# ON-BOARD DATA ANALYSIS AND REALTIME INFORMATION SYSTEM - SOFTWARE DEVELOPMENT CONCEPT FOR NEW SPACE

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## Abstract

In this talk we want to provide an overview over the software development concept of the "On-board Data Analysis and Real-time Information System" (ODARIS) developed at the DLR. The ODARIS technology demonstration will be performed within the upcoming SeRANIS mission of the University of the Bunderswehr Munich, scheduled for 2025, utilizing a state-of-the-art ARM-based on-board computer architecture and software stack. We will focus on our approach for the software development and adaptions from terrestrial application development to the space proven ODARIS software.

## Keywords

real-time communication, software development, embedded systems, satellite platform

## 1. INTRODUCTION

In the last century, the space sector experienced a rapid increase of new generation satellites, equipped with modern hardware architectures [1]. Within the upcoming century, several governmental space agencies, commercial service providers and scientists plan for an even higher demand for different kinds of space systems, ranging from earth observation satellites over internet-based networks up to new space stations. This will lead to an increased access to space for serval stakeholders and offer new opportunities including newer satellite concepts and services [2].

A major key aspect is the communication link between satellites and involved centers for mission control and payload data on ground. In the current classical approach, the communication concept between satellites in lower orbits and ground follows the store-and-forward principle. All scientific data and time-critical information like health status needs to be stored on-board until the satellite can establish contact to one of its assigned ground stations. These limited time windows can lead to information gaps between 6 hours up to 24 hours. Furthermore, the size of the time window can be too short to transmit all necessary data to ground. In this case, the process would need to be split over multiple time windows leading to more delay until the information is fully available on ground. From an operator perspective the upload of telecommands has also to be performed within the same time window, leading to intensive planning and preparation of telecommand lists. In case of critical errors on-board the satellite, the operators would have to wait for the next time window to perform an appropriate countermeasure.

To address this common issue, we are currently developing a cost-efficient approach to decrease the latency until information, derived from the on-board satellite data, becomes available for different stakeholders on ground as well as enable operators to immediately take action after a problem on-board the satellite occurred.

The "On-board Data Analysis And Real-Time Information System" (ODARIS) establishes a real-time service available 24/7 during the mission. Additionally, due to the reduced bandwidth and to shorten the analysis time on ground, critical information shall be generated directly on-board as soon as any kind of sensor data is available. A proof-of-concept flight experiment is planned for ODARIS, targeting small- to mid-sized satellites.

Within this article we will present our concept and development process for ODARIS. Starting with an insight of our system design, we will follow on with the description of the upcoming satellite missions. As we are currently in a mid-level phase of the flight experiment preparations, the focus will be on an overall description of the software as well as our current development process. In the end, this article concludes with our further approach for the ODARIS flight experiment.

## 2. THE ODARIS OVERVIEW

In this section a brief introduction and overview of the system is presented. For a more detailed insight, please have a look at the predecessor articles of ODARIS [3] [4].

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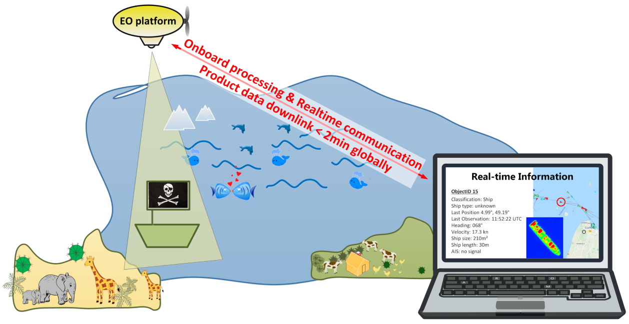

FIG 1. AMARO concept for a real-time ship detection application

## 2.1. Background

The kick-off took place in 2015 in form of a requirements analysis and conception phase for a real-time information system. A first prototype was demonstrated within the "Autonomous real-time detection of moving maritime objects" (AMARO) mission, which performed a real-time ship detection on-board of an airplane [5] [6]. The scope of the experiment was to detect larger ships that don't send mandatory Automatic Identification System (AIS) signals, which is an indicator for illegal activities at sea. The results were immediately made accessible to scientists on ground via a global satellite network for SMS-based message transmission. In Figure 1 the concept is summarized.

ODARIS is a direct successor flight experiment, which aims for deployment on satellite platforms. The system is currently in preparation for an in-orbit demonstration within two upcoming satellite missions and additionally in a case study for the use within the field of terrestrial rescue missions. All projects will be described in more detail in Section 3. Follow on an overview of all features of the system will be described.

## 2.2. System features

After examination of typical bottlenecks in the field of operation for experimenters and satellite providers, the following key features have been set for ODARIS:

### On-board data processing

During the flight experiments nearly all kind of scientific data shall be processed directly on-board the satellite platform. The results of these analyses serve as the basis for an interactive information system. For post-experiment examination as well as cross-validation, the raw science and logging data shall also be stored within an on-board mass storage and periodically send to ground via the satellites TM/TC link or a dedicated high-bandwidth link for scientific data. The data processing concept and algorithms are not limited to specific fields and shall be easy to integrate into the overall ODARIS ecosystem.

### Service platform for third-party applications

The system is designed to serve as a flexible service platform with the ability to integrate third-party applications and give them access to its internal information and real-time communication system. The integration of such applications should take place in form of a high-level standardized service-layer. The application developers only have to provide this layer and link their application in form of binary-libraries. For demonstration purposes during the upcoming space flight missions, a facility-internal image analysis application as well as a mission-operation based application serve as example implementations.

### Real-time messaging capabilities

The real-time communication system is one of the core aspects. The goal is to enable near instant access to on-board scientific data and to some extend satellite telemetry data. All kind of stakeholders like mission operators, scientist or service customers shall be able to access time-critical data anywhere and anytime.
Typical examples for time-critical data are

- detection of environmental disasters within the field of earth observation
- continuous monitoring of experiment or overall satellite health status in the field of "Fault Detection, Isolation, and Recovery (FDIR)

To realize a continuous bi-directional message transfer between the satellite and ground, it is planned to use one of the well-established satellite networks. These kind of networks were initially designed to ensure a full network coverage on earth and not for use of high-altitude platforms. One of the major challenges for a reliable real-time communication link is the connectivity to these intermediary global satellite networks. Since the experiment satellite will fly in a Low Earth Orbit (LEO), several gaps could occur in this orbit, where no connection with the network is possible. This potential issue is sketched in Figure 2.

A continuous measurement of the connectivity is therefore one of the major objectives for the in-orbit demonstration as well as the determination of the minimum and maximum duration for message transfers between the on-board ODARIS software and a user terminal on ground. As part of the experiment objectives, it is planned to continuously send time-stamped messages over several orbits to determine the percentage of connectivity and average duration of the message transfer.

### Interactive information system

Next to the hardware-based real-time communication system, the internal information system is the supplementary software component in this concept. While the communication system implements the low-level hardware interfaces and enables the bi-directional message transmission, the information system is the

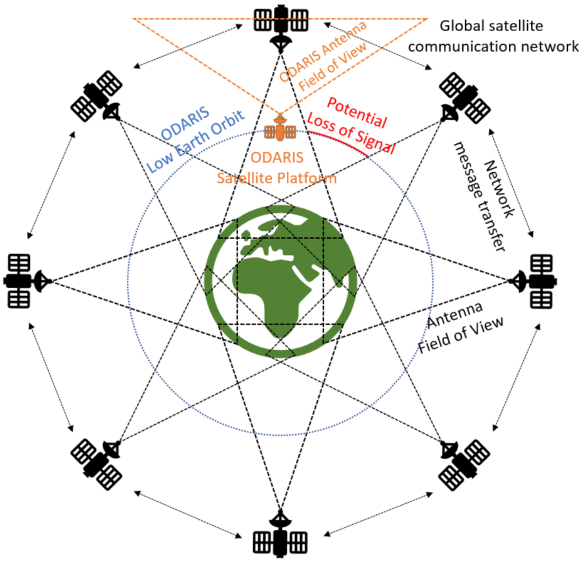

**FIG 2. ODARIS connectivity to a global satellite communication network**

entity to process incoming user queries and handles a customizable event-based notification system.
Both functionalities will be implemented in the services Query & Push. More details will be presented in section 2.4.

### Broad platform support

The former AMARO mission was designed for an airplane mission. The upcoming ODARIS flight experiments will be developed for different satellite platforms. The support for various more platforms and hardware architectures is another targeted feature. This includes newer generation flight platforms like High Altitude Platforms (HAPs) [7] or different kind of drones [8] [9], e.g. used in civil services for aerial examination of critical areas like wood fires. The system is in general not only limited to flight platforms and could also be used for other kind of vehicles used in rural areas with limited communication capabilities.
Further important aspects will also be considered during development:

- **Scalability**: Ranging from edge computers up to high performance server environments
- **Compatibility**: Support and testing on different popular edge-computer ecosystems which could become interesting for future satellite missions
- **Extensibility**: Flexible increase of data processing capabilities and different communication networks
- **Interchangeability**: Fluent routing adjustments to alternative components, e.g. change of communication link from real-time to satellite TM/TC link in case of connectivity issues

## 2.3. ODARIS design

To implement all of the different features, various approaches for software development and proven architectures were reviewed. The ODARIS concept follows a service-based approach, the messaging concept can be compared to the "F Prime" Framework developed at the NASA Jet Propulsion Laboratory [10]. Every service is a self-contained entity which performs only a single task within its internal running cycle.
The key aspect is the communication between the services in form of a shared database. All services track specific tables within the database and become active if entries, assigned to their ID, are placed from another service. This inter-service messaging concept ensures most flexibility with a highly asynchronous information exchange. As suitable database engine SQLite [11] was chosen, since it is proven on edge devices and provides the complete functionality of SQL-queries within the experiment setup. The mechanism of the information system is based on the use of the SQL language for data collection.

## 2.4. ODARIS services & interfaces

A schematic of the full ODARIS ecosystem from a services perspective can be seen in Figure 3. The following services are currently implemented or in preparation for the satellite platforms:

### Service RT-Com

The service RT-Com is the software interface for the real-time communication link. The low-level serial communication functionality is implemented within this service. The received messages from ground will be stored in a post-inbox within the ODARIS database. Additionally, the service automatically forwards all stored messages from the post-outbox to the real-time device. For later examination on ground, all transferred messages will be stored in an archive table within the database.

### Service TM/TC

The service TM/TC is the software interface to the satellite TM/TC communication link. It has two main functionalities. First, it is responsible to send all experiment telemetry data via the satellite platform to ground and processes incoming telecommands from the mission operators and experimenters. Second, it is used as a reference communication link during the in-orbit demonstration for validating the transferred messages via the real-time communication link. Due to this architecture, it can also be used as a backup communication link in case of fatal errors on the real-time device side.

### Service Query

The service query handles all incoming user queries from ground, collects the demanded information from the ODARIS database and prepares an answer messages for the user. Finally, it stores the message within the post-outbox to hand it over to the service RT-Com.

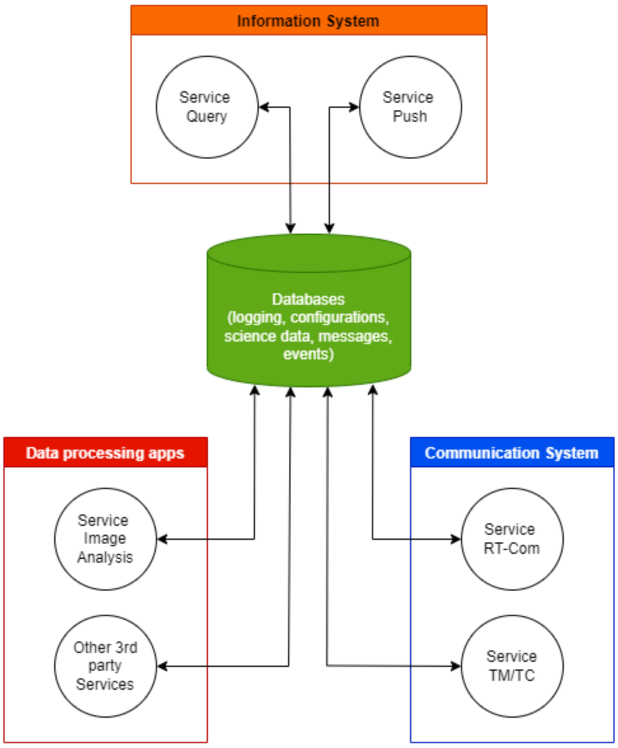

FIG 3. ODARIS Ecosystem - Services layer

### Service Push

This service is responsible for the event-based notification system. Different events can be configured either before the mission or in-orbit in form of a user query message. Events can be triggered via the occurrence of specific database entries, e.g. a targeted object was detected during the on-board image analysis, or it can send messages periodically, e.g. to monitor the health status of services.

### Service Image Analysis

In addition to the real-time communication capability, the on-board data processing concept is another core feature. This will be demonstrated in form of an image analysis service. Furthermore, this service can be used as reference for later third-party application and services integration into ODARIS. The data processing is based on an Artificial Intelligence (AI) algorithm for object detection on images in form of a Convolutional Neural Network (CNN). Afterwards, the notification system shall immediately be triggered, if an object of interest was detected. The images will be provided by an on-board camera system. For the software implementation of the AI Inference, the machine learning framework TensorFlow (TF) with its edge computing library TensorFlow Lite Library (TFLite) [12] was used.

### System Interfaces and hardware

There are several common interfaces of ODARIS, applicable to all planned flight experiments.

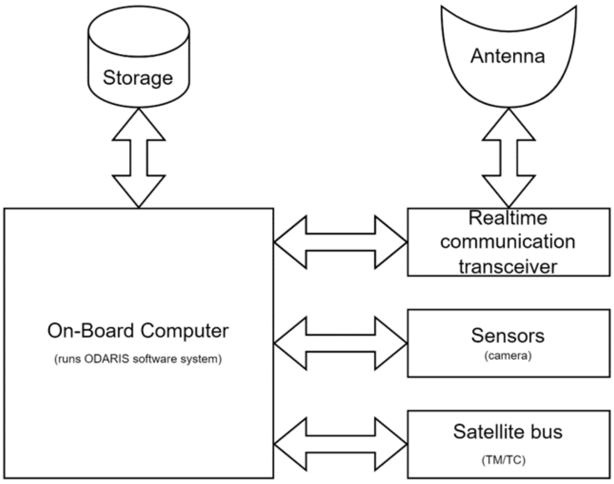

FIG 4. ODARIS Ecosystem - Interface layer

These consists of access to

- a sensor for on-board data processing, e.g. a camera for the image data analysis
- a power supply for the real-time device and serial interface to the on-board computing system (OBC), where the system software is running
- a mass storage for scientific data and internal databases
- the satellite TM/TC link, mainly for experiment operation but additionally as a reference communication link

The interface are presented in Figure 4.
ODARIS is principally designed in form of a software experiment. Nevertheless, to establish a connection to a global satellite communication network, additional hardware in form of a transceiver unit and an antenna is necessary. To keep the focus on the software part, a suitable provider for the hardware was found, located in the U.S. [13]. One of their newest products will be integrated in our system and provides a L-Band radio transceiver based on the Iridium network [14]. Derived from their official product page, the real-time device offers a maximal data rate of about 13.5 Bytes per second, or around 1 MB per day, and a latency ranging from 5-30 seconds [15]. The typical available message size is around 200 Bytes. Within the upcoming flight experiment the applicability of this product shall be evaluated for the ODARIS concept.

## 3. SPACE FLIGHT EXPERIMENTS

In this section the upcoming satellite missions for the ODARIS flight experiment will be discussed. Afterwards the preliminary experiment setup will be presented. To cover every aspect of the experiment development, the other projects, in which ODARIS is involved, will be briefly described at the end.

### 3.1. The SeRANIS Mission overview

The Seamless Radio Access Networks for Internet of Space (SeRANIS) mission [16] is a satellite mission by the University of the Bundeswehr Munich [17]. The goal of this project is to establish a publicly accessible multifunctional experimental laboratory in orbit. The small- to mid-sized satellite platform called "ATHENE 1" will be produced by OHB LuxSpace and is based on the Triton-X platform [18] [19].

The mission is defined in a larger scale with over 15 experiments on-board, while the main focus is on the different concepts for satellite communication to ground. In July 2023 the project finished the Preliminary Design Review (PDR) phase and is currently in preparation for the Critical Design Review (CDR). For in-depth testing of all hardware and software components, a complete Flat-Sat setup within a lab environment is planned in 2024. The launch is scheduled for 2025.

### 3.2. Experiment setup and experiment preparation

The ODARIS flight experiment setup can directly be derived from section 2.4. All AI-related experiments will be executed on a custom AI-OBC based on the NVIDIA Jetson platform. The software systems will be deployed and operated in form of self-contained docker images and managed by the OBC system team. The interfaces are similar to the generic requirements of ODARIS shown in Figure 4, including

- an internal storage for scientific data and on-demand camera sensor data access
- a UART serial connection to the real-time device
- access to the satellite TM/TC link for experiment operation
- access to satellite telemetry data for scientific evaluation

A special requirement for the real-time device is the positioning of its antenna in zenith direction to enable communication with the Iridium network satellites in higher orbits. Images for the Service Image Analysis will be provided by an on-board optical camera system via the internal mass storage of the AI-OBC. Additionally, parts of the satellite telemetry data will be made accessible to feed the interactive information system. Next to the image analysis, an additional mission operation-based experiment of the German Space Operations Center (GSOC) will be integrated into the ODARIS ecosystem. The experiment evaluates the processing of real-time telemetry data for accelerated mission planning on ground.

In the current stage of the experiment preparation, the implementation of the serial interface to the real-time device is complete as well as first message transfers via the Iridium network could be successfully performed.

### 3.3. Further project participations

Besides the predescribed SeRANIS mission, ODARIS is also in preparation for an additional flight mission and a case study for usage in the fields of quick emergency notifications.

The flight mission will be prepared within the framework of the ScOSA Flight Experiment (ScFE) [20]. Scalable On-board Computing for Space Avionics (ScOSA) a next generation on-board computer developed at the DLR starting in 2012 [21]. The computer nodes are based on the COTS Xilinx Zynq7020 System On a Chip (SOC). It provides an ARM Cortex-A9MPCore CPU and an embedded Field Programmable Gate Array (FPGA). ODARIS will participate as one of the application experiments [22]. The start of the flight experiment is scheduled for 2024. More details about the current project status can be found here [23].

The project Koordinierte autonome Boden-Luft-Systeme für eine neue Rettungsmobilität (KoBoL) is a DLR-internal project from the resarch field of "DLR Transport" [24]. Its goal is to improve the cooperation between ground- and air-based vehicles and assist rescue workers in case of emergencies and will be performed together with the fire department of Braunschweig. ODARIS will be evaluated for usage as a satellite-based first-response notification system for detection of larger catastrophes, e.g. wood fires.

## 4. SOFTWARE DEVELOPMENT

In the following section the handling of the on-board software as well as the development workflow from a software developer's point of view shall be presented.

### 4.1. On-board platform conditions

For the preparation of the SeRANIS Mission there are several facts about the platform environment to consider:

- Processor architecture: The OBC platform is based on the ARMv8 architecture [25]
- Operating system: A full embedded Linux environment will be available
- Containerization: The SW experiments will be deployed in form of self-contained docker images [26]
- Interface: Different interfaces like the satellites TM/TC protocol as well as the serial connection to the real-time device needs to be implemented

These conditions are nearly equivalent for application development in terrestrial environments ranging from edge computing up to cloud servers, leading to the usage of state-of-the-art tools and techniques in the field of software development.

### 4.2. Software development concept

ODARIS services are written in C++ and follow the C++17 standard as well as the C++ Core Guidelines [27]. For configuration, building & testing, a customized build system, based on CMake scripts [28], has been created. The development environment will be provided in form of a Linux-based VirtualBox image [29]. For a quick setup of the complete development and testing infrastructure as well as migration to new hardware systems, the content of the image will be hosted and maintained in form of Infrastructure as Code (IaC) via Vagrant [30] and Packer [31].

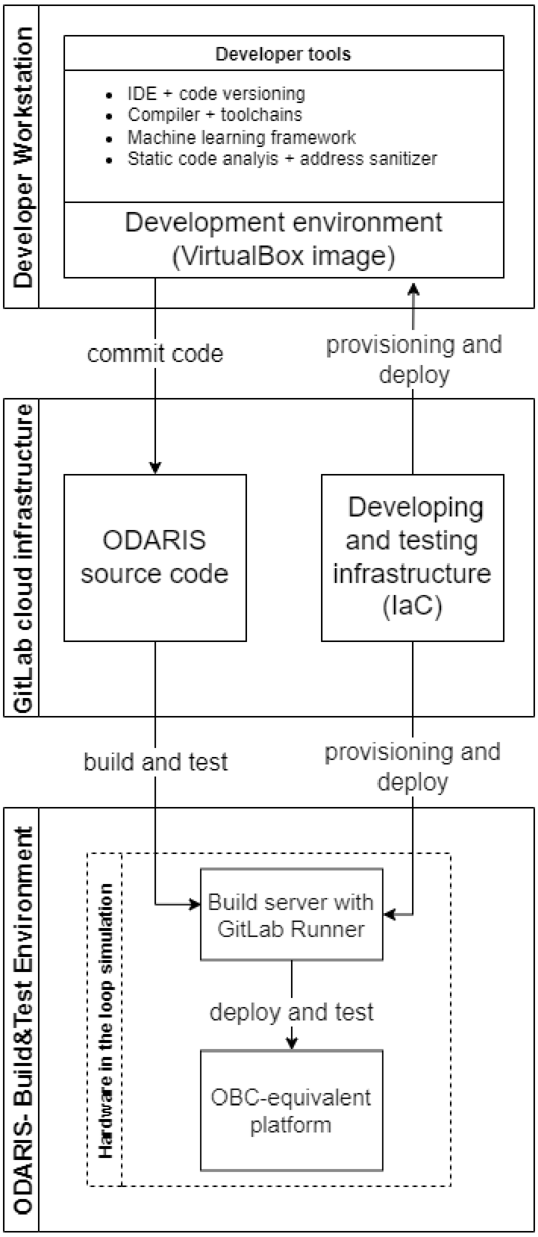

**FIG 5.** ODARIS development infrastructure

The development process follows the methodology of Continuous Integration (CI) & Continuous Delivery (CD) and is implemented via the CI/CD-pipeline feature of GitLab. To ensure a high code quality and support different architectures, multiple configurations will be tested during every pipeline. Additionally, several linter tools, like Clang-Tidy [32] and address sanitizer will be used during the compilation process. Following the technique of Hardware In the Loop (HIL) simulation, an OBC-equivalent platform was also integrated into the Gitlab-pipeline. This enables early-stage testing of the experiment system software close to the complex environment conditions of the physical satellite hardware, which is only available in a later stage of the mission preparation. A schematic of the complete ODARIS development infrastructure can be seen in Figure 5.

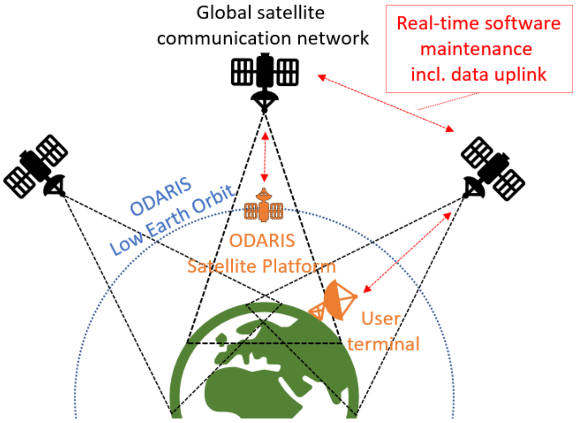

**FIG 6.** ODARIS real-time software maintenance incl. update

### 4.3. Software maintenance and update approach

The availability of a real-time communication link as well as the service-based architecture of the software enables new concepts in the field of software maintenance and update routines. During the ESA OPS-SAT mission [33], the upload of new software to active flight missions could already be proven but with the restriction of limited contact times to ground stations. Intermediary satellite networks could enable real-time access to the on-board satellite software at any time and facilitates the use of proven terrestrial software handling concepts.

Within ODARIS it shall be possible to change the smaller services configuration .ini-files, add additional service binaries in form of a hot plugging concept and update the image processing AI-model file. The real-time communication link is visualized in Figure 6. The real-time communication bandwidth of the upcoming flight experiments is limited to 13.5 Bytes per seconds or 1 MB per day [15]. With a message size of around 200 Bytes within the Iridium network, the updated files must be sent in multiple messages to the satellite platform.

Due to these limitations, not all update routines can be performed in real-time but will be tested via the satellites TM/TC link. The main focus of the flight experiments is on the reconfiguration capability of the services and the update of the AI-model parameters in form of a diff-file. The forthcoming satellite missions will be used as an overall proof-of-concept for all presented ODARIS features and routines. In later successor flight experiments, an evaluation of next generation satellite networks with higher bandwidth capabilities, e.g. Starlink [34] or OneWeb [35], will be performed.

## 5. CONCLUSION AND WAY FORWARD

In this article the "On-board Data Analysis And Real-Time Information System" along with its upcoming flight experiments was presented.

After a brief historical background, its core features as well as the internal conceptual design &

architecture of the system were highlighted. Furthermore, the upcoming satellite missions for the in-orbit demonstration of ODARIS with the main focus on the SeRANIS mission were introduced. Finally, the current development process and possible use cases for future handling of on-board software were discussed.

The availability of a real-time link to the on-board software of a satellite would allow the use of terrestrial techniques already proven in various computing segments. For future enhancements of the real-time communication concept, the applicability of imminent communication satellite constellations shall be evaluated.

Within the last year, the implementation of the serial communication between the software and the real-time modem were completed in ODARIS. In addition, the first successful ground tests of the messaging transfer via the Iridium network were performed in a lab environment. Follow-on the preparation of the experiment for full-scale testing on the upcoming SeRANIS FlatSat will be the main focus of the experimenters.

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