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NorSat-1: Enabling High Performance and Multipurpose Microsatellite Missions

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ABSTRACT

The NorSat-1 mission demonstrates a low-cost collaborative approach to science in space through the innovative integration of multiple payloads within a small microsatellite platform. Successfully launched on 14 July 2017 into a 600 km polar orbit from the Baikonur Cosmodrome, the satellite carries three distinct payloads with different requirements.

The mission's scientific objectives are to investigate total solar irradiance and the effects of space weather on the upper ionosphere using payloads from Switzerland and Norway, respectively, while simultaneously advancing Norway's operational capability for detection and management of maritime traffic.

Developed by the Space Flight Laboratory (SFL) for the Norwegian Space Centre (NSC), the design leverages SFL's space-proven, cost-effective, and modular Next-generation Earth Monitoring and Observation (NEMO) microsatellite platform. Continuous on-orbit operation of payloads is enabled by 45 W power generation in sunlight. Sub-degree attitude control achieved with low-cost sensors and actuators has outperformed pointing requirements needed to satisfy scientific objectives. Downlink rates exceeding 1 Mbps, averaged over available contact time, have been sustained in any satellite orientation.

At 15.6 kg, the successful on-orbit performance of NorSat-1 is a major leap forward in the evolution of microsatellite miniaturization, enabling high performance and multipurpose missions in smaller microsatellites.

INTRODUCTION

NorSat-1 is a high performance multi-payload microsatellite mission integrating three diverse payloads, selected based on their interest to Norway's evolving satellite program. It achieves its multidimensional mission objectives through continuous and simultaneous operation of its three payloads:

1. Automated Identification System (AIS) receiver, for observation of maritime activities;
2. Compact Lightweight Absolute Radiometer (CLARA), to study total solar irradiance (TSI), an absolute measure of solar energy input to Earth; and
3. The multi-Needle Langmuir Probe (m-NLP) instrument, to study ambient space plasma characteristics.

NorSat-1 joins a constellation of satellites owned and operated by the Norwegian government providing space-based AIS detection capabilities to enable observation of maritime activities in Norwegian coastal areas. Ambient space plasma has a direct impact on many aspects of space-based applications such as satellite navigation systems, while TSI is a critical input to most climatic models and is essential to climate research.

NorSat-1 is a collaborative international mission with funding from the Norwegian Space Centre (NSC) and support from the Norwegian and Swiss investments in the European Space Agency (ESA) for payload development by Kongsberg Seatex AS (KSX), the University of Oslo (UiO), and the Physikalisch Meteorologisches Observatorium Davos/World Radiation Centre (PMOD/WRC). The Space Flight Laboratory (SFL) at the University of Toronto Institute for Aerospace (UTIAS) designed and built the satellite, and integrated the three distinct payloads provided by different organizations in Norway and Switzerland.

This paper provides insight into the novel and challenging aspects of the integration of three different payloads for continuous simultaneous operation (for the full orbit) within a small microsatellite platform, and discusses the mission objectives, operations concept, bus design, and the on-orbit performance obtained through commissioning and daily operations. Table 1 provides a summary of key mission characteristics.

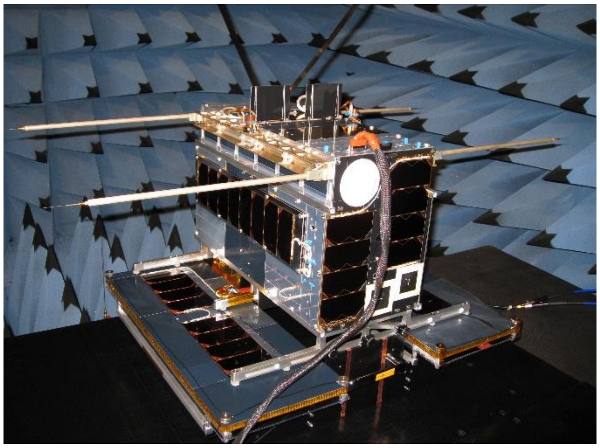

Figure 1: NorSat-1 Spacecraft in SFL's Anechoic Chamber

Table 1: NorSat-1 Mission Summary

Parameter		Value
Satellite Mass		15.6 kg
Structure		Primarily aluminum, rectangular form factor
Spacecraft Dimensions		440 mm x 200 mm x 267 mm (central bus)
Power Generation		Up to 45 W
Data Storage		3 GB
Uplink		4 kbps (Command)
Downlink		Up to 4 Mbps (Telemetry & Data)
Pointing Control		0.5° (3σ)
Power Generation		6 fixed solar panels, 28% triple-junction cells
Power System		Battery-regulated bus: series peak power tracking (PPT) topology
Battery		6-cell Li-Ion, 9.6 A·h capacity
Communications		Omni-directional S-band uplink and downlink
Attitude Determination		3-axis; sun sensors, rate sensor, magnetometer
Attitude Control		3-axis; reaction wheels, magnetorquers
Position Determination		NORAD TLEs, GPS receiver
Command & Data Handling		2 computers for housekeeping, attitude control 1 computer for payload operations
Orbit		600 km Sun Synchronous Orbit
Launch	Date & Time	Friday 14 July 2017, 06:36:49 UTC
	Site	Baikonur Cosmodrome in Kazakhstan
	Vehicle	Soyuz-2.1a/Fregat (secondary payload)
Ground Segment	Earth station location	Vardø, Norway (70 °N)
	Specifications	3.7 m (S-band uplink/downlink); G/T > 14 dB/K; EIRP > 48 dBW
	Downlink Throughput	Min. 490 MB/day; Min. 1 Mbps averaged over accumulated contact time over a 24 hour period

SATELLITE OVERVIEW

NEMO Bus Platform

The NorSat-1 spacecraft is based on SFL's Next-generation Earth Monitoring and Observation (NEMO) bus platform. NEMO is an inter-related family of flight-proven bus technologies, providing a modular and extensible bus design enabling scalability to high-performance small microsatellite missions within aggressive system budgets. It derives its primary direct heritage from SFL's existing Generic Nanosatellite Bus (GNB) bus platform while extending its bus capabilities to accommodate payloads with larger size and power requirements. NEMO has resulted in several other successful missions, including NorSat-2 and GHGSat-D, and several others currently under development at SFL[1,2]. NEMO's modular and extensible bus design has enabled the integration and simultaneous operation of the three separate payloads on NorSat-1, each satisfying different mission objectives.

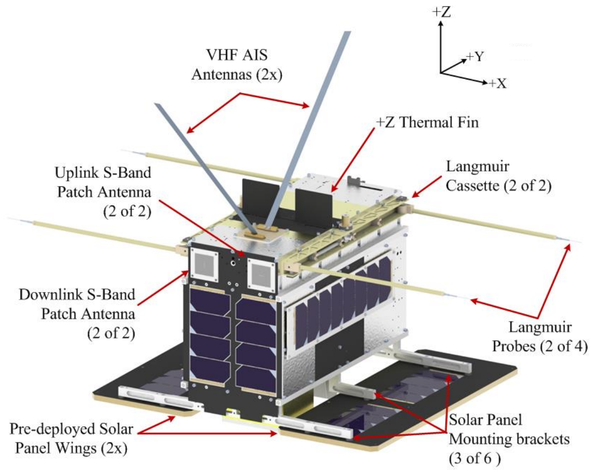

Figure 2: NorSat-1 Spacecraft Exterior View

Structure

NorSat-1 has an overall satellite mass of 15.6 kg, with a primarily aluminum structure in a rectangular form factor. The central bus structure, with outer dimensions of 440 mm x 200 mm x 267 mm, houses the avionic and the payload components, which are attached to two aluminum loadbearing trays and are enclosed by six body panels. Special considerations were made in the design phase of the main solar arrays to ensure they could be easily mounted and dismounted, and to avoid shadowing of the main body of the satellite during the normal course of operations, which would complicate the thermal design. The following attachments connect to the central bus structure, as shown in Figure 2:

- Two pre-deployed solar array wings to extend power generation capabilities;
- Two orthogonal AIS antennas leveraging a tape string design from a previous GNB design by SFL[3], attached to the central bus in a stowed fashion and released upon separation from launch vehicle; and
- Four Langmuir probe booms, stowed inside two cassettes and deployed upon command on-orbit.

Figure 3 shows the internal layout and components, discussed throughout the rest of this paper.

Thermal Control

NorSat-1 mission requirements demand a design capable of operating in any orbit. Usually, small satellites are designed to operate in a particular orbit, though efforts are made to be able to adjust orbit without major redesign. In this case, however, the thermal design considers the full range of beta angles in a single design. To achieve this, NorSat-1 uses a primarily passive thermal control design relying on thermal tapes for heat exchange control, and systematic component layout and thermal interface design for heat distribution across the spacecraft.

Throughout all mission phases and design scenarios, the spacecraft maintains a benign thermal environment for its components, between -20 °C and +60 °C for operations. The active modes of control pertain to heaters on batteries to heat up in certain cold conditions, and the added precautionary measure of temperature sensors at critical locations providing a fail-safe monitoring system implemented in onboard software to deactivate payloads under unlikely corner case conditions.

Command and Data Handling

Command and data handling tasks are divided across two identical Onboard Computers (OBCs): Housekeeping OBC and Attitude OBC. Housekeeping tasks include controlling power switches, executing time-tagged commands received from ground, and system-wide telemetry collection. The Attitude computer implements the attitude determination and control algorithms, and interfaces with attitude sensors and actuators. The two OBCs are cross-connected and differ only in software, allowing their functionality to be swapped or combined into a single OBC, thus providing a layer of functional redundancy. A third, identical OBC is dedicated to interfacing with the three payloads. A Serial Interface Board (SIB) provides an interface to perform signal level translation between the payloads and the payload computer. Each OBC contains 1 GB of flash memory, able to store up to 20 orbits worth of payload data without loss of data, and runs on an ARM7 processor, with clocking frequency of 40 MHz. NorSat-1 also carries a GPS receiver with an antenna in the L1 band, providing high accuracy clocking signals to achieve high-fidelity timing capabilities, within 100 ns of GPS time.

Power System

Power generation, energy storage, and power distribution functionality is provided by SFL's Modular Power System (MPS), implementing a battery-regulated bus with a series peak power tracking (PPT) topology. Through a passive backplane and a series of modular cards performing dedicated power management tasks, the MPS system realizes reconfigurable power architecture adaptable to different mission power capability requirements while retaining flight-heritage. Power generation is provided by 8-cell 28% maximum efficiency solar arrays. Each body panel on the central bus structure contains one array for safe-hold operations, while the solar panel contains six arrays for power generation during operations when pointing at the sun. The spacecraft is able to produce 45 W of peak power to provide orbit-average power of 23 W in the nominal operations mode. Energy storage is realized using a 6-cell battery pack, providing a capacity of 9.6 A·h. The battery is connected to the power system through the Battery Interface Module (BIM), which provides battery protection and monitoring capabilities.

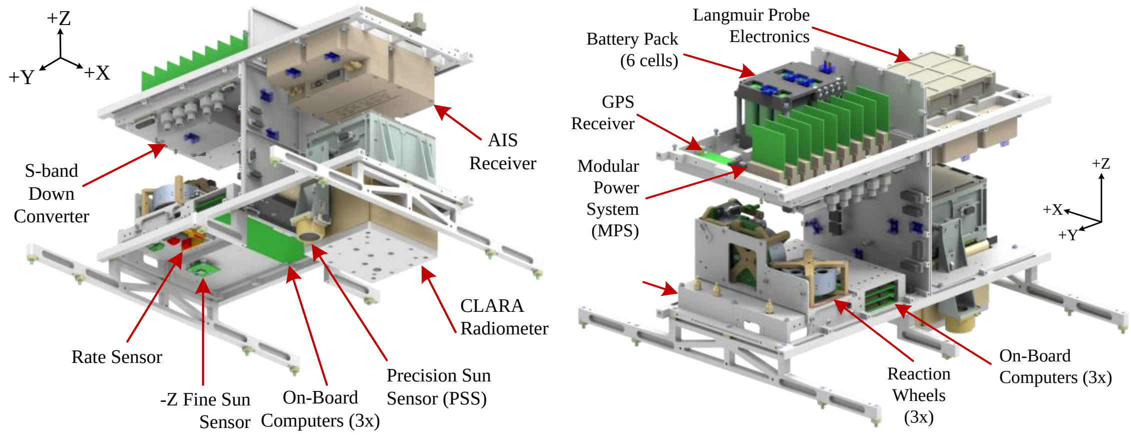

Figure 3: NorSat-1 Internal Layout

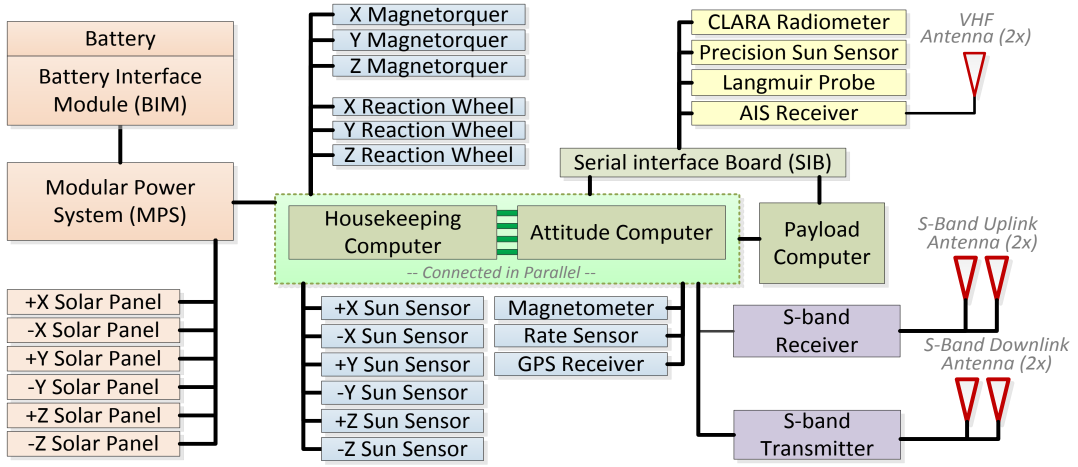

Figure 4: NorSat-1 Electrical Architecture

Telemetry and Command

Full-duplex, bi-directional radio communications between the spacecraft and ground are realized through the standard Space Research / Space Operations Service S-band frequency allocations. A dual-patch antenna system with antennas on opposite sides of the spacecraft is utilized for both uplink and downlink, for a total of four antennas operating on Right Hand Circular Polarization. Effectively omnidirectional coverage has been achieved through passive connection of antennas with a combiner and splitter for uplink and downlink, respectively. The uplink chain comprises of an external band-pass filter and an S-band receiver, and operates at a constant bitrate of 4 kbps. The downlink chain is a fully integrated S-band transmitter, with Radio Frequency (RF) output power amplification up to 28 dBm, and can be configured by command to operate between 32 kbps and 4 Mbps, depending on link conditions and operational requirements. The Satellite Control Centre (SCC) is capable of automatically adjusting the downlink data rate based on the link conditions, maximizing the amount of data that can be downloaded. The downlink chain on NorSat-1 achieves a data rate of at least 1 Mbps when averaged over the accumulated contact time over a 24 hour period, and is able to deliver at least 490 MB of data per day to a high latitude station in Vardø, Norway.

Attitude Determination and Control

The control of the spacecraft attitude profile is handled by the attitude determination and control subsystem, comprising of sensors, actuators, and control software implementing the attitude control algorithms. The algorithms are implemented by SFL’s Onboard Attitude System Software (OASYS) package, which provides a hardware-independent, modular, and mission-configurable attitude software platform to maintain flight-heritage across missions and to minimize costs. Nominally, at a cadence of one second, data measurements from attitude sensors are processed through an Extended Kalman filter (EKF) to estimate the satellite attitude and angular rates, which are subsequently used by OASYS algorithms to generate torques and command actuators to achieve desired attitude.

The primary mechanism of control for fine-pointing operations is realized through three orthogonally mounted reaction wheels. For de-tumbling and reaction momentum management, the spacecraft affects its attitude through interaction with the local magnetic field using three orthogonally mounted digitally-controlled electromagnetic torque coils (or *magnetorquers)*, developed by SFL.

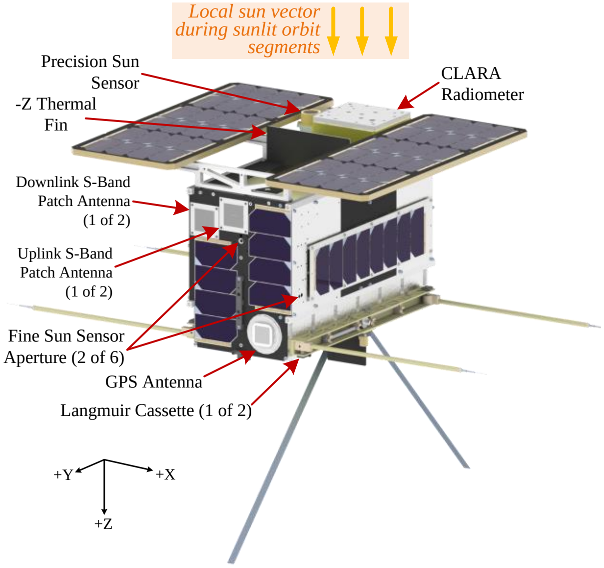

Figure 5: NorSat-1 Spacecraft, showing CLARA's aperture in relation to local sun vector

Attitude determination is realized using four types of sensors, all developed by SFL. Six fine sun sensors, one on each body panel, determine the local sun vector in the body frame using a CMOS profile-array sensor, while coarse estimates are provided by solar array current sensors. A three-axis magnetometer senses the local magnetic field, and a three-axis Micro-Electro-Mechanical Systems (MEMS) rate gyro complements the attitude estimation for when sun sensors are not available, such as in eclipse.

Additionally, a high-fidelity sun sensor is mounted on the same geometric face as CLARA’s radiometer line-of-sight. This allows the attitude control system to align the centre of the radiometer’s Field of View with the centre of the sun to achieve a pointing accuracy of ±0.5°, 3-σ when the sun is visible, as illustrated in Figure 5. Furthermore, the GPS receiver introduced previously provides an Orbital Extended Kalman Filter (OEKF) algorithm with the orbit state solution required to produce orbital navigation for on-orbit control trajectory generation.

Each payload on NorSat-1 has independent attitude requirements, while the mission design requires simultaneous operation of all three. During the sun-lit segments of each orbit, the radiometer apertures on CLARA, mounted on the –Z axis of spacecraft, are to be aligned with the local sun vector with an accuracy of ±0.5°. As well, occasional calibrations require the spacecraft to slew the radiometer aperture at deep space and back, up to 180 degrees, at 0.5°/s or faster while settling within 2 minutes at the end of the slew. The Langmuir probes are sensitive to the plasma wake created along the spacecraft path of motion, and are kept perpendicular to the ram and anti-ram directions. The Langmuir probe booms, four in total, are kept parallel to each other while orthogonal to CLARA's line of sight. As well, AIS antennas are placed externally and orthogonal to each other, while remaining orthogonal to the Langmuir booms.

MISSION AND PAYLOAD OVERVIEW

This section provides an overview of the mission objectives, how each payload satisfies these objectives, and discusses key challenges associated with integration of three separate and diverse payloads on a small microsatellite platform.

Automatic Identification System (AIS) Receiver

Space-based AIS detection provides an effective means of monitoring maritime traffic over vast ocean bodies, which is of especial importance to Norway given the large ocean areas within the country's jurisdiction. Land-based AIS detection is typically able to track within 40 nautical miles within coastal region, leaving large areas of water outside its reach[4]. NorSat-1 joins a constellation of satellites built by SFL in recent years, successfully providing the Norwegian Coastal Administration with the ability to monitor maritime traffic in areas beyond the reach of coastal networks and utilize this information as part of an operational decision cycle:

- Automatic Identification System Satellite-1 (AISSat-1)[5], launched in 2010;
- Automatic Identification System Satellite-2 (AISSat-2)[6], launched in 2014; and
- NorSat-2[1], launched alongside NorSat-1 in 2017.

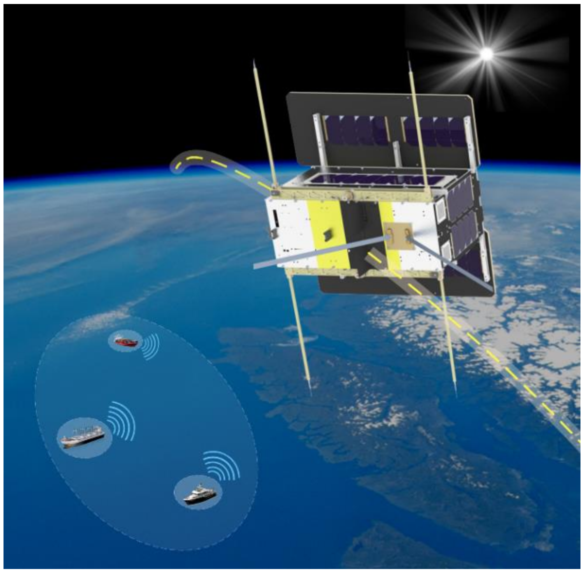

Figure 6: An illustration of space-based AIS detection on NorSat-1

The AIS receiver on NorSat-1 is built by Kongsberg Seatex AS (KSX) of Trondheim, Norway. It is a more sensitive, upgraded version of the receivers flown previously on AISSat-1 and AISSat-2, and advances the state of art in space-based AIS detection. It is a very high frequency (VHF) receiver with a deployable two-antenna system, and a data processing unit for acquisition, decoding, and forwarding operations. It is based on a reconfigurable software-defined radio, and enables in-flight updates to its algorithms, which can serve as a test-bed for new algorithms. The receiver is able to detect and process an increased number of AIS signals through simultaneous antenna diversity and detection on its four channels, and is capable of receiving *Message 27 (Position report for long-range applications)* which enables detection of messages with increased propagation delays to provide better coverage of high traffic areas.

A key design consideration pertained to minimizing the impact of the satellite body, especially the pre-deployed solar panel and the multi-needle Langmuir Probe (m-NLP) instrument, on the AIS antenna pattern. A further constraint was the need for the antennas to be deployable, owing to their size and the satellite layout. Instead of having an in-orbit deployment mechanism, the antennas are placed orthogonally as per mission requirements, and held down by the separation system itself. Upon separation from the launch vehicle the antennas are released and deployed through their own stored energy. Discussions with the launch provider ensured this design posed no risk of contact with any other satellites or upper stage equipment.

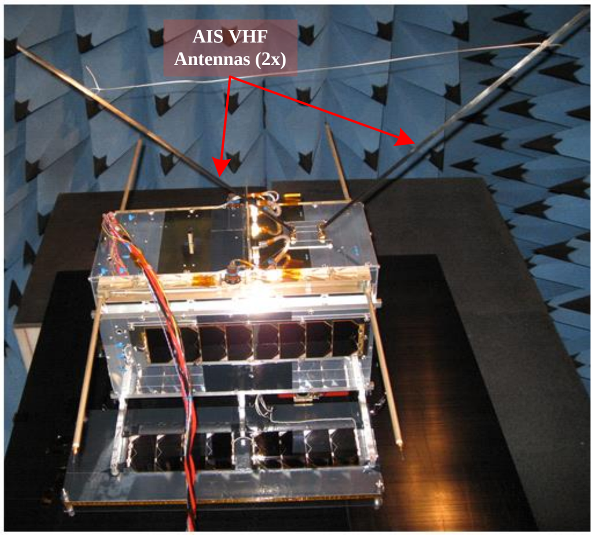

Figure 7: NorSat-1 Spacecraft inside SFL's Anechoic Chamber, showing AIS VHF Antennas and Langmuir Booms deployed

The AIS receiver is an extremely sensitive VHF radio receiver, and any noise generated by either the platform or other payloads on the frequencies of operation result in lost messages. Based on experience from previous AIS satellites, an EMC strategy was devised very early on in the mission design to ensure a design and test approach that would result in a very quiet satellite. In order to verify the EMC performance, a fully-representative satellite was built with engineering model hardware and tested, demonstrating that the design approach was successful. This was further verified in-orbit, as discussed later in this paper.

Compact Lightweight Absolute Radiometer

The Compact Lightweight Absolute Radiometer (CLARA) built by PMOD/WRC is a scientific payload instrument on NorSat-1 contributing to a seamless continuation of space-borne total solar irradiance (TSI) observations since 1978. Continuous and precise TSI measurements are indispensable to monitoring short and long-term solar radiance variations[7]. The existence of a potential long-term trend in the solar irradiance and whether such a trend could affect the Earth's climate is still a matter of debate, as the Sun has not yet shown large variations within the 40 years of space measurements.

CLARA is a digitally-controlled Electrical Substitution Radiometer based on a new three-cavity detector design for built-in redundancy and degradation tracking capability (Figure 8). In the measurement procedure, the radiative heating at the cavities is substituted by electrical heating[8]. Figure 8 shows the various parts of the CLARA instrument, including the three conical cavities (TSI detectors) connected via heat-resistant labyrinths to the common reference block. CLARA is the first flight of a new and versatile type of TSI radiometers designed to be small and lightweight to fly on low-cost microsatellites.

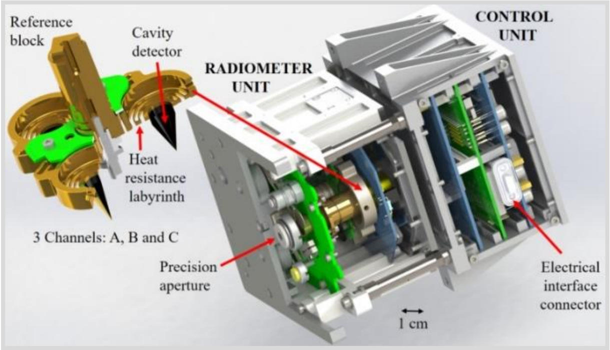

Figure 8: Interior view of CLARA solar absolute radiometer

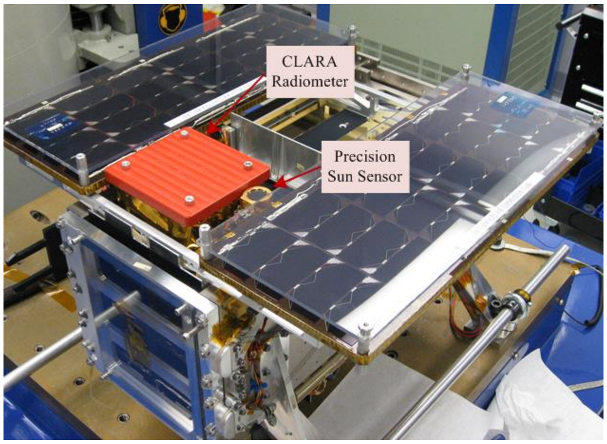

Figure 9: A view of CLARA (covered) on NorSat-1 during Vibration Testing at SFL Facilities

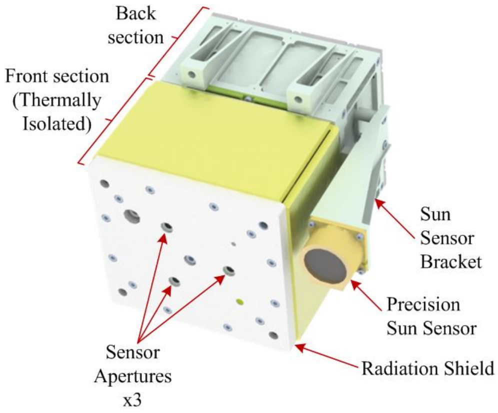

Figure 10: CLARA Instrument Exterior

CLARA demands the strictest pointing stability requirements compared with the other two payloads, with required accuracy of ±0.5°, 3-σ in two axes. This would typically necessitate the use of a more precise attitude sensor, such as a star tracker. NorSat-1 needed to be able to accommodate operation in any orbit, which would complicate the satellite layout and likely require multiple sensors. Instead, the high-fidelity precision sun sensor is used; this sensor is mounted directly to CLARA to minimize the potential mechanical misalignment and relative dynamic thermo-optical distortions. This allowed calibration of the misalignment on ground, at the instrument level, and then again in-orbit.

multi-Needle Langmuir Probe

The study of plasma characteristics in the ionosphere is a key factor in monitoring and forecasting space weather, which directly affects satellite navigation and communication outages[9]. NorSat-1 carries the m-NLP, developed by the University of Oslo (UiO), which relies on a novel concept for high-resolution measurements of ionosphere electron density and temperature along the satellite orbit without a need for knowledge of the spacecraft potential[10,11,12].

A pair of miniaturized cylindrical Langmuir probes, 25 mm in length and 0.51 mm in diameter, is attached to the ends of two deployable booms. The assembly is housed within a single *cassette*, shown in Figure 11. The deployment mechanism is implemented using a pre-loaded spring and shape-memory-alloy pin-puller. NorSat-1 carries a total of four probes, housed within two cassettes.

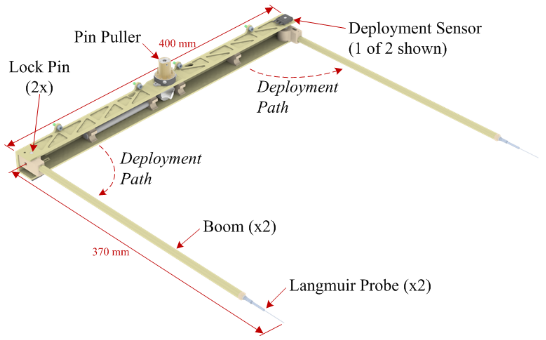

Figure 11: Langmuir Probe Instrument

The mission requires the booms to be extended as far as possible from the satellite plasma wake. To retain a small pre-launch spacecraft volume (to maximize the opportunities for launch), the design uses a deployable boom to place the probes sufficiently away from the spacecraft. UiO had complete responsibility for the design of the booms, with input from the platform team. A key requirement was to ensure simple deployment testing and re-arming, even after assembly on the satellite. The design implements a resettable pin-puller and a latching hinge, allowing the booms to be deployed and re-armed within minutes.

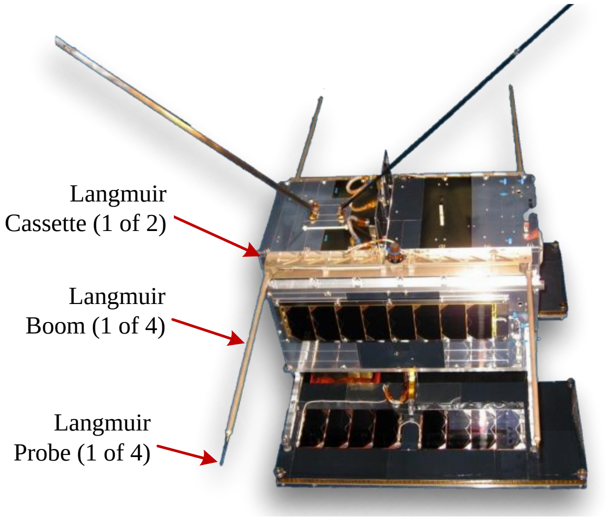

Figure 12: multi-Needle Langmuir Probe instrument components on NorSat-1 Spacecraft

GROUND SEGMENT

The ground segment for NorSat-1 is comprised primarily of two key facilities: the Earth station and the Satellite Control Centre (SCC). The primary Earth station for NorSat-1 is located on the Norwegian mainland in the far north on a hilltop near the town of Vardø. From this vantage point at over 70 °N, the Vardø Ground Station (VGS), shown in Figure 14, is nearly ideally suited for tracking polar satellites; typically 12 of 15 orbits per day can be tracked. Additionally, antennas operated by Kongsberg Satellite Services at the SvalSat facility located at 78 °N on the island of Spitsbergen in the Svalbard archipelago may be called upon in situations where the extra coverage is required. Figure 13 shows a map of key geographical locations.

The VGS antenna was installed and commissioned by UTIAS/SFL in the spring of 2015 in cooperation with StatSat AS and various subcontractors, on behalf of the Norwegian Space Centre (NSC) and the Norwegian Coastal Administration. The site currently includes two radome-protected antenna systems: a 3.7 m diameter reflector with S-band uplink and downlink capability, and a quad-Yagi UHF uplink antenna. The S-band antenna is used for all of the Norwegian AIS satellites, including NorSat-1, while the UHF antenna supports the older generation of AIS satellites prior to NorSat-1.

Table 2 outlines key specifications of the VGS S-band antenna.

Table 2: Vardø Ground Station Specifications

Parameter	Value
Reflector Size	3.7 m
Frequency Bands	2200-2300 MHz (Rx) 2025-2110 MHz (Tx)
Polarization	RHCP or LHCP
G/T @ 20 °C	> 14 dB/K
EIRP	> 48 dBW

The SCC is located in Oslo, in the same building as the Norwegian Space Centre. The satellites are operated by StatSat AS on behalf of the Norwegian Space Centre from this site. All uplink and downlink data are routed to/from this site and the Earth stations. An advanced mission planning system was developed by StatSat and coupled with the core ground segment and satellite control software developed by UTIAS/SFL to facilitate operation of the many current and future satellites in Norway's fleet.

Figure 13: Map of key locations in NorSat-1 Mission Operations

Figure 14: Aerial Perspective Vardø Ground Station

OPERATIONS CONCEPT

NorSat-1 is designed to support simultaneous operation of all three payloads. The mission budgets are sized accordingly, providing sufficient energy, onboard data handling & buffering capability, and downlink capacity. Each payload is independently controlled and operated, with little interaction or constraints occurring between the payloads apart from their contention for optimum spacecraft orientation.

CLARA's operations profile dictates that, while in sunlight, its aperture is to be pointed at the sun in a precision sun-pointing mode. The other payloads may be active, but the attitude of the satellite is not optimized for their operation. Outside of sunlight, the spacecraft may be reoriented to optimize one of the other two payloads. In general, the m-NLP instrument would be optimized by entering an orbit-tracking mode and aligning the probes such that they are away from the wake or ram directions. The AIS instrument would be optimized by orienting them in the local horizontal plane (although investigation of the optimum orientation is part of the mission). The payload data downlink capability is maximized, up to 2 Mbps based on the licensed bandwidth, by pointing the antenna bore-sight at the Earth station during a contact, while the 1 Mbps average data rate, a mission requirement, is achieved without mandating any attitude constraints.

There are two methods of interaction with the payloads: real-time operations can be performed directly by the SCC, and operations can be performed by time-tagged commands. For real-time operations, this could be at the direct request of the payload operator. Any command that can be issued in real-time by an operator can also be queued for time-tagged execution. Typically, the payload operator provides high-level direction to the SCC as to how the payload should be configured, when it should be operated, and in what mode. The SCC will enter this information into its mission planning system, which considers the operation of other payloads and operational priorities, as well as spacecraft resource constraints (e.g. power generation and available downlink capacity), and generates a sequence of time-tagged commands. These commands are then uplinked to the spacecraft for execution at a later date.

Payload or science data may be polled when it is collected at low cadence by an instrument. However, the majority of this data is pushed (automatically sent) and handled in two ways. Data products are generated automatically by the payload either at a fixed cadence or in response to an external event (e.g. reception of a valid AIS message), and automatically forwarded and stored in Payload computer's non-volatile storage system. Payload data can also be immediately downlinked when an Earth station is in view, to minimize latency. Data aggregation is the normal mode of operations for all of the payloads, while the latter method is an additional mode used primarily for real-time forwarding of live AIS messages.

LAUNCH AND COMMISSIONING

NorSat-1 was successfully launched as a secondary payload onboard a Soyuz-2.1a/Fregat, which carried its main payload, the Russian Earth-observation satellite *Kanopus-V-IK*, along with 71 other smaller satellites. It lifted off from Launch Pad No. 31/6 at the Baikonur Cosmodrome in Kazakhstan on Friday 14 July 2017 at 06:36:49 UTC (Figure 15).

NorSat-1 was placed into a 600 km sun synchronous orbit at approximately 09:01:45 UTC by Fregat following several orbit changes to drop off other co-passengers. NorSat-2[1] was also deployed at the same time. At the time, the satellites were flying over the South Pacific as shown in Figure 16.

For the early stages of operations, in order to ensure every-orbit coverage, the Earth station at Svalbard was used. The first contact with NorSat-1 was made at 09:54:32 UTC on the first attempt. Initial telemetry indicated a perfectly healthy satellite.

A special operation for NorSat-1 that was performed immediately upon acquisition prior to any other commissioning tasks was to power up CLARA and verify the cavity shutters were closed following launch.

A basic checkout of the core platform avionics followed over the remainder of the first contact and into the second contact.

Figure 15: NorSat-1 Lift-off on Kanopus-V-IK Cluster Mission 2017

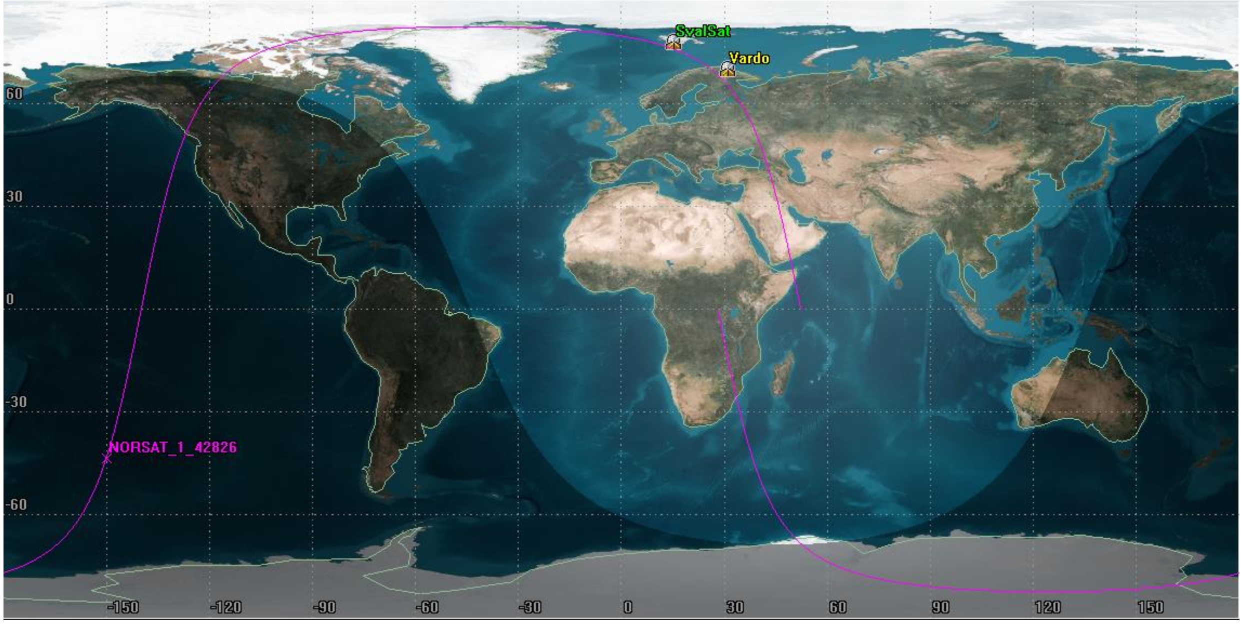

Figure 16: NorSat-1 at Separation from the launch vehicle

The next major milestone was the reception of the first live AIS messages by the AIS receiver, which occurred on the second contact at 11:34:15 UTC. From this point onwards, the AIS payload was effectively operated continuously in parallel with other activities. The attitude determination system was activated and subsequently verified at 16:31 UTC. At 18:08 UTC, the de-tumble controller was activated to eliminate the rates imparted by the separation from Fregat. The measured tumble rate was approximately 5°/s which is within expectations, and was made null within one orbit.

The following morning, at 05:26 UTC on 15 July 2017, the three-axis control mode was activated and the satellite was commanded to point at the sun. Following verification of successful sun-pointing, the majority of the platform functionality was now coarsely confirmed. Subsequent activities concentrated on performance verification, tuning, and payload commissioning. At this point, NorSat-1 formally entered into a month-long *outgassing phase*, to allow time for any residual outgassing to occur before opening the shutters and exposing the sensitive surfaces within the cavities. In this phase, NorSat-1 was maintained in a sun-pointing attitude continuously, with the CLARA shutters closed.

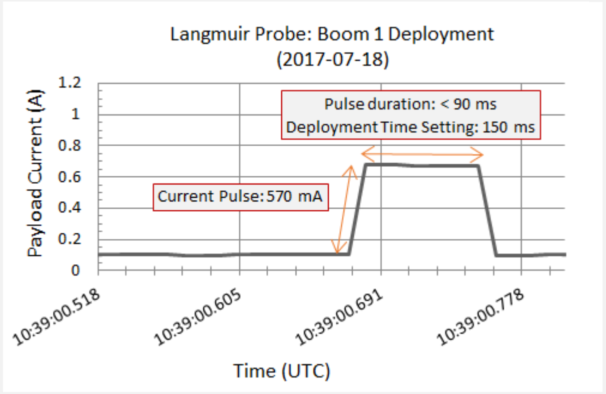

Figure 17: m-NLP Cassette Deployment Current Pulse

On 18 July 2017, the m-NLP booms were deployed. A sample deployment current pulse from one of the two cassettes is shown in Figure 17. The deployment signal is activated for a maximum deployment time setting; a shorter pulse indicates successful deployment. On 28 July 2017, the final major commissioning milestone was achieved when the precision sun sensor was activated and its behaviour verified in the three-axis control loop for the first time. Before this step, the attitude determination system used the six fine sun sensors, sufficient for power generation and operation of the other payloads. Initial performance verified expected behaviour, and over the following days, minor adjustments were made to the sensor's operating parameters which further improved the measurements and pointing accuracy.

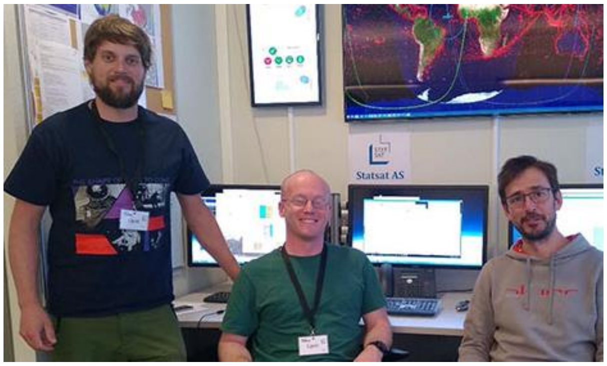

Figure 18: CLARA First Light Team at the StatSat SCC (Benjamin Walter/PMOD, Alexander Beattie/SFL, Dany Pfiffner/PMOD)

ON-ORBIT PERFORMANCE

During satellite commissioning, a complete evaluation of the performance of each subsystem was performed. A summary of key areas of particular importance to the NorSat-1 mission and payloads is presented below.

Communications

While the communication system used in NorSat-1 is largely a heritage system, the mission requires a relatively highly efficient usage in order to meet the overall downlink data rate.

Figure 19 demonstrate the achieved data rate over a typical low and high elevation pass, selected arbitrarily. In both cases, the satellite is sun-pointing and does not attempt to point a downlink antenna at the Earth station. The effect of the variation in the link conditions due to the satellite range and antenna pattern is clearly visible as the data rate is adjusted. Furthermore, it is quite apparent that the downlink spends much of the time even on low elevation passes at or above 1 Mbps.

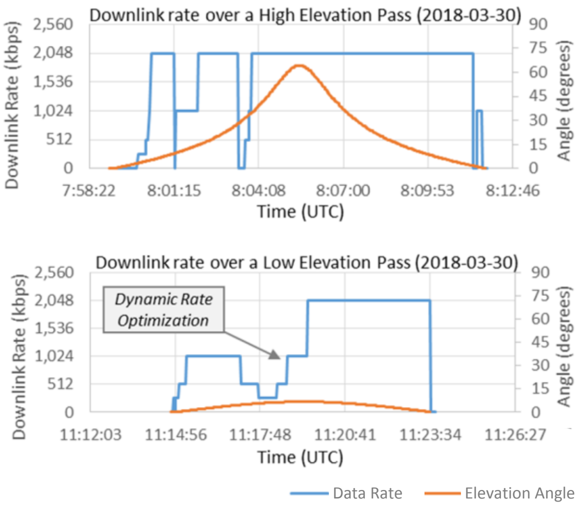

Figure 19: Elevation downlink rates during a typical high (top) and low (bottom) elevation pass

Electromagnetic Compatibility

As discussed in the previous section, early operational results from the AIS receiver successfully verified its expected behavior. To analyze the noise levels presented to the AIS receiver from the rest of the spacecraft, a dedicated test was performed to verify the platform's electromagnetic compatibility (EMC) performance in-orbit. To accomplish this, the receiver is operated in a *spectrum analyzer* mode, where the received noise power can be measured across frequency and compared against requirements and the measured receiver-only noise power levels.

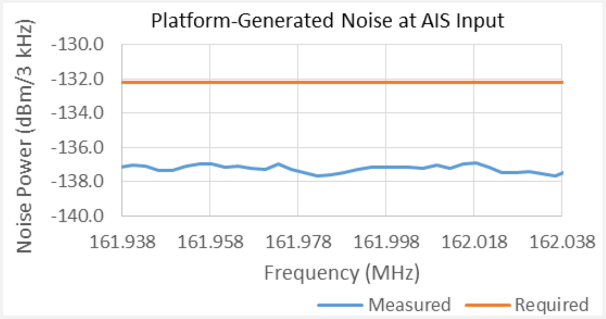

Figure 20: Platform Noise Measured by AIS Receiver

On 1 August 2017, in order to minimize the amount of ambient (i.e. non-satellite) noise, this test was performed over Antarctica, with the satellite platform in a fully operational state with all systems operating (except the other payloads) to capture all noise sources from the platform. A sample spectrum capture, showing the band around the primary AIS channels, is shown in Figure 20, demonstrating it successfully meets the required performance level. In fact, the noise observed is indistinguishable from the thermal noise level of the receiver itself. This result verified the pre-flight measurements, following extensive consideration of EMC in the design phases and early prototype testing.

Attitude Control

As discussed previously, high pointing accuracy, within ±0.5°, 3-σ, in aligning CLARA at the sun is the driving attitude control requirement for NorSat-1. This implies that only the pointing error of CLARA's aperture relative to the sun is important; roll about the sun vector is not the critical parameter, and is only coarsely controlled.

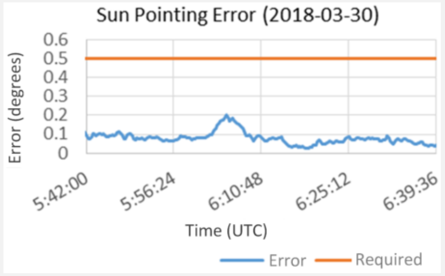

Figure 21: Sun Pointing Error

A sample dataset, showing the requirement and the pointing accuracy is shown in Figure 21, demonstrating that the achieved performance far outperforms the required stability level.

In-Flight Results from CLARA Radiometer

By pointing CLARA to Earth Nadir during the eclipse receiving longwave radiation from Earth, a very good thermal stability of the Radiometer Unit with variations < 1 K is obtained. During the commissioning phase of NorSat-1 and CLARA, the co-alignment of the CLARA optical axes with the satellite's sun sensor was determined. For the pointing measurements, the TSI values of the CLARA detectors is compared with the four quadrant coordinates of the spacecraft precision sun sensor for various angles. These measurements were already been performed on ground before launch; however, the nominal values needed to be verified in space to check for launch vibration. Figure 22 shows that CLARA Ch. C was off by only -0.134° relative to the coordinates determined on ground, proving that no major slipping or gapping has occurred.

Figure 23 shows sample TSI observations with Channels A and B. Ch. B shows relatively stable observations at a TSI level of about 1360 W·m^{-2} which agrees well with observations of other space radiometers, (e.g. VIRGO). Ch. A, on the other hand, shows some strong TSI variations, in particular at 01:45, which was found to coincide with small pointing variations. The TSI variations are most likely due to electromagnetic disturbances, an effect that is currently under investigation.

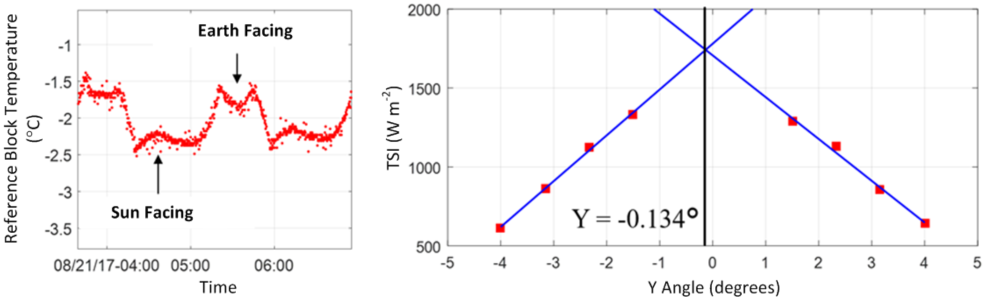

Figure 22: CLARA reference block temperature (left); pointing measurements performed in space (right). For pointing verification, satellite was rotated from -4° to +4° in steps of 1°; intersection of blue lines indicates projected 0° rotation.

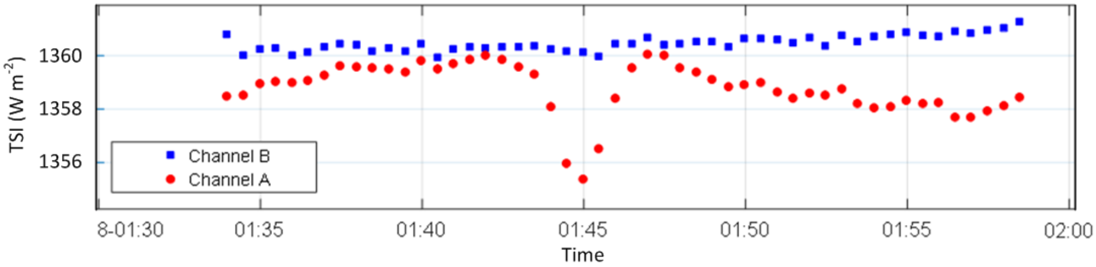

Figure 23: TSI observations for CLARA Channel A and B (3 January 2018)

In-Flight Results from AIS Receiver

The receiver on NorSat-1 is capable of intercepting more messages than receivers flown previously on AISSat-1 & 2. It has successfully demonstrated the ability to detect message types 1, 2, and 3, as well as the long-range type *Message 27*. Analysis of typical daily operations have demonstrated that ship detections have increased substantially, up to 60% to 70% more ships, compared with what was previously possible[13].

Figure 24 shows a comparison between the new, upgraded AIS receiver and receivers previously flown. The data was gathered on 6 August 2017 in the North Sea. Each data point represents an AIS observation, and data is colour-coded according to how many times a ship is observed via satellite-based AIS during the day. Table 3 compares the number of messages and unique AIS source identifiers, the Maritime Mobile Service Identity (MMSI), for the previously flown receivers on AISSat-1 & 2 and the receiver flown on NorSat-1 and 2[14].

Table 3: Messages and MMSI Reception Comparison of Previous and New Generation Receivers[14]

	Message 1, 2, and 3		Message 27	
	No. of Messages	No. of MMSIs	No. of Messages	No. of MMSIs
AISSat-1 & 2	500k	25k	N/A	N/A
NorSat-1 & 2	1.3M	36k	120k	13k

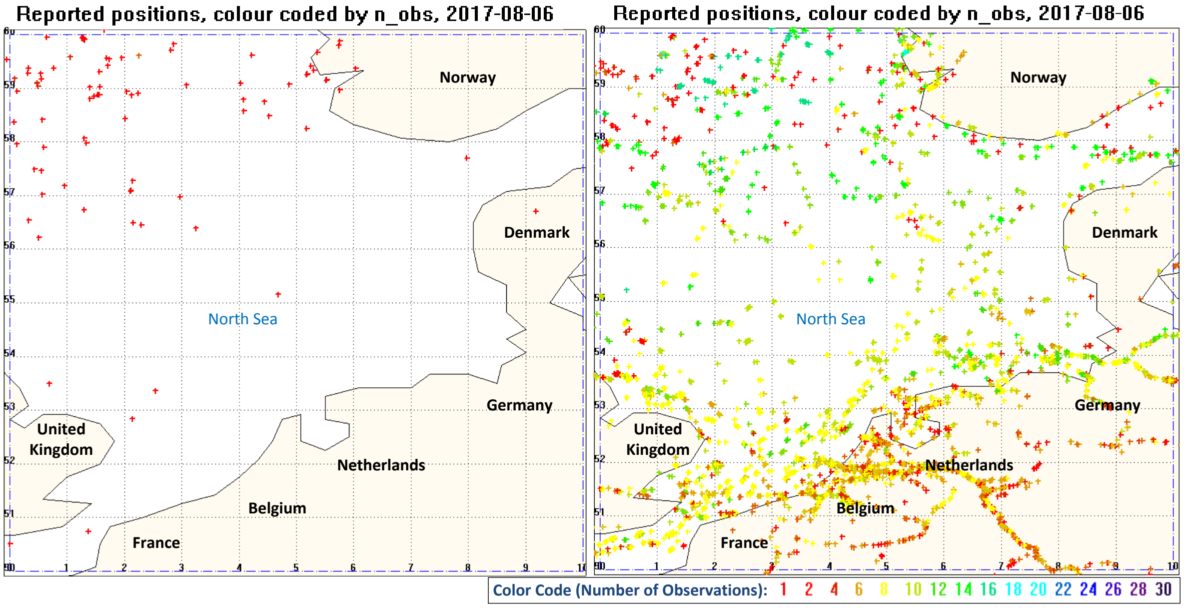

Figure 24: AIS Message detection comparison between previously flown receivers (left) and NorSat-1 AIS receiver (right) (Modified illustration; Original: Norwegian Defence Research Establishment[13])

In-Flight Results from Langmuir Probe Instrument

The m-NLP onboard NorSat-1 can be operated in two different modes: the sweep mode in which the bias voltage applied to all the four probes is swept from -10 V to +10 V, and the science mode, where fixed but different bias voltages are applied to the four probes. In sweep mode, the current collected by the m-NLP can be compared with well-known current/voltage characteristics obtained from theoretical plasma physics considerations; this mode was designed for in-orbit validation of the m-NLP performance.

On 30 August 2017, the m-NLP was operated in science mode as the satellite crossed over the northern polar region while pointing continuously toward the sun. Figure 25 shows the collected current measurements from the four probes (A), the calculated electron density (B), and the spacecraft potential (C). As shown in Figure 25 (B), the electron density fluctuates significantly between 21:10 UT and 21:13 UT; this is likely due to the crossing of the auroral region. A closer look at the electron density measurement for a one second interval is shown in Figure 25 (D), where small-scale ionospheric plasma density structures are observed. These structures lie at the heart of the scientific investigation made possible by the m-NLP onboard NorSat-1.

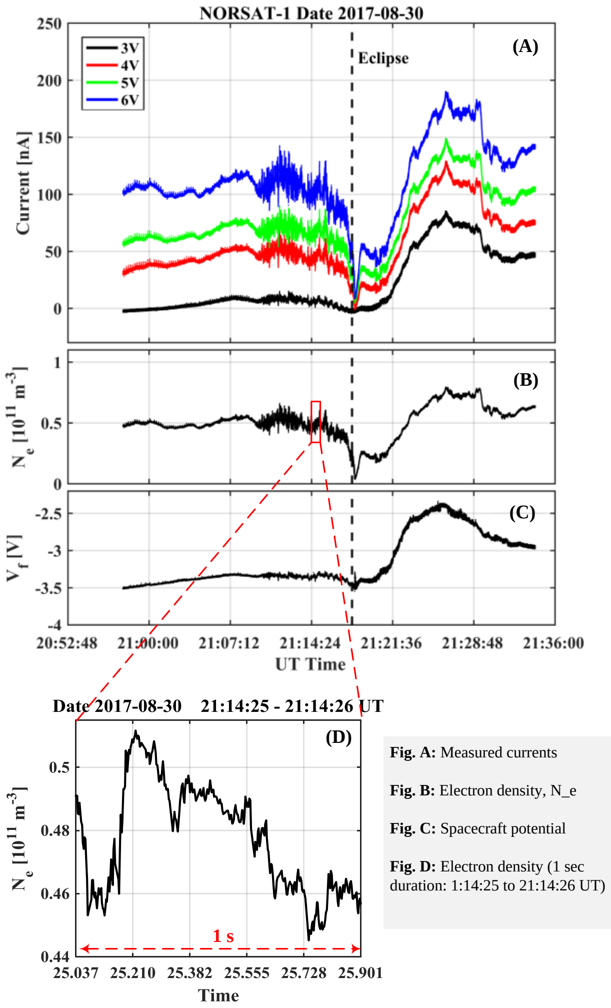

Figure 25: Measurement data from m-NLP (30 August 2017). Black dashed line indicates boundary between day- and night-side.

The vertical dotted line illustrates the boundary at which the satellite passes from sunlit orbit segment into eclipse. As seen on Figure 25 (C), before entering the Earth's shadow, the satellite potential fluctuates between -3.5 V and -3 V. Just after NorSat-1 leaves the auroral region and enters eclipse, all probe currents drop significantly and recover shortly after. A possible reason for this behaviour could be the sudden lack of emission of photoelectrons due to the absence of sunlight. Further investigation into this phenomenon is currently underway.

CONCLUSIONS

With a satellite mass of 15.6 kg, NorSat-1 has successfully integrated and enabled continuous operation of three diverse payloads, each satisfying different scientific and operational mission objectives: monitoring maritime vessels through space-based AIS detection and advancing science in space weather and solar research. Leveraging SFL's modular, extensible, and flight-proven NEMO bus platform has allowed reconciling the limitations and constraints imposed by each payload, achieving multidimensional mission objectives within a small satellite platform.

ACKNOWLEDGEMENTS

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