Development of a multi-purpose SDR payload for the HYPSO-2 satellite

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Abstract—**Recent developments in flexible Software Defined Radio (SDR) platforms provide researchers with a framework for small satellite missions that combine several parallel objectives. A part of the mission for the HYPer-spectral Smallsat for ocean Observation (HYPSO-2) satellite from the Norwegian University of Science and Technology (NTNU) is to provide a responsive and agile service to the users where the on-board application software can be updated in flight. The radio-oriented part of the mission objectives spans radio frequency interference measurements and channel characterization in the selected frequency band – 400 MHz UHF – as well as a demonstration of communication services between the satellite and terrestrial sensor nodes and robotic agents. Energy-constrained sensor nodes in remote areas, such as the Arctic, is one of the application scenarios that would benefit from a tailored communication service. Even with services from emerging mega-constellations, traditional satellite communication systems, and new Internet of Things (IoT) over satellite services, there is a service gap for long-range-long-endurance robotic agents and Arctic sensor networks. Therefore, a better understanding of the radio frequency environment, including in-orbit interference as well as channel characteristics, can aid the design of responsive and robust communication links connecting individual assets of a larger System-of-Systems. Instead of just focusing on average spectrum interference levels, the frequency monitoring software enables the estimation of the interference dispersion and temporal variability. The HYPSO-2 is an evolution of the HYPSO-1 satellite, thus leveraging an already implemented mission software framework. Parts of the SDR payload have been tested on-board another satellite, and the in-orbit results from those measurements will be used as input for the next generation of the radio interference application.**

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1. INTRODUCTION

In this paper, we outline the research motivation and the design of a flexible Software Defined Radio (SDR) payload for radio channel research and communication experiments in the polar regions. The payload is based on a Commercial-Off-The-Shelf (COTS) SDR platform, the Totem from Alén Space (Spain) and will be launched with the HYPer-spectral Smallsat for Ocean observation (HYPSO)-2 satellite. The goal is a payload design that can adapt to system requirements and environmental constraints, such as varying Radiofrequency (RF) propagation and interference environments. An SDR payload can be designed for different sub-missions (radio environment research and communication to robotic agents and remote sensor systems) and fulfill various mission objectives, including missions conceived after launch.

Firstly, the research motivation is presented, then the mission design and how this is linked to related work and background. Lastly, we describe how the payload is integrated into the HYPSO-2 satellite, a CubeSat being developed at the Norwegian University of Science and Technology (NTNU) together with Nanoavionics. The HYPSO-2 satellite will also have a HyperSpectral Imager (HSI) payload for ocean monitoring, which is described in detail in [1], [2] and will not be covered in this article.

A need for more communication infrastructure

Monitoring the polar regions and the surrounding oceans is fundamental for understanding the Earth's evolving climate. Despite their extreme environment, several research cruises visit these regions to collect in-situ measurements [3]. However, due to the vast area and lack of infrastructure [4], it is difficult to obtain good sampling coverage of environmental parameters.

The use of autonomous sensor agents with on-board processing capacity and the emergence of System of Systems (SoS) [5] for environmental monitoring [6], [7] may relieve this situation. In this context, the sensor agent is either a remote sensing satellite, an in-situ stationary sensor buoy or a moving vehicle, such as an Unmanned Aerial Vehicle (UAV) or Unmanned Surface Vehicle (USV). The UAV and USV may also perform remote sensing tasks. The traditional approach to gather continuous in-situ sensor data from remote areas with no communication infrastructure is to deploy a sensor system and then, either collect the system after a given time or relay raw data to an operations center for processing and analysis. Smart sensors with on-board processing (edge processing) can do parts of the data processing in real-time, and then make decisions based on processing results. This includes selecting the most important information to relay to other agents or to the operators [8], [9], saving bandwidth and decreasing system latency and response time.

However, to enable utilization of edge processing and to realize a responsive SoS, there must be a way for the different Constituent Systems (CSs) to communicate with each other. Ideally, this communication should take place in near real time, especially for delay critical systems. This is lacking today, and motivates research on novel communication systems, both on the network layer, but also on new enabling components such as UAV antenna systems [10], [11], [12], [13], [14].

Emerging satellite services and service gaps

There are many new and emerging satellite based communication services that enable connecting sensor systems together in remote areas. Some examples are the operational systems such as Iridium NeXt, the emergence of Starlink and OneWeb mega-constellations, in addition to the many satellite based Internet of Things (IoT) services of various properties. The properties and performance of those different systems vary, and may meet user requirements for various scientific missions.

However, there are gaps worth researching, when it comes to *long duration, low energy* missions that require more than the low throughput provided by emerging IoT-over-satellite systems, but do not require a full broadband connection. For example, sensors deployed in the Polar areas or autonomous USVs. Another benefit is to provide distributed computing, where the different CSs can optimize in which asset the computation happens, depending on energy, data links, data latency, etc. Additionally, operating many different assets adds resilience in providing the capabilities, as one asset may take over if there is a fall-out. For Delay Tolerant Application (DTA) systems [13], like forwarding sensor data from in-situ sensors by satellite [15], it is possible to relay information through each CS' inherent communication system (as shown in [6]). However, for Delay Sensitive Application (DSA) systems [13], the direct communication becomes important. Time-critical Search and Rescue (SAR) and disaster management applications are important examples of such DSA systems.

Figure 1 shows how using sensor assets with different spatio-temporal properties, sensing instruments and field of view can be combined together to provide a more complete situational understanding. An overview can be obtained using remote sensing satellites and UAVs, and slowly moving robots with in-situ sensors can provide more detailed information. Effective and efficient relay of sensor data and metadata between the various assets help fusion of data from cameras and oceanographic sensors, such as temperature, salinity and bio-optics to better understand the biological phenomena.

Sensor agents are typically constrained in several ways, such as range, duration, energy, and size. Such constraints limit the use of otherwise efficient communication systems, as it is vital to adapt to the individual requirements for each asset. To meet the trade-offs between energy, physical size and usable data throughput, the choice of the frequency band is essential. Low frequencies, like VHF or UHF, provide better link budgets for simple antennas and enable low power applications to close the link between the satellite and the sensor agents. Higher frequency systems (broadband systems) require advanced antenna pointing and larger terminals [16], which may not be suited for small sensors and UAVs. The emerging IoT constellations target thousands or millions of sensor units, making the effective throughput for each of the sensors too small to be practical in a scientific operational context. For all these reasons, we argue that research on tailored communication services is needed, targeting the best possible utilization of the RF spectrum.

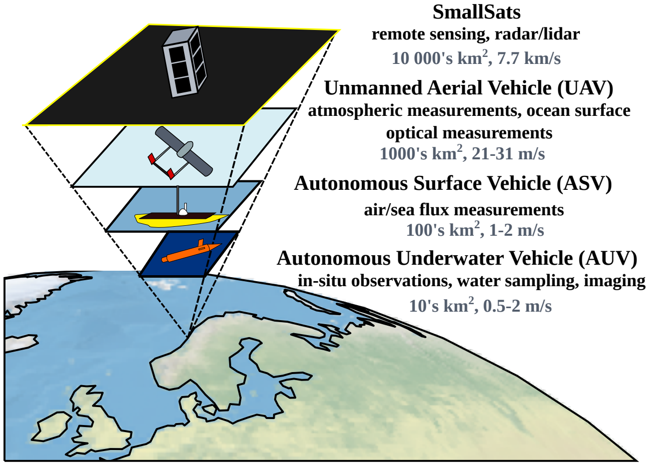

Figure 1. **The observation pyramid. A selection of agents observing a target with different spatial, temporal and spectral resolutions**.

In the next section, we describe the mission, its objectives and the preliminary concept of operations. In Section 3, we explain the related work, background and motivation for the research of the different sub-missions. In Section 4, we describe the implementation and integration of the payload into the HYPSO-2 satellite, as well as the hardware-in-the-loop setup for testing the communication missions. Finally, the findings and conclusions are outlined.

2. COMMUNICATION MISSION DESCRIPTIONS

Improvement of communication systems for harsh environments has been a topic of research at NTNU for several years [17], [18], [19], [20], [21]. At the NTNU SmallSatLab[2], the development of a flexible communication mission is an important objective [22].

This mission will be carried out through the second satellite from NTNU SmallSatLab. The main objective of the HYPSO-2 mission is to demonstrate a flexible in-orbit platform for near real-time oceanographic observations in coastal areas. It builds on the knowledge generated through the

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[2] `http://ntnu.edu/ie/smallsat`

HYPSO-1 mission. The satellite will be an edge computing node. Autonomously processed data will be shared between assets in an SoS, seeking to enable a concert of robotic agents through different communication architectures [6]. The flexible communication platform will also be used to characterize the RF environment, and to provide communication links between the satellite and other assets. In this paper, we will only address the communication-related parts of the HYPSO-2 mission.

The first satellite, HYPSO-1, will be launched in Q1 2022. The satellite is part of a science oriented mission featuring an HSI instrument that will observe ocean color. Analyzing the data will derive the presence of algal blooms [1]. Harmful Algal Blooms (HABs) can cause dramatic loss of live-stock in fish pens. Data from hyperspectral satellites can be a part of a monitoring and warning system alleviating this problem. For HYPSO-1, on-board processed data will be transmitted to the ground segment of the system, where data will be further processed and distributed to end users. Further improvement of this system is possible by allowing direct communication between the sensing satellite and sensor agents on or in the ocean [6], which is part of the objectives for HYPSO-2. A *system-of-systems* [23] consisting of multiple levels of sensor systems will be able to investigate the nature of an algae bloom more closely, compared to utilizing only Remote Sensing (RS) or in-situ measurements. As discussed above, the UHF band at 400 MHz is selected for this study.

Communication mission objectives

From the start, the communication payload on HYPSO-2 supports three main objectives, in a consecutive step-wise approach, where the final objectives build on the first two. Due to the flexible nature of the mission, new or changed objectives may be added at a later stage. The first objective is the most mature, and the last two will be further developed before and after launch of the satellite:

- **MO1**: Spectrum monitoring in the UHF (400 MHz) band.
- **MO2**: Characterization of the satellite channel for the UHF (400 MHz) band.
- **MO3**: Demonstrate two-way communication with sensor nodes (stationary or moving) in remote areas, including the oceans and the Arctic.
  - **MO3a**: Relay sensor data from remote sensor networks through the satellite.
  - **MO3b**: Forward Earth Observation (EO)-data from the satellite to autonomous in-situ sensor agents.

Spectrum monitoring—With HYPSO-2, we will be able to measure the time and frequency variability of the interference to contribute to the public state-of-art and use this information to design better communication systems.

A low complexity algorithm to measure the time and frequency characteristics of interference in the UHF radio amateur band has been designed, implemented and executed on-board the LUME-1 satellite in 2020 and 2021 [21]. An algorithm designed to detect opportunity windows in between interference events has been tested in the lab [24]. This is planned to be tested on-board a satellite in the near future. These two algorithms will be the first radio applications to run on HYPSO-2. The long-term goal is to implement an adaptive system capable of: 1) sensing the radio environment, and 2) perform Adaptive Coding and Modulation (ACM) to maximize the data throughput.

Channel characterization—While **MO1** considers measuring in-orbit RF interference, it is also important to characterize the channel from the satellite to the ground stations and sensor nodes. The first step is to estimate the impulse response of the communication channel by transmitting a known pseudorandom sequence to the different sensor nodes and correlating it with the received signal at the nodes. This will enable a characterization of the individual links in the system.

Direct communications to sensor assets—The final mission objective (**MO3**) is to enable direct communication between sensor agents and the satellite, either stationary sensors or moving robotic agents. There are two cases, the first one (**MO3a)** is where a terrestrial sensor has data to be distributed or relayed through the satellite. The second (**MO3b**) is where the satellite, HYPSO-2 as an example, makes observations that should be forwarded to in-situ sensors.

Since the communication payload is co-hosted with an HSI instrument, **MO3b** is given more consideration in this project. Distributing recent satellite sensor data to in-situ agents will aid real time planning of responsive in-situ measurements in the same area that the satellite observed. In order to reduce the response time and ease the requirements for terrestrial infrastructure (e.g., dedicated RF links, 4G, 5G or similar), the satellite should have a direct link to sensor agents. The agents can be informed by the satellite without first having to send satellite data to the Mission Control Center (MCC) through a ground station. This can reduce latency and increase the responsiveness of the system [6]. The mission research challenge is to design a robust and efficient communication link between the agents, based on the actual interference and channel characterization from **MO1** and **MO2**. This communication link needs to be implementable on the in-situ agents, within the constraints of a CubeSat and complying with the limitations on energy, mass and volume for the sensor terminals.

Suitable packet structures, modulations, effective error correction coding and interleavers will be implemented and tested. Furthermore, sensing the RF environment and adapting the communication to the channel and interference will enable the increase of the data throughput using ACM techniques.

The aim is not to create a generic IoT service, but rather show the possibility of making a mission-tailored communication system to support projects in need of responsive communication. This, within a reasonable cost and lifetime, compared to the overall project. A small satellite launched into an orbit of 500-550 km altitude will have an orbital lifetime of a few years, on the same order of a research project and expected lifetime of COTS electronics in space.

Operational concept

The operational concept for the different mission objectives are presented in the following:

Frequency monitoring and channel measurements—A simplified sequence for the frequency monitoring mission is shown in in Figure 2. The steps are:

1. **Upload measurement parameters**: When a ground station is within reach of the satellite, measurement parameters will be uplinked or added in the satellite schedule using a S-band communication link.
2. **Measurements**: The communication payload performs

the scheduled spectrum monitoring measurements, preprocesses and saves the results.
3. **Downlink results** The satellite will downlink the measurement results to the ground station using the S-band link.

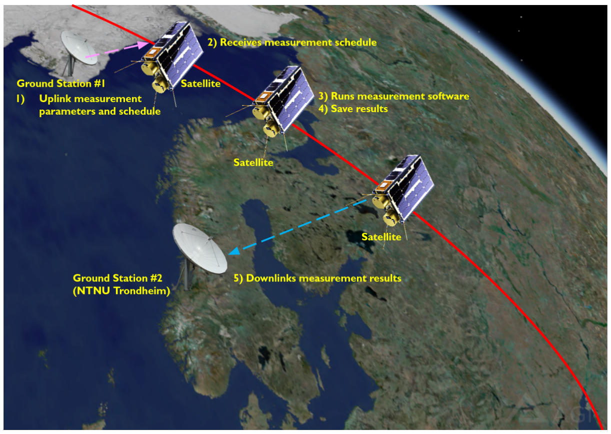

Figure 2. Operational concept for frequency monitoring.

For channel measurements the concept will be similar. First, a schedule and plan is uploaded, but instead of performing measurements, the satellite transmits a data sequence when it is over a ground station or terminal.

Test of communication link— In Figure 3, the operational concept of the direct communication between the satellite and sensor agents are shown.

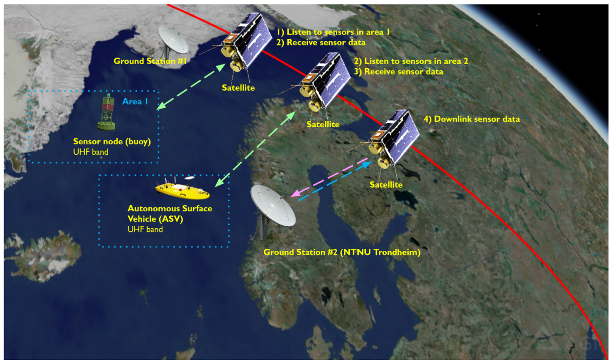

Figure 3. Operational Concept for direct communication with sensor assets.

For **MO3a** – relay measurement data from terrestrial sensors to mission operations:

1. **Listen for sensors**: The satellite will power on the payload and enable listening mode when it approaches an area with deployed sensor systems.
2. **Receive sensor data**: The satellite receives sensor data from sensors, and stores it.
3. **Downlink sensor data**: When the satellite is over a ground station, retrieved data from sensor nodes is downlinked and relayed to the mission operations center.

For **MO3b** – instruct in-situ agents based upon in-orbit processed EO measurements:

1. **Upload parameters:** Location and observational parameters for HSI-observations are uploaded when the satellite is over a ground station.
2. **Perform observation:** When the satellite is over the selected coordinates the observation is recorded.
3. **Process data:** After an observation the satellite processes data. If specific events or features are detected in the data, the satellite prepares instructions for the remote agent.
4. **Instruct remote agent:** The satellite forwards a measurement plan to the remote agent.
5. **In-situ measurement:** Based on the plan received from the satellite, the in-situ agent navigates to the area of interest and performs in-situ data collection
6. **Send data to operations:** The in-situ agent sends data about the observation to the mission operations (either through the satellite again, or through its designated network for command and control).

3. RESEARCH MOTIVATION AND RELATED WORK

The two research areas that the communication payload will address are radio environment measurements and communication with robotic agents. The first area includes both channel measurements and in-orbit frequency monitoring. The term frequency monitoring refers to interference signals and channel measurements refers to other degradation in the signal quality. Each research area has a different motivation and background, which are explained in this section.

Radio environment research

Link budgets are used in satellite communication system design to estimate the performance of the system. Depending on the frequency band selected, different effects must be considered. For frequencies below 1 GHz, ionospheric effects become more important than effects in other parts of the atmosphere [25]. These ionospheric effects are: Faraday rotation due to the Total Electron Content (TEC), time delays and excess rotations caused by ionospheric irregularities, dispersion because the effects mentioned above are not linearly dependent with frequency, and ionospheric scintillation that affects the amplitude, phase and angle-of-arrival of the signal [25]. There are models to estimate the ionospheric losses for satellite systems [25], but ionospheric physics are complex phenomena. Satellite measurements are important to validate and improve models. The TEC and radio scintillation can be measured by transmitting radio beacons from Low Earth Orbit (LEO) satellites, as in the Coherent Electromagnetic Radio Tomography (CERTO) constellation [26], [27] and analysing the signal received [28]. More general LEO satellite channel measurement campaigns in the UHF band were carried out in the end of the 20th century at 435.128 MHz [29] and 435 MHz [30]. In the second study, the measurements were used to model the channel and simulate the performance of different error correction codes. This approach can be taken a step further by testing the error correction codes in-orbit after measuring the channel to improve the system design.

In addition to the channel effects, interference signals can degrade the system performance further. Measuring interference through in-orbit frequency monitoring is important for several reasons. There has been an increase of satellite missions in the last years, such as the IoT-over-satellite constellations [31], [32], and the satellites from these missions need to communicate with the Earth not only for operations, but also to provide their service in the case of communication missions. In most cases, this communication uses the RF spectrum and requires frequency coordination with the International Telecommunication Union (ITU) and with the International Amateur Radio Union (IARU) for radio amateur purposes [20]. However, not all satellites apply to these organizations for frequencies and therefore, it is difficult to know the real availability in the frequency spectrum unless it is measured. In addition, satellite operations in certain bands have been challenging due to unexpected interference [33], [34], [20], [21].

Both universities and companies working with small satellites have identified the need to perform spectrum measurements. University of Würzburg, University of Berlin, University of Vigo and NTNU have published interference measurements in the UHF amateur radio band (430–440 MHz) in the last years [33], [34], [20], [21]. The European Space Agency (ESA) launched the OPS-SAT satellite, a flying laboratory capable of supporting many on-board experiments, including interference measurements [35]. In 2020, University of Berlin launched a satellite to continue spectrum monitoring activities. Companies like HawkEye 360, Aurora Insight, Kleos Space, Umbra and Horizon Technologies also work with RF spectrum monitoring and geolocation of interfering emitters.

Knowing the current status of the channel and interference characteristics allows for ACM, increasing the throughput of the system. This is especially useful for narrow-band communication where the bandwidth is already limited. In an SoS, where there are several communication nodes, the channel can differ from node to node, thus a system that can measure the status and adapt the link to that specific channel would be also be beneficial. The individual CSs in the SoS thus can be able to share information and adapt and re-configure in response to events [23], [36].

Communication with robotic agents and remote sensor systems

In-situ data obtained by different robotic agents is important for environmental monitoring, as RS has limited use in some cases. RS may not be able identify the signatures, or measure concentration, of all biological or chemical components in the water column, or measure under the ice. In addition, comparison of in-situ data and EO satellite data is important to validate the EO-data from satellites. A combination of both RS and in-situ measurements is beneficial to enable the scientific community to better understand environmental phenomena.

Kodheli et.al [37] and other studies discuss the various roles satellites may play in current and future heterogeneous communication systems, including 5G and beyond. Kodheli et al. discuss multiple use cases like back-haul of data from IoT networks. It is also discussed how new technologies including edge computing and prototyping based on SDRs may allow for flexible platforms where functionalities can be updated when needed. This also plays a role for creating enabling technologies for connecting UAVs and satellites [13], [14].

Enabling a near real-time integrated sensor agent concept as shown in Figure 1, depends on a communication link between the agents that currently is not available. In this case, *real-time* means that there is a link between the different assets so sensor data can be forwarded between CSs directly, not relayed through other ground systems. By exploiting existing communication systems to maintain a near real-time communication link latencies down to 30 minutes or below are possible [6]. Currently, there are no turnkey solutions for enabling the direct connection between a satellite and an in-situ robotic agent. The architecture shown in Figure 4 does currently not exist, and thus, is one of the research lines we pursue.

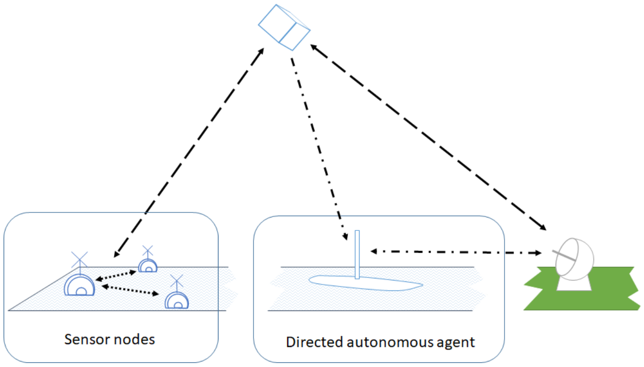

Figure 4. A flexible small satellite: The satellite can relay data from sensor nodes to a ground station, or it can direct an autonomous agent to an area of interest, based on observations made by, for example, a camera on-board the satellite.

In the case of remote sensors (on ground, in water or on ice), they operate in energy-constrained environments with batteries that may or may not be recharged by solar energy. Sensor nodes in the Arctic will not get any solar energy during the winter. Hence, they must consume as little energy as possible to maximize sensor operational time. A direct link to satellites will enable relaying of sensor data back to the researchers (or other end-users of the data). Such sensors generate a varying amount of data [38], [15]. In some scenarios on the order of a few megabytes per day. Further environmental constraints for sensors deployed in extreme environments, such as Arctic areas, call for no moving parts, i.e., mechanically tracking antennas. To summarize, there are common constraints to consider when mounting radio terminals on constrained sensor platforms (both stationary and moving):

- No moving parts (excludes terminals with mechanical tracking antennas).
- Moderate battery capacity (excludes high power and broadband solutions).
- The communication link must support a moderate data volume, on the order of megabytes per day [15].

Usability of existing or planned systems—For relaying sensor data from remote sensor (networks) to the operators or end-users through a satellite, there exist several solutions with different characteristics. These can be classified into three types (systems not covering the polar regions are excluded, and the list is not exhaustive[3]):

1. Broad-band
   - Existing examples: Iridium, Inmarsat
   - Emerging examples: Kepler, Starlink, OneWeb
2. Narrow-band (stream of data)

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[3] Information about the systems has been found on company web-pages or community databases such as [39], [40], [41].

- Existing examples: Iridium
- Emerging examples: VDES

3. IoT-over-satellite (single messages)
- Existing examples: Iridium
- Emerging examples: Astrocast Nanosatellite Network, Lacuna Space, Myriota, OQ Technologies, Swarm

The broadband solutions operate on higher frequencies, requiring higher transmit power or high gain tracking antennas. Therefore, they are of little use for many robotic agent applications and also individual sensors. The IoT constellations may trigger a revolution in accessing environmental data, health data for livestock and various forms of tracking data directly from a small sensor, by sending the data through a satellite network and deliver this information to the customer in near real-time. However, one of the common features of those systems, is the low data volume allowed for each sensor, which is on the order of 100 bytes a few times per day [42], [43]. This means that none of the IoT systems seem suitable if it is desired to transmit several megabytes per day.

Iridium has been used for stationary sensors and drones, both for command and control and to relay small amounts of sensor data [15]. Thus, Iridium can fulfill mission requirements in some cases, but more energy-efficient solutions operating on VHF or UHF bands may be desired [16]. These solutions represent a viable trade-off between energy requirement, non-moving antennas and the possibility of a large enough throughput if used in a dedicated, tailored system.

4. PAYLOAD IMPLEMENTATION AND INTEGRATION

The following sections describe the mission implementation, including the satellite platform, the selected communication payload, and the framework for development and hardware-in-the-loop (HIL) testing.

The HYPSO-2 spacecraft

The HYPSO-2 satellite is based on a similar platform to HYPSO-1, namely the Multipurpose 6U Platform (M6P) satellite bus from NanoAvionics(Lithuania) [1], and features the SDR communication payload in addition to a similar HSI payload as on the HYPSO-1.

The subsystems of the satellite include a Flight Controller (FC) for onboard data handling in cooperation with the Payload Controller (PC), that also acts as a router between the subsystems and the payloads. The FC also manages the pointing and orientation of the satellite through hosting the Attitude Control and Determination System (ADCS) functions. One important part of that system is a SatLab Global Navigation Satellite System (GNSS) for orbit determination and time synchronization. Furthermore, the satellite is equipped with an Electrical Power Subsystem (EPS) for power management and a UHF radio for Telemetry and Telecommand (TM/TC) and basic communications. The internal communications bus is based on CubeSat Space Protocol (CSP) over Controlled Area Network (CAN), where each subsystem is a network node with its dedicated CSP address. The satellite will be equipped with a SatLab SRS-4 S-band transceiver, capable of up to 4 MBps downlink and up to 200 kbps uplink transfer rates. Compared to HYPSO-1, there will upgrades of the power system, such as deployable solar panels providing extra power and energy for the payloads. In addition, there will be an upgraded communication link between the HSI payload processor and PC and a higher downlink speed.

In order to enable flexible missions, the payload itself must be adaptive and re-configurable in-flight. Hence, an SDR is the best payload implementation for this type of missions. The key feature with an SDR is that it is re-programmable and can be used to run very different radio applications. The payload shall be a platform and framework suitable for ensuring mission success for different communication missions using the same payload but acting as different virtual payloads. Also, this flexibility enables re-organising and changing mission objectives throughout the full spacecraft lifetime, adapting to in-flight experience and newly discovered to research needs.

Selected communication payload

An SDR survey was performed in 2018 [44] and complemented in 2019 [22] to choose the right platform for the HYPSO satellites. The most suitable SDR was the *Totem* SDR from Alén Space (Spain).

The Totem physically consists of two main parts: 1) the motherboard with the processing system, based on the Xilinx 7020 Zynq System on Chip (SoC), which includes both ARM processors and an Field Programmable Gate Array (FPGA) [45]; and 2) a radio front-end with filters and amplifiers for the selected frequency band. The system runs an embedded Linux operating system. Radio applications on Totem can be developed on different abstraction levels from high-level Python, C programming to low-level FPGA-implementations. In addition, the SDR has flight heritage through the LUME-1 mission [46] and frequency monitoring research activities carried out from the same satellite [21].

Payload software architecture

The HYPSO software stack mainly consists of two parts: an operator interface named `hypso-cli` and the payload service program called `sdr-services`. The operator interface is run on ground on a computer with a communication interface to the satellite. This may be either directly through the CAN bus for testing in the lab, or through the mission control system including a radio link. For the operator, this connection is nearly transparent. The service part runs on the payload processor as a normal program.

The HYPSO-1 payload software architecture is described in [47]. For HYPSO-2 this architecture is expanded so that the architecture supports multiple payloads. Much of the basic on-board software services share a common base code, with some adaptations and tailoring to the specific payload systems. In practice, this means that each payload hosts its own Linux-based operating system, and individual services related to the *payload functions*, such as operation of cameras or the radio applications for the SDR. Other common services, such as telemetry, file transfer, CSP interface and Operating System (OS) service are similar and share a common base code. Through this architecture, it is easy to add different types of payloads to future satellites with a high degree of code reuse with little effort. The SDR software payload architecture is shown in figure 5. The *Radio service* serves as the interface to the SDR functions, and is used as an interface layer between an operator and the SDR. Strictly speaking, the SDR interface may be directly accessed through the use of the *File Transfer Service* and the *OS service*, but the *Radio service* wraps functionality and operations into a more user-friendly environment.

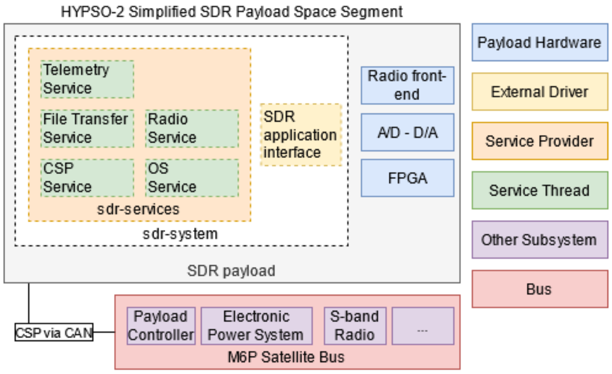

Figure 5. **Payload software architecture.**

Payload functions (radio applications)

The main advantage of an SDR payload is its flexibility and re-programability. Programs can be uploaded in-flight as soon as they are developed and tested. There are two radio applications for frequency monitoring that have been developed for the LUME-1 satellite that will be used as a base for the first applications in HYPSO-2. These applications were designed to conform with the constrained downlink data rate from LUME-1, but the program can be modified to take advantage of a better downlink. Due to the capacity of the S-band radio link that will be used in HYPSO-2, a lot more data can be downloaded, as the gross downlink rate increases from 4.8-9.6 kbps from LUME-1 to up to 4 Mbps for HYPSO-2. Future work will involve the development of new radio applications for channel characterization and communication with sensor nodes and robotic agents.

Local Mean Estimator (LME) algorithm—The first application measures the time-frequency characteristics of the in-orbit radio environment using a Discrete Fourier Transform (DFT) and a Local Mean Envelope (LME) estimator [21]. The application consists of: 1) a shell script that manages individual measurements, and 2) a C++ program based on GNURadio. The script calls the measurement program at the set time, compresses and prepares the generated files for download. The measurement program acquires the raw In-Phase Quadrature (IQ) samples from the transceiver, calculates the magnitude of the DFT of the number of samples specified and estimates the LME. The second order moment (m_2) of the mean for different window lengths is calculated. By analysing how the m_2 varies depending on the length of the window, the time variation of the interference can be estimated. The number of time windows can be four, six or eight, and the length of the first window and the step between them can be specified. The center RF frequency, bandwidth, sampling rate, duration of measurements and number of frequency bins can also be configured. By doing this processing in orbit, it is possible to measure over a larger area while still keep the generated data volume manageable for download.

Opportunity window algorithm—The second application has a similar software architecture and focuses on the time characteristics of the interference. A shell script controls the timing of execution of the measurement program, and then, compresses the resulting processed files. The program is written in C++ and estimates when there are time windows with low interference level. The power of the received signal is calculated from raw IQ samples. An opportunity window is detected when the power is below a certain threshold continuously for a defined time (configurable). The signal will spend time in opportunity windows of different lengths, and these windows can be grouped in intervals. Furthermore, the opportunity windows can be estimated for different power thresholds. The output of the program is the opportunity distribution that estimates how long the signal is in windows of opportunity of different lengths for different power thresholds. The opportunity windows indicate time slots where transmissions can be performed to avoid loss of packets due to high power interference.

Testing and Hardware-in-the-loop

The development and testing of the radio application followed a step-wise methodology. First, the applications were developed in a high-level programming language (Matlab). Interference signals were generated in software and the algorithms were tested in the simulation framework. Second, the software was ported to C++, and executed on a computer. The program collected raw IQ samples from the Totem using a remote connection over Internet Protocol (IP). The third step involved porting the software to the Totem platform and run it on the Totem itself. The full testbed for functional testing consisted of two SDRs (see Figure 6). A USRP-2901 SDR was connected to a computer to transmit simulated in-orbit interference (different test signals). This was achieved by running GNURadio programs on the USRP. The USRP is connected to both the Totem SDR to receive the input test signals for the radio applications, as well as to a spectrum analyser for debugging purposes. At this stage, the Totem SDR operated independently of the rest of the satellite system, remotely controlled via Secure SHell (SSH) and powered by a stand-alone power supply.

At a later stage of the project development, the Totem SDR was integrated into the FlatSat for HYPSO-1, to aid subsystem integration. This was achieved by replacing the external power supply and connecting Totem directly to one of the EPS output channels. The CAN interface of the Totem was connected to the payload CAN bus of the FlatSat, as shown in Figure 6. In addition to the sub-systems physically in-house at NTNU, the FlatSat has a network connection to the satellite suppliers site, giving remote access to other subsystems, such as the FC. For all subsystems and the operator, the physical location of the subsystems does not matter, as in the end they are all connected to the same physical CAN network. This setup enables parallel system integration and a full hardware-in-the-loop testbed, where SDR applications can be run from the FlatSat. Furthermore, multiple students can work with the same system at the same time. This process builds on, and extends, the work described in [48].

5. MAIN FINDINGS AND DISCUSSION

In this paper we have described the development of a flexible smallsat communication platform that can enable multiple missions, spanning three main mission objectives. The selection of a COTS SDR platform and the preparation of the implementation for the first mission objective are described. Furthermore, we show how the SDR was integrated into an existing satellite platform and software framework with little effort.

The main advantage of an SDR, reprogrammability, is exploited to define multiple flexible missions using one satellite payload. The main mission objectives should be defined

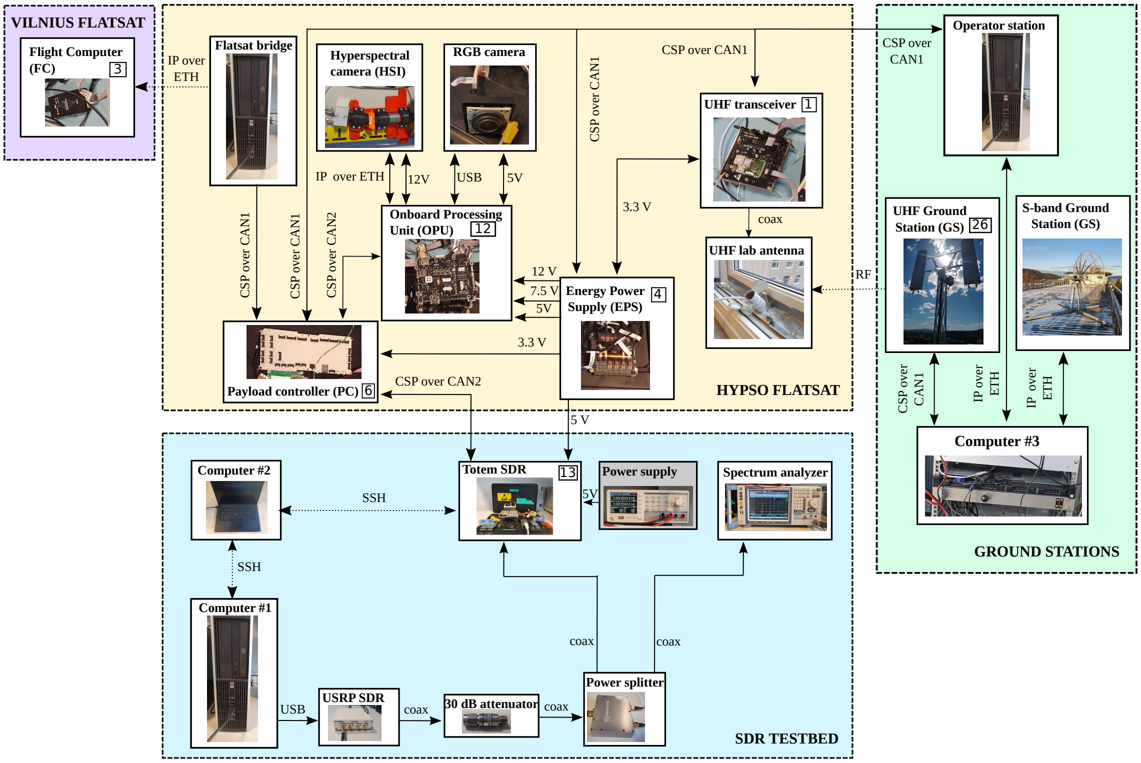

Figure 6. **The HYPSO-2 testbench and FlatSat architecture. CSP addresses are indicated with a small square inside the component.**

early, but the specific functionality can be specified at a later stage. Since the radio applications can be updated throughout the mission it is possible — and desired — to design the mission in such a way that functionality for the first mission objective is completed by launch. Development of radio applications to fulfill the other objectives rely on outcomes and results from the previous mission, and will therefore be developed iteratively while the satellite is in orbit. Frequency monitoring measurement methods and processing algorithms have been tested in orbit on the LUME-1 satellite [21], and will be further developed and adapted for the HYPSO-2 satellite with different downlink and power constraints. The HYPSO software framework was extended and refactored to accommodate a second payload with little effort [47], and the SDR was incorporated in the common HIL framework.

Results from this satellite project may contribute with more and global in-orbit interference measurement data in the 400 MHz band. It will also make a framework for incorporating channel estimation into an adaptive radio link that can bind sensor agents, such as the satellite itself and in-situ agents, together to deliver a more complete picture of environmental factors in selected areas. This is a vital enabler for resilient and responsive SoS for environmental monitoring. The 400 MHz UHF band is selected as non-moving antennas and low power devices can be used while still closing the link between a remote agent and a satellite. We argue that the emerging IoT constellations do not fit the use case of relaying moderate amounts of data from remote sensors, nor enabling connectivity between an EO-satellite and an in-situ agent. A tailored communication service, adapted to the specific needs of a mission should be the goal, and this can be realized by utilizing the flexibility of an SDR platform to maximize the system data throughput using limited RF spectrum.

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