Establishing Responsive Space: A Maritime Situational Awareness Experiment

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***Abstract*— Dependence on space-based infrastructure for navigation and communication on seas, as well as on land is at an all-time high. The failure of a satellite that provides these capabilities can have catastrophic consequences for civil and military end users. Thus, the need to protect this critical infrastructure has risen in priority. Here Responsive Space Capabilities come into play, which aim to recover and extend existing capabilities or integrate payloads onto satellites, launch them into orbit and operate them as fast as possible. These capabilities increase resilience and deterrence in a defensive way, but are still far from being reality, considering that the development chain until a satellite can actively be used in space usually takes several years instead of a few weeks or even days. As a first step towards this ability, the Responsive Space Cluster Competence Center (RSC³) of the German Aerospace Center (DLR) aims to establish a technology base for research and development in this area, starting off by capturing todays baseline of industrial capabilities with a Maritime Situational Awareness Experiment (MSAE). This experiment includes planning, integrating, testing, launching and operating a small satellite together with industry partners. During these phases, current capability gaps are identified and research areas to speed up space processes are derived for the launch-, ground- and space segment. As payloads for this small satellite mission a camera and an AIS (Automatic Identification System) receiver are planned, which serve the demand to detect AIS signals of cooperative maritime targets and optically confirm their position.**

Keywords—Responsive Space, Resilience, AIS

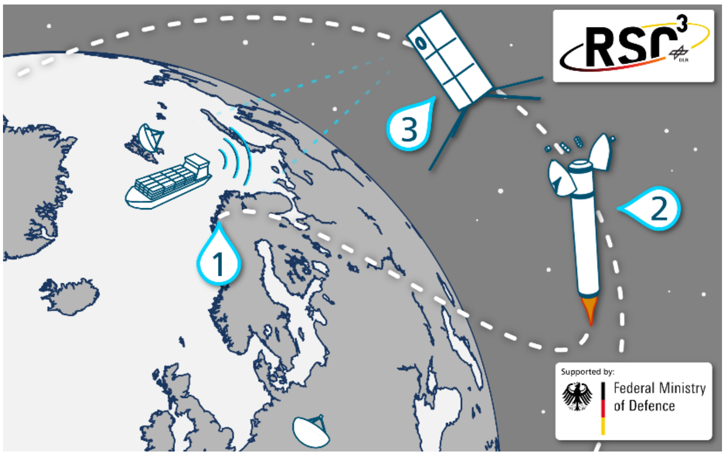

Figure 1: Concept of Operations for MSAE-OTTER
(1) Launch with ISAR Aerospace from Andøya (Norway)
(2) Separation on a 250 – 350km Low Earth Orbit
(3) OTTER satellite reads ship's AIS signals and confirms the position visually

I. INTRODUCTION

Satellite constellations, cosmic radiation, component errors, ASAT-Weapons (anti-satellite) and cyber-attacks all have one thing in common: They are few of many threats to our existing space-based systems. Be it through natural causes like sun eruptions, active human causes like attacks or passive human causes like space debris collisions: A satellite's probability to fail increases not only with its age, but also with these rising threats [1]. Christopher Jackson, director of Acuitas Reliability, said "around 35 percent of small satellites fail to complete their mission, with almost 20 percent being Dead on Arrival (DOA)." While the causes in the small satellite sector may have their roots in "design, manufacturing, and testing flaws", as he stated, the growing satellite industry, especially containing constellations, will populate and pollute common orbits, increasing the danger of getting hit by debris [2].

Today's society, however, is very dependent on these space-based systems. Two significant examples of dependency on land and sea are:

1) A discontinuation of an AIS service satellite leads to lack of location information and identification capabilities on sea outside the costal zones. Without these satellite capabilities, maritime surveillance, search and rescue and vessel coordination at high seas cannot be provided gapless.

2) A discontinuation of a global navigation satellite system (GNSS) which provides positioning and navigation capabilities and high-precision time signals, would have an enormous impact on the transportation infrastructure on earth. Disruption within individual traffic and global supply

chains, especially in air and sea traffic, would occur, because securing airspace and sea routes depends on exchange of position, velocity and directional data of the vehicle anywhere on earth via satellites. On top of that, the high precision time signals of the GNSS are vital for global market trades, which depend on a constant, reliable availability of reference times. Thus, the demand for resilience, safety and security of space-based infrastructure increases, as the dependence rises.

The worst case of a sudden satellite failure would be irreversible damage, so that it has to be redeveloped, built, integrated, launched and made to operate on demand. Bigger satellite systems however take multiple years to be built and made ready to operate [3].

In a call for proposals from June 2022 for EU action grants in the field of collaborative defence research and development under the European Defence Fund, the EU asks for research to the end that the "time between request for launch and positioning into orbit should be less than 72 hours" [4]. This requires tested launch- and space components to be stored and ready for use.

Finding out how to shorten the timespan from demand to its fulfilment and building up the necessary technology base for doing practical research on Responsive Space Capabilities, is one of the goals of the Responsive Space Cluster Competence Center. As stated in the Journal of the JAPCC from summer 2021: A major element for the RSC³ "will be the involvement of users and industry already in the Research and Development (R&D) process. The RSC³ takes on a coordinating role in Germany aiming to accelerate the technological refresh cycle significantly. For this purpose, it is essential to accomplish ongoing technological demonstrations and to ensure a regular technological transfer of data from research to industry in order to operate the latest state-of-the-art […] products in Space" [5].

The best way to achieve progress in this challenging task is, to start with a small CubeSat mission, which offers a fast, flexible and feasible experimental environment to go through all the processes a bigger satellite has to go through as well. On this journey hurdles can be identified, that currently keep us from going "into space in 7 days" or less [6].

II. METHODS AND MATERIAL

The Responsive Space journey starts with an occurring demand for a space-based system. Since MSAE is a scientific experiment, the exemplary demand for earth observation in maritime regions is chosen. More specifically the position of cooperative targets (vessels) shall be determined by their AIS signal and then be optically confirmed via camera. The combination of receiving data and optical verification on the same platform, including their sources, is an interesting concept for future space assets, as it provides an independent, secure and quick access to situational awareness in maritime regions.

With the MSAE mission statement being to "Establish initial operating capability for Responsive Space Cluster Competence Center", the primary objectives are described as follows:

- To pioneer holistic capabilities of all segments (space, launch, ground segment and technology demonstration) for RSC³
- To identify Responsive Space capability gaps in all program phases from concept phase over design, fabrication, assembly, integration, testing, launch, operations and closeout
- To enable gap filling technology research in cooperation with industry partners

Secondary objectives are:

- To launch a satellite to detect AIS signal of a cooperative target and optically confirm their position via camera
- To demonstrate key elements of RSC³ in a responsive timeframe

For this task RSC³ cooperates with DLR's Institute for the Protection of Maritime Infrastructures, who confirmed the existence of several relevant observation scenarios, which can be used to simulate a need for space-based capabilities in a responsive manner. These scenarios can be vessels in distress, oil spills, illegal unreported unregulated (IUU) fishing activities or smuggling activities, that can be detected by satellites with AIS receivers and cameras and can be communicated to emergency centers [7]. High traffic areas, like the English Channel, have proven to offer a frequent occurrence of these scenarios [8][9]. However, as later described in detail, the satellite is a demonstration and thus constrained in budget and size. This results in the use of small off-the-shelf components, which limit the amount of AIS signals that can be received, until the antenna is oversaturated. One of these areas meeting the conditions can be the Barents Sea in the north of Russia and Norway. Other technical available regions of interest can be investigated during operations.

The next step on this journey is, to figure out how to fulfill a risen need in the most responsive manner. Optimally there already is an existing satellite pointing at the area of interest, which can be requested to fill the capability gap for the required time, but this is unlikely. In the worst case the satellite has yet to be planned and built. For MSAE this is the scenario that will be inspected further.

To find out how long it will take to develop such a satellite currently and how this timeframe can be further reduced, the RSC³ asked the European industry via tender to deliver a 3U CubeSat turn-key-solution, that meets the requirement to launch in the third quarter of 2022 on the maiden flight of the Spectrum rocket by ISAR Aerospace. That implicates a, by today's standards, very short timeframe of 6 months for the suppliers to achieve Flight Readiness after planning, assembling, integrating, testing and shipping the satellite to the launch site. Even though the maiden flight has recently been delayed to second quarter of 2023, the timeline from Kick-Off to a flight-ready satellite delivery within 6 months, as defined in the contract with the satellite supplier, stays the same. This will result in the satellite being flight ready almost half a year before launch. During this time, the storage of the already tested, flight ready satellite will be used as a research scenario for Responsive Space Capabilities, to find out, if satellites can be reactivated and, especially their batteries, can be stored or need to be replaced after a certain time of aging on ground. It also shows the need of storage infrastructure required for multiple satellites and gives a baseline for future research on artificial aging processes done in the Responsive Space Research and Technology Center (RSTEC), RSC³'s own research laboratory in Trauen, Lower Saxony.

Winner of the tender was German Orbital Systems, who not only agreed on delivering the satellite within this strict timeline, but also exceeded the expectations by offering a CubeSat turn-key solution with all necessary payloads, propulsion, integration, workshops in all satellite phases and operations of 6 months.

The Spectrum rocket's maiden flight starts from Andøya (figure 1, marker 1) and has been chosen for MSAE specifically, because of its timely close launch window, pressuring a strict timeline to both the industry and the RSC³. The launch opportunity on the Spectrum rocket (figure 1, marker 2), has been secured through winning a call of opportunity from ISAR Aerospace and the German Space Agency.

Concerning the risk coming along with a maiden flight, the primary mission objectives of MSAE can mostly be met before the actual launch happens.

Expected key learnings on this journey will result in further research areas for the RSTEC, including how to reactivate a satellite in a fast manner and what degree of standardization will be needed on payload and satellite bus side to enable Plug and Play capabilities with different payloads. Additionally, accelerated test cycles, automation in assembly and integration and a quick single-day LEOP (Launch and Early Operation Phase) will be highly interesting research subjects to establish Responsive Space capabilities, that can be identified and initiated with this CubeSat mission.

III. THE SATELLITE

The hardware solution for this MSAE will be a 3U (ca. 34x10x10cm³) CubeSat, called OTTER (Optical Traffic Tracking Experiment for Responsive Space). A model of it can be seen in Figure 2, highlighting its key components.

The CubeSat standard fits perfectly into the necessary standardization concept that is needed for a faster and more feasible way into space: with standardized sizes, roughly predefined masses and a defined launcher interface the launch provider has sufficient information beforehand to plan his payload spaces on the rocket.

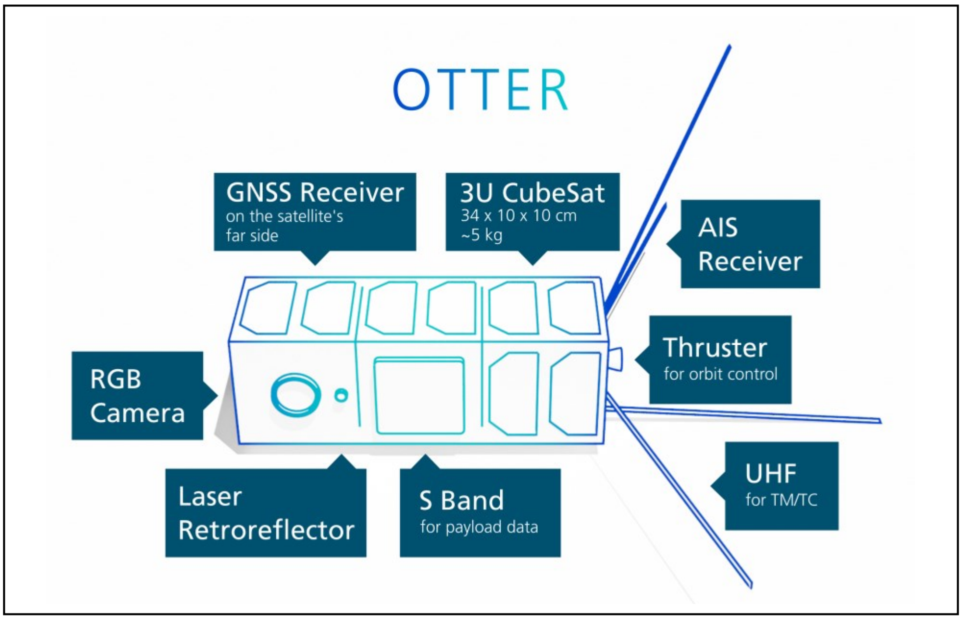

Figure 2: Key components of the OTTER CubeSat

As seen in figure 2, onboard the satellite will be an AIS receiver and a camera to meet the secondary mission objectives. As a secondary payload, the Institute of Technical Physics from DLR deliver retroreflectors, that will be attached on the earth pointing side of the satellite, to enable laser tracking experiments. One of these experiments will include pointing a laser from ground towards the satellite, to verify possible pointing accuracy and another experiment will be, to track the satellite while the on-board camera is taking a picture, to research the effects of laser ranging on optical equipment in space. The latter will be done towards the end of the satellite's lifetime to avoid impact of possible damages to the camera before its mission objectives are met. This procedure requires precise timely coordination of multiple parties involved: The ground station network (KSAT), over which the satellite is commanded, the physicists from the laser station and the RSC³ operators to calculate when the retroreflectors reflected signals can be seen and to give the go for execution. The expected time window of contact is about 10 minutes, in which this chain of events has to happen. With the experimental nature of this demonstration, more than one try will need to be executed. Pictures will be taken before, while and after the blinding by the laser to achieve a comparison of the effectiveness of the blinding and possible irreversible damages to the camera.

According to the Interface Control Document expected spacecraft separation orbit altitude will be >250km to achieve a Low Earth Orbit of 250km x 350km with an inclination of 96,2° (figure 1, bubble 3). At this orbit the OTTER satellite will be exposed to high atmospheric drag, resulting in a decline of height until deorbiting within a few weeks, if no propulsion system is installed to sustain it. To slow down this process, a Field Emission Electric Propulsion (FEEP) system will be installed on one of the smaller sides of the satellite (see figure 2 on the right), resulting in an expected lifetime of up to 8 months. This propulsion system will be provided by Morpheus Space and has following parameters stated in TABLE I. Additionally, the satellite will reduce atmospheric drag by facing towards the flight direction with its smallest side. With these measures the mission will be extended up to 9 months in total.

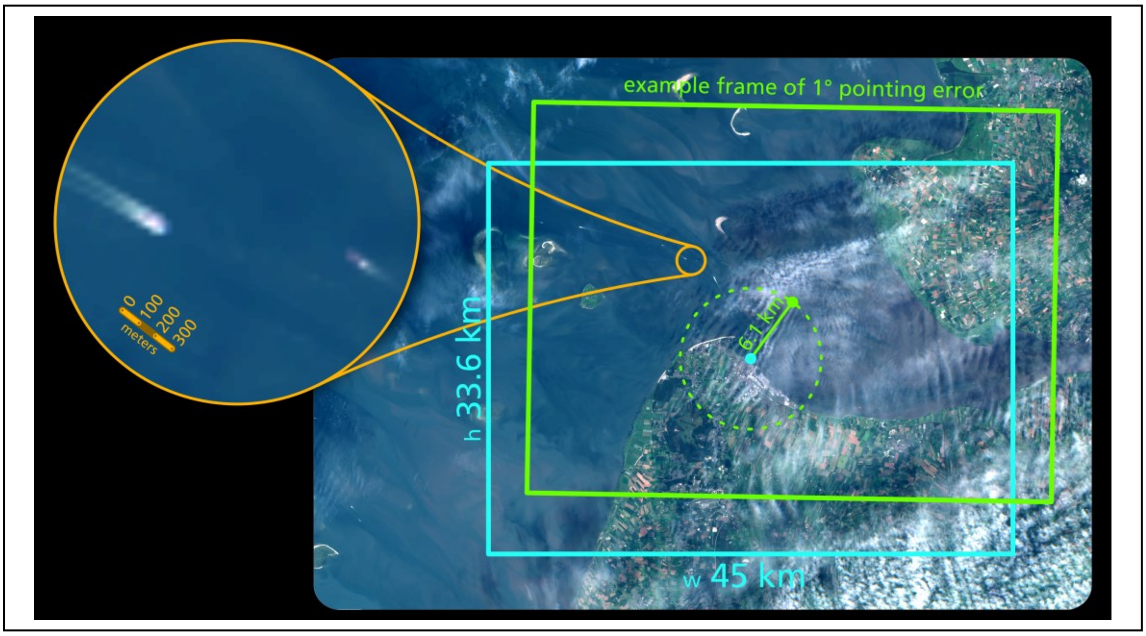

Figure 3: Image of Cuxhaven taken by Sentinel 2A (Level-1C, True Color Image, resampled to 30m ground sampling distance) [10]; Rectangles outline OTTER's image size @ 350km orbit altitude, Nadir pointing and the worst case 1° attitude error Circle zooms in onto vessels about 100m and 200m long

TABLE I. FIELD EMISSION ELECTRIC PROPULSION PARAMETERS

Source: morpheus-space.com/products/multifeep

Parameter	***Value***
Dynamic Thrust Range	1 – 252μN
Specific Impulse	>7000s
Total Impulse Range	0.9 to 11.5 kNs
Total System Power	0.4 – 22W
Total System Mass (wet)	0.3 – 0.5kg

For attitude and orbit control sensing of the satellite, Sun sensors, magnetometers, gyros, a star tracker and a GNSS receiver (*global navigation* satellite system) will be on board. As actuators magnetorquers and a reaction wheel system will be installed. With these elements a pointing accuracy of ~1° shall be reached to enable the camera to reliably target and capture pictures of larger ships and their wake. The optical camera shall provide a ground sampling distance (GSD) of <30m. The importance of such high accuracy and small GSD can be seen in following example picture in figure 3. The pixelated image of a over 200m long vessel can be seen, that is highlighted and enhanced by a yellow circle, which still needs a good eye to be caught. The white wake behind it makes it easier to identify as a moving object on sea. The expected outcome of a picture taken from 350km altitude with such a small CubeSat camera and its impact of a pointing error of 1° can be seen by comparing the blue and green rectangle in figure 3. The 1° worst case pointing accuracy results in a 6.1km discrepancy between the vessel's real position and the one calculated via the taken image, the satellite's attitude and its orbital position. Thus, the precise calculation will rely on additional markers in the image like coastal lines. These calculations are very demanding on the processing hard- and software. Thus, for the MSAE mission they are done in post on the ground rather than on the satellite. The gathered data will help developing the needed algorithms for on-board processing with future missions.

Power supply to bus and payloads will be realized via extendable solar panels and batteries, leading to 5 modes for the satellite: standby, downlink, maneuver, payload operations and charging mode.

For communications an S-Band patch antenna and for Telemetry and Telecommand UHF will be used. The satellite will be operated as a service by the satellite supplier. To improve the amount of contacts, especially while the satellite's short single-day LEOP, KSAT's lite ground station network will be used additionally to the supplier's own ground station. In the future DLR's own expertise and infrastructure with the German Space Operations Center (GSOC) will be used to operate RSC^3's satellites.

Nevertheless, the insights and lessons learned of the MSAE mission are a valuable contribution towards the reactive ground segment that RSC^3 is developing in cooperation with GSOC.

IV. LESSONS LEARNED AND FUTURE STEPS

Even though the project MSAE-OTTER is still between phases C and D (Detailed Definition and Qualification and Production), many lessons with regard to Responsive Space Capabilities have been learned already. One of those lessons stands on the very beginning of each satellite acquisition procedure: it is the procurement challenge. Being bound to the European procurement law and DLR's internal procurement structures, months long tendering processes must be gone through before ordering any hardware or service of higher cost. In case of an emergency happening on sea while a satellite for communication is down, the person in distress cannot wait for multiple months until his communication is restored. Therefore, alternative concepts will be subject of research, like storing different sizes of flight ready satellite buses with modular, open satellite architecture, that can be quickly assembled and integrated for any incoming demand. This leads to a high need of standardized interfaces for both hardware and software or respective adapter concepts. It will be one of the future tasks of the RSC^3 to analyze and evaluate existing standards and highlight this need for standardization. Institutional organizations need to be convinced to move from proprietary systems, to more open, flexible solutions and services.

Furthermore, new ideas of how to get around long procurement processes come up, including a regular preorder of different satellite bus classes, that run through tendering processes before demand occurs. For this the requirements of the technical solution need to be as open and modular as possible to react to different operational scenarios. This can provide the industrial companies a secure, regular demand for hardware, making it more attractive to develop such platforms. Looking at applications like satellite constellations, this form of mass order can also minimize costs per satellite to the recurring costs. A constellation of many cheap nanosatellites like OTTER can help to achieve a continuous situational awareness for sea regions, where the short development and lifetime of the individual satellite is an advantage regarding the possibility of staying up to date with newest technologies with each time an older satellite is replaced.

A small satellite may not offer the wide, long lasting spectrum of high-quality technologies that a big satellite offers, but it can be used as a quick gap filler and technology enabler until it gets replaced by a better solution. Additionally, a nanosatellite platform can be used to execute cheap and quick technology demonstrations to reduce risk during big satellite developments and to increase space access for small companies and startups.

Future steps to achieve a responsive supply chain will contain identifying industry partners, that are capable of offering responsive launch capabilities for small satellites, for example micro launchers and partners that offer quick assembly, testing and integration capabilities for Responsive Space scenarios.

Another lesson learned is, that Responsive Space Capabilities must require less time-consuming project management activities and documentations or shift these activities to the planning phase, before any demand occurs. That means strictly following ECSS standards is not the way to go, unless you are done with it before an emergency situation breaks out. Therefore, a tailored ECSS approach has been used for MSAE-OTTER, which will give a baseline for future small satellite missions in terms of reducing paperwork.

When looking at the small components on OTTER there are still a few technical challenges to be faced. One of it is the saturation of the AIS receiver due to its wide-field-of-view antenna, which will quickly be reached within busy coastal regions like the English Channel, where there are plenty of AIS signals to be received. As a workaround the receiver will only be turned on when flying over less frequented areas, where a predefined AIS source shall be found. However, this is in contradiction to the required coastal lines needed as markers for the image calculations, so a compromise has to be found. Next steps for this will be to find a cooperative target together with DLR's Institute for the Protection of Maritime Infrastructures in Bremerhaven, which can be placed at a fitting, low frequented area.

Upcoming steps for the MSAE mission, will include the design phase and satellite construction together with the winning bidder German Orbital Systems, where workshops for mission design, CubeSat architecture, electrical engineering checks, integration campaign, testing campaign and early operation phase, as well as satellite operations are to be expected within the next 3 months.

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