

Shining a Spotlight on Maritime Dark Traffic

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ABSTRACT

The ability to support Maritime Domain Awareness from space using Synthetic Aperture Radar (SAR) has been successfully demonstrated in the past, however practical challenges in achieving the necessary area coverage, temporal coverage and spatial resolution for a practical system has eluded wider adoption. Yet demand for Maritime Surveillance has increased in recent years, to protect important maritime energy and communications infrastructure, fisheries, and maritime reserves, and especially for maintaining national security and territorial integrity. A novel approach to the SAR payload design solves these challenges, and smallsat technologies have also matured to the point where a High-Resolution Wide-Swath (HRWS) system can be implemented within a modest satellite form factor in a constellation, with the ability to persistently cover large, strategically important maritime areas. The HRWS minisatellites will have the ability to fit within the Falcon-9 XL launch slot, delivering with 0.5x3m resolution in strips of up to 400x4000km. Extending this to a constellation will allow vast areas to be monitored continuously, significantly improving domain awareness and leading to more efficient use of maritime and aerial assets towards specific areas of interest.

Introduction

Modern maritime security is challenged by vast areas of interest, rapidly evolving threats, and adversaries increasingly exploiting gaps in existing surveillance capabilities. Monitoring maritime activities around the world is increasingly important with 80-90% of the world trade by volume is carried by sea, a multitude of off-shore gas, oil and wind farm installations, delicate fisheries and fish farms, and critical undersea pipes and cables related to energy and communications, as well as search and rescue obligations, and in some cases protected marine environments to monitor. Although “dark targets” are of significant interest, having a holistic overview of maritime activities fulfils a much wider range of objectives and can lead to economic gains through improved efficiency and awareness. Traditional methods to track shipping use coastal sensors and instrumented buoys, maritime patrol vessels, drones, and aircraft, but are limited by range, weather, endurance, and the need for vessel cooperation. Automatic Identification System (AIS) has emerged as a useful tool for monitoring shipping, although required for all vessels over 300 gross tonnes and all passenger ships by the International Maritime Organisation’s Convention for Safety of Life at Sea, it can be turned off, spoofed, or manipulated by naval vessels. Beyond narrow coastal strips, activity monitoring and tracking becomes increasingly challenging, and the area-coverage and costs associated with viable solutions can become prohibitive for larger regions which is why large areas of the seas and oceans remain unobserved.

To date satellites have almost exclusively been used to extend coverage of AIS tracking. Imaging satellite solutions have lacked the maturity in area coverage, and value-for-money.

Satellites can provide a logical means to extend the areas that can be effectively monitored, whilst still providing a cost-effective solution. Optical satellites suffer from cloud cover and therefore lack true real-time responsiveness under all conditions. Furthermore, in the “High North” the long winter periods with almost permanent darkness would significantly reduce the effectiveness of optical systems. Radar imaging satellites are therefore an obvious choice, as these can provide imagery day and night in all-weather. Satellites will not replace any other assets already in operation but would complement them. Allowing them to be used in a more targeted and cost-effective method, and a maritime surveillance system will comprise of a range of different assets.

Satellite solutions also require high area coverage rates at high enough resolution to detect, classify, and identify targets of interest across vast ocean areas, fast enough to ensure nothing could be missed. This implies generating

huge data sets which must be temporarily stored on-board, downlinked, stored (and archived) and processed, exploited and disseminated. In order to minimise costs, a high degree of automation would be required, with automated analysis and delivery of actionable insights instead of imagery.

With the emergence of small satellite radar satellite technologies, advances in data processing through Machine Learning and Artificial Intelligence, and the criticality for Maritime Surveillance rising, the situation is changing and Synthetic Aperture Radar (SAR) satellite systems are for the first time becoming viable solutions.

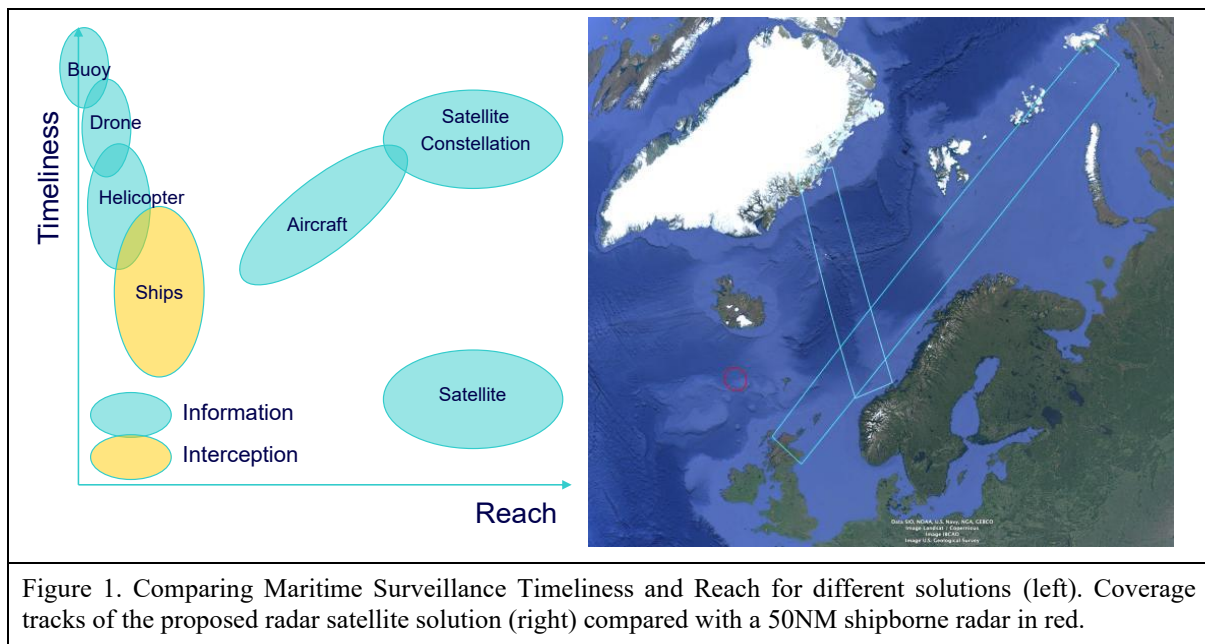


Figure 1. Comparing Maritime Surveillance Timeliness and Reach for different solutions (left). Coverage tracks of the proposed radar satellite solution (right) compared with a 50NM shipborne radar in red.

The Challenges of Synthetic Aperture Radar on small satellites

Traditional SAR missions have been developed by governmental agencies for years, addressing predominantly scientific and security application. As such spacecraft were considered costly, they often had to address a wide range of use cases and end-users leading to large complex spacecraft that support numerous applications and operational modes, delivering exceptional performance and very high-quality data.

Many applications for Synthetic Aperture radar require higher temporal resolution than can be achieved with a single satellite, ultimately driving towards a system comprising multiple smaller satellites that can be launched in groups, and that can be built sharing the same overall system budget. Higher temporal resolution opens up a wider range of applications that such a satellite system can address, making it more likely that a satellite system can be commercially exploited or provide a Return on Investment. In the mid-2010s the proven capabilities and lower costs of “small satellites”, coupled with the emergence of much more efficient Gallium Nitride pulse power amplifiers would make it possible to achieve acceptable Synthetic Aperture Radar performance on much smaller spacecraft. Iceye is one of the pioneers in this area, and have deployed 62 small spacecraft by the end of 2025, and the number of small SAR spacecraft launched around 140 in that same time period. In the same period there are a further 21 individual small SAR spacecraft launched that are not (yet?) part of constellations. Figure 2 highlights that small SAR spacecraft only really becoming viable around from 2017.

Inevitably by making the spacecraft smaller, so that the financial budget afford multiple spacecraft to provide higher temporal resolution, there are compromises that must be accepted in performance [3]. These tend to come down to compromising on (1) data quality and more specifically Noise Equivalent Sigma Zero (NESZ) which is a measure of Signal to Noise, (2) payload duty cycle, which is a measure of how much imaging can be achieved on each orbit, and (3) design life time. Many of these small spacecraft are in the 80-160kg class which tends to be the minimum viable commercial product with today’s technology, and a few spacecraft are in the 200-300kg range where fewer compromises are accepted. Another observation is that spacecraft series that started relatively small

have gained weight in later generations, in order to address design challenges, improve capabilities, and provide a better return on investment.

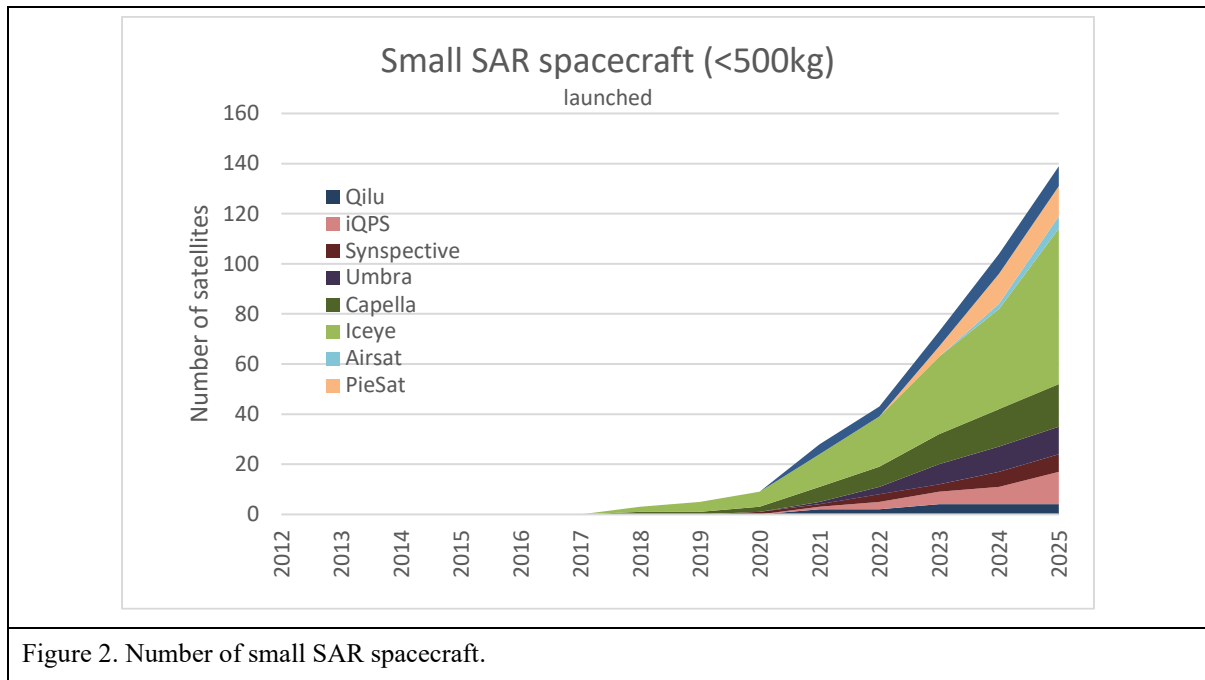


Figure 2. Number of small SAR spacecraft.

Two of the individual spacecraft launched in this time period are SSTL’s NovaSAR-1 and CarbsAR-1. SSTL has built up considerable expertise to accommodate SAR payloads on its standard satellite platforms and adapt those platforms to the unique challenges imposed by SAR payloads in relation to power, thermal, attitude control and mechanical configuration.

The SAR payload can introduce additional charge-discharge cycles every time the payload is switched on, as solar power generation tends to be significantly lower than the multi-kilowatt demand of a typical SAR payload. SAR payloads therefore tend to need higher capacity batteries than usual to deal with high discharge current capability, and to preserve mission lifetime so that it is not limited by the battery. The pulsed nature of the DC power can also introduce additional complications and a “standard satellite platform” might not cope well with that, and the EMC design of “standard platforms” may not be compatible with SAR payload radiating high power RF signals and requiring high receiver sensitivity at the same frequencies.

Modern SAR payloads tend to only be 25% efficient in relation to DC-to-RF power conversion at best, and so most of the multi-kilowatt power is dissipated as heat, which must be conducted away from the payload and radiated from the spacecraft in order to minimise temperature cycling.

The payload configuration on the spacecraft will also need to be carefully considered and also does not always work with a standard off-the-shelf bus solution. The antenna tends to require deployed dish or phased-array antenna panels, power demand usually leads to a solution using deployed solar panels, and battery and radar electronics tend to be heavy and need careful placement inside the spacecraft structure.

Finally, when designing for constellation, these design problems can escalate even further if spacecraft need to operate in different orbit planes instead of a nicely constrained sun-synchronous orbit.

These challenges and trades favours integrated designs where the satellite platform and payload are designed concurrently, so that these trades balance payload and platform requirements, and do not lead to an overly complicated payload or platform design. Furthermore, the nature of these trades also makes it usually challenging to use a “standard off-the-shelf satellite platform” in an efficient design, as it may be overly constraining or underspecified for a SAR payload.

NovaSAR-1 and CarbSAR-1

NovaSAR-1 [4] was SSTL's first radar satellite, which started its design in around 2012, and was eventually launched in 2018. It has been operating successfully for over 7 years providing a range of services and applications for governments of the United Kingdom, India, Australia, and the Philippines amongst others.

NovaSAR was designed to fit on an SSTL minisatellite class spacecraft, carrying an Airbus UK phased array antenna to address a range of applications including maritime surveillance. To this end the spacecraft carries an Automated Identification of Ships (AIS) receiver, allowing it to closely match ship detection by SAR and AIS from the same data set, reducing the need to extrapolate ship location from the AIS location, heading and speed information, thus increasing the probability of match between the SAR and AIS data.

The spacecraft supports a wide range of software configurable modes including Stripmap, ScanSAR, and dual- and tri-polarisation. In order to support maritime surveillance, the mode was designed specifically with a 400km swath, 6x14m resolution and HH polarisation, and accepting of along-track ambiguities as a trade-off for achieving the swath width. As illustrated in the image below, the same ships are likely to show up multiple times in the image, but in most cases can be located to a unique position by careful processing and analysis of the data set. This is also an ideal application for AI processing which has been explored with Craft Prospect Ltd. in the UK [5].

NovaSAR was designed to operate at S-band, limiting resolution to 6m, but at that wavelength the imagery was not affected much by wave structures in the water, making it ideal for detecting objects in the water against the waves.

Although this early attempt at a SAR satellite with Maritime Surveillance capability has been effective, the satellite technology of the time provided still limited area coverage. Also, resolution limits classification and identification of objects, especially for smaller ships.

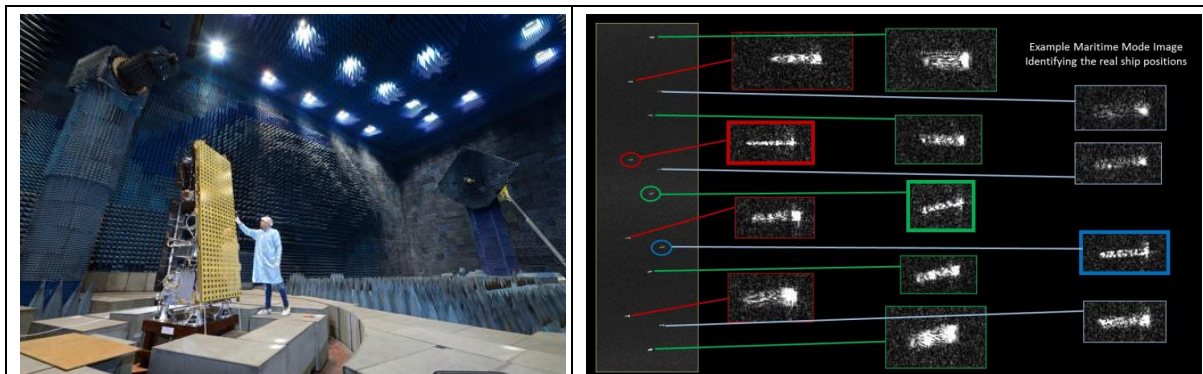


Figure 3. NovaSAR in antenna test chamber at Airbus

CarbSAR was designed by SSTL to re-use the SSTL-Carbonite small satellite platform as best as possible, which has been extensively used to carry high resolution optical payloads including optical video and thermal band video. CarbSAR complements this series of spacecraft allowing spotlight operation in 5x5km areas at 0.5m resolution.

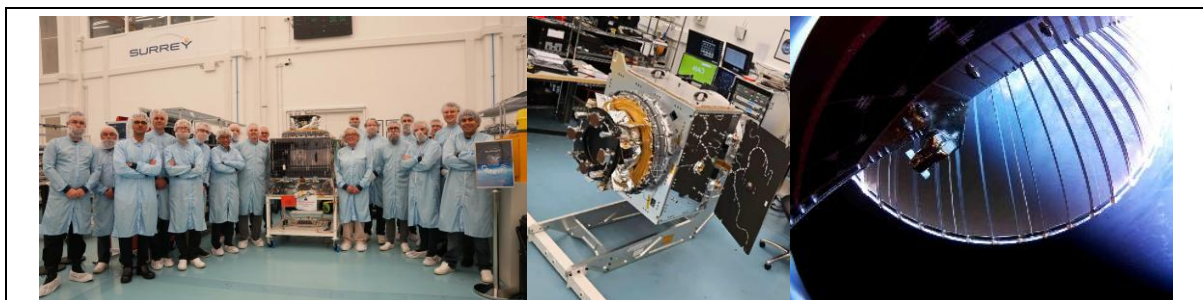


Figure 4. CarbSAR spacecraft (left) and deployed parabolic dish in-orbit (right)

CarbSAR utilisation in maritime surveillance is also relatively limited. Although it provides better resolution, that is achieved by sacrificing swath. The CarbSAR spacecraft supports 3-minute imaging, with the achievable swath is constrained by the beamwidth of the deployable antenna allowing it to capture narrow strips of 5x1200km. Operation at X-band also results in a high amount of clutter in the imagery over the ocean, as water wave structures are of the same scale as the imaging wavelength.

Saga “No Vessel Unseen” Pilot Mission

Maritime surveillance of the High North and the North Atlantic is a strategic priority for the Norwegian government. Norway has extensive fisheries, energy infrastructure, and search and rescue obligations. With the northern seas projected to be increasingly free of ice, shipping routes through the High North will become increasingly important, simultaneously raising the need for security and surveillance of Norwegian waters to protect sovereignty, the Norwegian economy and environment.

These needs are not dissimilar to the needs in other regions in the world, and Space Norway has identified that in implementing a space based maritime surveillance system for their own government, there are also opportunities to make the additional capacity of any satellite system available as a commercial service to other end-users around the world.

By considering a space-based radar maritime domain awareness system, it achieves:

- All-weather, 24/7 surveillance across vast maritime regions, independent of daylight or cloud cover
- Detection of non-cooperative and AIS-off vessels, including those engaged in smuggling, illegal fishing, or grey-zone operations.
- Continuous vessel tracking across entire ocean theatres through constellation-level optimisation.
- High-resolution wide-area imaging at a scale unmatched by current commercial SAR systems
- Actionable, automated intelligence outputs, reducing the burden on human analysts.
- Cost-effective, risk-free global coverage, at a fraction of the cost and complexity of aircraft, ships, or drones
- Sovereign, secure infrastructure, operated by a fully state-owned Norwegian entity with deep maritime and defence heritage.
- A robust surveillance system can deter undesirable behaviours in the region of interest.

Space Norway is wholly owned by the Norwegian Ministry of Trade, Industry and Fisheries, and acts as their space mission implementation arm. Space Norway operates a number of GEO communications satellites having acquired Telenor in recent years, as well as operating VDES LEO maritime communications spacecraft amongst others. The Saga maritime surveillance project was initiated by Space Norway in 2016 with the Norwegian Armed Forces (NOAF) as their anchor customer, with Surrey Satellite Technology Ltd. (SSTL) in the UK becoming involved in 2018. The Saga “No Vessel Unseen” capability provides military and government users with a persistent orbital perspective of maritime activity which is a step change in awareness, readiness, and operational advantage. The mission is named after the Norse goddess Sága, whose name is linked to seeing and storytelling. True to its name, Saga will watch over the world’s oceans from orbit, transforming complex maritime activity into timely, actionable insight

SSTL is a small satellite specialist with experience of manufacturing and priming nearly 80 satellite missions, with specific focus on operational Earth Observation missions for commercial operators and governments in recent years, including Synthetic Aperture Radar. Following a series of design and technology development projects that identified key suppliers in the mission and payload including FFI, WideNorth, Eidel, and KSAT in Norway, and Oxford Space Systems in the UK. A pilot mission spacecraft was contracted as the spacecraft prime in 2022 [1], to design the spacecraft around the Space Norway payload, and to bring it into operation.

Although the system will require multiple satellites in constellation to achieve the latency targets, the first spacecraft can already provide a full pilot service for the Norwegian Armed Forces. The spacecraft leverages leading-edge technologies in the payload and spacecraft to solve the challenges of an operational space-based maritime surveillance system. Space Norway will commercialise the spare capacity of the system, allowing it to provide a service in other key shipping areas around the world.

The spacecraft will be operated to provide a continuous service over the area of interest, much akin to the way that communication missions work. As such the spacecraft CONOPS will be fully automated with radar imaging and downlink sessions optimised to maximise coverage and minimise data freshness over the area(s) of interest. The spacecraft is compatible with KSAT Lite and can use the KSAT ground segment in Trømso as well as Norwegian government ground stations. On average the spacecraft will have potential ground station contact time for at least 12 orbits per day.

Spacecraft overview

The Saga pilot spacecraft is a 400kg class minisatellite designed to be able to detect, classify and identify ships, through C-band SAR and AIS sensors, and deliver information within 15 minutes of acquisition to the end-users. It is designed to fit a SpaceX Falcon-9 rideshare launch slot and will be launched into a near polar orbit in late 2027 to provide regular coverage over the Norwegian area of interest and the mission ground station network. The choice of orbit gives the spacecraft global reach.

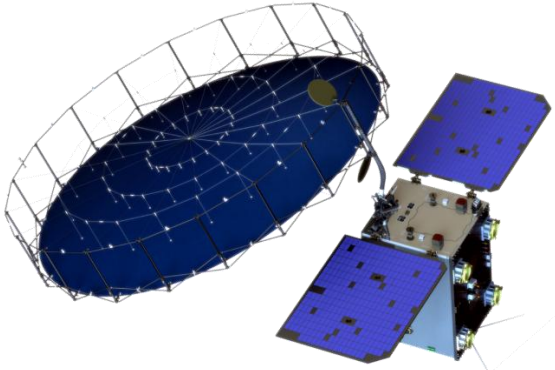
Parameter	Value	
Orbit	Polar LEO 510-600km range	
Band of operation	C-band	
Resolution and swath	0.5x3m 350-450km	
Field of Regard	Up to 1000km	
Orbital duty cycle	10%	
Polarisation	VV	
Responsiveness	<15min from acquisition to customer delivery	
Wet mass and volume	440kg (incl. margin) Designed to fit in SpaceX Falcon-9 XL slot	
Design life	5 years with 7-year target	

Table 1. Saga pilot spacecraft key characteristics

The spacecraft orientation during flight is such that the radar is side-looking during imaging, and the spacecraft would be pre-steered to be left or right looking as required before reaching the area where it will image. As the spacecraft is not in a sun-synchronous orbit, there are also constraints on pointing the radiator away from the sun line. As illustrated in the Beta angle evolution plot in Figure 5, (the angle between the orbit plane and the sun vector), the spacecraft will experience the nearly the widest possible range of sun-angles. Another implication is that the spacecraft coverage will cover all times of days from all possible vantage angles over the mission, leading to a more robust coverage solution. When not imaging or preparing to image, the spacecraft can be oriented in a “sun-basking” mode to aid faster battery charging.

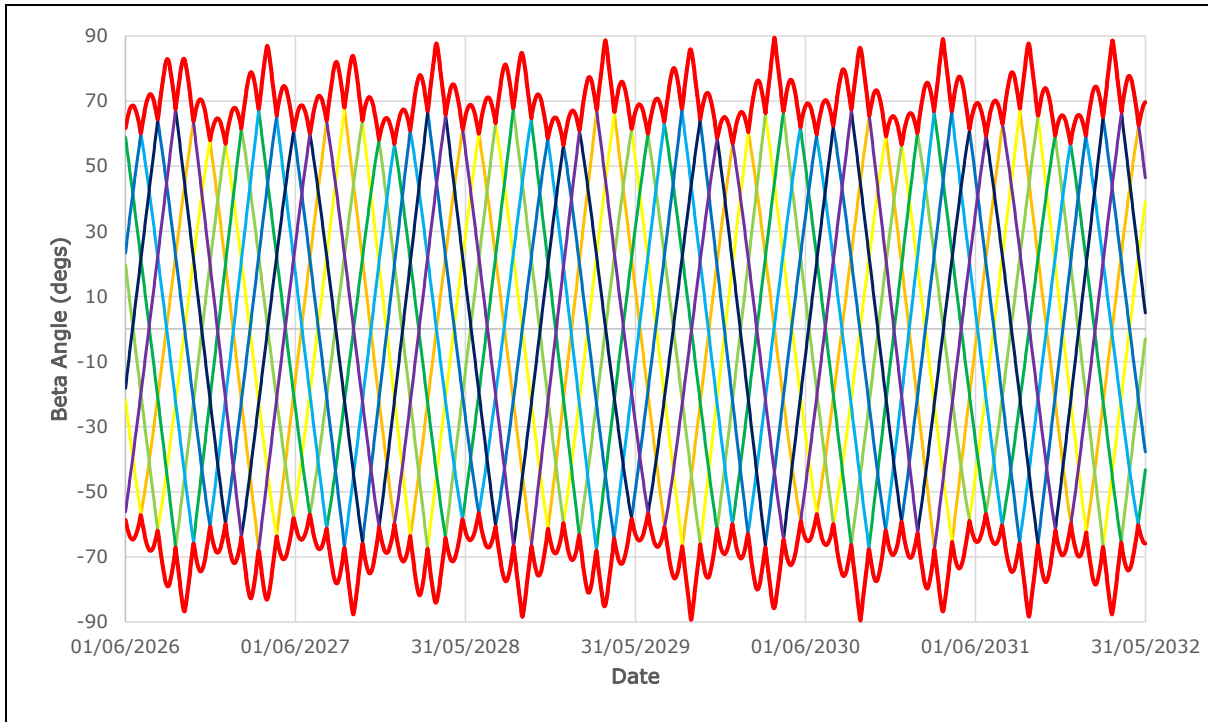


Figure 5. Solar beta angle indicates that the sun can be in any direction with respect to the spacecraft (colours indicate different launch dates, with red indicating extremes).

The SSTL product name for this spacecraft is “NovaSAR-C”, and Space Norway and SSTL have reached agreement to jointly make spacecraft and/or services available to third parties [2]. That would permit other interested parties to own and operate similar spacecraft, which can then be opted in or out of the Space Norway Constellation depending on circumstances, as well as receiving a service from the Space Norway Saga constellation. This model addresses potential sovereignty concerns for users that rely on such a space-based maritime surveillance solution.

Payload

The Saga Pilot mission SAR payload comprises an electronics unit with RF electronics, signal processing and data recorder electronics, a deployable offset reflector antenna, and Ka-band downlinks on antenna pointing mechanisms. Two telemetry cameras are included to confirm successful deployment of the dish. The SAR payload electronics is provided by FFI and WideNorth, with another element provided by Eidel.

The main radar antenna is supplied by Oxford Space Systems and is a deployable parabolic offset reflector antenna which is carefully stowed and locked through a hold-down mechanism during launch ascent, and once on-orbit is deployed to the side of the spacecraft through a deployment arm before the dish itself is unfurled. The antenna-feed is fixed on the main body of the spacecraft. Telemetry cameras provided by SSTL are included to confirm successful dish deployment.

The antenna feed is connected to an electronics module containing the radio frequency electronics signal processor and data recorders. They are also thermally connected via heat pipes to a thermal radiator on the outside of the spacecraft.

The spacecraft and payload have various unique features developed specifically to meet the specific maritime surveillance mission requirements, and can support several SAR imaging modes. Descriptions of these cannot be disclosed in this paper at this stage in time.

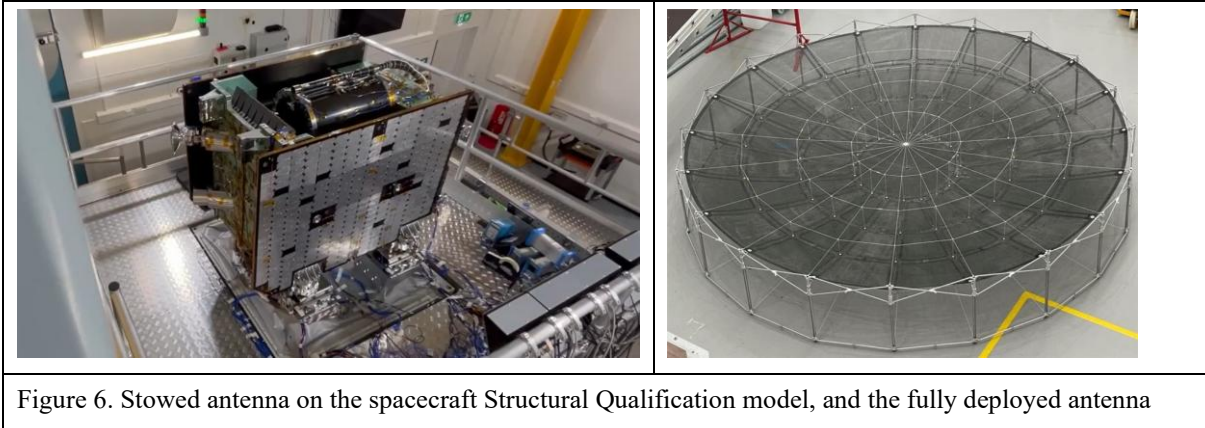


Figure 6. Stowed antenna on the spacecraft Structural Qualification model, and the fully deployed antenna

The spacecraft payload downlink is via Ka-band, and includes two antenna pointing mechanisms provided by SSTL, so that the spacecraft can image at the same time as downlinking.

Platform

The system block diagram is that of a standard SSTL bus, with a level of hot and cold redundancy that ensures that a credible single point failure does not lead to the loss of a mission. For the Saga pilot spacecraft the satellite platform is configured for a minisatellite with larger reaction wheels and additional power handling capability, and with a much higher capacity 28V Li-Ion battery than usual. The data handling system is based on SSTL's CoreDHS on-board computers with dual redundant Control Area Network TM/TC busses. The CoreDHS single board computer includes GNSS receiver, an Attitude and Orbit Control System Interface Module (AIM), and S-band Telemetry and Telecommand Radio Frequency systems.

The power system includes a Battery Charge Regulator (BCR) and Power Distribution Module (PDM) which each include internal redundancies.

The electrical interface to the payload is through the dual redundant CAN network, a connection to the Pulse-Per-Second timing network, and through power switches. As the deployable antenna has complex deployment mechanisms embedded, a dedicated Payload Interface Unit module provides the necessary electrical interfaces logic for the antenna deployment and also includes redundancy. The mechanical and thermal interfaces are much more complex and demanding and drive the need for a dedicated structure. The launch configuration is using the full mass and volume allocation for a SpaceX Falcon-9 rideshare XL slot and is attached through a four-point separation system.

The attitude control system uses a standard set of sensors and actuators used on all SSTL spacecraft, relying on star trackers for nominal operations. The software is updated to support the specific modes required for the SAR imaging operations. The spacecraft has four reaction wheels in tetrahedral configuration, in such a way that a single wheel failure might lead to graceful degradation in performance in some circumstances.

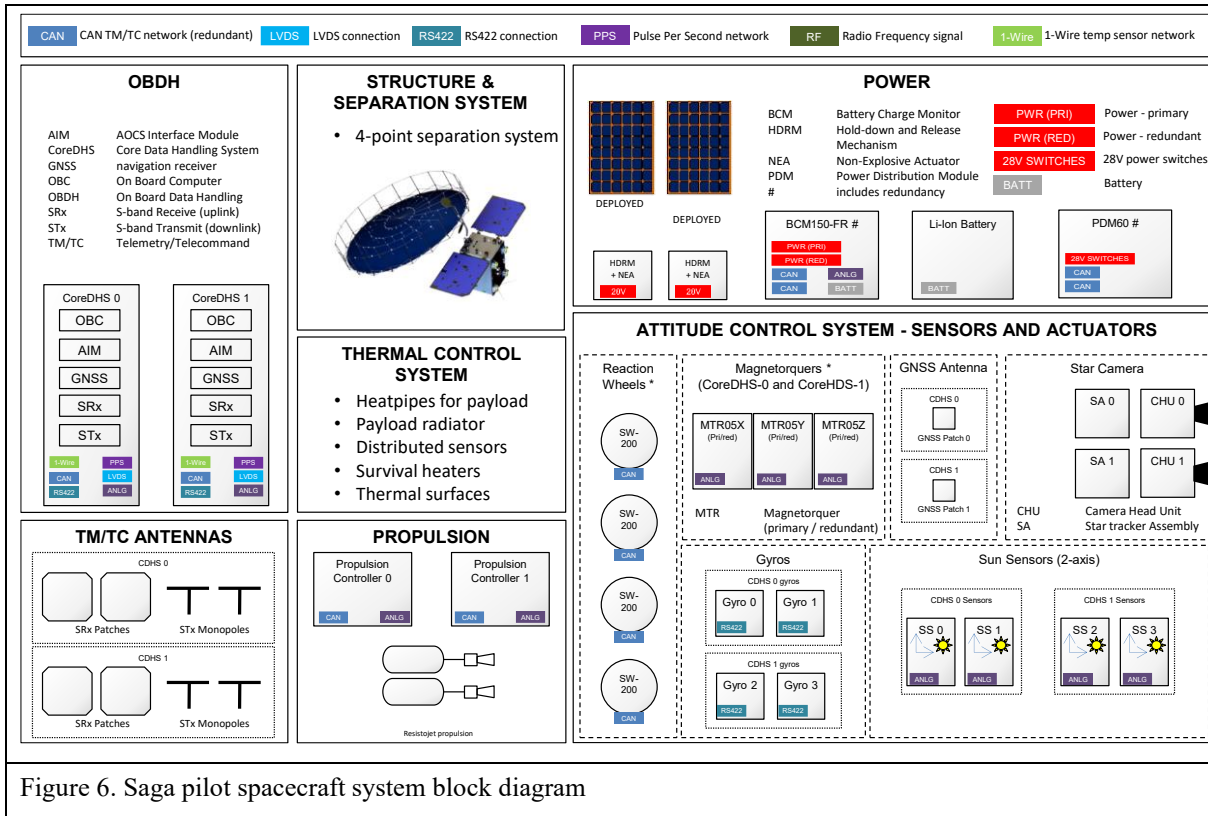


Figure 6. Saga pilot spacecraft system block diagram

The Saga pilot spacecraft propulsion system supports orbit injection corrections, orbit maintenance, collision avoidance manoeuvres, and end-of life disposal. The system is based on an electric Resistojet system with water propellant system manufactured fully by SSTL. The system carries 34kg of water in two spherical tanks, and it provides a thrust of 30mN for up to 20 minutes at a time, with an Isp of ~165s.

Apart from water being a green propellant, there are two significant benefits of a water Resistojet system. Firstly, this system provides the highest thrust per unit power of any electric propulsion system, which can help constrain the thrust time required for orbit maintenance and collision avoidance manoeuvres. Secondly, as it is a low pressure green propellant system, it makes it possible to ship the spacecraft with filled tanks, potentially saving on cost and time related to the EVT phase and launch campaign.

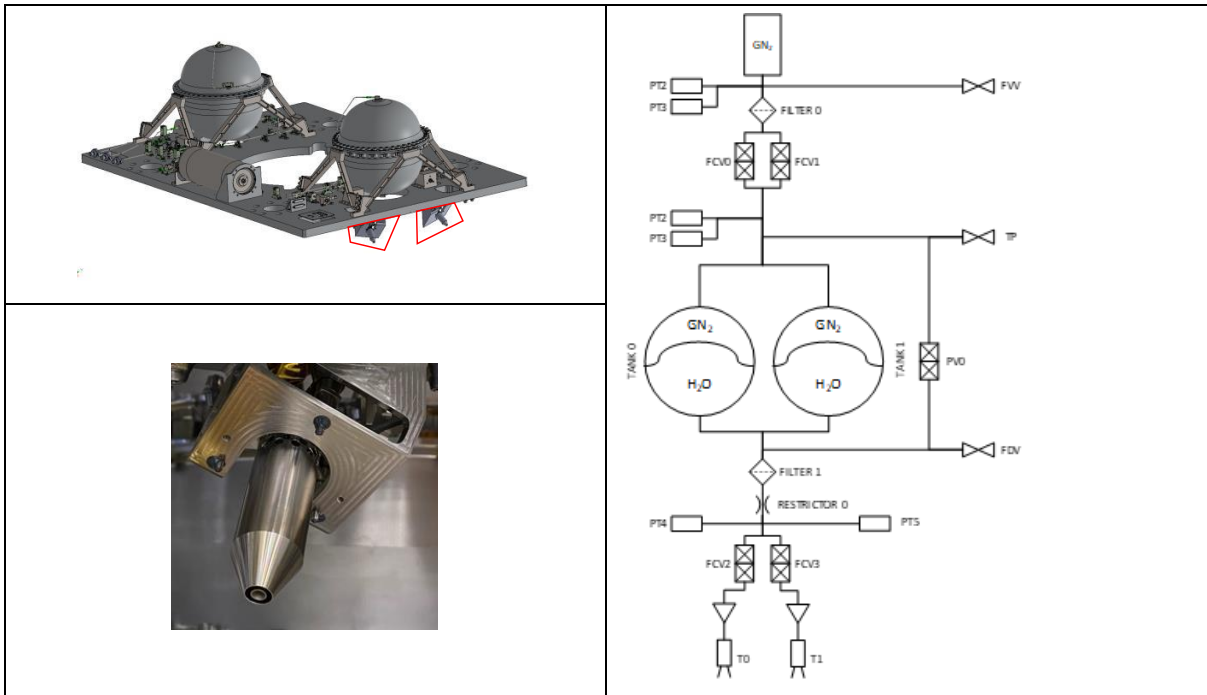


Figure 7. Saga pilot spacecraft water Resistojet propulsion system

Constellation

Ultimately the Saga “No Vessel Unseen” system will be implemented as a constellation of six or more spacecraft, distributed in batches across multiple orbit planes. As with many LEO satellite systems that have a specific restricted geographic focus, the satellite system will also have capacity on orbits that do not pass through the primary geographic area of interest providing access capacity and availability in that region. That would permit the constellation to support additional service areas around the world.

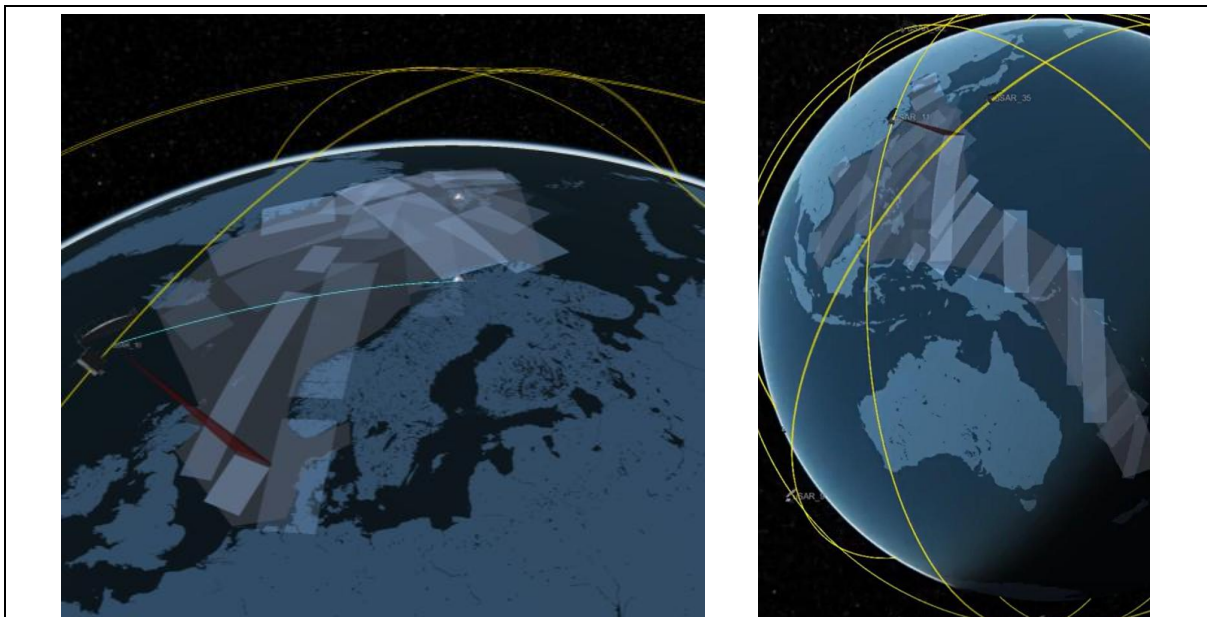


Figure 8. Example Saga satellite constellation coverage of the North Atlantic region, and over the South Pacific region over a 3-hour period.

Conclusions

Achieving persistent, theatre-scale maritime awareness has long been constrained by the fundamental challenge of area coverage. Conventional radar satellites, AIS limitations, and weather-limited optical systems cannot scale to the vastness of the world's oceans nor meet the operational tempo demanded by today's threat environment. Addressing these limitations requires a purpose-built approach rather than incremental improvements to legacy sensors or platforms.

Space Norway's High Resolution Wide Swath space-based maritime surveillance system represents a unique and innovative solution specifically engineered to deliver wide-area, low-latency maritime surveillance as an operational capability. By combining very wide swaths with high-resolution C-band SAR, and by orchestrating satellites as a unified "always-on" constellation, the system provides continuous visibility of both cooperative and non-cooperative maritime activity — day, night, and in all weather.

Developing a suitable spacecraft depends on more than adding a SAR payload to an off-the-shelf spacecraft bus. High-performance SAR requires deep integration between platform and payload, with concurrent design ensuring the power, stability, thermal performance, and data handling needed for wide-swath, high-resolution operation. This vertically integrated approach underpins the reliability and operational effectiveness of the constellation.

Once deployed, the HRWS pilot spacecraft and the constellation spacecraft that follow will deliver a sovereign maritime surveillance service to the Norwegian government, while additional space capacity will be made available commercially through Space Norway. This dual-use model maximises national security benefit, strengthens allied situational awareness, and provides a cost-effective path to global maritime monitoring.

With "No Vessel Unseen", spaceborne radar moves from a supplementary intelligence source to a strategic, persistent maritime domain awareness layer — one capable of transforming how nations monitor, secure, and understand activity across their maritime regions.

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