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NorSat-3 – next generation Norwegian maritime surveillance

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ABSTRACT

The NorSat-3 mission, with expected launch Q2/Q3 2020, aims to enhance the Norwegian recognized maritime picture with an experimental ship navigational radar detector (NRD) in addition to an AIS receiver. The NRD aims to geolocate ship navigation radars within 10 km circular error probable and verify AIS positions. The 10º NRD antenna field of view will nominally be pointed towards the horizon in order to maximize the area coverage and view of the ships' navigation radar main lobe. Operating in a near polar low earth orbit the Norwegian area of interest may be covered between 10 and 15 times per day if pointing the antenna suitably. Achieving the desired geolocation accuracy and area coverage, while minimizing polarization loss, requires a highly capable attitude determination and control system. The signal processing capabilities of the Zynq Ultrascale+ system-on-chip enables the radar signal processing in orbit, although also requiring a large platform power generation capability.

The mission, payloads and platform are described in this paper, including some of the lessons learned. All flight subsystems and payloads have completed their relevant unit environmental tests, including proton irradiation of NRD electronics. Final system verification and environmental testing begins August 2019, with a target flight readiness review November 2019.

INTRODUCTION

Ever since the launch of AISSat-1 in 2010[1,2], small satellites have played an important role in building the Norwegian recognized maritime picture. Satellite AIS systems have gone from being an experimental service to being a fully operational capability with an unprecedented ability to monitor ship traffic on a global scale[3]. The significant value added by space-based AIS systems to the recognized maritime picture convinced Norwegian authorities to provide long term funding of a space-based AIS program to continually replenish the space infrastructure and maintain the operational capability[4]. AISSat-1 and its follow on missions[4], AISSat-2 (a copy of AISSat-1) and NorSat-1[5] and -2[6], provide information on ship identities, positions, course and speed beyond line of sight of land-based receivers. However, the AIS system is a cooperative system with intentional and unintentional errors, and verification of information and fusion with independent sources is important for the creation of the recognized maritime picture and efficient allocation of resources[7].

In addition to securing the long-term space-based AIS operational capability with a state-of-the-art AIS receiver, the NorSat-3 mission aims to further enhance the Norwegian recognized maritime picture with an experimental ship navigation radar detector (NRD) for uncooperative ship detection and geolocation. Similar small satellites projects have recently been flown or proposed, often employing a constellation of satellites flying in formation[8-10]. A single satellite NorSat-3-like concept for maritime surveillance has been maturing at FFI since before the turn of the millennium, and finally it is considered that both the signal processing technology and platform capability are compatible with a low-cost navigation radar detector small satellite mission.

Building on past success, the NorSat-3 project is realised in cooperation between the Norwegian Space Agency (NOSA, formerly Norwegian Space Centre, NSC) and the Norwegian Defence Research Establishment (FFI), on assignment from the Norwegian Coastal Administration and the Norwegian Ministry of Defence. The satellite is built by the University of Toronto Institute for Aerospace Studies' Space Flight Laboratories (UTIAS/SFL), that also delivered the previous AISSat and NorSat platforms. The AIS payload is procured from Kongsberg Seatex (KSX), while the NRD payload is a custom development by FFI undertaken in parallel with the satellite design and development.

From the Norwegian Space Agency perspective, AISSat-1 and -2 not only gave Norwegian governmental users invaluable data and improved greatly the maritime picture in remote areas, they also provided industrial growth in a whole new segment and showed Norwegian authorities and politicians that small satellites were a sensible and cost-efficient way for Norway to use new technology to the benefit of a variety of user groups. However, it was clear that the mass, volume, power and data budget resources available on the AISSat platforms were inadequate for a significant development of the AIS payload and potentially auxiliary payloads. Therefore, a larger and more powerful satellite bus was selected for the NorSat missions.

When launched together in 2017, NorSat-1 and -2 became Norway's first multi-payload microsatellite with scientific payloads in addition to a more advanced AIS receiver. The larger and more powerful platform allowed additional instruments to do continuous measurements, though in case of conflicts between the payloads, the AIS receiver would get full priority.

The NorSat program has ensured AIS coverage in areas hard to reach with land-based stations, and increased redundancy and update frequency for the monitoring bodies. The introduction of auxiliary payloads has enabled the development of technologies that can enhance the maritime safety in Norwegian waters, while also allowing Norwegian space industry to gain experience in developing competitive products for space based maritime surveillance. The dual use concept has also allowed for multiple sources of funding and maximum distribution of the data among Norwegian governmental users.

Strategically, it is profitable for Norway to develop and operate national satellites in niche areas where NewSpace[11] technology allows better coverage and ownership of data at a reasonable cost. New sensors are developed and space qualified in a stepwise manner as auxiliary payloads, thus allowing risk to be kept at a reasonable level, all while steadily improving the national capabilities. The developments take place nationally, where the knowhow and experience of research laboratories and industry have allowed for competitive technological developments, again allowing Norwegian industry to position itself on niche market segments on the payload side.

THE MISSION

As previously stated, the primary objective of the NorSat-3 mission is to secure the long-term space-based AIS operational capability of the Norwegian Coastal Administration. The secondary objective is to demonstrate the operational capability of a ship navigation radar detector (NRD) to uncooperatively detect and geolocate ship radars operating on frequencies which the International Maritime Organization has allocated for civil navigational radars.

A typical ship navigation radar use a rotating antenna to scan its surroundings by emitting a narrow beam of radar pulses and measuring both the delay and returned pulse energy reflected from the surroundings for obstacle size, bearing and distance estimates. When unobstructed, the emitted radar pulses can also be detected in space with a suitably sensitive receiver such as the NRD payload. If the incoming radar pulse direction can be estimated, as the NRD payload does, a location on the earth surface for the radar may be calculated.

The NRD detections are further intended to be used to verify AIS positions. Unverified AIS positions and ship radar positions without corresponding AIS information can be prioritized for further scrutiny. The main area of interest is the Norwegian High North and to enable frequent revisits and near real time data distribution for maximum operational capability, a near polar inclination orbit is required. The target altitude is between 550 and 720 km resulting from the trade-off between signal strength, area coverage, and minimum and maximum orbital lifetime considerations.

The NRD antenna array consists of four (4) patch antennas, mounted in a specific geometry to enable single satellite angle of arrival (AoA) estimates based on interferometric phase difference measurements with minimal ambiguity. Angle of arrival estimates can then be converted to locations on the earth surface when combined with satellite attitude information. The estimated geolocation accuracy is typically within 10 km circular error probable.

While the antenna pattern for the two monopole AIS antennas on NorSat-3 are near omnidirectional and less sensitive to the satellite attitude, the NRD antenna has ca. 10º field of view and must be pointed suitably. Nominally, the NRD antenna will be pointed towards the earth horizon in order to maximize the area coverage and view of the ships' navigation radar narrow main lobe.

By default, the satellite attitude will be fixed in order to scan an area as the satellite moves as shown in Figure 1.

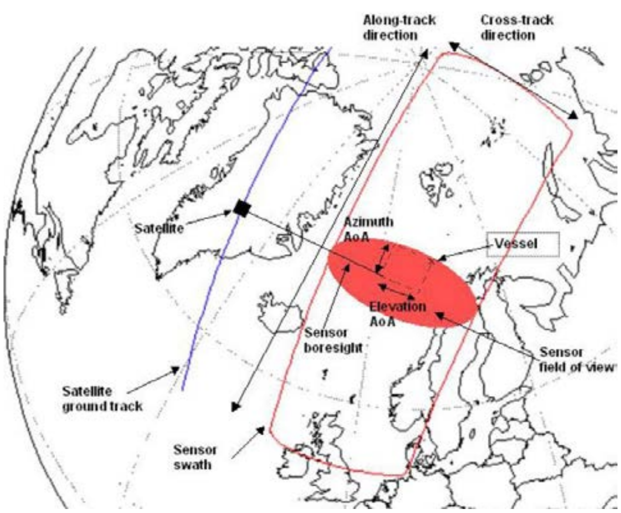

Figure 1 Example satellite pass over Greenland showing instantaneous coverage (filled red ellipse) and swath for 8 minutes of operation (area inside red line). Key terminology used in the text is also illustrated.

The instantaneous footprint when pointing towards the horizon is 1400 km along the antenna boresight axis and 450 km across. If the antenna boresight is pointed perpendicular to the satellite velocity direction as shown in Figure 1, the width of the track would be 1400 km as the satellites moves. If the antenna boresight is pointed parallel to the satellite velocity direction the width would be reduced to 450 km.

As the mission progresses more complex attitude strategies involving slews about the nadir axis will be tested in order to 1) increase the total coverage of a large area or 2) increase the view time of a particular area or 3) enable multiple views of multiple areas with different viewing angles. Viewing the same area with different viewing angles may increase geolocation accuracy by improved triangulation trigonometry.

A significant amount of on-board processing will take place to reduce the data volume from individual radar pulse samples, to pulse description words and finally to scan description words where numerous pulse description words are associated with a single ship radar source. The scan description words are then downloaded in near real time and final geolocation calculations are done on ground by triangulation of multiple direction estimates from associated scan description words. Furthermore, similar to the principles of a star-tracker, the AIS positions can be used as a reference map for the NRD positions. By matching the NRD positions with the AIS positions, time varying or fixed NRD phase measurement offsets can be calibrated out and improve the geolocation accuracy of the NRD geolocation estimates as illustrated in Figure 2.

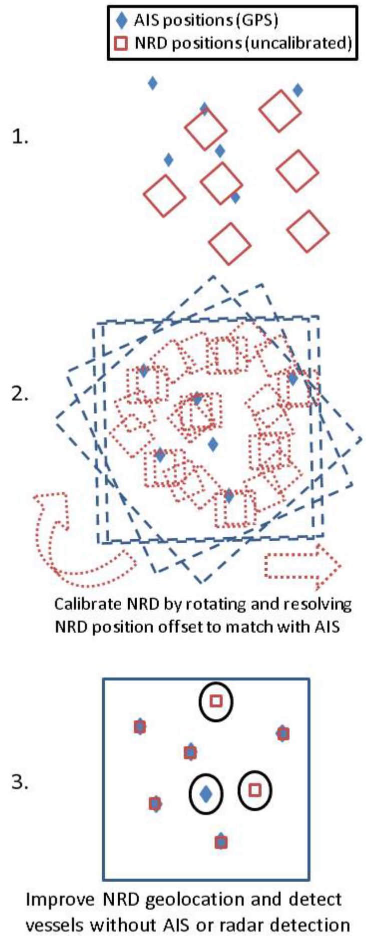

Figure 2 Illustration of calibrating and improving the gelocation accuracy of NRD data using AIS data.

The key design parameters from the phase A study to enable the described mission are listed in Table 1.

Table 1 NorSat-3 mission key design parameters

Parameter	Value	Note
Orbit	550 – 720 km altitude, high inclination	Design must comply with low earth orbit debris mitigation guideline
Payload power budget	NRD: Nominal: 25W Max: 30W AIS: 3.75W	20% duty cycle @ 25W for the NRD, but the satellite power system should accommodate 30W peak with reduced duty cycle equal to 5W orbit average.
Payload data budget	25 Mbyte	Orbit average
Payload mass budget	3.5 kg	Mounting plate/interface for antennas not included, assumed part of satellite structure.
Pointing requirement	0.5 deg, 3-axis	
Attitude knowledge requirement	0.05 degrees	Short term during measurement of a radar sweep, up to 3 sec.
Antenna element thermal range	-100°C to +100°C	Survival

THE PAYLOADS

NRD

The space-based NRD payload design is based on heritage design from experimental terrestrial navigation radar detector systems developed by FFI. Performing similar tasks as the terrestrial heritage systems in space poses a series of new challenges for the payload. The environment is very different, with more extreme temperature loads and variations, vacuum and cosmic radiation to name a few differences. In addition, the much increased distance between the ship radars and the navigation radar detector yields significantly lower signal levels.

The NRD payload consists of both an antenna and receiver electronics. Both are developed by the Norwegian Defence Research Establishment (FFI) with partners. Often the receiver electronics is referred to as the NRD payload or simply the NRD, and the antenna as the NRD antenna, but strictly the NRD payload comprise both receiver electronics and antenna.

NRD receiver electronics

The NRD receiver electronics are developed by the Norwegian Defence Research Establishment (FFI) in cooperation with Kongsberg Seatex (KSX). The NRD leverages both FFIs experience developing similar instruments for use on earth, as well as KSX experience from space-based AIS receiver design and other relevant positioning and navigation systems designs. KSX was responsible for the re-design and production of the electronics, while FFI were responsible for the specification, all S/W and testing. The structure was based on KSX ASRx50 AIS structure, modified and produced by FFI for the NRD.

The NRD functionality is distributed over three (3) highly integrated printed circuit board (PCB) assemblies as shown in Figure 3.

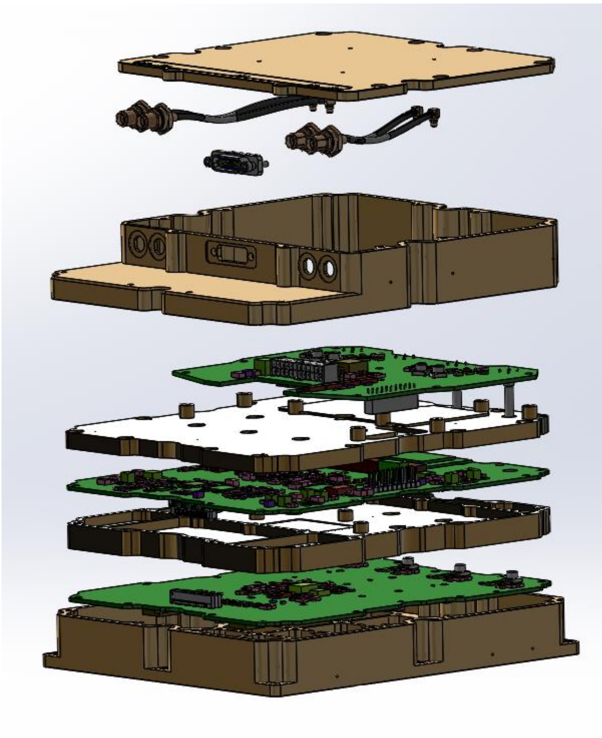

Figure 3 Integrated NRD electronics exploded view

The input/output and the first part of the analogue front end are implemented on the top board. The remainder of the analogue front end and the intermediate frequency channels are implemented on the bottom board. The analogue to digital converter and remaining digital signal processing as well as the command and control S/W is implemented on the middle board. The boards are shielded from each other as much as possible for electromagnetic interference mitigation in addition to aiding heat transfer. The NRD is made entirely of industrial, or in some cases automotive, grade commercial off-the-shelf components.

The signal processing capabilities are enabled by the latest generation Xilinx Zynq Ultrascale+ multi-processor system-on-chip (MPSoC) ZU9EG, together with an AD9694 Analog-to-Digital converter from Analog Devices. The digital signal processing functionality of the ADC offloads significant data processing out of the FPGA domain. Paired with the flexibility of the Zynq Ultrascale+ MPSoC, this allows us to create a powerful yet power efficient system, where the available resources can be largely tailored to our specific use-case.

When the preliminary design work/brainstorming for the NRD began in 2017, the Zynq Ultrascale+ MPSoC series stood out due to its built-in safety features and general versatility. The 16 nm Fin Field-effect transistor (FinFET) process the chip is manufactured in also promised increased radiation tolerance compared to previous generations of the Zynq family. At the time of project initiation, very little radiation test data was available for the Zynq MPSoC series. During the development, some radiation test results began to emerge[12-15] and while no instantaneous destructive latch-up was reported, latch-ups were a common occurrence. The total dose tolerance was seemingly excellent. All NRD receiver electronics were put through a proton irradiation test at the TRIUMF facilities in Vancouver, Canada, 18-20 December 2018. The test aimed to investigate the likelihood of destructive events and understand the expected in-orbit upset rate for the entire NRD electronics equipment and specific flight S/W implementation when subjected to ionizing radiation. Two beam energies were used, 480 MeV and 105 MeV with no destructive failures or death modes induced. First, individual components were targeted with small beam sizes using the 480 MeV beam as shown in Figure 4 to minimise the total dose accumulated while probing for latch-ups and mapping individual component single event upset behaviour. Finally, the full NRD electronics stack was irradiated with the 105 MeV beam as shown in Figure 5, with a beam size large enough to cover the entire instrument for a most in-orbit representative configuration and single event effect impact.

Figure 4 Two of the NRD electronics boards mounted on the 480 MeV proton irradiation beamline. The beam size was small to enable individual component irradiation. The Zynq can be seen in the middle of the board on the right hand side.

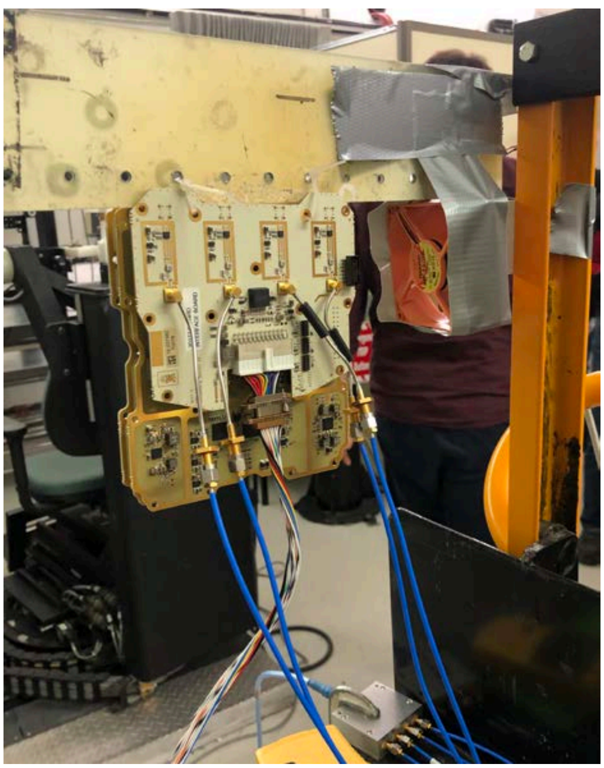

Figure 5 The full NRD instrument stack mounted on the 105 MeV proton irradiation beamline.

With the combination of regular power cycling (implicit from the 20% NRD duty cycle), external monitoring by the satellite and very low worst-case upset rate estimates of 1-3 upsets requiring a power cycle per year, the operational availability of the NRD is expected to be excellent and near 100% of the required duty cycle. For the Zynq in particular, five (5) latch ups were seen during 480 MeV irradiation (2.4e10 protons/cm^2 fluence), and four (4) during 105 MeV irradiation (9e10 protons/cm^2 fluence). All latch-ups were cleared from power cycling and were tolerated by the significant margin and de-rating of the power design. Some very large latch-ups (>1A) were seen, and on two occasions, when the latch-up was small, the test continued without power cycling and it was noticed that additional latch-ups occurred, building on top of the existing current draw.

The NRD only makes use of a limited amount of the available resources in the Zynq. However, the advanced power management features of the Zynq enables tailoring of resources to a specific architecture, without wasting additional power on idle processing elements. The system as a whole has been designed with this headroom in mind, meaning the NRD has room for more advanced algorithms that can be uploaded to the instrument later on in the mission, a strategy used with great success for the previous AISSat and NorSat missions. The NorSat-3 platform is designed to sustain 25W NRD power consumption with 20% duty cycle, or 30W with a corresponding reduction in duty cycle, but the current implementation only uses ca. 19W, leaving significant margin for future upgrades. The Zynq MPSoC system also functions as a versatile utility for other projects to build on in addition to future iterations of the NRD itself.

In addition to being a piece of very sophisticated hardware, a Zynq Ultrascale+ is a very software "heavy" component. In the NRD, four (4) software applications work in concert for the system to process data. First, the bootloader initiates the Zynq system and puts all other peripherals on the NRD to sleep. On command, the Zynq power management application software is loaded, as well as the NRD's main command & control (C&C) application, which functions as the system master from that point on. When commanded again, the C&C application loads the FPGA configuration and data processing application. In terms of Zynq resource usage, the C&C application runs on the real-time processing unit (RPU) and the data processing application runs on the application processing unit (APU) processor cores of the Zynq, and are completely independent of each other.

NRD antenna

The NRD antenna consists of four (4) array antennas with separate phase centres. The array antennas are mounted in a specific geometry to enable single satellite angle of arrival (AoA) estimates based on interferometric phase difference measurements. While many different antenna element designs were considered, in the end a probe-fed patch antenna was selected due to the size, weight and extreme operating environment (secondary launch and +/- 100°C survival temperature) limitations imposed by the small satellite mission. In addition, the whole array antenna with feeding network could be made as a single printed circuit board (PCB), with the stack-up as shown in Figure 6.

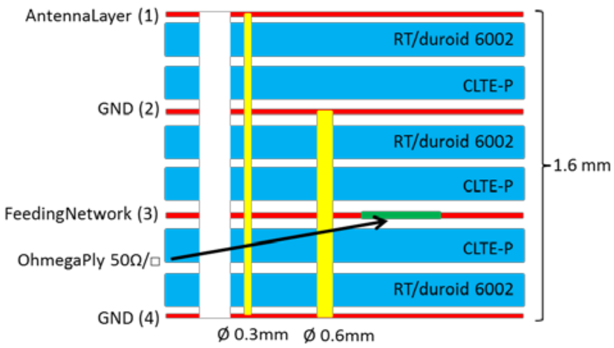

Figure 6 NRD antenna array stack-up. The arrays are made as single printed circuit boards.

Due to the wide thermal range, it was especially important to match the thermal expansion coefficient (CTE) of the substrate with that of copper to minimise the stress on the vias (vertical interconnect access - VIA). The first material considered was the RO4003C which is a commonly used substrate for microwave applications. It was considered because of availability and flight heritage. However, the z-axis thermal expansion coefficient of RO4003C was poorly matched to copper. Calculations based on the IPC-TR-579 failure model showed that the vias would begin to fail due to thermal expansion induced fatigue well within a year in orbit. A redesign of the antenna elements using RT/duroid 6002 and fewer layers was therefore started in Q1 2018, with valuable support from the French Space Agency (CNES).

RT/duriod 6002 is a polytetrafluoroethylene (PTFE) based substrate with a thermal expansion coefficient well matched with copper and has prior flight heritage. CLTE-P, ref. Figure 6, is an adhesive used to bond PTFE substrate layers together. In addition to these materials, OhmegaPly embedded resistors were used in the feeding network. None of these materials had defined properties over the entire temperature range specified, so thermal testing and characterisation was required. Antenna characteristics were measured during thermal cycling and an accelerated life time test was performed. The antenna characteristics did not change drastically over the temperature range and no failure in the vias or bonding were observed after the life time test.

The production of the antenna was a big challenge. Firstly, it was difficult to find a PCB manufacturer that had the necessary equipment and experience to work with the required materials. Secondly, making high quality vias in a PTFE based substrate is difficult because of smearing. Smearing occurs when the friction between drill bit and material causes the material to melt and smear around the inside of the hole. This leads to poor or non-existing contact between via and copper traces. The only way to avoid smearing in PTFE based substrates is to find correct drill parameters and use a low hit count for the drill bit. Determining the optimal drill parameters proved to be very difficult and the EM and QM antennas were delivered with smearing in Q3 2018. However, electrical and accelerated life time tests were successful and it was decided to build the FM. The PCB manufacturer continued extensive testing to find the optimal drill parameters and a maximum hit count of 50 was used in the end. This resulted in the FM antennas being produced without smearing and they were delivered Q1 2019.

Phase interferometry requires the phase difference between antennas phase centres to be measured. Ideally this phase difference only depends on the frequency, baseline and angle of arrival (AoA), such that the AoA can be estimated from the phase difference measurements. However, the actual positions of the antenna phase centres, and implicitly the baseline, are dependent on the angle of arrival. Thus, to be able to calculate the true angle of arrival estimates the NRD antenna must be characterised and the measured phase centre locations must be used in the AoA estimates. Furthermore, the cables, connectors and even the NRD electronics itself introduce a phase offset that must also be calibrated for true angle of arrival estimates. The phase offset introduced by cables and electronics is independent of angle of arrival however, but may vary with frequency and temperature.

Several calibration methods are possible, from fully in-orbit, via large outdoor test ranges, to smaller anechoic chamber facilities or a combination thereof. For the NorSat-3, the NRD antenna phase center offset and phase center variation as a function of signal direction are characterized in the far field for each antenna independently using an anechoic chamber. The final calibration will be performed continuously in-orbit based on recorded data and AIS association. While a very precise antenna characterisation on ground should make the in-orbit calibration simpler, launch and temperature variations in-orbit would likely introduce additional offsets that could not be accounted for during ground calibration in any case. As long as the antenna characterisation is not too coarse, there should be low vessel density areas where it is possible to associate radar locations with AIS positions to better characterise the antenna and calibrate the system in-orbit.

AIS

The AIS receiver in NorSat-3 is the state-of-the art ASRx50 AIS receiver from Kongsberg Seatex AS, identical to the flight proven AIS receivers in NorSat-1 and NorSat-2. The ASRx50 has been shown to yield a significant AIS message and ship detection performance increase compared with previous generation AIS receivers, resulting in substantially improved ship tracking performance[16]

THE PLATFORM

The NRD payload relies on a highly capable spacecraft platform. A precise 3-axis attitude control system is required to point the NRD antenna and to allow for post-processing of the NRD payload data to geolocate ships. A large power generation capability is required to support the power intensive on-board signal processing capability of the NRD payload. In addition, a large surface area is needed to support the NRD antenna. All of these needs are met by SFL's NExt-generation Monitoring and Observation (NEMO) microsatellite platform.

The NEMO platform is highly configurable and has been tailored specifically for the NorSat-3 mission. The NRD and AIS payload electronics are housed within the platform. The NRD antenna is supported by a large fixed composite panel that also doubles as the spacecraft's primary solar array. Two deployable AIS monopole antennas are also supported. The platform relies on a heritage suite of avionics to provide power conditioning and distribution, command and data handling, communications, and attitude control.

The NorSat-3 platform is shown in Figure 7 and some key design characteristics and performance metrics are summarized in Table 2.

Table 2: NorSat-3 platform key parameters

Design Characteristic / Performance Metric	Value
Spacecraft Mass	16.0 kg
Bus Dimensions - without Array	0.44 x 0.27 x 0.2 m
Bus Dimensions - with Array	0.62 x 0.56 x 0.33 m
Peak Power Generation (end-of-life)	48 W
Energy Storage	108 W·h
Command Uplink	S-band, 32 kbps
Data Downlink	S-band, up to 2 Mbps

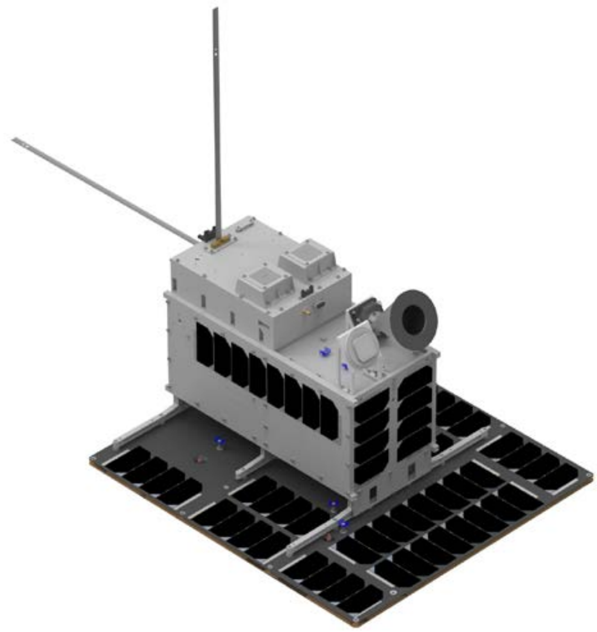

Figure 7: NorSat-3 spacecraft platform

The spacecraft is compatible with SFL's XPOD deployment system which allows for large pre-deployed appendages such as the NRD antenna and solar cell array. The deployment system also allows the AIS antennas to be held in a stowed position for launch and automatically released when the spacecraft is deployed from the launch vehicle. Power generation in all attitudes, along with omni-direction coverage for the S-band radio links ensures that the spacecraft is highly robust. A star tracker and reaction wheels allow for precise attitude control, enabled by SFL's heritage on-board attitude software.

PROJECT STATUS

In spite of the significant problems and delays in manufacturing the NRD antenna, the overall schedule has not been delayed much thanks to a close cooperation between the partners. Furthermore, the NRD payload did not secure full funding until Q3 2017, which made the parallel development of the NRD payload and satellite challenging. With a project start mid Q1 2017 the original target flight readiness review was ambitiously scheduled for the end of Q2 2019. As of June 2019, all payload flight models and satellite subsystems have passed their relevant unit environmental tests and a risk reduction integrated satellite level EMC test has been successfully completed after some debugging. The satellite integrated system level test campaign is scheduled to begin August 2019, with the flight readiness review now scheduled for November 2019.

Once launched, based on previous experience, the AIS payload will go fully operational as soon as basic commissioning of the spacecraft is complete. The NRD instrument will possibly require a longer commissioning period to calibrate the instrument, followed by an experiments phase. The experiments phase will investigate the basic performance parameters such as detection probability and geolocation accuracy in addition to experimenting with instrument and satellite parameters to maximise said performance and the value added to the recognised maritime picture. The next step in the experiment phase is to develop operational procedures to configure and operate the instrument and satellite to maximise the utility for the users. The goal is to enter an operational capability demonstration phase after 1 year of experimentation.

REFERENCES

1. Narheim, B.T., Helleren, Ø., Olsen, Ø., Olsen, R., Rosshaug, H., Beattie, A.M., Kekez, D.D., Zee, R.E. (2011). "AISSat-1 Early Results." Proceedings of the AIAA/USU Conference on Small Satellites, Reflections on the Past, SSC11-III-6.
2. Helleren, Ø., Olsen, Ø., Narheim, B. T., Skauen, A. N., Olsen, R. B. (2012). "AISSat-1 – 2 years of service." Proceedings of the 4S Symposium, Portorož, Slovenia.
3. Eriksen, T., Skauen, A., Narheim. B., Helleren, Ø., Olsen, Ø., Olsen, R. (2010). "Tracking Ship Traffic With Space-Based AIS: Experience Gained in First Months of Operations." Proceedings of the Waterside Security Conference, Marina di Carrara, Italy. DOI: 10.1109/WSSC.2010.5730241
4. Harr, J., Jones, T., Andersen, B. N., Eriksen, T., Skauen, A. N., Svenes, K., Blindheim, E. V., Spydevold, I., Beattie, A., Bradbury, L. M., Cotten, B., Kekez. D., Mehradnia, P., Zee, R. E., Storesund, F. (2018). "Microsatellites for maritime surveillance – an update on the Norwegian smallsat program." Proceedings of the 69th International Astronautical Congress (IAC), Bremen, Germany, 1-5 October 2018. IAC-18.B4.4.2x45204
5. Pehradnia, P., Beattie, A., Kekez, D., Zee, R., Walter. B., Koller, S., Pfiffner, D., Finsterle, W. (2018). «NorSat-1: Enabling high performance and multipurpose microsatellite missions." Proceedings of the AIAA/USU Conference on Small Satellites, Year in review, SSC18-I-06
6. Bradbury, L. M., Diaconu, D., Laurin, S. M., Ma, C., Beattie, A., Spydevold, I., Haugli, H., Zee, R., Harr, J., Udnæs, F. (2017). "NorSat-2: Enabling Advanced Maritime Communications with VDES." Proceedings of the AIAA/USU Conference on Small Satellites, Next on the Pad 2, SSC17-XIII-08.
7. Skauen, A. N., Helleren, Ø., Olsen, Ø., Olsen, R. (2013). "Operator and User Perspective of Fractionated AIS Satellite Systems." Proceedings of the AIAA/USU Conference on Small Satellites, Around the Corner, SSC13-XI-5.
8. Sarda, K., CaJacob, D., Orr, N., Zee, R., (2018). "Making the Invisible Visible: Precision RF-Emitter Geolocation from Space by the HawkEye 360 Pathfinder Mission." Proceedings of the AIAA/USU Conference on Small Satellites, Next on the Pad, SSC18-II-06.
9. Brodecki, M., de Groot, Z., "SIGINT: The Mission CubeSats are Made For" Proceedings of the AIAA/USU Conference on Small Satellites, Science / Mission Payloads II, SSC18-VII-03.
10. Delmas, C., Hourtolle, C., Prevot, Y. (2018). "Formation flight handling with 4 satellites – Electronic Earth Observation as an application" Proceedings of the 2018 SpaceOps Conference, Marseille, France. DOI: 10.2514/6.2018-2325
11. https://en.wikipedia.org/wiki/NewSpace [Accessed 16. May 2019]
12. Hiemstra, D. M., Kirischian, V., Brelski, J. (2017) "Single Event Characterization of the Zynq UltraScale+ MPSoC Using Proton Irradiaton" Proceedings of the 2017 IEEE Radiation Effects Data Workshop (REDW), New Orleans, LA, USA. DOI: 10.1109/NSREC.2017.8115448
13. Maillard, P., Hart, M., Barton, J., Arver, J., Smith, C. "Neutron, 64 MeV Proton & Alpha Single-event Characterization of Xilinx 16nm FinFET Zynq Ultrascale+ MPSoC" Proceedings of the 2017 IEEE Radiation Effects Data Workshop (REDW), New Orleans, LA, USA. DOI: 10.1109/NSREC.2017.8115449

14. Koga, R., Davis, S., George, J., Zakrzewski, M., Mabry, D. (2018) “Heavy Ion and Proton Induced Single Event Effects on Xilinx Zynq Ultrascale+ Fielf Programmable Gate Array (FPGA)” Proceedings of the 2018 IEEE Radiation Effects Data Workshop (REDW), Waikoloa Village, HI, USA. DOI: 10.1109/NSREC.2018.8584319

15. Lee, D. S., King, M., Evans, W., Cannon, M., Perez-Celis, A., Anderson, J., Wirthlin, M., Rice, W. (2018) “Single-Event Characterization of 16 nm FinFET Xilinx Ultrascale+ Devices with Heavy Ion and Neutron Irradiation” Proceedings of the 2018 IEEE Radiation Effects Data Workshop (REDW), Waikoloa Village, HI, USA. DOI: 10.1109/NSREC.2018.8584313

16. Skauen, A. N., (2019) “Ship tracking results from state-of-the-art space-based AIS receiver systems for maritime surveillance” CEAS Space Journal. DOI: 10.1007/s12567-019-00245-z