Mission Operations Technologies

DLR

Mission Operations Technology at GSOC

The operation of satellites requires engineers to deal with a wide range of information. The state of health of satellites is to be evaluated on the basis of tens of thousands of telemetry parameters and in case of failure the appropriate reaction is to be chosen from several hundred flight control procedures. Technical systems generate countless logs that contain information about detailed processes. The engineers have to consider all these different sources of information, study them and combine the contained information and draw the right conclusions.

The goal of the Mission Operations Technology (MBT) group at DLR Space Operations is to simplify these steps for the engineers and support them with modern tools. Supporting measures help to make operations **safer**, because errors in the complex flood of information are made visible. In the event of an error, relevant information can be made available quickly to **shorten response times**. Particularly important is the presentation of information allowing an **intuitive understanding** of the given situations in operating a satellite. This provides clarity, which ultimately prevents wrong decisions. In this sense, **comprehensive** information is also very important, which means that all relevant information sources (e.g. about earlier comparable incidents) are displayed, even if the engineer is not aware of its existence. In order to be able to evaluate the degradation of the satellite's health and performance, it is necessary to be able to carry out more **in-depth performance analyses**. For this purpose, the long-term data must be made available in an efficient manner and supporting tools for analysis and plotting must be provided.

In summary, the MBT product portfolio aims to provide the following solutions:

- Automatic detection of anomalies in telemetry parameters
- Easy and direct access to information without tedious searching
- Provision of appealing, dynamic and interactive visualizations
- Combined presentations of events and telemetry
- Provision of advanced possibilities to investigate the data in an exploratory way

Currently, these goals are pursued by developing the two main applications ATHMoS and ViDA. Another branch of Mission Operations Technology is the Application of Quantum Technologies in Satellite Operations.

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1.1 Visualization and Data Analysis framework (ViDA)

The Visualization and Data Analysis framework enables engineers to **view** and **interact** with telemetry in a pleasant and flexible manner. ViDA allows the user to gain a better understanding of the satellite behavior by giving context to the pure telemetry data. Novelty detections assist the engineers in identifying anomalies in a huge amount of time series data. ViDA is the main product by the MBT devops team and functions as GUI for the novelty detection service being pushed forward by the MBT AI research team. The ViDA framework consists of a central web-based user interface and underlying micro-services supplemented by the custom analysis API. It is based on a modular service-oriented architecture, where each component is designed as an independent, controllable, scalable and robust micro service with its own specific scope. All standard interactions with telemetry itself or with derived data are made easily and quickly accessible via the web-interface, further customized investigations are possible making use of the custom analysis API.

The ViDA framework is currently in development. Therefore the following features are classified as available (A) and as planned (P), respectively.

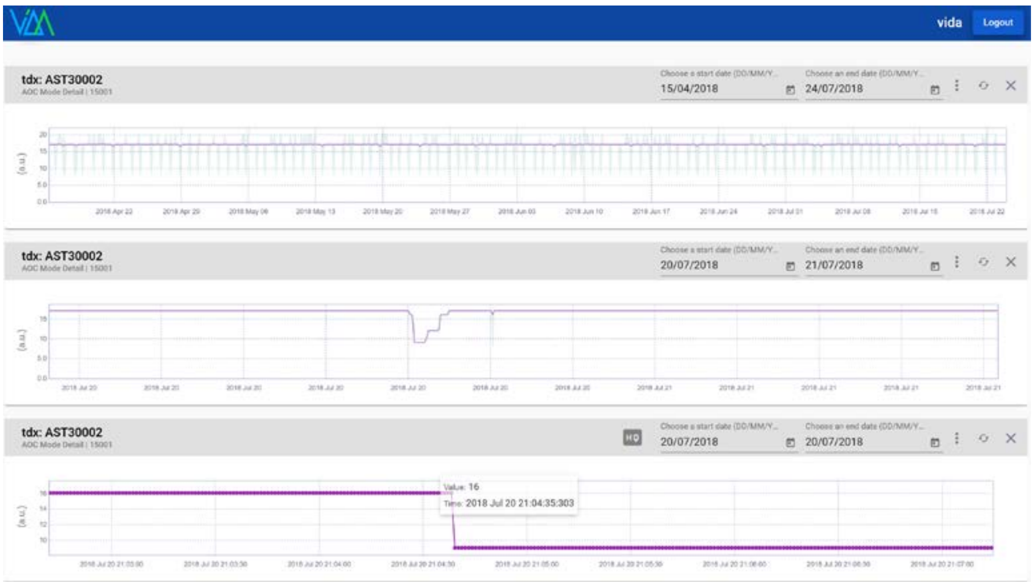

Fig. 1-1 Visualization of telemetry in ViDA for three different times ranges. The top panel depicts several months of telemetry data. The data is visualized using downsampling techniques to allow instant rendering. In contrast, the lowest plot shows all data points in full resolution for a short time range of several minutes.

- **Very fast long-term plots:** Inspection of the time evolution of sensor reading in all mission plots is crucial step in gaining awareness on performance degradation and aging effects of on-board devices. The challenge is that long-lasting missions, for example the TerraSAR-X/TanDEM-X mission with >12 years in orbit, generate very long time-series data. Typically, on-board sensor data are sampled with 1Hz which sum-up to over 300 millions data points in Ten years for a single sensor. In order to avoid overdrawing and to enable quick access to all mission data a data-down-sampling service is established. An hierarchical level approach enables zooming in and out in data sets. Ten years of data can be plotted in fractions of a second, zooming can be done almost instantaneously (A).
- **Automated novelty detection:** Routinely inspection of telemetry data by humans have to be restricted to key sensor readings for time reasons. However, also in further sensor data, novelty might show up and indicate a potential on-board failure. A novelty detection service supports the engineers to scan the full data set of sensor readings available. ViDA acts as an alarming tool highlighting detected novelties in a dashboard (P) as well as in long-term plots novelty regions are highlighted (A).
- **Automated trend detection:** During routine inspection by humans trending sensor readings might not be noticed because gradual changes might not become noticeable in the time interval considered by the engineers. Trending parameters are highlighted in ViDA.

- **Provision of context:** Changes of reading in sensor data are to be set in relations to the context given at the moment in time they happened. They might be caused by telecommands sent from ground, executed on board or might be due to external circumstances like the satellite entering Earth shadow. Understanding of telemetry is facilitated by making context information (telecommands, on-board event history, flight dynamics events) easily available to users. Integration into the operational ViDA framework is still outstanding (P).
- **Prediction and statistical analysis toolbox:** Interrelationships and time histories represented in long-term plots often require an extrapolation into the future to estimate when a critical value will be reached. ViDA will feature a prediction tool suite, making use of statistical tools and machine learning algorithms (P).

1.1.1 The ViDA web application

The ViDA web application is the central user interface to interact with the **ViDA framework**. After log-in with the credentials the user accesses a customizable dashboard with configured and grouped views on telemetry data and related products. The user can interactively work with telemetry plots, relate the time-series data to context information or take advantage of the **data micro-services** and **data mining services**. In order to provide a smooth and convenient user-experience, the ViDA web application is based on state-of-the-art technologies, which are widely used and supported. ViDA is designed as a web application with a server (backend) serving multiple clients (using the frontend of the ViDA application) to partition tasks and workload. The frontend is based on the Angular framework, which supports developing an interactive and reactive application according to newest standards. Using this foundation also provides a lot of flexibility for the design of the application. This freedom can be used to develop ViDA in close cooperation with the operation engineers, to tailor ViDA and its "look and feel" specifically to their needs. For the server side, scalability, robustness and a reactive design were the drivers for choosing Scala/Akka as the foundation of the backend. The ViDA backend is responsible for accessing the databases which hold satellite data and user preference data. To keep the frontend as slim as possible, the backend shoulders the resource demanding processing and serves preprocessed data to the frontend. Communication between both end-points is established via GraphQL.

The users can conveniently access the application through a web browser from all machines that can connect to the server on which the ViDA backend is running. By logging in with the user's credentials, each user can have access to the full functionality of ViDA. A personalized dashboard is the entry point to the application and gives an overview of the ViDA features. From the dashboard, users can navigate to all components, such as the weekly telemetry overview or the in-depth analyses.

1.1.2 The ViDA custom analysis API

Whereas the **ViDA web application** provides a wide variety of means to display and to analyze telemetry data, special use cases remain that cannot be foreseen by the developers. Giving the user the freedom to access the data via an API allows for custom analysis and integration of the raw and preprocessed data from the various ViDA services into their own routine workflows.

This API is encapsulated into a library called **Mission Data Access Library (MiDA)** which can be installed locally or, without the need for a local development setup, be used via a Jupyter Hub environment that integrates well with the ViDA universe. The Jupyter Hub environment provides a well-established multi-language development platform, providing a highly scalable per user notebook application using the resources of the ViDA hardware cluster. This especially enables the user to overcome the limits of local resources for big amounts of data. The ViDA Jupyter Hub environment comes equipped with a variety of language kernels e.g. Scala, Python, R, C#, C++ etc., where the user can develop his/her own tools for data processing. MiDA is in the first place provided for the Python language, but with the power of multi-language Jupyter notebooks, interaction with user code written in other languages is simply possible within the same code block.

MiDA provides, next to others, a bunch of generic methods to access data from the various **ViDA micro-services** for its in-memory analysis as well as generic transform-reduce operations to extract results from long time periods, thus freeing the user from the load-analyze-dismiss cycle of memory compatible chunks of data.

1.1.3 The ViDA micro-services

The data services in the background of the ViDA framework are developed as micro-services according to the reactive manifesto. It assures good and scalable performance, maximum stability and predictive behavior in case of errors, with a minimum of user interaction. The heavy-duty services are implemented in Scala, whereas prototyping and calculation-heavy services may be developed in Python initially. Once stability of the prototype has been reached and more performance is needed, the decision to orchestrate the existing code or to convert into a Scala service can be taken.

Ingestion service

The ViDA data ingestion service imports necessary input data, telemetry data (A) and other operational products (P), into a timeseries database.

Data derivation service (P)

The derivation services will pre-compute statistical calculations that are required by operations engineers on a regular basis for reporting or analysis purposes. Which statistics will be computed by the service can be defined in detail. Examples might be the standard deviation, average, or more elaborate calculations. For defining custom algorithms for computing statistical measures, Jupyter notebooks can be used. Once the algorithms have been tested, the statistical calculations can be implemented in an automated data derivation service.

1.1.4 The ViDA database

Telemetry data are stored in a central ViDA database. As technology TimescaleDB (extension to PostgreSQL) was chosen which is especially suited for working with time-series data in a relational database. Telemetry data is ingested in an step-by-step but yet heavily parallel approach to ensure complete and up-to date information. Data micro-services as well as data mining services write to the central ViDA database. Further databases containing supplementary data may be connected to the ViDA framework.

Downsampling in Timescale DB

One of the key features of ViDA is the possibility to display long-term TM time series, spanning the full lifetime of a satellite very fast. This is achieved through the downsampling service, which pre-processes the data and downsamples them into hierarchical levels of detail, which are then displayed instead of the full-resolution data. The concept behind this service comes from the fact that it would be impossible for the user to clearly visualize millions of data points into the space available in a standard computer screen without overdrawing. Overdrawing occurs when the screen resolution is lower than the number of data points to visualize, resulting in the data points overlapping. This overlap can become so severe that it is impossible to perceive the number of points in a given region of the plot, thus obscuring outliers, hiding data distributions, and making the relationships among subgroups of data difficult to discern. TimescaleDB offers a built-in Continuous Aggregates functionality which applied as downsampling service.

Fig. 1-2 ViDA highlighting novelties in telemetry. The bars mark the time ranges in which novelties occurred. The color indicates the severity of a novelty.

1.2 ATHMoS – the Automated Telemetry Health Monitoring Service

The ViDA framework is supported by data mining services making use of machine-learning techniques to automatically detect anomalous behaviors and trends in telemetry data.

The **Automated Telemetry Health Monitoring Service (ATHMoS)** is specifically developed for analyzing large quantities of satellite telemetry data from a huge number of parameters. This is a novel algorithm for statistical outlier detection which makes use of the so-called Intrinsic Dimensionality (ID) of a data set. Using an ID measure as the core data mining technique allows us not only to run ATHMoS on a parameter by parameter basis, but also monitor and flag anomalies for multi-parameter interactions, without a-priori manual training or parameter-specific tuning. The method analyses the past 12 months of telemetry data of every parameter as the training dataset, extracting various statistical features, and using a semi-supervised machine learning algorithm to distinguish between nominal and anomalous (novel) behavior. Newly received TM data are then compared to the cluster of nominal data, and the "Outlier Probability via Intrinsic Dimensionality" (OPVID) algorithm is applied to assign anomaly probabilities, based on the density of the cluster and the distance of the new data points to those of the nominal cluster. From the comparison with "historic" and "recent" nominal clusters (which include only one month of data), and the resulting anomaly probabilities, the anomalies are classified as "high priority" (HP) or "low priority" (LP). Trends in the data, which might lead to a more severe anomaly in the near future, are also identified ("trending detections", TD).

This service is designed to run daily in the background, analyzing newly received TM from every parameter to identify potential anomalies. The results from the ATHMoS analysis are stored in a database and can be displayed in plots and visualizations, on dashboards, or serve as a basis of automated alerts in our ViDA web application.

A key principle of the method is that any false positive (or negative) detection can be corrected and re-labelled by the user through the ViDA frontend. The new label will be considered during future data processing; thus, the detections will become more accurate and reliable over time. Moreover, by performing a periodic retraining of the models using past and recent TM data, the method adapts to changes in the nominal behavior that can occur over a mission's duration.

2. Application of Quantum Technologies in Satellite Operation

Another branch of Mission Operations Technology is the Application of Quantum Technologies in Satellite Operations. MBT currently leads all quantum activities at GSOC. Supported by all other GSOC departments, our joint expertise concentrates on:

Quantum Hardware

We support the DLR Quantum Initiative in setting up requirement specially for Spin-based Quantum Qubits, like Nitrogen-Vacancy in Diamonds.

Quantum Optimal Control

With two PhDs in the field, MOT was asked to work out quantum optimal control theoretic part of the Munich Quantum Valley. The consortium will build at least two quantum computers that will need hardware adapted optimal control steering sequences to fight noise and relaxation by cutting gate impementation times or incorporating relaxation effects by using relaxation poor subspaces.

Munich Quantum Valley:
- **Consortium Member for full stack Quantum Computer Development**
- **K8 – Hardware Adapted Theory – Optimal Control on Qubits**

Application of Quantum Methods

GRAPE4Space: Robust Satellite Attitude via Control Theory (with Technical University of Munich, University of Burgundy)
- **Master thesis – 'Robust Satellite Attitude via Control Theory'**
- **Cooperation with SatelliteFlashFinder Project (with DLR Space Operations and Astronaut Training & DLR Institute of Communications and Navigation)**
- **Cooperation with Seranis Satellite Project (with Universität der Bundeswehr Munich)**

Quantum Computing

Satellite operations offer many challenges which are currently under investigation to be transformed into a quantum algorithm:

Scheduling Problems

Specific challenges that arise at various places in satellite operations are scheduling problems, like e.g. scheduling of oncall shifts, groundstation contacts or datatake aquisitions. We are currently extending our first running quantum algorithms to a generic interface of the classical mission planning system.

SQOS: Spacecraft Quantum Oncall Scheduling (with Ludwig-Maximilians-Universität München, DLR Institute for Software Technology)

- **Bachelor thesis 'Scalable quantum algorithm for scheduling problems'**
- **'OnCall Operator Scheduling for Satellites with Grover's Algorithm', DOI: 10.1007/978-3-030-77980-1_2 In book: Computational Science – ICCS 2021**
- **'Quantum Shift Scheduling' – A Comparison to Classical Approaches, IWPSS2021**

Telemetry Analysis

Another everyday job of a subsystem engineer is TM analysis. Next to our classical anomaly detection suite ATHMoS, we are currently about to implement a scalable interface to the quantum realm.

QAthMOS: Anomaly detection in telemetry data using QML, Graph theory, Nearest Neighbour Problem

Quantum Error Correction

Bringing together the expertise of quantum computing and quantum control, we also focus on implementing a quantum circuit that efficiently realizes quantum error correction codes on quantum computers.
This is a cooperation with the DLR Institutes of Communications and Navigation, Software Technology and Quantum Technologies.

Quantum Communication

A fundamental challenge in satellite operation is security of data. This comes in many flavors like:

- secure communication with satellites in terms of telecommanding and telemetry,
- encryption of payload data, e.g. the high resolution radar data of the TerraSAR/TanDEM Mission or
- protection of communication of customers with the control center.

MOT is part of the project MuQuaNET to esatblish a quantum secure internet in the area of munich. This finally shall demostrate quantum communition between the Universität der Bundeswehr Munich, the German Quantum Space Operations Center, other DLR institutes on the campus at DLR Oberpfaffenhofen, and the DLR groundstation in Weilheim.

Furthermore, we are planning to investigate in how to build a SpacecraftQuantumOnboardCryptotransponder, that shall enable S/C to use quantum keys in the S-Band communication line used for nominal operations of satellites.