Enhancing Spacecraft Operations with Digital Twins Solutions

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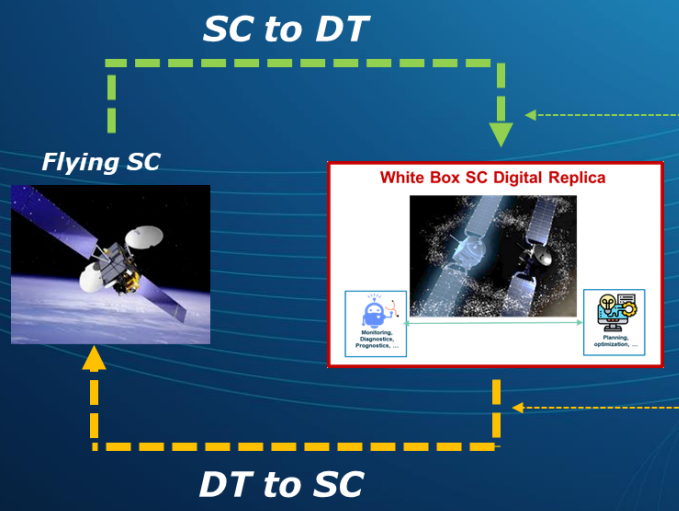
What is a Digital Twin (DT)?

How a DT supports Operations?

Vision: Digital Twin Spacecraft (DTSC) in Operations

Data, Models, Tools, Infrastructure → Digital Twin 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
- 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 assistant

Is this what users need?

How do we effectively develop the solution?

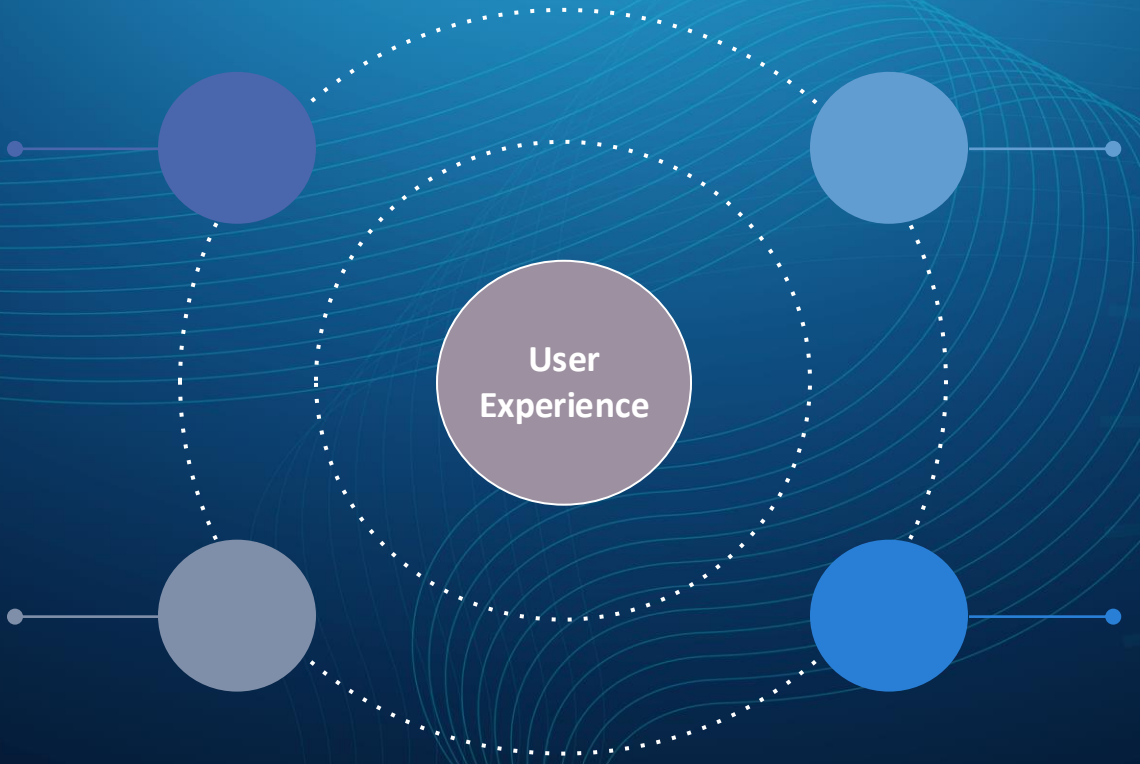
User Centric Development

User Requirements

Develop a list of user requirements to guide design work.

User Pain Points

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



UI Prototype

Develop a mock up of a UI for Spacecraft Digital Twin.

Insights

Provide insights from user research and potential solutions to explore

What is the futuristic vision to enhance the operational capabilities?

	Use Cases
	High fidelity simulation / validate procedures
Monitors health state	Visual representation of spacecraft current conditions
Enhanced simulation	OOL / event detection
	Prediction of telemetry trends
Failure prediction	OOL / event mapping to FOP / root cause analysis -> validation on simulator.
Improved planning	Status of components systems, consumables
Improved data handling	Remaining life estimation
	Data retrieval (chat-bot)
Extend mission/RUL	Command acknowledgement
	...

FCT

Vision and Capabilities to be Developed

- Smart Simulation Suite (engine)
  - SC-simulators aligner
  - Surrogate models
  - Enhanced fidelity operational simulator
  - Data assimilation tool
  - AI and probabilistic models
  - What –if analysis
  - …
  - Assisted scenarios setting
  - Assisted verification and reporting
  - Status-aware procedure validation
  - …
  - XR visualizer
  - …
- DT Architecture, interface and DSc Data Management
  - Digital continuity and interoperability
  - MBSE, semantics, data management
  - Connect to Mission Infrastructure
  - Collaboration and governance
  - UI and smart assistance
  - …
- Smart Suite of Applications for Analytics and Decision Making
  - Anomaly detection
  - Status (degrad/health) assessment
  - Root-cause analyses
  - Resource forecasting
  - Prognostic, trends, predictions
  - Remaining Life Assessment
  - …
  - Planning
  - Optimization and Decision Making
  - …

Technologies Development Timeline

Assisted Setting — Operations, Preparation (FCT, Sim Officer)
Assisted identification and setting of sim param. to simulate a condition

Automated Alignment — Operations (FCT)
Process TM/TC to assess the SC status and automatically set simulator parameter

Situational Awareness — Operations (FCT)
Map the updated Sim param. to reflect physical properties, degradation and consumables

Enhanced Visualization — Operations, Preparation (FCT, Sim Officer)
3D, XR and user experience-centered tools

Health Monitoring — Operations (FCT)
Enhanced anomaly detection and troubleshooting

Predictions — Operations (FCT)
Embed high-fidelity sim and intelligent models to predict SC long term behaviour

Planning — Operations (FCT)
Use the info on SC status to inform planning

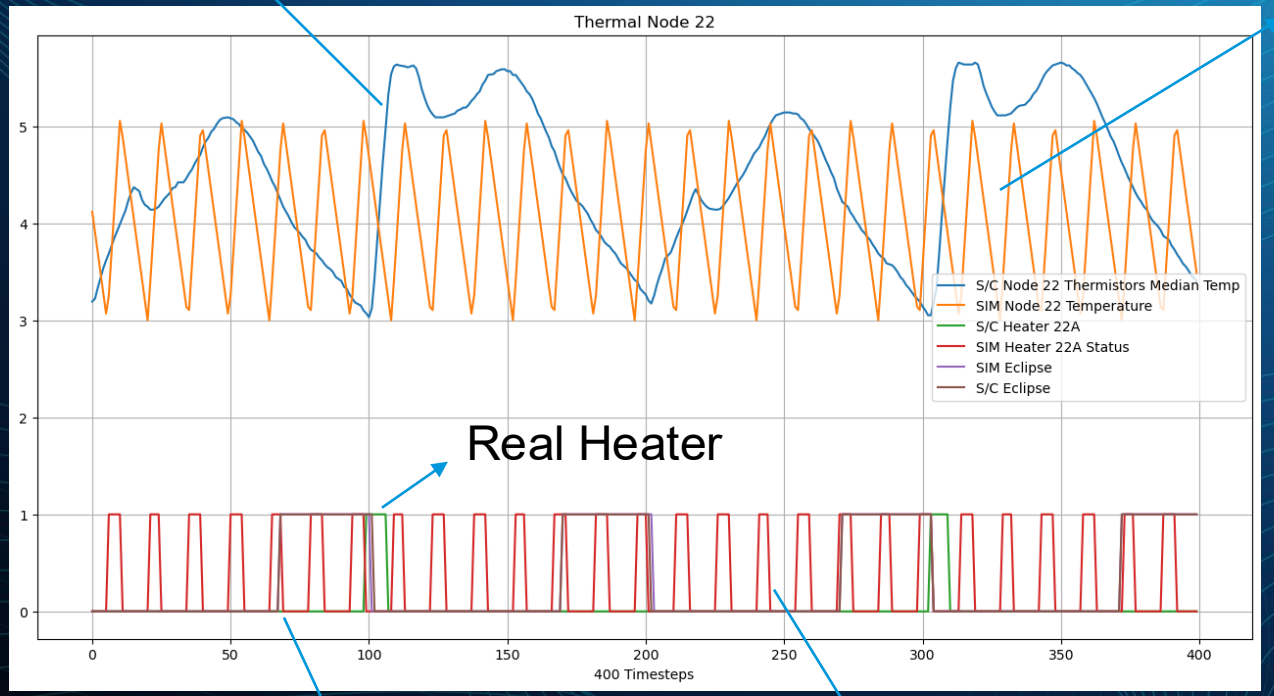
Some Examples and Success Stories

More representative simulations

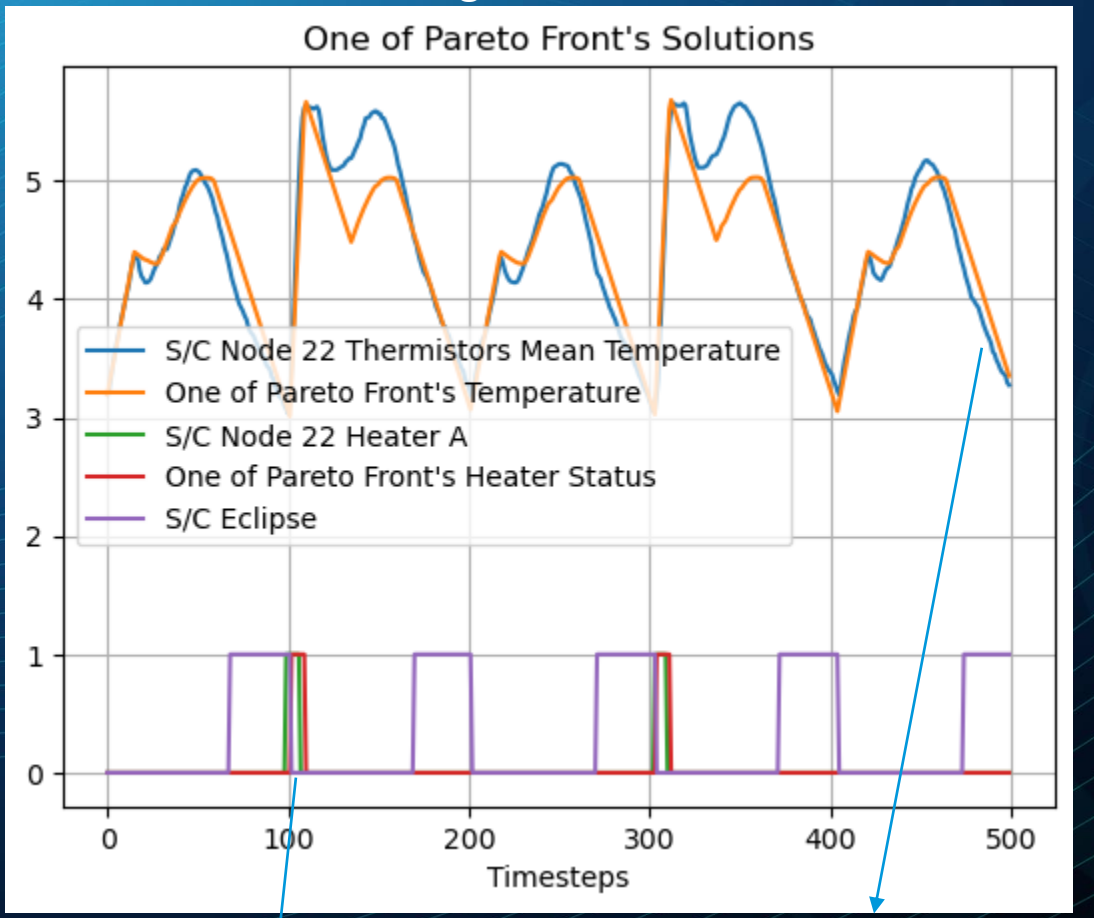
Real Temperature

Simulator's Temperature

Before Changes and Calibration



After Changes and Calibration

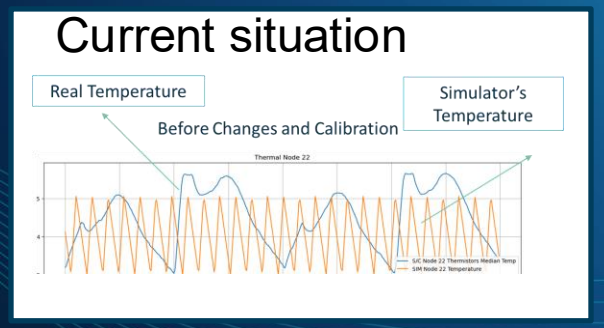


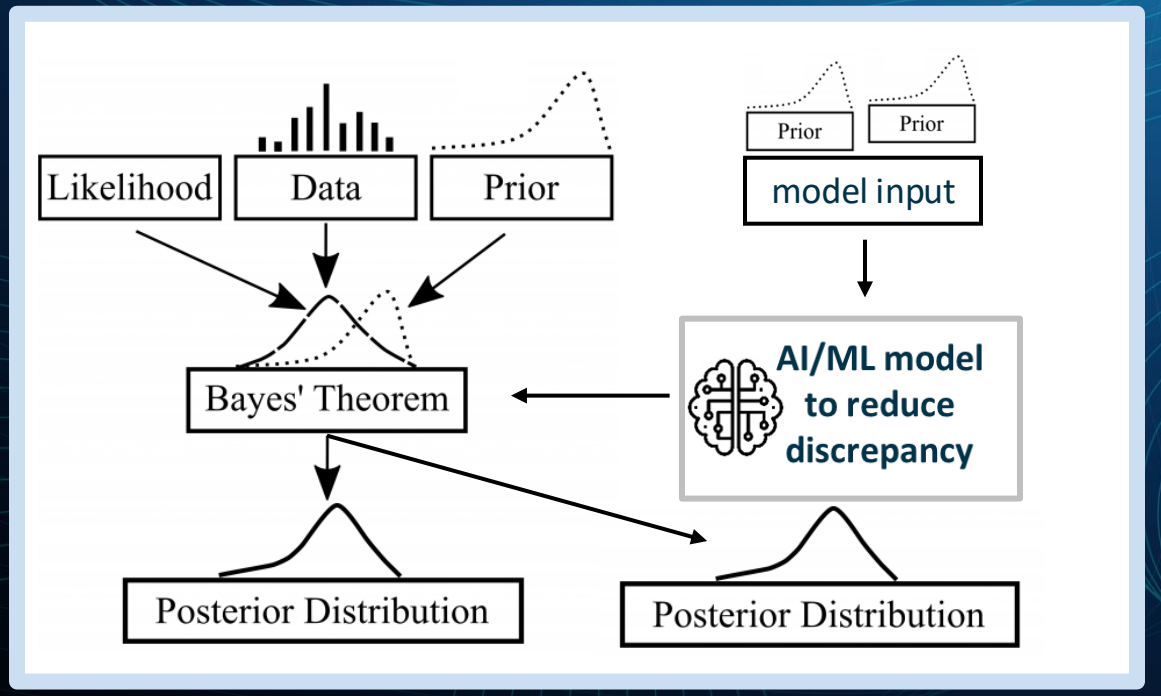
Eclipse (Synchronized times)

Simulator Heater

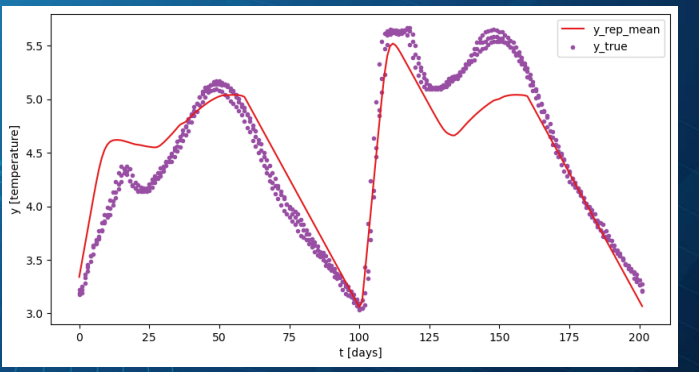
Heater Similar Behaviour

Stochastic Calibration and model discrepancy reduction for more representativeness simulations

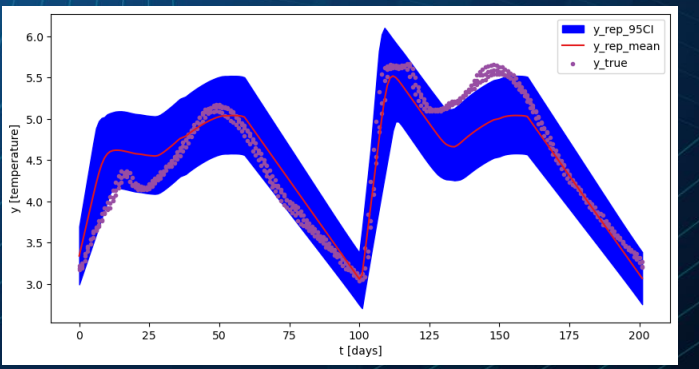




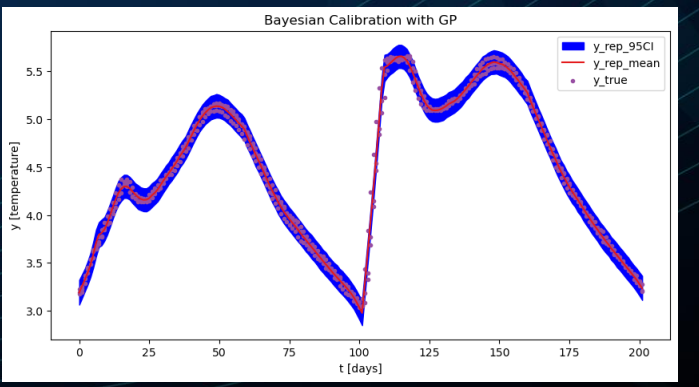
Evolutionary Optimization



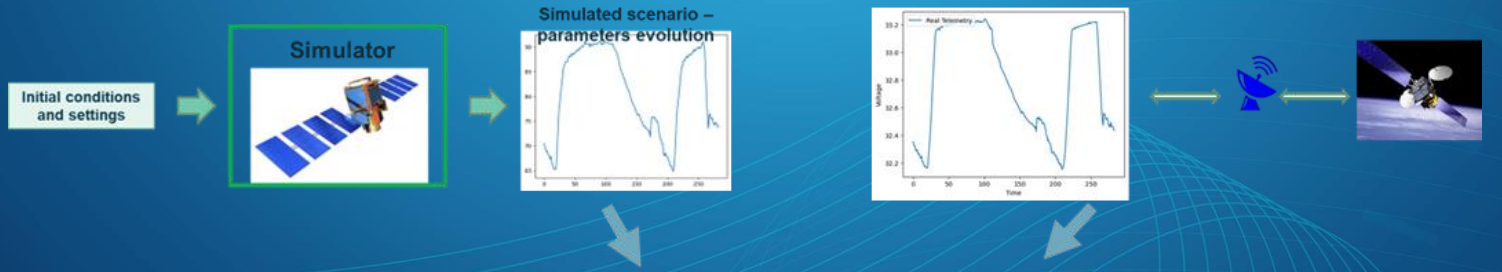
Stochastic Optimization



Stochastic Optimization and discrepancy reduction

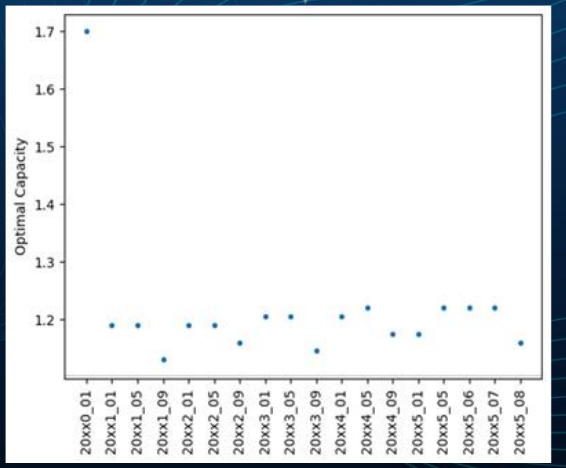


Digital state update to enhance situational awareness



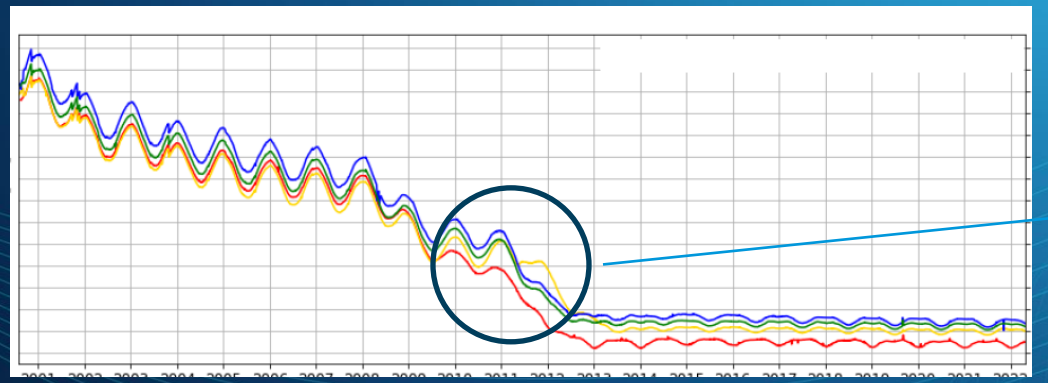
Surrogate model-based calibration

Digital State Update

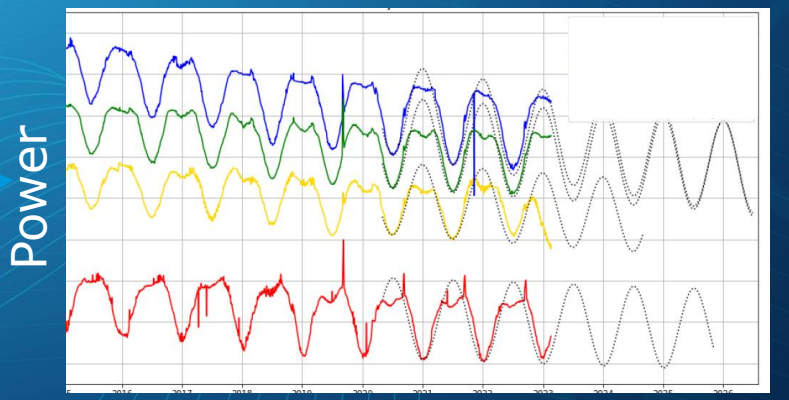


Solar Arrays Power Production under degradation

Monitoring data



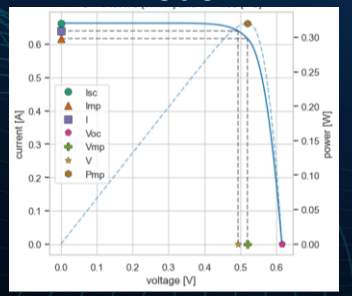
Equivalent predictive model



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

SOLUTION

Physics-based model



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Optimization algorithm

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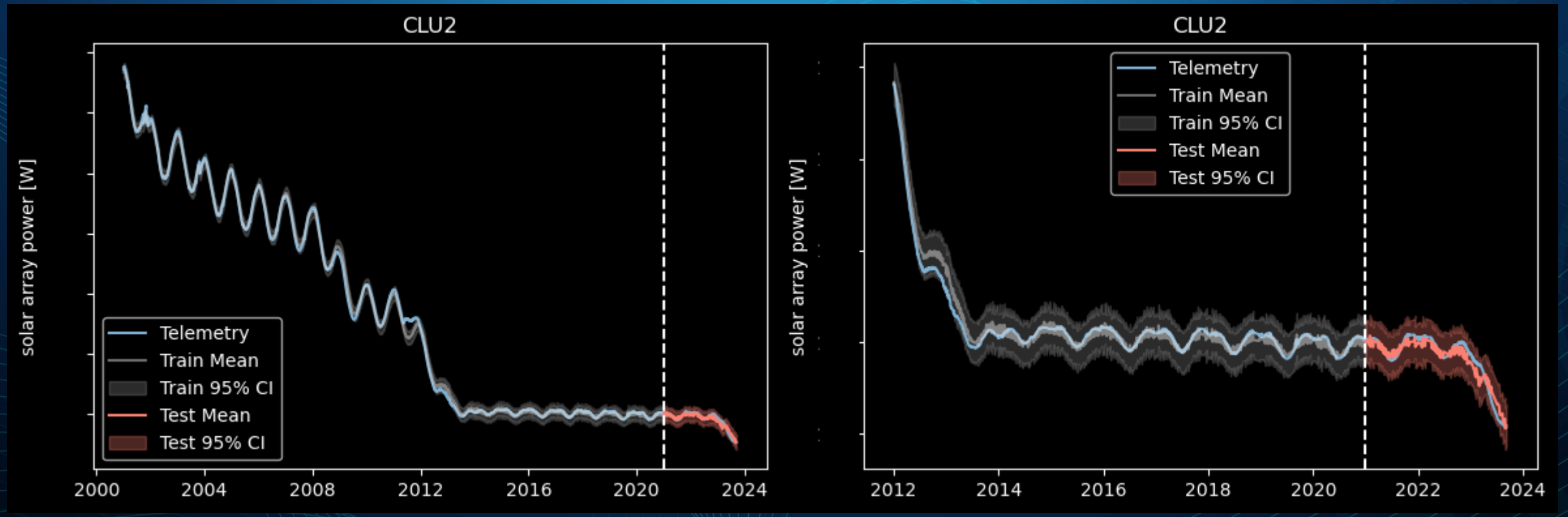
AI/ML model to reduce discrepancy

Solar Arrays Power Production under degradation



- The model fits well the data before 2021.
- **The model predicts the further drop that occurs in 2023**.

Predicting Remaining Life of Components

Critical components

Data

Processing

Model

Health Indicator

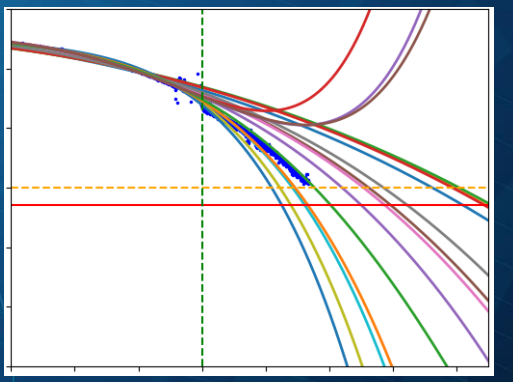
LIMIT

Estimation

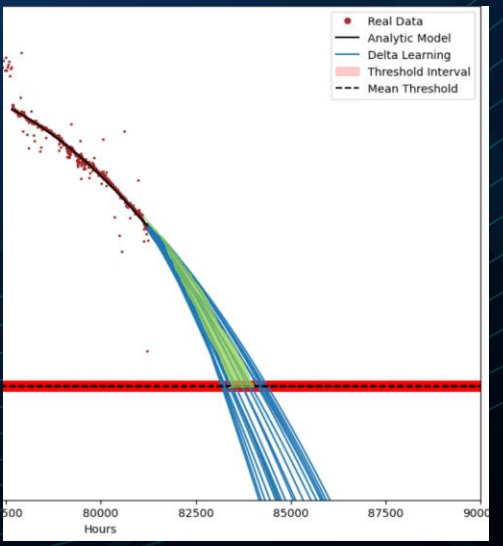
Prediction

LIMIT

Previous approach



DT-Based GAM ensemble



Conclusions

- Spacecraft Digital Twin in Operations: not an easy concept to digest
- The importance of User Experience
- The role of Success Stories to engage key stakeholders
- Results prove the potential of the technology
- DT can support key use cases on prognostics and health management

Thank you for your attention

Questions?

Talks at GSAW 2025

- Artificial Intelligence for mission operations automation roadmap
- Continual Learning for on-ground satellite health monitoring
- Enhancing Spacecraft Operations with Digital Twins Solutions
- Data-X: Pioneering the Future of Data in Mission Operations

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