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An SDR mission measuring UHF signal propagation and interference between small satellites in LEO and Arctic sensors

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ABSTRACT

Enabling communication to sensor systems in the Arctic is a challenge due to the harsh climate, limited infrastructure and its remote location. In this paper a communication system for Arctic back-haul serving low- power devices to complement existing services is discussed and two small satellite missions are defined. The communication mission objective is to provide Arctic researchers with faster access to scientific data. However, a precursor mission is needed to gather data about the UHF communication channel and interference in the Arctic to design a reliable communication system between Arctic sensors and LEO (Low Earth Orbit) satellites. An SDR (Software Defined Radio) payload is proposed to fly on a small satellite as a secondary payload in order to carry out the radio measurements in a flexible way. The challenges of being a secondary payload are also outlined.

INTRODUCTION

The areas where global warming effects are most dramatic are the Arctic, Antarctica and the Tibetan Plateau. Monitoring of these places is very important to the World Climate Research Program (WCRP) and International Geosphere-Biosphere Program (IGBP) [1]. The specific use-case addressed in this paper is based on The Arctic ABC programme [3], working on the deployment of sensor nodes in Arctic ice to measure various parameters, such as temperature and light in the water column [2].

However, collecting data from those nodes is challenging as there is not sufficient telecommunication infrastructure in this area [4]. Researchers that make long and expensive expeditions to retrieve their data face the dangers and the cold of this region. Thus, reducing the frequency of their trips, and maintaining or increasing measurement data collection is beneficial. Some satellite service providers can offer a communication service in the Arctic depending on the requirements [5].

An emerging alternative to complement existing data retrieval methods is to deploy a coordinated infrastructure. It can be composed by different types of vehicles and platforms, such as Autonomous Underwater Vehicles (AUVs), Unmanned Aerial Vehicles (UAVs) and small satellites [6].

This paper describes how to approach the design of this Arctic communication system. First, identifying the stakeholders and their needs, defining the problem statement and outlining the current alternatives to collect sensor data in the Arctic. Second, two small satellite missions are defined: the *Communication Mission* and the *Precursor* or *Measurement Mission*. Third, since there may be a flight opportunity for the *precursor mission*, some mission and design parameters have been adapted to it. The system architecture, the impact of the potential orbit, mass and volume considerations, placement of antenna ad challenges as a secondary payload are described. Finally, a short conclusion is included.

IDENTIFICATION OF STAKEHOLDERS AND NEEDS

The stakeholder analysis is a vital part of developing a mission to ensure that the system satisfies the needs and requirements of the interested parties [7]. The stakeholders for the long-term goal of the Arctic communication system have been identified in Table 1 and classified as primary or secondary according to their involvement in the project. The stakeholder analysis is updated continuously through the project and is important especially during critical design decisions to maintain a focused system design.

Table 1: System stakeholders

Stakeholders	Involvement	Needs
Arctic researchers	Primary	-Need frequent access to scientific data. -Affordable service
Sensor equipment	Primary	-Antennas and transceivers that fit in the structure -Low power transceivers
Environment	Primary	- Mechanical structures must be fixed -No solar energy during winter
Suppliers	Primary	Exchange of models and requirements in a simple format. Usually a known, standardized format.
Regulatory organizations	Secondary	Compliance

Researchers	Secondary	Communication researchers needs: learn, make a feasible solution and publish.

The *Arctic researchers* are the primary stakeholders in this system because they are the ones who need the data. Furthermore, the *Sensor equipment* influences the type of system architectures and design parameters such as frequency, data budget, mission and concept of operations (CONOPS) design. The *Environment* and *Regulatory organizations* impose the limiting constraints for the system, such as frequency band, operating temperature range, maintenance limitations, etc. Researchers (communication researchers) need to learn about the communication channel to be able to develop a feasible solution and to publish results. The needs of these researchers are the reason why a *precursor mission* is suggested before the *communication mission*.

PROBLEM STATEMENT

Communication infrastructure in the Arctic is limited [4]. The harsh climate has a direct impact on system implementation. The equipment must be designed for power efficiency as in the winter there is no sun to charge the batteries with solar power. In addition, the structures must deal with icing of mechanical parts which makes mechanical design challenging.

To achieve high data rate links in satellite communications, it is common to use dishes as high gain antennas. They close the link and achieve high data rates, but they are steered mechanically. Due to this issue, antennas need to be either omnidirectional or steered electrically to track a satellite. Since robust energy efficient high gain antennas are unavailable for sensor nodes in the Arctic, lower frequencies bands such as VHF (Very High Frequency) and UHF (Ultra High Frequency) are desired.

CURRENT ALTERNATIVES

The traditional ways of retrieving scientific data are (1) to go on expeditions to physically collect sampled data from the sensors, or (2) to use existing satellite services. Expeditions are costly due to the harsh conditions of the area. There is extreme cold and dangerous local fauna. In these remote areas existing satellites services are also quite expensive and dependent on service providers. Iridium is a satellite service that is commonly used. It has coverage in the poles and offers services to transmit short data messages from monitoring equipment to host computers. Data rates are quite low, energy consumption for the data transmitted has room for improvement and the cost per gigabyte is high. Iridium NEXT is meant to increase the data rate with speeds of 22 Kbps to 1408 Kbps [8] with Iridium Certus. It should be operational in 2019, but there is no publicly available information about the specifications of the transceivers, such as size and power consumption. Low power consumption is an important constraint in this scenario.

The use of a flexible communication system for heterogeneous network using small satellites and AUVs can complement expeditions and existing satellite services [9]. This solution can be more tailored to the problem using Arctic ABC as a use case. Currently, this Arctic programme uses Iridium Short Burst Data (SBD) messages and an airplane solution [2]. They rent a Dornier DO-228 (Lufttransport AS, Norway) and establish a communication link between the radio of the sensor node and another radio in the aircraft to retrieve large amounts of data. Both alternatives are costly. Data requirements for Arctic sensors are shown in Table 2.

Table 2. Data requirements from sensor nodes [2].

Sensor nodes	Data size per year	Data size per month
AZFP 1	1 GB	83 MB
AZFP 2	2.84 GB	236 MB
Echosounder	100 GB	8,333 MB

COMMUNICATION MISSION

The *Communication Mission* is described in the following section. It is a mission that fulfills the problem with the architecture described in the previous sections.

A flexible communication mission can be carried out using a Software Defined Radio (SDR) as payload. Measurement software can be upgraded in-flight after analyzing results to maximize capacity when possible. Communication parameters can also be modified in-flight and Adaptive Coding and Modulation (ACM) may be developed in software. The capability of reprogramming the SDR both for measurements and communication makes it a key component in the design of the mission.

The mission statement is: a space-based SDR system shall provide Arctic researchers easier and faster access to scientific data products. This mission is a technology demonstrator. It will prove concept and system viability by acquiring sensor data where there are harsh environments that induce high operational risk and costs.

Table 3. Communication mission objectives.

MO-001	Spacecraft shall gather data of different types from ground sensor nodes in the Arctic.

SMO-001	Reduce or eliminate the need of manned expeditions, by enabling access to data from sensors in the Arctic.
SMO-002	Maximize data throughput by using ACM depending on current channel characteristics

Satellite communication using UHF frequencies gives lower data rates than S-band and X-band. In addition, there is a lot of interference in this band due to the growing number of small satellites launched [10]. Thus, to maximize data throughput both the channel and the interference should be measured and characterized.

PRECURSOR MISSION

The first part of the mission consists of channel and interference measurements to be analyzed and considered for the design of the communication system. The results obtained will narrow down possible communication parameters (modulation, protocols, …) to be used.

The second part of the mission will deal with the communication link to the sensor nodes. This operational mode will include a technology demonstration for retrieval of scientific data from sensor nodes in the Arctic.

In Table 4 user needs for the precursor mission are specified as user requirements. The first three requirements are related to the data products needed to learn about the channel and the interference. The technological demonstration aspect is reflected on SDR-UR-004. The last two requirements come from the Arctic use case, the area of interest and the target frequency bands. Even though the communication mission is focusing on the Arctic, measurement further south, starting from 60 degrees north (southernmost part of Norway), are still relevant. The specific band of 400-440 MHz is selected because: there are bands for Earth Exploration Satellite Service (EESS) in 401-403 MHz for uplink, a band in 400.15-401 MHz for space research and space operation for downlink, and amateur service within 430-440 MHz [11]. Amateur band can be measured since many small satellites are using for operations and the other bands can potentially be used for the communication mission.

Table 4. Precursor mission user requirements.

SDR-UR-001	Create spatial-frequency heat maps of radio interference
SDR-UR-002	Estimate time and frequency statistics of radio interference.
SDR-UR-003	Estimate downlink channel impulse response.
SDR-UR-004	Establish a communication link with a sensor node prototype
SDR-UR-005	The area of interest is north of 60 degrees north.
SDR-UR-006	The frequency band shall be UHF: 400-440 MHz

The precursor mission objectives are less ambitious, as the main goal is to learn. The new objectives are described in Table 5. The first two objectives are purely for measurements and learning, whilst the following two are oriented towards the technology demonstration. In order to test different communication schemes depending on measurement results, SDR-SMO-004 was added.

Table 5. Precursor mission objectives.

SDR-MO-001	To measure radio interference and perform downlink channel measurements for future communications in the Arctic.
SDR-SMO-001	To measure downlink channel in UHF using sensor node antennas.
SDR-SMO-002	To establish a basic communication link to a sensor node prototype.
SDR-SMO-003	To demonstrate communication in the Arctic.
SDR-SMO-004	The system shall allow for update in flight.

To achieve the first objectives (SDR-MO-001 and SDR-SMO-001), three types of measurements will be performed with the SDR payload. The purpose of these measurements is to understand channel characteristics and interference so that they can be used in future missions. Measurement types are:

- *Interference calibration*. Reference signals will be transmitted from our ground station to calibrate the measurements for real interference.
- *Interference*. SDR payload will sense the radio environment for interfering signals.
- *Channel measurements*. SDR payload will transmit a specific training sequence that when received on ground is used for downlink channel impulse response estimation.

As stated in Table 5, a secondary objective (SDR-SMO-002 and SDR-SMO-003) is to establish of a communication link between the satellite and a sensor node. The sensor node can be a lab prototype or even a buoy in the Arctic to demonstrate the whole system. An antenna has been designed for the sensor considering the constraints imposed by the Arctic environment. This objective is planned to be tested in future updates of the SDR software.

FLIGHT OPPORTUNITY

The HYPer-spectral Smallsat for Ocean Observation (HYPSO) mission [12] will be launched in a sun-synchronous polar orbit to observe ocean color along the coast of Norway. Its specific mission is to detect and characterize ocean color features such as algal blooms, phytoplankton, river plumes. etc. The spacecraft will be a 6U CubeSat structure, provided by NanoAvionics LLC. The CubeSat is equipped with a hyperspectral push-broom imaging payload (hereafter called HSI) which has on-board processing capabilities. The volume of the HSI payload, requires a 6U satellite bus, but the HSI payload does not occupy the full space.

The SDR payload can be a part of this CubeSat mission, where the SDR functions as a secondary payload. The SDR can fit in the extra space of the HYPSO mission to “fill in the whole space” and ensure maximum utilization of the launch opportunity. The secondary mission of HYPSO can then be the *Precursor Mission*.

The established HYPSO mission requirements will be considered *constraints* and the SDR payload, including the antenna, will be adapted to fit HYPSO. The chosen SDR platform is a *design decision* from which some of the requirements are *derived* from. The requirements have been developed through workshops using the software CORE9 from Vitech Corp, VA, USA supporting Model-Based Systems Engineering (MBSE). The requirements have gone through several iterations, with the focus of being lean by limiting the number of requirements and making them usable to the designers. The following gives a short background from the HYPSO mission parameters that influence the SDR mission.

A. System architecture

The system architecture of the SDR (Figure 1) mission consists of the ground segment and the space segment.

In the ground segment there will be a ground station network and sensor node prototypes for the future Arctic communication system. The S-band ground station will be used as main Telemetry, Tracking and Command (TT&C) for the HSI, and to downlink interference measurement data. The UHF ground station is a backup for TT&C and it is also used to perform downlink channel measurements and transmit reference signals for calibration. Sensor nodes prototypes for future Arctic communications will be used to do channel measurements for the use case and to demonstrate a communication link.

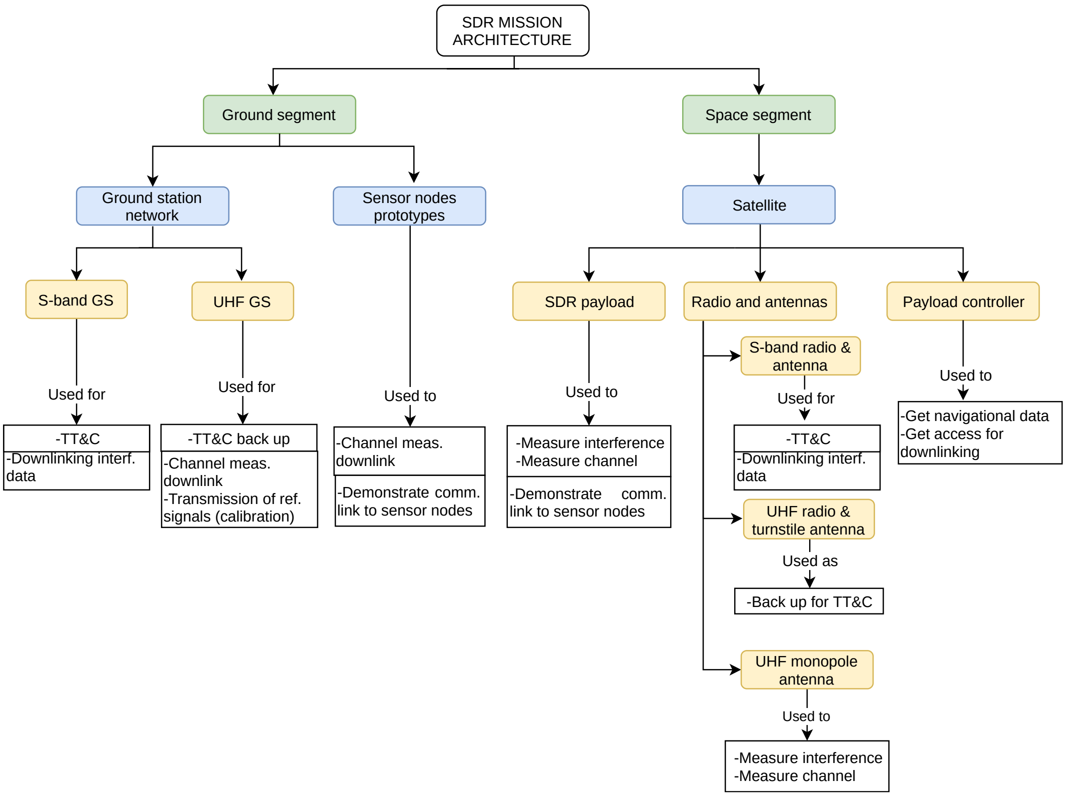

Figure 1: System architecture

The space segment is formed by the satellite. The SDR payload will measure both radio interference and communication channel. It will also demonstrate a communication link with sensor nodes prototypes. The S-band communication components will be used for the same as the S-band ground station. The UHF radio and turnstile antenna will be TT&C backup. The SDR payload will use the UHF monopole antenna for the measurements to avoid interfering with main communications or data link of the spacecraft. The SDR payload must communicate with the payload controller of the satellite bus to downlink data through S-band and get navigational data.

The main constraints for the design of the payload are cost and development time. Schedule constraints are very important in the trade-offs for the secondary mission to be compatible with HYPSO project.

A total of 21 SDR platforms have been analyzed and have been part of a high level assessment in [13]. An extra alternative was found after that study, TOTEM SDR from Alén Space. Power consumption is quite low compared to the alternatives, it includes the Radio-Frequency (RF) front-end and its noise figure is 2 dB. The transceiver chip has only one transmitter and one receiver chain. Nevertheless, as cost is reasonable, and it provides high level of flexibility it was decided that this platform will be the SDR payload of the mission. Since SDR-UR-006 states that the frequency band should be between 400-440 MHz, but the front-end filters have a bandwidth of 10 MHz, a bypass was included. Signals in this branch (additional RF I/O in the picture) will not pass through the filters and amplifies of the front-end. This was the only solution found to avoid connecting another front-end board. More detailed characteristics can be found in Table 6.

Table 6. TOTEM characteristics.

Extra components required	None
Interface to CubeSat bus	CAN
Space readiness	Space proven
Power consumption	TX: 5.1 W @30 dBm RX: 2 W Idle: 1.4 W
Dimensions	22.93 x 89.3 x 93.3 mm (PC104)
Shielding	Included
Mass	150 g
Frequency range	70-6,000 MHz
Bandwidth	0.2-56 MHz
Transceiver	AD9364
Noise figure	2 dB (front-end)
Processing unit	Based on Zynq-7020 SoC -Dual ARM Cortex-A9 -FPGA
SDR framework	Access to low (VHDL) and high-level programming (C, C++, GNURadio)

In Figure 2 the architecture of TOTEM platform and how it can be connected to the antenna is shown. This platform is formed by two boards: RF front-end (analogue part) and SDR motherboard (analogue stage, analogue/digital conversion and digital processing). The SDR motherboard consists of an RF transceiver (AD9364) and a System on Chip (SoC) based on Xilinx boards, which has a Zynq 7020.

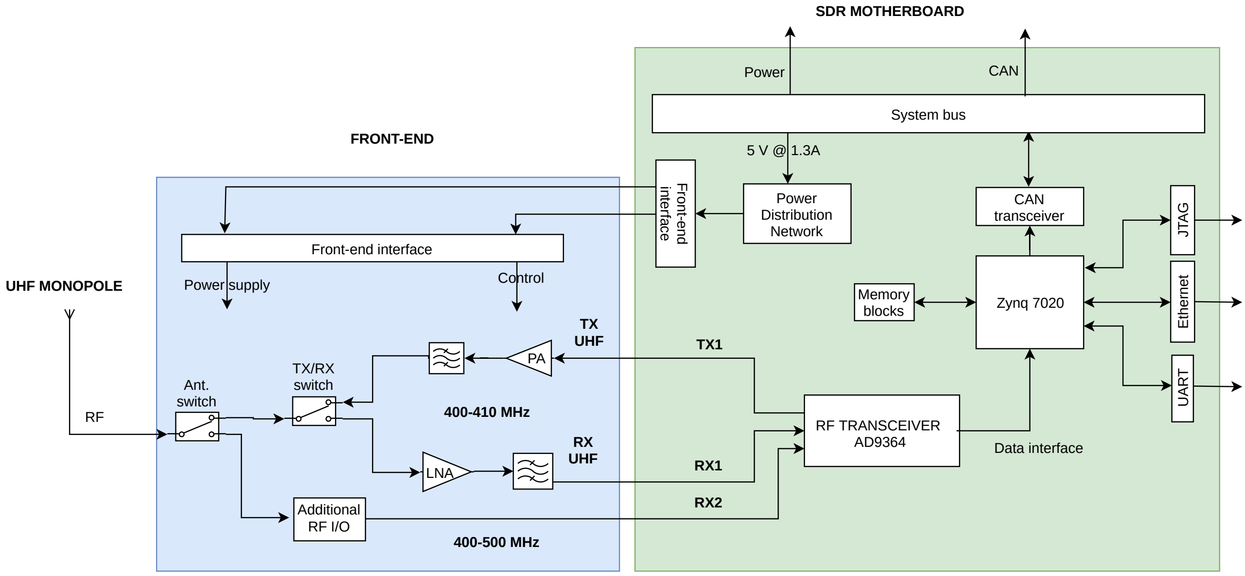

Figure 2: SDR payload architecture.

B. *Orbit*

The orbit in the flight opportunity is the same as for the HYPSO mission. The chosen orbit for HYPSO is a morning sun-synchronous orbit (SSO) at 500 km altitude because of a preferred observation area on the coast of Mid-Norway, and ground infrastructure in Trondheim and Svalbard. It is expected that the inclination will be 96-98°.

The area of interest of the SDR measurements are north of 60°. Having a polar orbit is the only requirement needed to do so. Given the orbit characteristics above, the satellite will fly over the area of interest 15 min per pass approximately.

C. *Mass/volume*

The volume of the spacecraft is 6U, leaving room for the SDR payload in conjunction with the HSI payload. Because the SDR payload radio does not require much mass nor volume, the constraints imposed by the HYPSO mission do not influence the radio module itself. Except for the choice of antenna and antenna placement, described in the next section. The SDR radio has masses that influence the spacecraft's moment of inertia and center of gravity, but the internal configuration and the arrangement of subsystems within the spacecraft do not influence the mission significantly.

In addition, a mechanical interface for TOTEM is required. The SDR has a PC104 form factor, but due to the placement of the HSI and other components in the bus, the SDR has no available space to be mounted on stacking rings used for PC104. Therefore, an alternative mounting assembly had to be designed. The custom hardware interface (Figure 3) consists of: mounting plate, base plate as a platform for mounting, cylinder spacers to extend the support from the base plate to the SDR and provide a stable base and a support plate to provide support for the rods and reduce the moment that the SDR may impact on them.

Figure 3: Mounting assembly for the SDR payload.

The SDR mission designers must work closely to ensure transparent and up-to-date communication with the HYPSO spacecraft designers not to compromise the main mission of the spacecraft. Thus, a mass budget for the secondary payload is required. The payload mass budget of the SDR payload is shown in Table 7. The UHF monopole antenna is not included in the payload budget as it is included in Nanoavionics satellite bus.

Table 7. Payload mass budget.

Subsystem	Nominal mass (g)	Margin (%)	Mass with margin (g)
SDR front-end (TOTEM)	20	20	24
SDR motherboard (TOTEM)	130	20	156
SDR mounting assembly	299.7	20	359.64
Total (payload)	449.7		539.64

D. *Antenna*

The HYPSO mission is equipped with two imaging payloads that need a specific FOV (Field of View) to operate. These parameters give the main constraint on the antenna design for the SDR: SDR antenna placement shall not interfere with any of the imaging payloads. The FOV of the HSI is assumed to be ±4.22° and the RGB camera has a FOV of ±35°. The HSI will be placed in the middle of the 2U side of the satellite (3U axis aligned with Earth radius) and the RGB in the middle of one the 1U in the same side.

The satellite bus has three antennas: one S-band patch antenna, one UHF turnstile and one UHF monopole antenna. For channel measurements a turnstile antenna with an omnidirectional pattern would be desired to easily distinguish the effect of the antenna pattern from the channel or interference effects. However, the turnstile antenna in the bus is used for communication during Launch and Early Orbit phase (LEOP) and as a backup for TT&C. Thus, the SDR can only utilize the UHF monopole which may only be deployed if it does not interfere with the FOV of the imagers.

Figure 4 shows a placement of the antenna to get compromise between an omnidirectional antenna pattern and camera FOVs. Assuming a 15 cm monopole, the antenna must be placed so that $\Delta x_1 > 1.1$ cm and $\Delta x_2 > 10.5$ cm, shown in Figure 4. Monopole will be placed 11 cm from the center of the RGB camera.

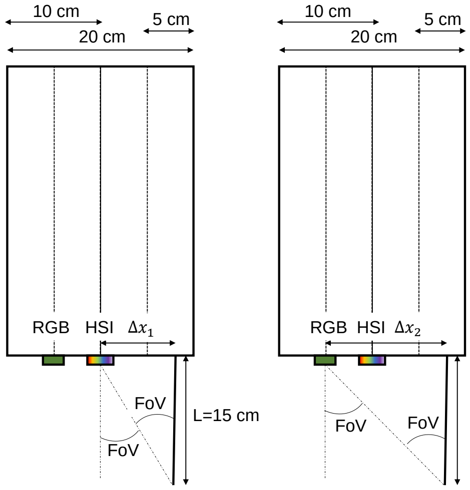

Figure 4: Antenna placement (a) impact on the HSI, (b) impact on the RGB camera

E. Challenges as a secondary payload

If a secondary payload is added to the satellite after the satellite bus is selected, this payload must be adapted to the bus. The most important requirement for a secondary payload in this case is to limit the impact on the primary mission. This must be ensured during integration, thermal analysis, system budgets and testing.

Integration of a payload consists of mechanical, electrical and software integration. The secondary payload must be mounted in the satellite bus. A custom mechanical interface may be required to attach it, as has been explained in section C. Secondary payload software should be integrated with primary payload to ensure compatibility and consistence. Control software to communicate with the bus and to downlink payload data could be reused from the primary payload if properly adapted to the secondary payload. Software development time can therefore be decreased. In addition, electrical interfaces of the secondary payload must comply with the interfaces of the bus for electrical integration. Thus, the secondary payload can only use the types of interfaces that the satellite bus can offer, reducing the flexibility of operations.

Thermal analysis must be carried out both for the secondary payload alone and the complete satellite. Turning the payloads on and off during operations will have a high impact in the thermal analysis. The temperature of a component that has no power supply will be very low. The contrast with a payload that is transmitting signals, for example, can be drastic. Thermal simulations should consider all payloads modes.

System budgets must be modified to include another payload. Not only the mass increases in the mass budget, but the center of gravity and moment of inertia are also altered. The power budget is critical since both payloads will consume power. The depth of discharge of batteries should not decrease below the recommended threshold. Thus, idle power consumption may become a problem. In HYPSO a solution that is under consideration is to turn off the secondary payload during primary mission operations. Not being capable of turning off secondary payload after operations or turning it on by accident become new risks to the mission. The data budget is also affected by adding a new payload, since more data must be downlinked. Primary payload data will have priority, and this must be accounted for in secondary mission operations. Furthermore, the pointing budget must be revised. Mapping and pointing errors should be calculated again because they depend on the spacecraft assembly, for example on thermal distortion and mechanical jitter.

Operations should also be updated. The scheduling of operations, automatic generations of commands and telemetry data must accommodate for both payloads. Operations from secondary payload shall not interfere with primary mission. In addition, the Mission Control Centre (MCC) must be modified. Its software must include a new database and new graphical user interface for the secondary payload operations. New frequency filings may be required to control the new payload.

The main mitigation of all risks is for the secondary payload to undergo thorough testing including environmental testing and Electro Magnetic Compatibility (EMC) tests. Furthermore, automatic tests should be run on all software. A proper Assembly Integration and Test (AIT) plan should be developed including two payloads.

CONCLUSION

To complement some expeditions and existing satellite services, a coordinated infrastructure with different types of vehicles including small satellites is proposed. The long-term goal is to provide Arctic researchers with easier and faster access to scientific data.

Through systematic stakeholder analysis needs and requirements for an SDR-based communication system are established. Following this, a *Communication Mission* aiming to fill the gap in the Arctic is described and a *Precursor Mission* is required to learn more about the communication channel.

A flight opportunity in HYPSO may be granted to the *Precursor Mission* to characterize the UHF satellite channel and interference to enable the design of the

Arctic communication system. This is the first step to improve data retrieval for Arctic researchers. The SDR-based communication system can act as a secondary mission to the main HSI mission, and the mission design must be adapted accordingly. HYPSO mission parameters and the interactions with the SDR have been outlined. It is very challenging to add a secondary payload in a mission, especially if it is not included from the start. The secondary payload may impact the success of the primary mission, thus more work must be carried out if the SDR payload flies on HYPSO.s

Future work will include a full system design breakdown of the SDR secondary mission, development of the software needed for performing measurements, verification and validation activities, and AIT activities to integrate the SDR platform with the satellite bus. It is assumed that there will be more user requirements added as the prototype is being developed, in close collaboration with the Arctic ABC project.

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