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Satellite Digital Twins

Dr. Zhenping Li

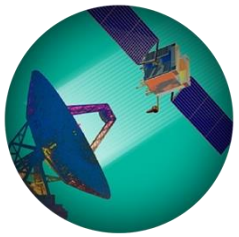
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Agenda



1. Satellite Digital Twins (SDT)
2. Digital Twin Architecture
3. Satellite Operations as a Finite State Machine
4. Data Model Recalibration in SDT
5. Summary

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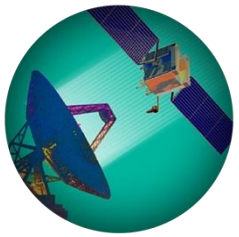
Satellite Digital Twins (SDT)

- **A virtual representation of its physical satellite**
  - Form a feedback loop with its physical states to monitor its health, safety, and decision support
  - A satellite digital twin connects and synchronizes with its physical satellite via a ground system
- **SDT functionalities and operations:**
  - Model-based data monitoring and engineering analysis
  - Model-based high fidelity Satellite simulations
  - Conditional-based maintenance
- **Data fusion in STDs**
  - SDTs receive telemetry data in real-time or near real-time
  - SDTs receive mission planning data
  - SDTs receive the same satellite commands as their physical satellites
  - SDTs send the simulated telemetry back to ground systems
- **SDT operations**
  - Periodical recalibrations for data models to adapt to the latest data trends in the physical satellites



- **Digital Twins is an engineering approach for dynamic systems**
  - It is a platform for ML/AI or data analytics to model dynamic states and enables predictions of future behaviors to optimize operations
- **Digital Twins have been applied in many areas**
  - Healthcare, Aerospace, Agriculture, Urban planning, Industry 4.0, and Earth Science

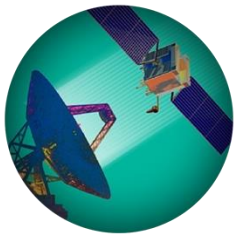
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SDT Development Challenges

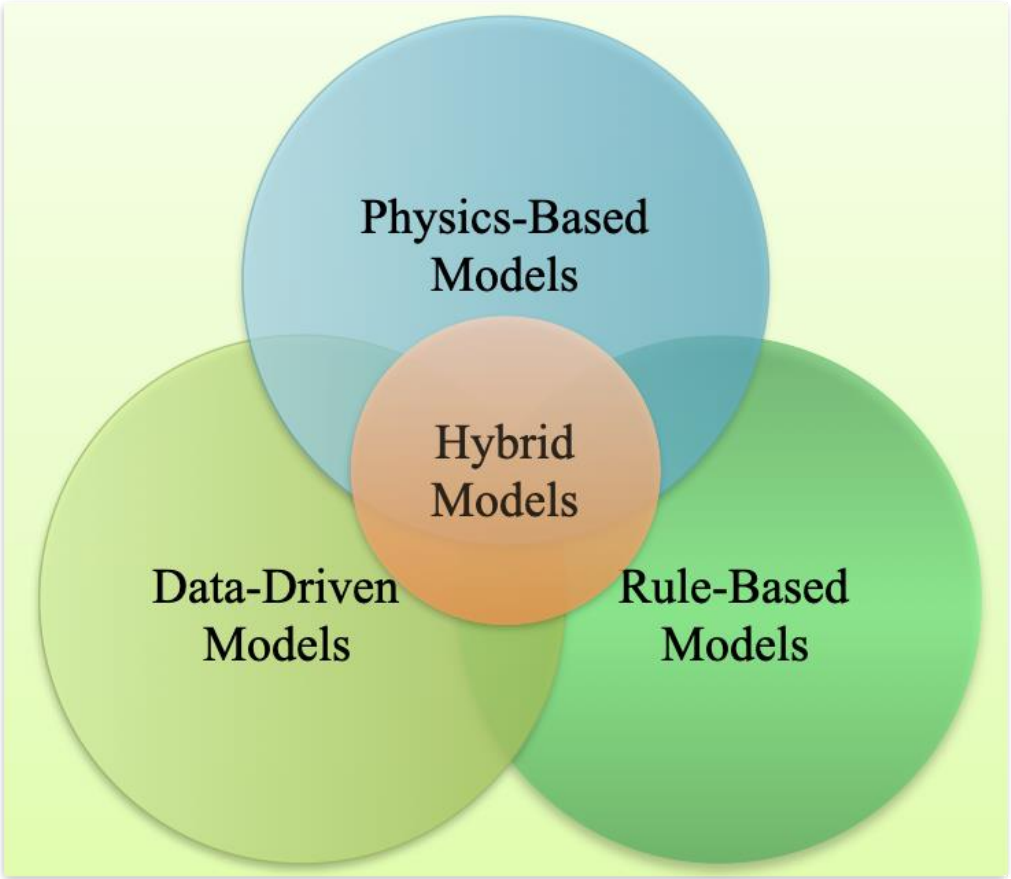
- **Software Development:**
  - Need to develop a reusable, scalable, and extensible software architecture
  - Enable rapid deployments into new missions
- **Data Model Development and Recalibrations:**
  - Data model recalibrations are performed in operation environments for highly diverse satellite data, and the training set generally contains outliers:
    - Data model recalibration involves data training and outlier detection.
    - Model recalibrations require efficiency, accuracy, and robustness
  - Satellite operations are not static and involve operation events, such as maneuvers,
    - Operational events are dynamic and could happen at any time
    - The data patterns during operation events are generally different from standard patterns
    - Data models are dependent on satellite events.
- **Leveraging the expanded data scope**
  - Integrate the data models for telemetry data with the command and orbital event data in model-based monitoring and simulations.

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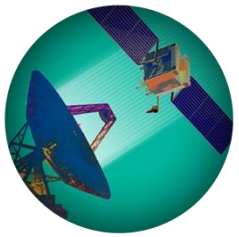


Data Models for Satellite Datasets

- **Rule-based models represent discrete datasets.**
  - Represent the system OPS status, such as on/off
  - Integers can be translated into OPS status strings
  - Changes are triggered by satellite commands or external events
- **Physics-based models are derived from physics or astronomy**
  - Satellite ephemeris data, such as orbit positions, velocity, and attitudes.
- **Data-driven models are for time-dependent and noisy datasets and follow certain data patterns**
  - Obtained from statistical collections, data analytics, or machine learning algorithms depending on the complexities of data patterns
- **Hybrid models combine physics-based, data-driven, or rule-based models**
  - Example: relationship models: the relationship is determined by underlying physics, but parameters in the relationship are obtained from data training

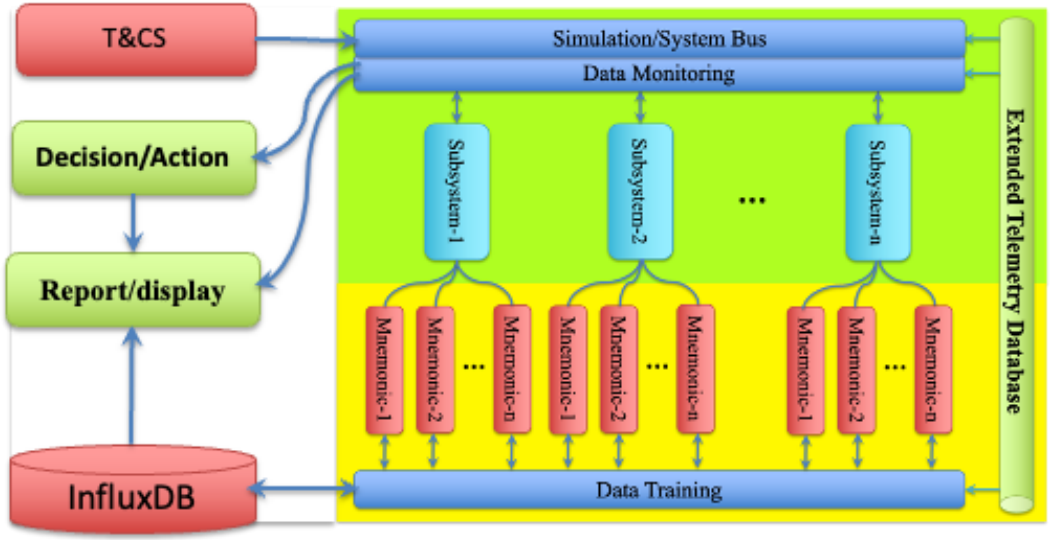


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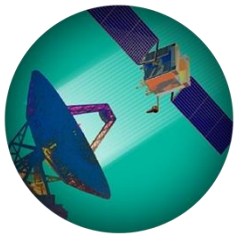
Hierarchical Component Reference Architecture

- **A collection of subsystem digital twins as components can be added or removed for a specific mission**
  - Reusable components at the subsystem level for well-defined functionalities.
  - Reusable data models at the mnemonic level for time-series data.
  - Scalable and extensible
- **The extended telemetry database (ETD) defines model recalibrations and de-commutation**
  - The ETD defines telemetry data commutation/de-commutation.
  - The ETD defines each telemetry dataset's data model and training attribute.
  - Hierarchical structure maps the physical structure.
  - Parallel computing is implemented for model recalibration to boost computing efficiency.
- **Two functional layers**
  - Data model calibration layers
  - Virtual operational layer for model-based simulation and monitoring



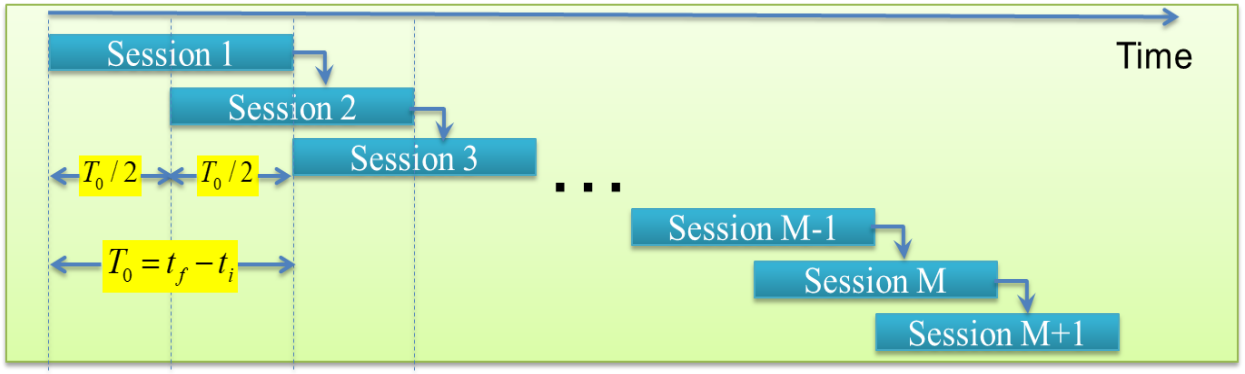
- **Database for Time Series Data: InfluxDB**
  - Consolidated Archive for telemetry, mission planning, and data models.
  - A critical part of SDT infrastructure in ground systems.
  - Standard I/O interface for SDT implementation

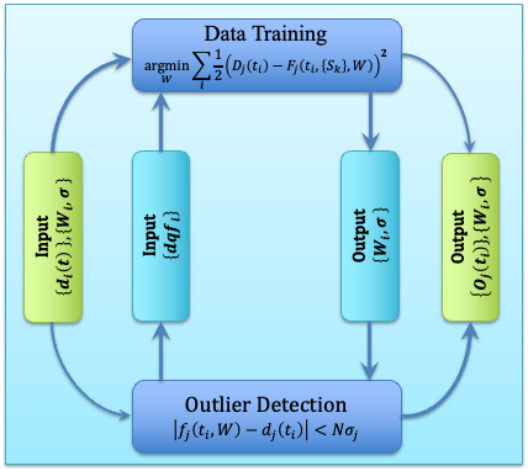
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The Iterative Training for Model Recalibration

- **Iterative training trains data models and detects outliers in the same process**
- **Model recalibrations are performed in sessions**
  - The model parameters generated in the previous session are inputs for current sessions
    - Changes in model parameters are small increments
  - Data retraining of models of previous sessions is much more efficient
    - Critical for the data training of neural networks in OPS environments
- **Overlapping training period: ensure training output stability**
  - Data Training periods T_0 needs to cover multiple orbits

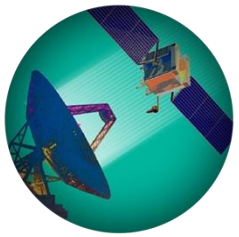




Iterative Training:

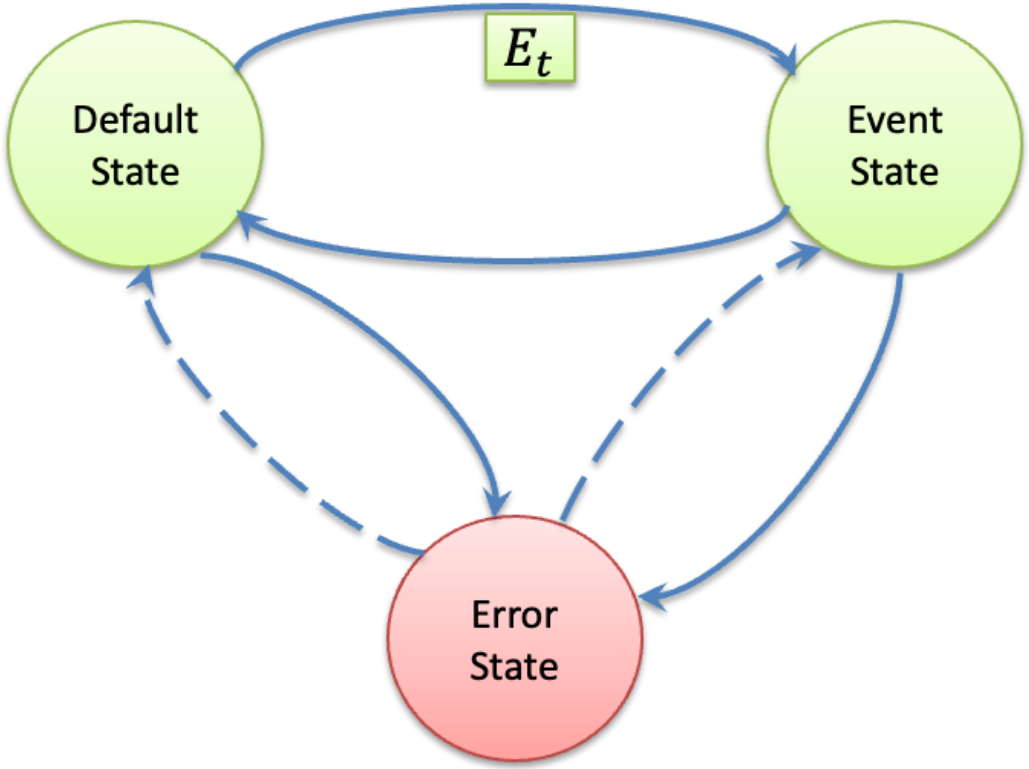
- **Associate each data point with a data quality flag dqf_i initialized to 1.**
- **Data training generates time-dependent trend $\{f_j(t, W), \sigma_j\}$**
- **Outlier detection detects outliers and updates data quality flags for each data point.**
- **Perform data training again with updated data quality flags.**

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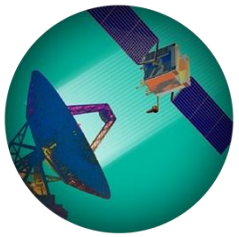
Satellite Operations as the Finite State Machine.

- **Satellite operations are dynamic and characterized by various operational events, including orbital maneuvers and momentum dumps**
  - A normal operation is defined as the default state (or ground state)
  - An operational event is the event state (or excited state)
    - Data within operation events follow different patterns from the default state
    - Data patterns in event states can be modeled and monitored
  - The primary event states in operations are maneuvers (mnvr), eclipse (ecl), and momentum dumps
  - Event States are dynamic
- **Finite State Machine provides a framework for training, monitoring, and simulations.**
  - Leveraging the data fusion of telemetry, mission planning, and log messages



The state transition diagram in the TFSM E_t is an event trigger.

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The SDT State Equation for Satellite Operations

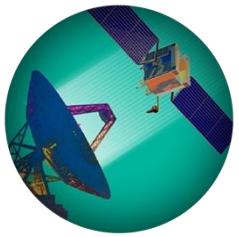
- **The state equation**
  - integrates satellite telemetry, command, orbital events data
  - provides a formalism for model-based simulation and more proactive anomaly detection
    - The state profile $\{\boldsymbol{L^e}, \boldsymbol{q_l^e}, \boldsymbol{f_k^e(\delta t)}\}$without the event trigger C corresponds to the default state
    - An event state $\{\boldsymbol{L^e}, \boldsymbol{q_l^e}, \boldsymbol{f_k^e(\delta t)}\}$ is associated to a specific trigger C, or a satellite command
    - A state with an unknown trigger C is a potential anomaly
  - can be learned by integrating telemetry, command, and orbit event data in the data training process

The State Equation

$$\boldsymbol{\lambda: C \rightarrow \{L^e, q_l^e, f_k^e(\delta t)\}}$$

- The transition λ from the default state to an event state $\{L^e, q_l^e, f_k^e(\delta t)\}$ is triggered by C
- The trigger C are satellite commands and orbital events from the mission planning data
- L^e is the event label coming from event messages
- q_l^e is the discrete datasets, such as on or off status
- $f_k^e(\delta t)$ is the continuous datasets, including
  - physical based data, such as orbital data that can be predicted by models derived from physics and astronomy
  - Data driven data modeled by ML algorithms, such as the temperature profiles

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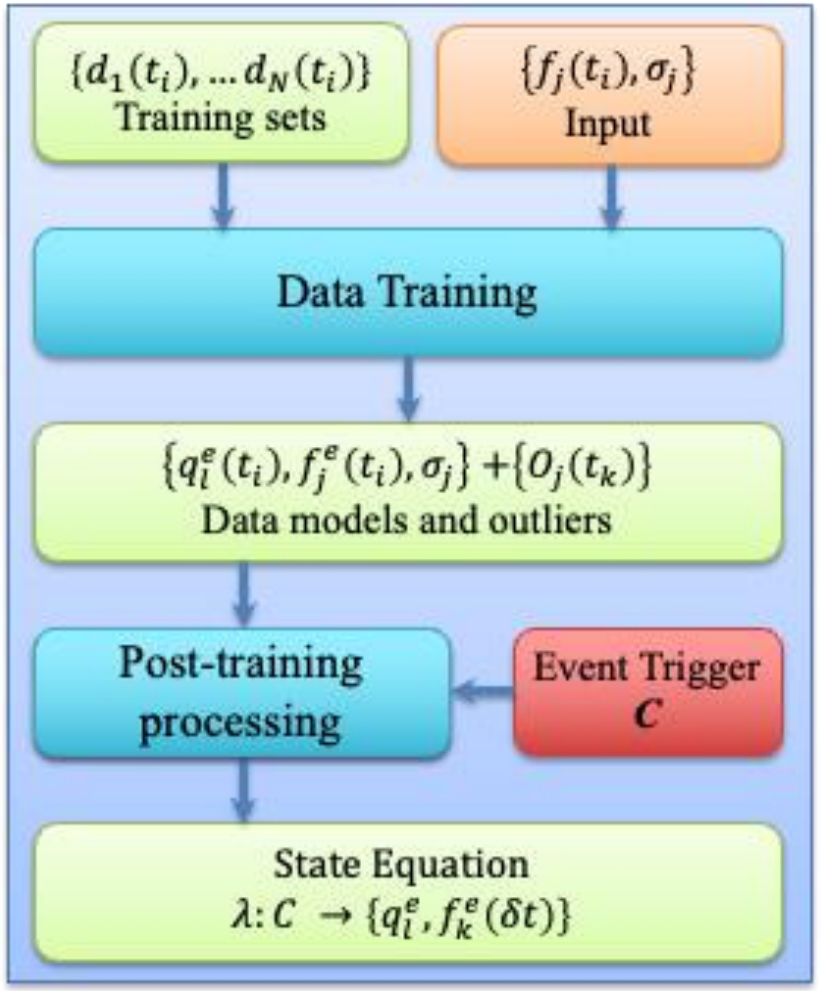
Data Model (Re)Calibration

- **The objectives of the data training in an SDT are to recalibrate the data models in different states and to learn the state equation for satellite operations**
  - Establish the default state as the baseline
  - Associate an event state with a specific trigger C, or satellite command
- **The data model for discrete datasets:**

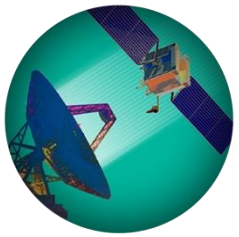
$$q_j^d(t - t_0) = q_j^d(t_0) + \sum_k \delta_j^k(t_k)$$

  - $q_j^d(t_0)$ is the initial value for a training period. δ_j^k is the change value at the time t_k
  - Correlating changes δ_j^k with event triggers generate the rule model
- **The data-driven models for continuous datasets are state dependent**

$$f_j^e(t) = f\left(\delta t^e, q_j^e\right)$$



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The Data Models for Satellite States

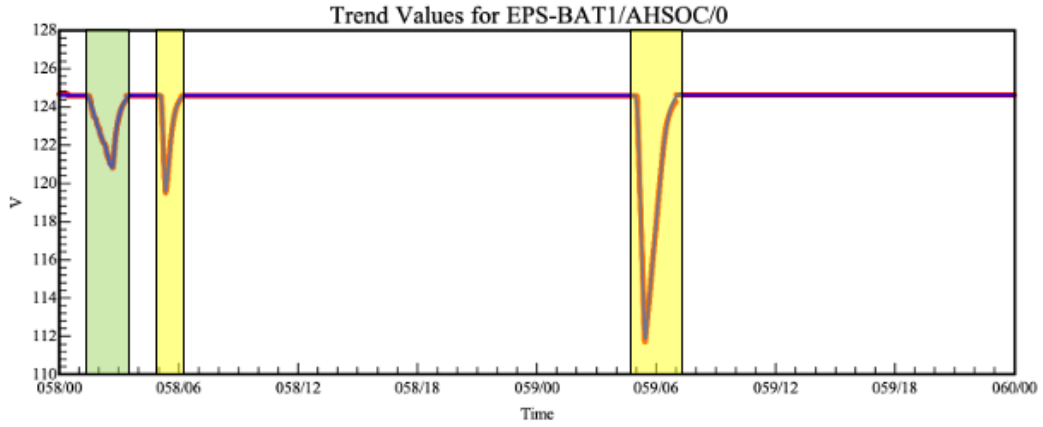
- **Data The time-dependent function for a telemetry dataset with satellite events can be expressed as:**

$$\boldsymbol{f\left(\delta t^{s}, q_{j}^{s}\right) = (1 - q_{k}^{e}) f_{k}^{d}(\delta t_{0}) + q_{k}^{e} f_{k}^{e}(\delta t_{e})}$$

  - $f_k^d(\delta t_0)$ is the data patterns for default states.
  - $f_k^e(\delta t_e)$ is the data patterns for event states.
  - $\delta t_0 = t - t_0$ and $\delta t_e = t - t_i^e$.
  - q_j^s is a state flag. For an event state with event period $\{t_i^e, t_f^e\}$:

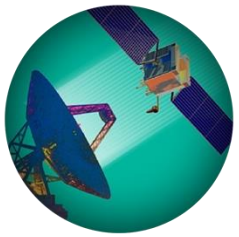
$$q_j^e(t) = \begin{cases} 1, & t_i^e \le t < t_f^e \\ 0, & t < t_i^e \; or \; t \ge t_f^e \end{cases}$$

- **Event states are dynamic and can happen at any time**



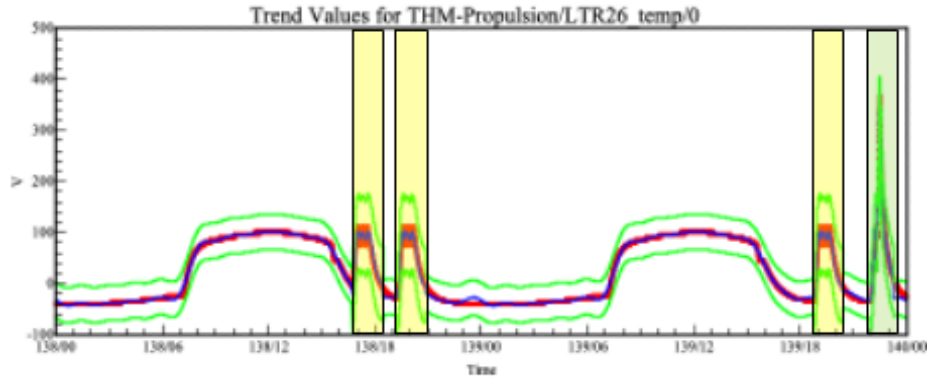
The battery's charge state is at the start of eclipse season. The yellow shade represents the eclipse state, and the green shade covers the maneuver state. The periods with no shade correspond to the default state. The different data models represent the default, eclipse, and maneuver states with different stddevs

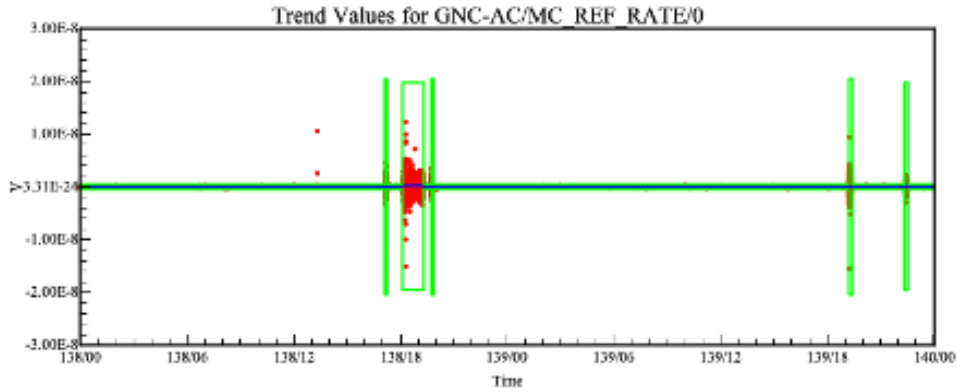
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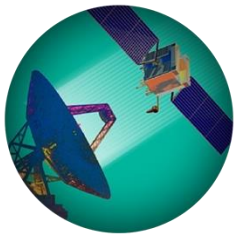
The Data Models for Satellite States

- **The temperature for a thruster (top plot)**
  - The maneuver flag (green-shaded) for satellite maneuver state:
  - The momentum dump flag for the RWA momentum adjustments (yellow-shaded) state
  - The period not covered by either green or yellow shade is the default state
- **A typical GNC subsystem (bottom) mnemonic has the maneuver and momentum dump states**
- **The data training outputs for different states have different standard deviations, leading to different data-bound**





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Summary

- **Hierarchical component architecture manages virtual operations and data training and monitoring**
  - Provides scalability, extensibility, and re-usability
  - It also addresses the efficiency, accuracy, and robustness requirements for data training in operational environments
- **TFSM offers the state equation for satellite operations to leverage the data fusion of telemetry data and Mission Planning data**
  - The state equation provides the formalism for both dynamic monitoring and simulations
    - It is more proactive and complete than the approach
- **The data training in SDTs integrates event triggers with telemetry data**
  - Establish the rule model for discrete datasets with event triggers
  - State-based data training to learn data models for satellite states
- **Algorithm developments and software implementations offer ample research, growth, and learning opportunities**
  - The Research and Development are ongoing and making progress

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Quyanaq!

Thank you!

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