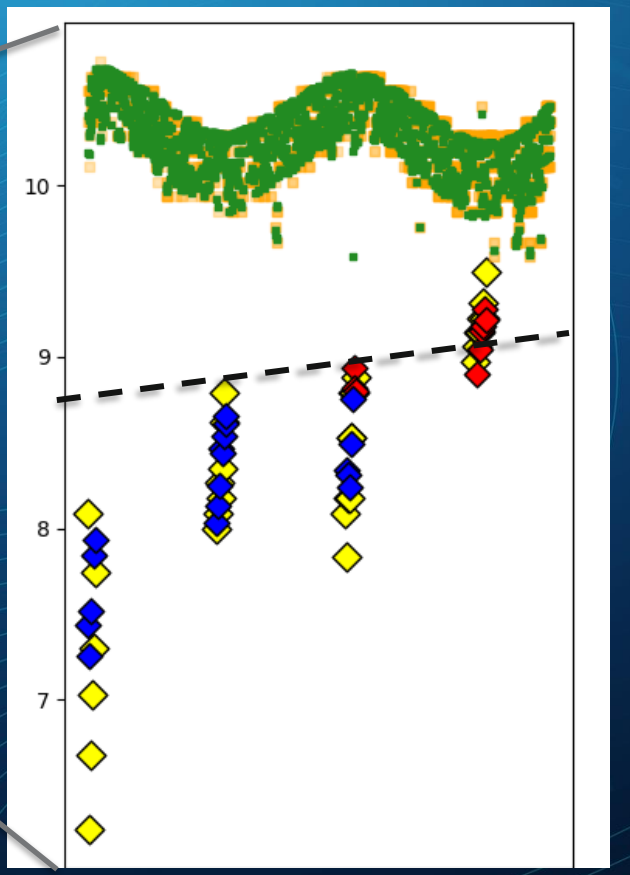
Physics model

Optimization Algorithm

2nd: Use predicted TM to predict degradation of sensor A:

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- Pred current
- TM current
- TM triggering
- Pred triggering Model 2024
- Pred triggering Model 2025

Impact: 1) Enables predictive analytics; 2) Extends mission lifecycle; 3) Operations optimization 4) Reduces effort for analysis and reporting

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AiSTRA-NOVA: Anomaly Investigation Through Knowledge Graph Reasoning

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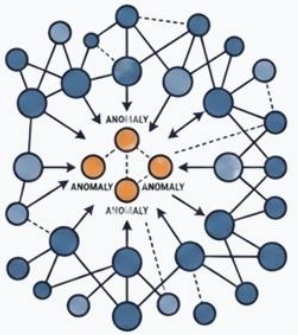
AiSTRA: Core Idea

Data Fusion

- Telemetry data
- Anomaly reports
- Context data
- Domain knowledge

KG Construction

Constrained KG centered on anomalies.



Application

Leverage the KG in downstream tasks.



Core KG Inputs

Telemetry
Computational descriptors - summarized with computational descriptors

Anomaly Reports
Filled by spacecraft operators

Context Data
Commands, space weather, flight dynamics, etc.

Domain Knowledge
From existing spaceops knowledge graphs (in the future)

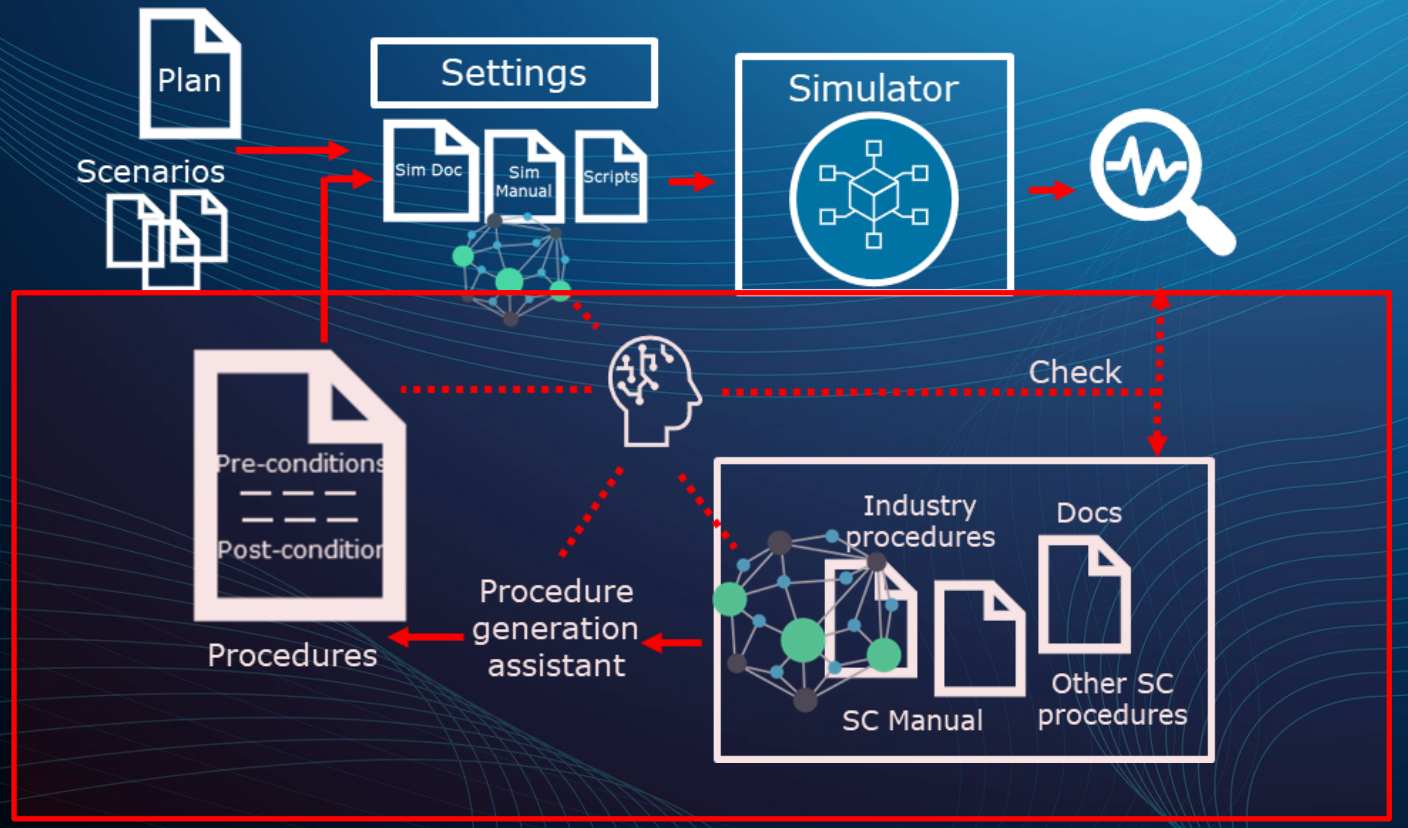
Properties

Format
RDF format

Lightweight
110 anomalies
1,000 - 5,000 triples

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AI-enhanced mission preparation: current status



AI enhanced Mission Preparation

Needs: Writing operational procedures faster and retrieve related information

Impact: hundreds of hours spent on writing and validating procedures

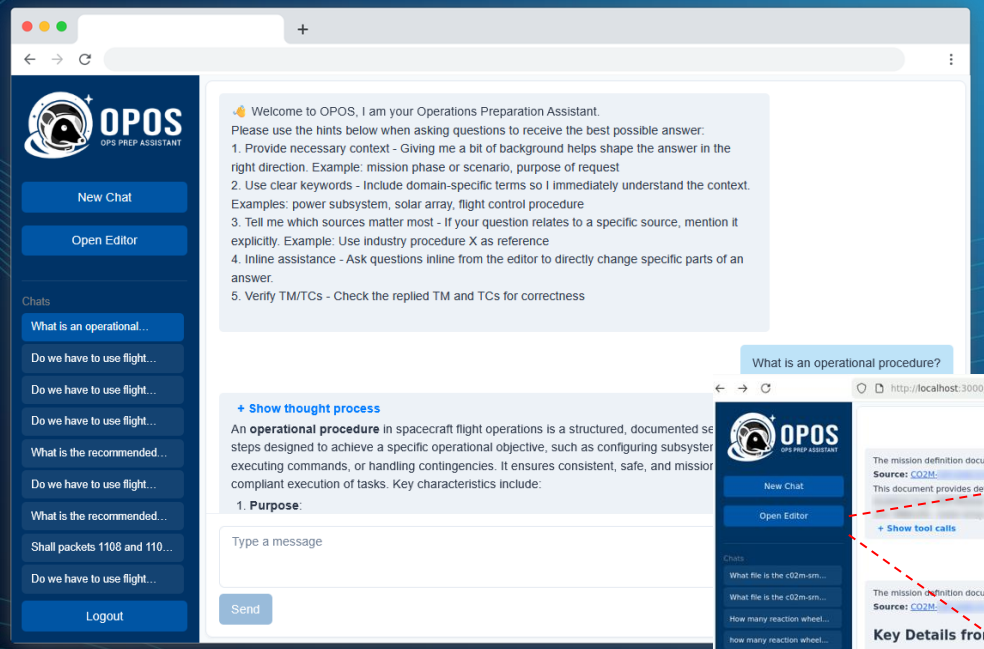
Enable: more accurate validation and personnel training

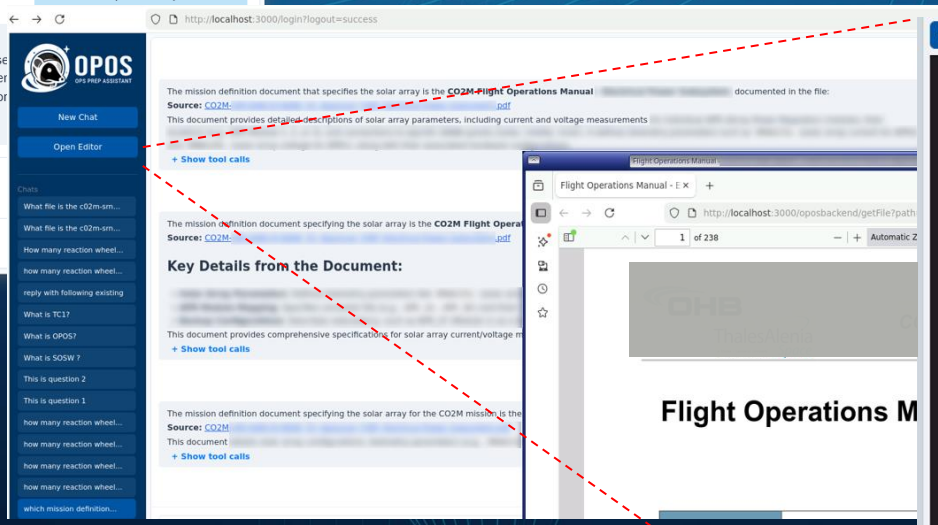
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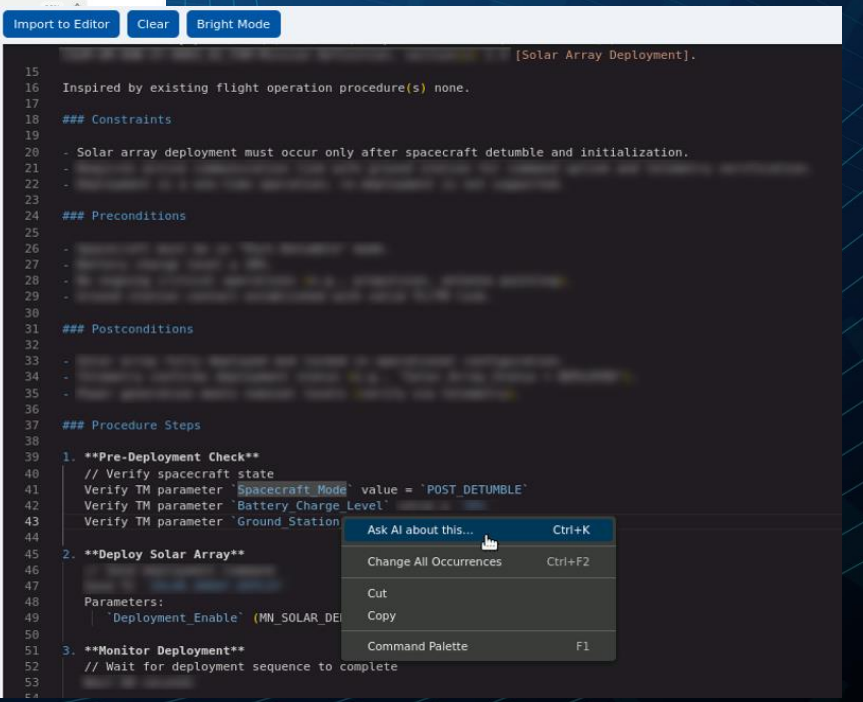
OPOS in a nutshell

AI for Automation of Operations Preparation and Operational Simulation (OPOS)

- 10-month project with 10 FTEs
- Fast prototyping and MVP in 3 months
- Tailoring and deploying with user feedback
- Deployed for 4 missions







Tailored to support mission preparation

Curated Knowledge-based

Info retrieval based on Vector search + Knowledge graph

Agentic architecture with (deterministic) tools

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Conclusions

- **Proven Operational Impact**: Current MVPs in procedure preparation, simulation, and predictive analytics are already driving tangible time savings and optimizing operations.
- **New Capabilities Unlocked**: Tools like digital twins and remaining useful life (RUL) estimation are enabling insights that were previously impossible.
- **The Unified Vision**: Our long-term roadmap will merge these isolated activities into a single, cohesive, and scalable solution.

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Thank you for your attention

Questions?

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