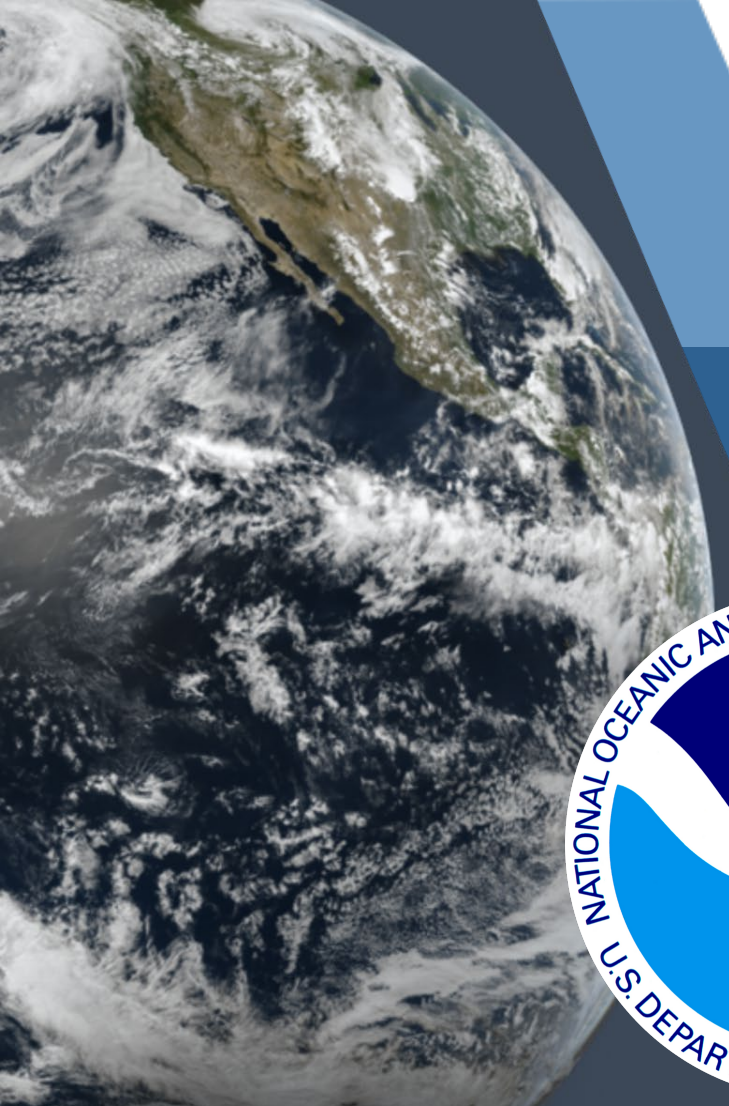

Ground Systems Architecture Workshop 2025

Implementation and Feasibility of Using AI/ML Methods for Satellite Anomaly Detection, Diagnostics, and Resolution.

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5
Months

The Challenge

One of the significant challenges in weather satellites is maintaining their health and keeping them continuously operational on orbit.

Satellites often experience on-orbit anomalies hence requiring real time detection, diagnosis, and resolution.

These processes are manpower-intensive, costly, and are addressed on an ad-hoc basis subject to the level of expertise and available resources at the time of the anomaly.

The Goal

Investigate the use of artificial intelligence and machine learning, AI/ML, technologies to handle satellite anomalies through three distinct phases, detection, diagnosis and resolution.

The premise is that AI/ML, if properly applied, have the potential to both improve responsiveness and accuracy of anomaly handling while reducing manpower requirements.

Anomaly Detection

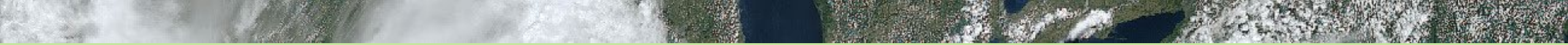
- Satellite telemetry is continuously monitored to identify anomalies.
- Real-time assessment of telemetry probes into related measurands.
- These are trending in a way that would reveal an underlying problem.
- Deeply understand healthy operation and nominal telemetry values.
- Deeply understand how different measurands are related.

Anomaly Diagnosis

- Real-time telemetry is analyzed along reference measures and compare values.
- Identify the likely state of the satellite systems that are creating the anomalous telemetry.
- Possible reasons include rising temperature, sensor malfunction, or battery overcharge.
- Reaching the correct diagnosis requires understanding how the telemetry reflects the nominal satellite state.

Anomaly Resolution

- Once Diagnosis is confirmed, remedial action is formulated for execution.
- Satellite commands or other actions are taken to resolve the anomaly.
- Examples include sending a command to stop charging the overheating battery, sensor recalibration, solar panels reorientation, or others.
- Confirmation of Resolution and Normal Operation



LEO Anomaly Example

(S-NPP CDP Reset)

S-NPP CDP Reset Example Overview

- Since 2012, The Suomi National Polar-orbiting Partnership (S-NPP) has had 6 occurrences of a Command Data Processor (CDP) reset.
  - *The CDP handles both Realtime & Onboard Commanding, as well as On-Board Data Processing to the Recorder*
- CDP Resets often do not manifest in the same manner, and its possible each occurrence could cause differing spacecraft impact(s)
  - *Once S-NPP is in a degraded state, it is further possible for additional unexpected anomalies to occur*
- Recovery from a CDP Reset is very operator-intensive and can span a duration from 1 day to more than a Month

S-NPP CDP Reset Challenge

- S-NPP only has a single mnemonic identified that will flag if a CDP Reset occurs.
  - *Sometimes, this "count" does not increment due to unique circumstances.*

SMCDPRS = 0	*SWCRS flag = Reset*

- Engineers then need to review TLM from other subsystems to reconcile if a CDP Reset is the potential root cause
- Depending on the state of each Subsystem, recovery steps for a CDP Reset can vary widely
  - *Quick Recovery (<1 Day) requires resetting the CDP within ~6 Orbits of the Anomaly, prior to Instrument Safing/Instrument Thermal Degradation*

S-NPP CDP Reset Goal

- Given S-NPP's various CDP Reset scenarios, it would be advantageous if a tool could correlate downlinked TLM against each possible scenario; For example:

	"Textbook Reset"	*"Anomalous Scenario 1"*	*"Anomalous Scenario 2"*
	SMCDPRS = 1 ***SWCRS flag = Reset***	***SMCDPRS = 0*** ***SWCRS flag = Reset***	***SMCDPRS = 1*** ***SWCRS flag = null***
Subsystem Status	TLM Enabled SMD Disabled Recorder Disabled Instruments Earth Point ACS/PWR/PROP Nominal	TLM **Disabled** SMD **Off-Nominal** Recorder Disabled Instruments **Safe Mode** ACS/PWR/PROP **Off-Nominal**	TLM **Enabled** SMD **Off-Nominal** Recorder Disabled Instruments Earth Point ACS/PWR/PROP Nominal

- Goal is not to replace Engineers in every scenario, however to assist in a more rapid recovery

S-NPP CDP Reset Anomaly Diagnostic States

- At first contact post S-NPP CDP Reset, The following could be the only information available:
  - Only Realtime TLM is available, No Backorbit Storage State of Health

Subsystem Status	*"Textbook Reset"* ***SMCDPRS = 1*** ***SWCRS flag = Reset***	*"Anomalous Scenario 1"* ***SMCDPRS = 0*** ***SWCRS flag = Reset***	*"Anomalous Scenario 2"* ***SMCDPRS = 1*** ***SWCRS flag = null***
	TLM Enabled SMD Disabled Recorder Disabled Instruments Earth Point ACS/PWR/PROP Nominal	TLM **Disabled** SMD **Unknown** Recorder **Unknown** Instruments **Unknown** ACS/PWR/PROP **Unknown**	TLM **Enabled** SMD **Off-Nominal** Recorder **Unknown** Instruments **Unknown** ACS/PWR/PROP Nominal

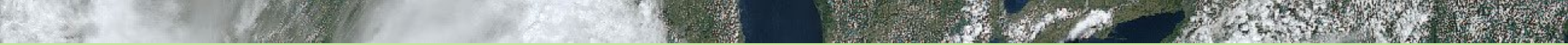
Limited Information Available

S-NPP CDP Reset Anomaly Resolution

- Based on prior anomaly handling experiences, it has taken from 2 Orbits to 2 Days to isolate the specific CDP Reset Recovery steps per reset scenario.
- Recovery from known CDP Reset Scenarios occurs more rapidly than in more novel occurrences.
  - *New Scenarios require significant Analysis to ensure no additional harm occurs to the Spacecraft prior to performing Recovery Commanding*.

S-NPP CDP Reset Anomaly Resolution, Cont'd

- However…..
  - *More automated Analysis of TLM to correlate TLM to known CDP Reset "Signatures" would be advantageous to Engineers*
    - *Having an AI/ML Tool be able to automatically develop signatures and recovery steps would be the ideal scenario.*
  - *As a Stretch Goal, automated recovery of the Spacecraft to CDP Resets that match known "Signatures" would be ideal*



Automated Spacecraft Anomaly Identification & Response

Realtime Detection, Diagnosis, and Resolution (Legacy Process)

- Spacecraft Operations nominally requires Engineers to review downlinked Telemetry via Realtime and Trending Tools to isolate anomalous signatures
- Oftentimes significant discussion is required amongst a diverse team to identify all potential constraints, recovery commands, and alternatives
- While this approach is adequate to safely recover a spacecraft, it is manpower intensive, time consuming, and costly.
- Furthermore, humans can induce further issues, uncertainty, and errors.

Realtime Detection, Diagnosis, and Resolution (Legacy Process, Cont'd)

In Addition….

- Spacecraft today include automated Fault Recovery Subsystems which provide onboard detection, diagnosis and commanding if fault signatures occur.
  - *Automated Fault Recovery capabilities are typically developed to only recover or safe from critical and loss-of-mission scenarios*
  - *On-Board Fault Recovery is typically not developed to recover from less impactful scenarios, and or trivial issues/anomalies identified during Ops*
- This "GAP" to allow for recovery from novel operational scenarios requires further focus by both the Government and Industry.

Automated Anomaly Identification & Response (Goal)

- A combination of two capabilities could exist to support Automated Spacecraft Anomaly Identification & Response
  - **Option 1 (Ground Based Identification & Response)**
    - *Ground System based recovery of Spacecraft Anomalies in an automated manner*
    - *Inclusion of Operator Developed Anomaly Signatures into a Ground Based Tool*
  - **Option 2 (Onboard Identification & Response)**
    - *Identification and Recovery of Spacecraft Issues/Anomalies is performed onboard via a Fault Recovery like Subsystem*
    - *Inclusion of Operator developed Issue/Anomaly Signatures into FSW*
  - **Combination (Both Ground & Onboard Identification & Response)**

Automated Spacecraft Anomaly Identification & Response (AI/ML Challenge)

- While possible to develop discrete recoveries based off of every known scenario, there can be a plethora of potential unknown signatures that require consideration
  - *Every constraint, per component and or subsystem, for each scenario is likely not included in most Fault Response signatures*
- Some type of machine learning and or AI/ML capability will need to be developed to support this desired functionality
  - *Removing the Engineer-in-the-Loop will reduce mission cost, w/ increased risk*
- Automated recovery capabilities, per individual scenario, will need to be tailored based off of each mission classification & risk posture

The Economic and Cost-Saving Driver

So why AI/ML…

- **Manual Resolution Cost:**
  - Based on experience: Depending on the Anomaly:
    - Up to 10 FTE are needed
    - Between 1 - 30 days in Duration
    - Locks other Resources, e.g., Station Time, Ground System, etc…

- **AI/ML Resolution Cost:**
  - Initial Development is resource intensive; Long-term its saves cost
    - Algorithms
    - Training Data
    - Testing, Validation
    - Reduction in Ops FTE's

The Cost of Failure

However both are prone to issues…

- **Manual Methods:**
  - Extended Time
  - Extended Labor
  - Lack of Success
- **AI/ML Methods:**
  - Poisoning Signatures and Training Data
  - Adversarial Vulnerabilities
  - Cascading Failures

Conclusions

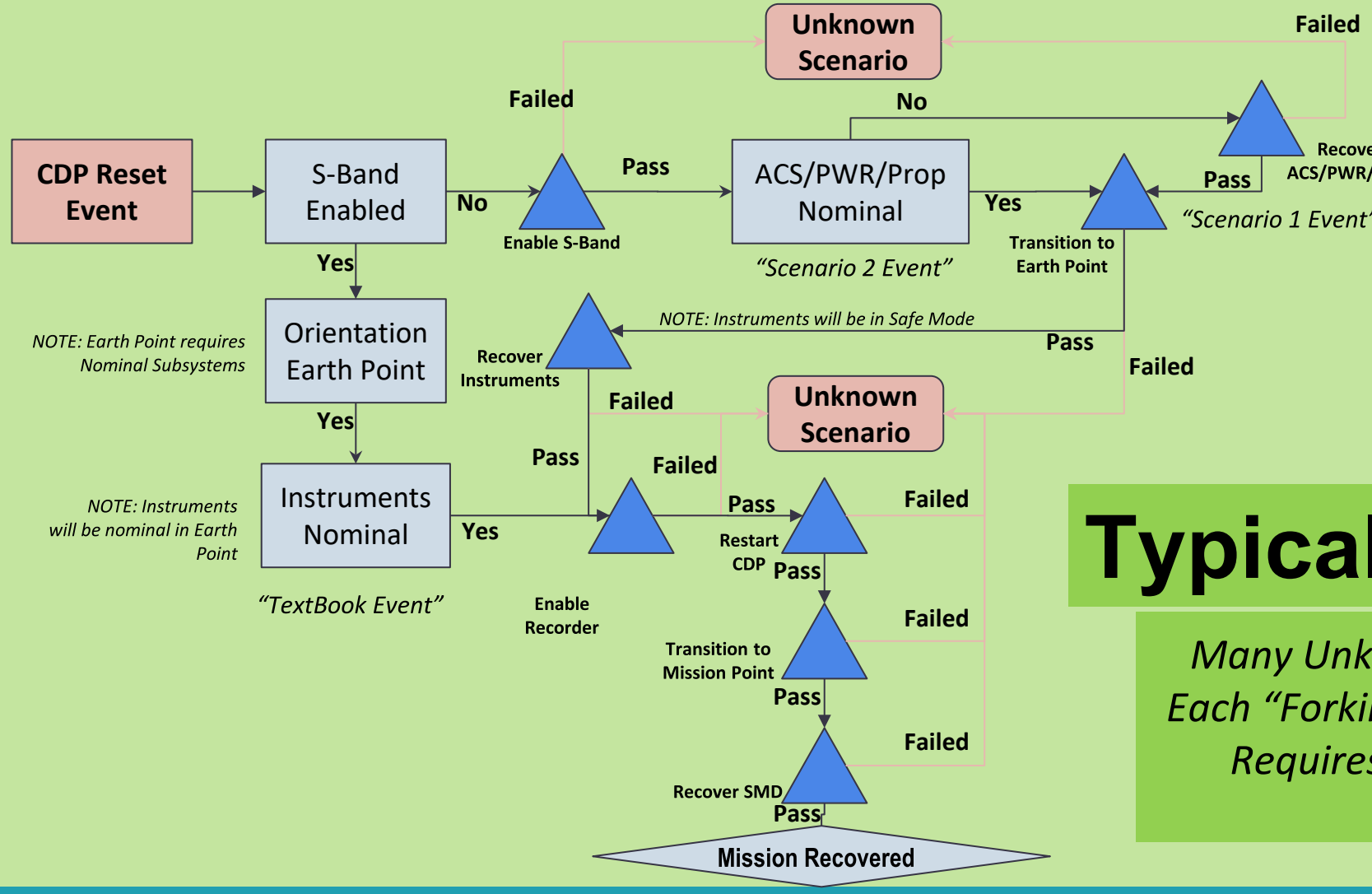
- Human driven anomaly handling capabilities exist today, but slowly evolving into AI/ML driven methods in new missions
- Investment is needed in developing AI/ML capabilities to remove the Engineer-in-the-Loop approach occurring today.
- Recognition that with AI/ML vulnerabilities are a core factor

Conclusions, Cont'd

- Space Cybersecurity is a fundamental aspect of AI/ML-Driven Anomaly Handling
- Space Missions Requirement and Formulation need to evolve to include AI/ML anomaly handling
- Requirements MUST INCLUDE vulnerabilities handling, adversarial scenarios, and prudent design and engineering.

Backup

S-NPP CDP Reset Anomaly Resolution, Cont'd



Typical Workflow

Many Unknown Scenarios Exist. Each "Forking" Scenario nominally Requires Extensive Analysis

S-NPP CDP Reset Anomaly Diagnostic States (Cont'd)

- At Subsequent contacts after a S-NPP CDP Reset, The following could be the only information available:
  - Likely only Realtime TLM is available; Still no Backorbit Storage State of Health

Subsystem Status	*"Textbook Reset"* *SMCDPRS = 1* *SWCRS flag = Reset*	*"Anomalous Scenario 1"* *SMCDPRS = 0* *SWCRS flag = Reset*	*"Anomalous Scenario 2"* *SMCDPRS = 1* *SWCRS flag = null*
	TLM Enabled	TLM **Enabled**	TLM **Enabled**
	SMD Disabled	SMD **Off-Nominal**	SMD **Off-Nominal**
	Recorder Disabled	Recorder **Unknown**	Recorder **Unknown**
	Instruments Nominal	Instruments **Unknown**	Instruments **Unknown**
	ACS/PWR/PROP Nominal	ACS/PWR/PROP **Off-Nominal**	ACS/PWR/PROP Nominal
	Orientation Earth Point	Orientation **Sun Safe**	Orientation **Sun Safe**

Additional Information Available