Satellite telemetry anomaly detection

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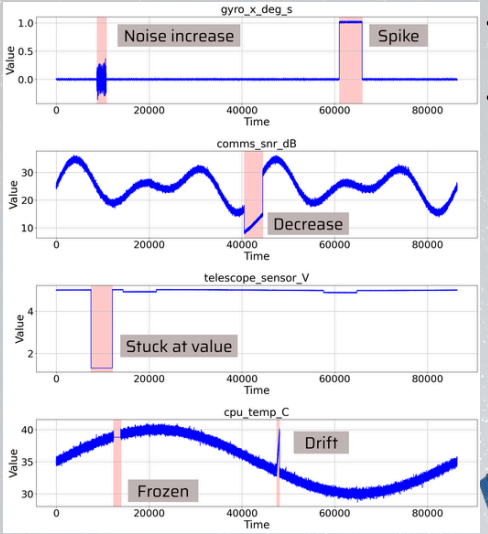
Telemetry

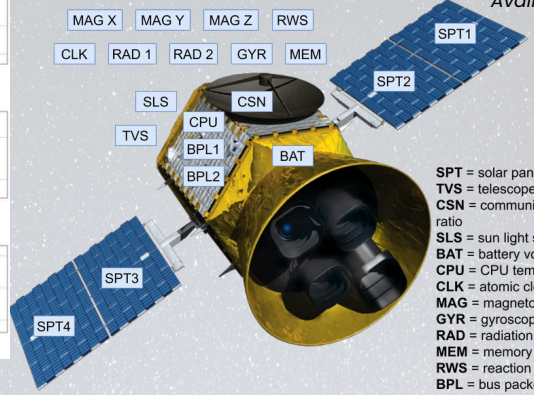
- The satellite telemetry is multi-variate timeseries (each serie is called **channel**)
- Channel is associated with sensor
- Telemetry monitors the satellite's health and operational status (voltages, temperatures and so on).
- Since launching a satellite into orbit is extremely costly, early detection of failures is essential
- Anomaly detection can be performed:
  - on the ground (on Earth)
  - **directly on satellite** (case of this work)



Examples of telemetry channels with 6 different types of anomalies

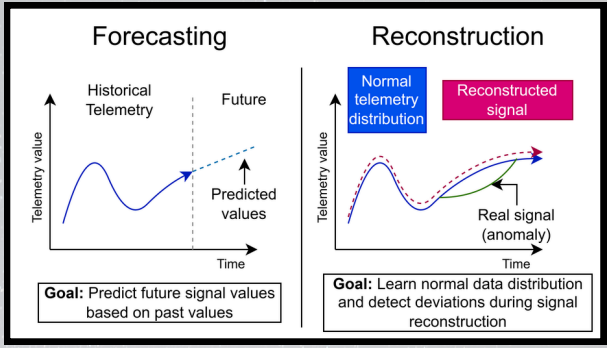
- Due to a lack of quality telemetry data a configurable **synthetic telemetry dataset generator was developed (20 channels)**
- This open-source tool allows users to generate datasets with anomalies over a specified number of days and sampling frequencies.

Available at GitHub



SPT = solar panel temperature (°C)
TVS = telescope voltage sensor (V)
CSN = communication signal-to-noise ratio
SLS = sun light sensor (0 is dark)
BAT = battery voltage (V)
CPU = CPU temperature (°C)
CLK = atomic clock drift (μs)
MAG = magnetometer x,y,z (μ Teslas)
GYR = gyroscope degrees
RAD = radiation sensor counts (per 1 s)
MEM = memory usage (percentage)
RWS = reaction wheel speed (rpm)
BPL = bus packet loss (percentage)

Anomaly detection



Anomalies in satellite telemetry can be categorized into two main types:

- **sensor-related anomalies**, such as hardware malfunctions, measurement drift, calibration errors, or permanent damage to onboard instruments.
- **environmental anomalies**, which arise from external conditions affecting the satellite, including radiation spikes, temperature extremes, space weather events, or unexpected interactions with the surrounding environment

Results

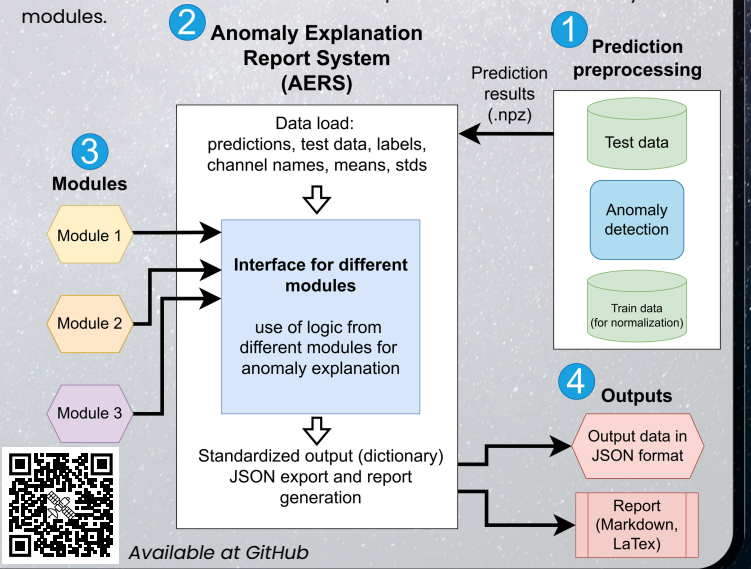
- **5 types of neural network architectures implemented in TensorFlow with multiple version (total 24 models)**
- Converted to TensorFlow Lite and ONNX for edge devices
- Dataset was generated using developed generator
- Tests run on PC, Raspberry Pi 4B, AMD ZCU104 and NVIDIA Jetson Orin Nano
- The fastest model achieved inference times under 0.01 seconds per 1000 input sequences (length=250) on the Jetson Nano. Inference power consumption was 13.04 W for AMD ZCU104, 8.02 W for Jetson Nano and around 3 – 5 W for Raspberry Pi 4

Metrics:

- Inference time
- Power consumption
- Area under Precision-recall curve (PR AUC)

Model (best version)	Size	PR AUC
Telemanom (baseline)	330 KB	0.768
Dense Autoencoder	18.64 MB	0.870
LSTM Autoencoder	3.21 MB	0.946
GRU Autoencoder	9.24 MB	0.874
ResNet	97.93 MB	0.841
TCNN	5.51 MB	0.788

- The last result of this work is **Anomaly Explanation Report System** (AERS) which is a Python-based modular wrapper for the explanation of anomalies and the generation of reports
- AERS ingests anomaly predictions and raw telemetry data to generate standardized reports (including JSON outputs).
- Modular architecture allows domain experts to write custom analysis modules.



Available at GitHub

Conclusion

This work considers satellite anomaly detection for spaceflight. Real satellite data is often restricted or hard to understand, an open-source generator was built to create realistic test data. It was found that while forecasting-based models work well for smaller systems (less channels), different approaches are needed to handle the complex realities of a real mission.

Created detection models are fast and lightweight enough to run directly on a satellite's limited hardware. Finally, the development of the AERS framework ensures that these rapid onboard detections can be effectively interpreted by ground-based domain experts, fostering greater trust and autonomy in satellite operations. This completes the whole processing pipeline that handles detection of anomalies in satellite telemetry.

The thesis was presented on **Brno Student Space Conference 2026** (presentation) and student conference **Excel@FIT at FIT VUT Brno** (poster).