A Roadmap for a SmallSat Program

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Biographies

Kanna Rajan: is affiliated with `NTNU` and the Univ. of Porto, Portugal. He was Principal Researcher for Autonomy at the non-profit Monterey Bay Aquarium Research Institute (`MBARI`) and Senior Scientist and Principal Investigator at the Autonomous Systems and Robotics group at the NASA Ames Research Center, all in California. His primary interests are in Artificial Intelligence (AI) Planning/Scheduling and Execution. At NASA, he was involved in the 1999 New Millennium Deep Space One Remote Agent Experiment (`RAX`) as a Principal and as the Principal Investigator of the 2003 Mars Exploration Rovers `MAPGEN` controller for the twin rovers, which as the longest running AI system anywhere, continues to command the *Opportunity* rover on Mars. He did his graduate work at the NYU Courant Institute, New York and at the Robotics Institute of the Univ. of Texas. He is the recipient of of the Exceptional Service and Public Service medals for his contributions to autonomy for space among other honors. At `MBARI`, he designed, built and deployed the AI-based embedded `T-REX` autonomous controller on autonomous underwater vehicles, as well as the shore-based `ODSS` decision-support system.

Tor Arne Johansen: received the MSc degree in 1989 and the PhD degree in 1994, both in electrical and computer engineering, from `NTNU`. From 1995 to 1997, he worked at `SINTEF` as a researcher before he was appointed Associated Professor at `NTNU` in Trondheim in 1997 and Professor in 2001. He has published several hundred articles in the areas of control, estimation and optimization with applications in the marine, automotive, aerospace, biomedical and process industries. In 2002 Johansen co-founded the company Marine Cybernetics AS where he was Vice President until 2008. Prof. Johansen received the 2006 Arch T. Colwell Merit Award of the SAE, and is currently a principal researcher within the Center of Excellence on Autonomous Marine Operations and Systems (AMOS) and director of the Unmanned Aerial Vehicle Lab at `NTNU`.

Asgeir Sørensen: obtained MSc degree in Marine Technology in 1988 at `NTNU`, and PhD degree in Engineering Cybernetics at `NTNU` in 1993. In 1989-1992 Sørensen was employed at MARINTEK as Research Scientist. In the years 1993-2002 Sørensen was employed in the ABB Groups in various positions - Research Scientist, Project Manager, Department Manager, and Technical Manager in the Business Area Automation Marine and Turbochargers. In December 2002 Sørensen and 5 partners founded the company Marine Cybernetics AS, where he was acting as President and Chief Executive Officer (CEO) until June 2010. In 2012 and 2015 Sørensen became a co-founder of the NTNU spin-off companies Ecotone AS and Eelume AS, respectively. Since 1999 Sørensen has held the position of Professor of Marine Control Systems at the Department of Marine Technology, `NTNU`. In the period 2003-2012 he was key scientist in the Centre for Ships and Ocean Structures (CeSOS). He is currently the Director of the Centre for Autonomous Marine Operations and Systems (NTNU AMOS). Sørensen has authored more than 180 scientific articles and book chapters.

Roger Birkeland: is a PhD-candidate at `NTNU`. His research is focusing on the use of small satellites to enable better communication coverage in the Arctic. He has a Msc in Electronics from 2007. His working career started as a researcher on underwater networked sensor systems at the Norwegian Defense Research Establishment. From 2010 to 2013 he was the project manager of the NUTS student CubeSat project. From 2013 he has been pursuing a PhD. During the whole period at `NTNU`, he has be active in enhancing space technology at `NTNU`.

Executive Summary

We propose a concerted and unified cross-disciplinary focus on designing, building and operating small satellites (`SmallSat`'s) for observing the Norwegian coastline and its oceanographic domain, and doing so collaboratively across disciplinary and institutional boundaries. The primary objective is to provide large-scale *synoptic* views of northern waters resident to Norway for scientific and civil oceanographic needs, as well as for dual-use maritime surveillance and security. A secondary goal is to build a long-term robust scientific and engineering program for pedagogy at `NTNU`'s Gløshaugen campus which brings together students and faculty in Engineering Cybernetics, Marine Technology, Electronics and Telecommunication, Civil Engineering and Biology, as also researchers from other research organizations.

In doing so, we will in partnership with national and international collaborators:

1. establish a national competence center for `SmallSat` system studies, use of `SmallSat` data, and development and integration of `SmallSat` payloads.
2. impact the scientific study of complex ocean bound processes across disciplinary boundaries
3. have substantial impact in cost-effective means of studying the changing climate and therefore directly impact societal needs by aiding the study of a critical question of our times
4. augment and cooperate with efforts with Norwegian agencies in the civil and security sector to establish Norway as a focal point for ocean observation especially in the rapidly changing northern waters
5. leverage substantial work in systems engineering, artificial intelligence (AI), statistics and hardware and software design for complex autonomous systems with `SmallSat`'s as key components
6. have a substantial pedagogical component to provide significant outreach to students to impact the next generation of researchers and therefore directly contribute to a skills based Norwegian economy
7. facilitate students and faculty towards innovative products and services in industry, government agencies, and potential commercial spin-offs related to `SmallSat` technologies in software or hardware

The program should be seen as an enabler in the climate and environmentally friendly restructuring of the Norwegian economy - *the green shift*. It will contribute to environmentally friendly solutions for surveillance, security, research and presence in the oceans and Arctic, and at the same time boost competence for the Norwegian knowledge-based industry and enable strategically important national autonomy.

Introduction

With the increasing reduction of sensor technology, coupled with the smaller form factor computational devices, technology is at a cusp with regard to space-based remote sensing hardware. Small Satellites (smle's) are vastly scaled down versions of traditional satellite technologies, albeit often for tailored single-use applications.

The general term 'SmallSat' refers to a class of vehicles across a wide nomenclature. The International Academy of Astronautics (IAA) considers a satellite small if its mass is smaller than 1000 kg [1]. SmallSat's comprise four sub-classes as shown in Table 1. In this white-paper, our focus will primarily be on Nano through Micro-Sat's which we will refer to as SmallSat. And the work is primary driven from the context of maritime applications in the context of NTNU's CoE, the Center for Autonomous Marine Operations and Systems (AMOS).

AMOS's vision is aimed towards the use of autonomous systems in a range of maritime environments including those related to the environment, transportation, surveillance, fisheries and oil and gas (Fig. 1). To robustly operate in the harsh oceanic environments, near real-time ocean conditions including sea state and ship traffic. While existing space remote sensing capabilities can be leveraged, having an affordable national space presence which can be configured to national needs is an important factor to consider. Further, SmallSat's can provide valuable data structured to the poorly served polar regions for a range of needs from observing climatic changes in upper water column, to observing and monitoring the increased ship traffic, to monitoring and responding to oil spills in addition to security related needs.

NTNU is the generating source of the largest pool of engineering graduates in Norway with a primary focus in advancing knowledge. One important domain working in the context of AMOS is the ocean. There is substantial ocean going activity related to both, the benthic and upper water-column communities that currently exists between the departments of Marine Technology and Engineering Cybernetics. Both departments are associated with AMOS and work closely with biologists and physical oceanographers at the university and SINTEF. Vehicles include ROVs (Remotely Operated Vehicles), AUVs (Autonomous Underwater Vehicles), ASVs (Autonomous Surface Vehicles) and UAVs (Unmanned Aerial Vehicles) [6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30]. Yet another critical part of such a pedagogical involvement in a SmallSat program would

Satellite Class	Mass [kg]	Cost [M]	Development Time [years]
Conventional	> 1000	> 100	> 6
Mini	100 - 1000	7 - 100	5 - 6
Micro	10 - 100	1 - 7	2 - 4
Nano	1 - 10	0.1 - 1	2 - 3
Pico	< 1	< 0.1	1 - 2

Table 1: Spacecraft classification associated with mass [2], cost [3], and development time [4]. From [5]

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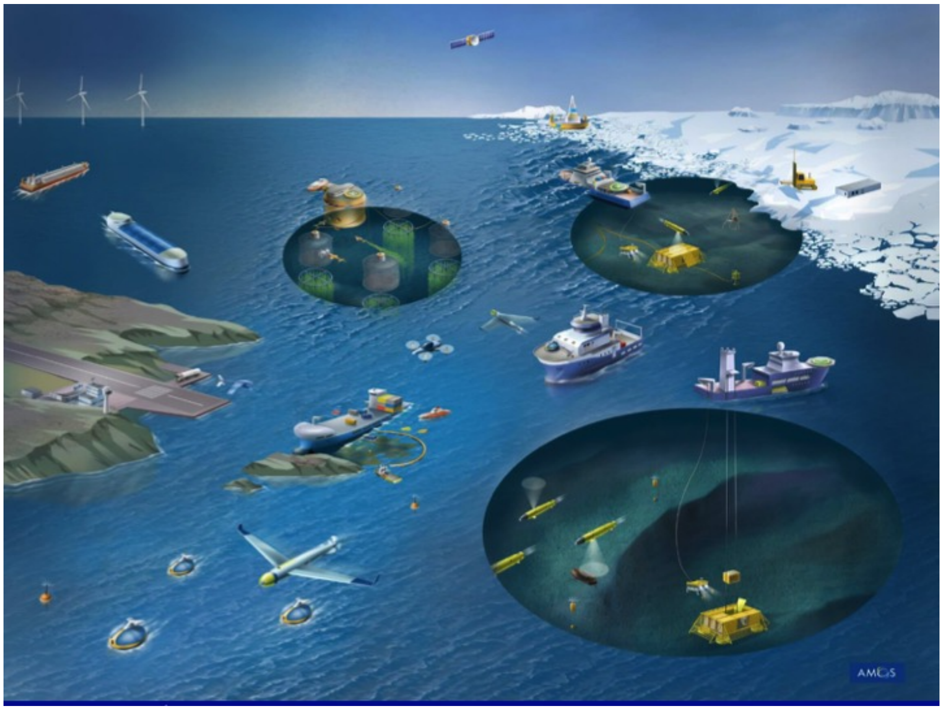

Figure 1: `AMOS`'s vision calls for autonomous systems for a range of applications including those in environmental and climate, maritime transport, mapping and surveillance of large ocean and coastal regions, offshore renewable energy, fisheries and aquaculture as well as deep-sea and Arctic oil and gas exploration.

be the fostering of a disciplined approach of Systems Engineering for building complex systems. Doing so would inculcate a future generation of researchers to develop and sharpen a valuable and marketable skill-set. Put together, the field driven experimentation and exploration, with a strong systems oriented inter-disciplinary bent in the quest for knowledge, with the inclusion of `SmallSat`-based remote sensing, make it "use oriented basic research" of Pasteur's quadrant [31].

`SmallSat` ownership (and therefore their design and controllability in orbit) is unique, even if they might not offer uniqueness in their observational capability in the space of all ocean observing observation platforms (Fig. 2). While currently less capable in comparison to traditional satellites in their data handling and payload capabilities where communications, optics and radar payloads in small form factors can be challenging, yet it is this ability to tune and place an appropriate payload sensor(s) on a satellite bus in the right orientation in space, that democratizes the needs of scientists for opportunistic and *synoptic* observations of our changing oceans in fine spatial and temporal scales. Together, therefore, with engineering professionals, we have a significant opportunity to bring about a revolution in how we observe and cohabit our increasingly endangered planet.

`NTNU` has had some exposure to `SmallSat`'s already, including the student satellite project NTNU Test Satellite (NUTS) [33] as well as on-going research on for example satellite communications related to the strategic research area Coastal and Arctic Maritime Operations and Surveillance (CAMOS) [34]. Through the NUTS project students from various departments have had central roles in planning, designing and implementing ideas, software and

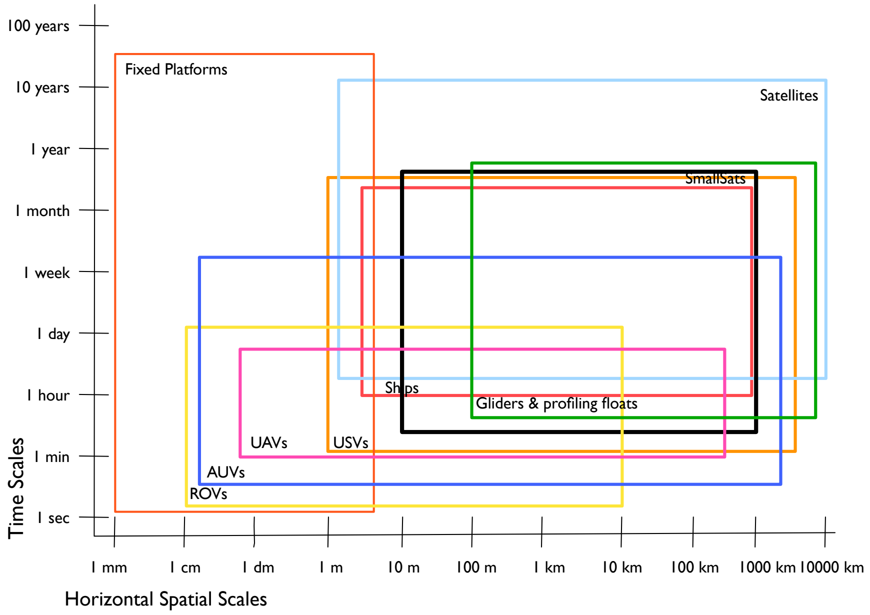

Figure 2: While `SmallSat`'s do not occupy a unique position in ocean observation, overlapping a range of other assets, their capability for controlled observations along institutional lines is a harbringer of complementary views of the earths oceans. Figure modified from [32].

hardware for a CubeSat mission. In addition, NTNU was part of the nCube-missions in the early 2000s together with University of Oslo, the former Narvik University College and the former Norwegian Agriculture University College.

Collaboration among commercial entities like **Kongsberg Seatex** and government agencies like the **Norwegian Defense Research Establishment (FFI)** and the **Norwegian Coastal Administration** have already made forays in the field of small satellites especially in deploying satellite borne AIS receivers. The concept we articulate here is for systematically building `SmallSat`'s for ocean observation and exploration via *student/faculty run space projects* and to connect that to actual field programs and to do so continuously as a veritable *pipeline* in the quest for knowledge.

An important motivation for `NTNU`, to have `SmallSat` capability, is to meet the near-term need for coordinated *space*, aerial, surface and underwater robotic platforms observing the same patch of the ocean at the same time (Fig. 3) for novel methods in ocean observation particularly in support of climate change studies. Decision-support systems on ship and shore, at the back end would then provide oceanographers near real-time data with the capability of command/control of assets in the field, which is currently not possible. Conversely, the needs of the oceanographers can be met by controlling a `SmallSat` platform to opportunistically direct its sensors and resources towards their specific objectives at the appropriate windows of time. This enables a coordinated and autonomous observation system based on robotic agents and `SmallSat`'s enabling a new class of oceanographic measurements both synoptically and in fine scale, towards the study of the global oceans and doing so cost-effectively.

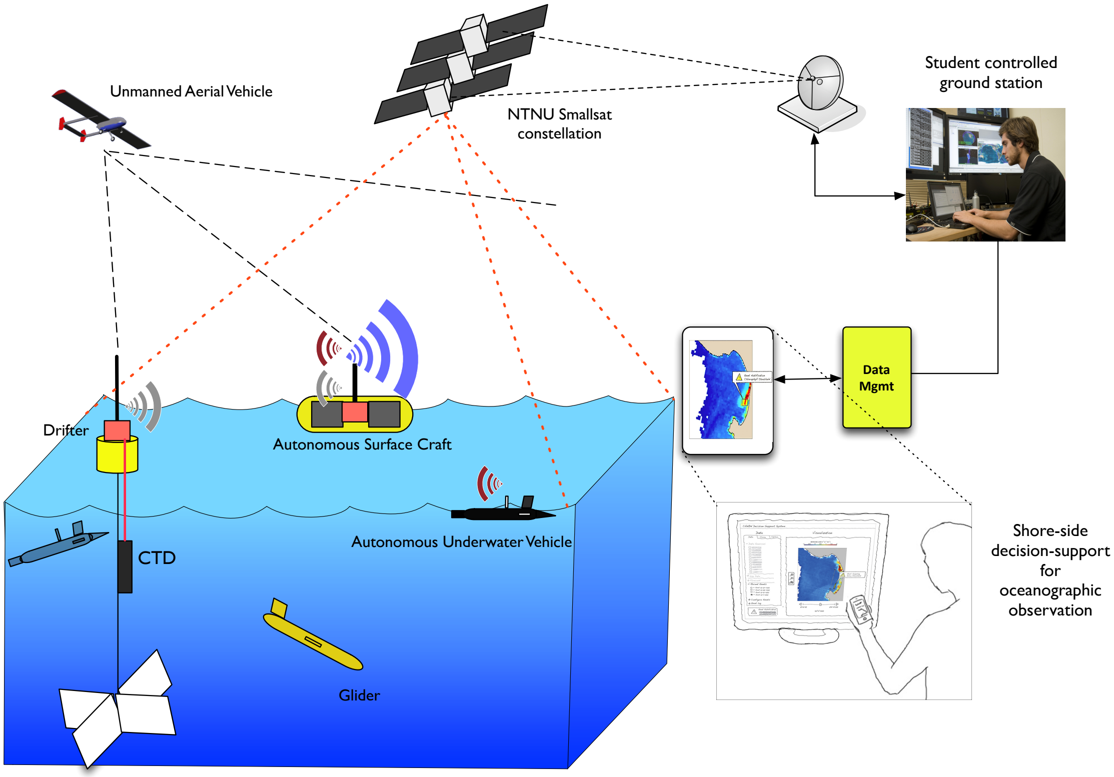

Figure 3: Envisioning the need for `SmallSats` for environmental monitoring and coordinated robotic platform control remotely or autonomously.

Having an in-house small satellite capability will allow `NTNU` to not only provide a new generation of researchers in Norway a capability that will mesh well with engineering skills honed on campus, but would provide a new and exciting world view of the impact of academics to the real world. Specifically we believe that:

1. space robotics is a new (and viable) way to look at the earth at far larger spatial scales than currently available
2. students will be excited by the possibility of thinking about the planet in vastly different ways to conserve and protect than generations past
3. space has always had a prominent role in human imagination in particular with the advent of the space age
4. it will provide students a new and highly marketable skill set given the ongoing robotics and Big Data revolution
5. we envision, participating in such an activity will generate an innovation activity contributing to Norways technology base

A key way to look at such a capability is that it also involves inter-disciplinary interaction. Not only will students need to understand how to design and build payloads and integrated them into the actual vehicles and systems (Electronics, Signal Processing, Communications, Physics, Mechanical Eng., Robotics, AI, Software Engineering), but they would need to understand science behind space-borne objects prior to is operation (Physics), consider various ways in which to harden and protect the vehicle (Material Science, Chemistry) and deal with its actual operation (Management, other soft skills) and ensuring it returns viable data for doing science (Environmental Sciences, Ocean Science, Oceanography, Marine Geology and Geophysics, Earth Sciences) for stakeholders.

NTNU and `SmallSat`'s: `NTNU` has had a rich background in being associated with `SmallSat`'s. The current student satellite project was initiated in 2011, even if it's early design ideas stretch back to 2006 [35]. The project was part of the national student satellite program `ANSAT` [36], partially funded by the Norwegian Space Center and administered by NAROM. Through this project, students from several departments and fields of study at `NTNU` have worked together on the design and development of the satellite; to date, 46 master theses have been submitted. The main goal of the project has been to educate students in the multidisciplinary field of space technology. The key achievements have been: to work on a novel carbon fiber frame, a new set-up of the ground station utilizing a modular software defined radio (SDR) as well as specifics of the satellite platform itself, such as hardware and software for the onboard computer (OBC), attitude determination and control system (ADCS) [37, 38, 39] in addition to the exploration of several payloads including visual and infrared cameras.

The main features of the spacecraft is the carbon fiber outer frame that will also serve as mounting point for solar panels and the magnetic coils for the ADCS. An inner frame serves as assembly for the electronics, that is mounted in a back plane as shown in Fig. 4[1].

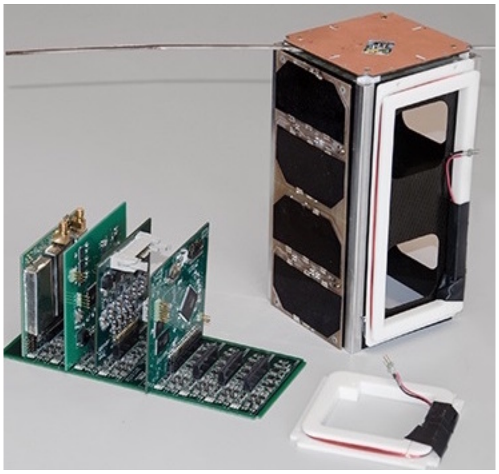

Figure 4: Prototype of the `NUTS` satellite, showing the mechanical model of the frame as well as a partially assembled backplane.

Through the Center of Excellence on Autonomous Marine Operations and Systems (AMOS), `NTNU` has established field laboratories for applied underwater robotics (AUR-Lab) and unmanned aerial vehicles (UAV-Lab). In this process, `NTNU` has built capacities for systems engineering, payload design, testing, verification, validation, and planning and execution of field operations. While some of this competence can be of direct benefit to the `SmallSat` domain, the processes successfully leading to the capacities are being used to establish the resources and organization needed to realize the `SmallSat` vision. This includes partnerships with leading national and international organizations.

Norwegian space industry consists of around 30-50 organizations of various size and make, spanning from small companies through the universities to the Kongsberg Group. An in-

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[1] For a full list of publications, see `http://nuts.cubesat.no/publications-and-reports` and `http://nuts.cubesat.no/master-theses`

crease in space related projects and education as envisioned here, will contribute to education of several high level masters and PhD candidates. Space technology is growing, and a pro-active educational effort in order to strengthen and expand the Norwegian industry is important.

Motivating Science & Engineering Use Cases

A class of candidate oceanographic scenarios exist to motivate our case. They go to the heart of technical problems that need to be addressed for (and by) the ocean science as well as security communities. And in doing so, these scenarios serve as the key drivers for the kind of networked autonomous observational platforms including `SmallSat`'s, proposed, where they would augment in-situ observation methods.

Monitoring the Polar Regions

The changing climate and its impact on the oceans has brought a concerted focus on the polar regions where the changes with dramatic loss of sea ice and coverage are disconcerting. Simultaneously, ship traffic (and its attendant dangers of anthropogenic change associated with spills and pollutants) as well as increased pressure from oil & gas companies for exploration and exploitation, are adding substantial pressure on the fragile environment. This is particularly alarming given the polar regions are marked with high primary productivity (Fig. 5) and as a consequence are critical transit and resident grounds for cetaceans. Increased ship traffic has had documented impact on collisions with such large mammals; spotting and separating human and cetacean traffic is therefore of critical importance.

Marine Protected Areas (MPAs) are another domain which have significance to the protection of habitat especially for fisheries and biodiversity, as well as for the environment in general (Fig. 6). MPAs are often designated as breeding grounds for wild fish species and/or their benthic habitat which provide rich feeding grounds for one or more species. Planning, designing or subsequently managing them by providing consistent monitoring facilities has often been a challenge. Protection of such fragile environments and their bio-diversity is a critical component of our very existence on the planet. Yet enforcing such large areas with traditional approaches such as manned ships or aircraft is not feasible in the long-term given the continuing tight fiscal climate. All weather `SmallSat`

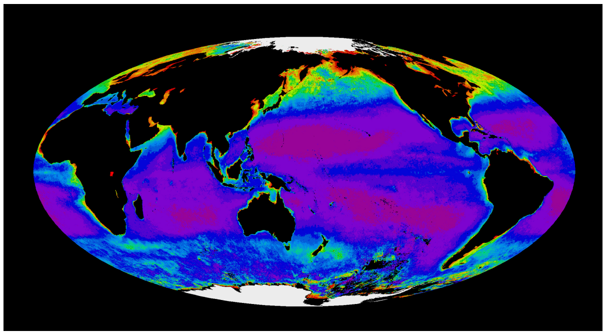

Figure 5: Global map of chlorophyll as a proxy for primary production (amount of Carbon fixed per volume unit and time). Colors correspond to surface chlorophyll content. The red end of the spectrum show high productivity, the blue/violet end the lowest. Polar regions show a skewed weightage in productivity and yet are challenging to work in.

radar-based observations provide a viable alternative that could link observations with known vessel activity using AIS transponders for verification. Such an approach could also be important for the monitoring of the ecosystem to give guidance on the maintenance and adaptative management of MPAs.

It hasn't helped that the Arctic in particular, has become strategic in a geo-political context. Put together, this poorly observed, catalogued and monitored environment, has evolved into a region of strategic importance for civil and security needs. Yet its harsh and unyielding environment is non-trivial for sustained human monitoring and surveillance.

In addition, increased human activity in the Arctic calls for increasing surveillance to help protection of ships and installations against icebergs, monitoring of the environmental, search and rescue capacity and monitoring ship traffic especially for pollution control. Such operations not only benefit currently from satellite remote sensing, but in the near future from also the use of autonomous vehicles such as UAVs, AUVs, ASVs, and buoys operating simultaneously and in coordination with larger (potentially manned) assets.

`SmallSat`'s with the right payloads can, we believe, make a substantial impact in this context. While their remote sensing capabilities are largely outside the boundaries of today's commercially available satellite systems, the specific requirement for autonomy, coverage, real-time data and cost are expected to tilt in favor of the use of small dedicated spacecraft that can be developed, instrumented and operated directly by the end users for the specific purposes of focused projects and measurement campaigns with a narrow operations window in space and time.

Robotic vehicles exist now, which can take on this job of monitoring as well as a means of collecting valuable scientific data in these environs. UAVs and ASVs coupled with `SmallSat`'s can provide effective coverage where it is needed and when it is needed, to characterize the upper water-column while also providing agencies with maritime domain awareness at high spatial and temporal scales. Networked assets observing such large swaths can systematically and cost-effectively collaborate to provide near real-time situational awareness simultaneously to the scientist community, as well as security agencies, by using `SmallSat`'s to provide broad coverage in each polar orbit, while allowing big-data driven in-situ assets to closely investigate opportunistically. Large transnational remote sensing assets cannot provide such demand-driven assessments; only national assets and one that are cost-effective.

Figure 6: An example of suggested MPA's for Norway. *Courtesy: Norwegian Environmental Agency* `http://www.miljodirektoratet.no/en/`

Networking Arctic Waters

As noted above, while the Arctic is characterized by its harsh and unforgiving weather, as well as remoteness and lack of infrastructure, yet it is of high, and increasing importance for reasons such as resource exploration and exploitation, fisheries, climate research, ship transit and national security. Although broadband satellite communication coverage [2] is emerging and is likely to expand deeper into this domain in the years to come, the size and power consumption of their user terminals are likely to remain prohibitive for small assets such as buoys and unmanned vehicles. Iridium with its Iridium `NEXT` [40] and similar services are also being upgraded and expected to give better data link capacity and reliability in the years to come, but will not be a solution for every use due to limitations in data rates, number of users, and high cost for users.

For example, the Arctic ABC (**A**pplied technology, **B**iological interactions and **C**onsequences in an era of abrupt climate change) project's emphasis is to provide new insights into a relatively unknown ecosystem where there are substantial gaps in knowledge, such as:

- (i) the extent of dependence on sea ice for an important species in the Arctic food chain - polar cod (*Boreogadus saida*),
- (ii) life-history traits and seeding processes of the flora and fauna assumed to be obligatory ice associates,
- (iii) the existence and magnitude of the biological carbon pump in ice covered waters responsible for sequestration of organic carbon and atmospheric CO_2 to the deep ocean.

By ensuring real-time monitoring of ice associated communities in the Arctic Ocean during the polar night and winter-spring transition and combining it with ocean modeling techniques to evaluate drift patterns of Arctic pack ice and ocean circulation, the Arctic ABC project expects to understand how climate-induced changes at the base of the food chain are likely to propagate through the Arctic ecosystem.

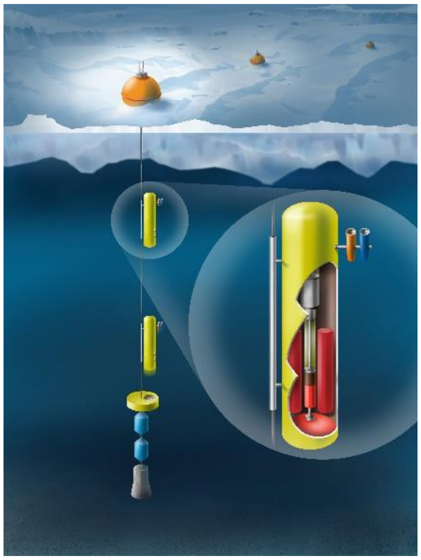

Figure 7: Observation platforms such as buoys and profilers planned for in the ArcticABC project. *Courtesy:* `http://www.mare-incognitum.no/index.php/arcticabc`

The primary observation platform of the project are buoys that are to be deployed in ice-prone waters, and must operate autonomously for extended periods of time (see Fig. 7). In order to monitor the operation of the buoys and collect acquired data, there would be substantial advantage to have radio communication via `SmallSat`'s as an alternative to aerial vehicles or ships as communication relays due to the prohibitive costs of operation in the

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[2] Traditional VSAT systems (within range of GEO satellites), or the planned OneWeb constellation providing planet-wide LTE coverage are notable examples.

harsh and remote environment.

A Heterogeneous Communication Infrastructure

The Arctic is poorly covered for satellite communication, in both the narrow and broad bands. Novel efforts need to be made in order to enable network connectivity for research activities in that area as noted above. Since the primary focus in Arctic science is to make measurements in this sparsly sampled domain, buoys and other instrumentation will need moderate data throughput while real-time coverage is nominally not required. Further, such instrumentation would need to be connected to the Internet though a delay-tolerant network (DTN) [41].

In addition to the Arctic ABC project, additional scenarios have been outlined[3], where it was determined that there is a substantial gap between very low/low-throughput services as Iridium, ARGOS and VHF Data Exchange System (`VDES`)[4] and more broadband services such as the proposed OneWeb constellation as well as the Norwegian HEO [42] project. Within this gap, a satellite communication system, based on `SmallSat`'s could be developed to provide connectivity to end-users by projects such as Arctic ABC as well as activities at research institutions like the Norwegian Polar Institute. Currently projects such as `CAMOS` and its related activities [5] represent ongoing research on this topic at `NTNU`.

In an integrated, heterogeneous network, the satellite link should function as one of several potential routes sensor data could take; other routes could be by a data-mule such as an UAV or a passing ship. The UAV or ship will have much less contact opportunities with a deployed instrumentation compared to spacecraft; however, their data throughput could be greater. In order to ensure near real time coverage of instrumentation in the Arctic, including the ability to change instrumentation configuration such as sampling rates and onboard data analysis software, a satellite link will be essential.

Different scenarios will have their individual needs. Depending upon each mission's specific requirements, various types of payloads and systems can be used:

- For very low-rate trickle data, Iridium or `VDES` can be a simpler solution
- For big clusters of buoys and more stationary installations with many nodes, prospective solutions as the OneWeb LTE-network can be a possibility
- For single nodes with need of higher data throughput than what would be supported through VDES or Iridium, new small sat payloads could be developed, either as single spacecraft or as a constellation. This option may be a part of a regional common Arctic infrastructure, or in some cases ”one mission, one (or several) satellites”, tailor made for the mission. Key design parameters to be considered would be:
    - Data throughput – leading to choice of frequency.

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[3] See project Følgemiddelrapport TEL 04.15.7 *”Satellite payload for CAMOS”*.

[4] A VHF-based system for ship to ship and ship to shore communication, will eventually consist of a terrestrial as well as a space component.

[5] `https://sinet.item.ntnu.no/`

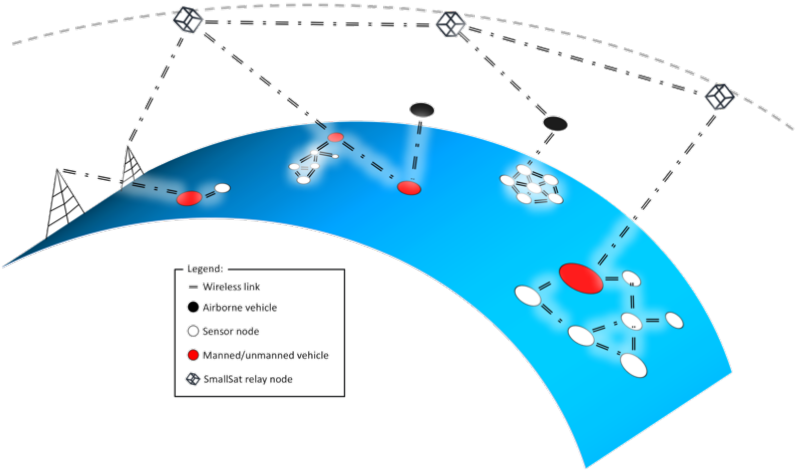

Figure 8: An integrated view on heterogeneous wireless communication technologies. *Courtesy: David Palma, NTNU.*

  - The frequency band leads to requirements for antennas, pointing and platform stability, as well as power, both for the space and ground segments
  - Number of satellites, spacecraft coordination, station keeping

General Network Requirements In order to ensure seamless integration of data through a network consisting of multiple technologies and physical carriers, the equipment employing the satellite link must be able to configure unique local IPv6 addresses. In addition to allowing for local communication between groups of nodes, a local network can be created. Moreover, whenever nodes capable of connecting to the Internet are in range of the local networks, unique global addresses should also be configured. These nodes are capable of providing connectivity, shall be considered as gateway and backbone nodes depending or their connection quality, and must be able to forward packets as relays or of storing them locally, taking custody and acting as data-mules. The long-term vision is depicted in Fig. 8 where satellites, moving vessels and sensor nodes are all acting together in one common network. The use of data mules are further explored in [43].

The interaction between the distinct types of nodes can for instance, be structured hierarchically. Resource-constrained devices expected to operate for long-periods of time and detached from communication infrastructures can be considered as leaf nodes while fixed infrastructures and nodes with adequate power, such as large vessels could be placed in the root of the hierarchy (Backbone) while using remotely operated nodes (e.g. UAVs, USVs) as intermediate gateways.

An immediate step in the process will be to enable communication between the sensor buoys and the satellites directly. An example of a buoy for fish detection and monitoring is shown in Fig. 9.

Arctic ABC Requirements The Arctic ABC project plans to deploy several buoys in the sea ice, for a 2–3 year mission duration. Some of the instruments onboard the buoys are expected to generate moderate amounts of data, totaling to around 3 MB/hour. In addition, there are instruments that will likely generate large amounts of data, up to several tenths of MB/hour.

It might not be realistic to develop (with regard to resources, power at the nodes) a payload able to transfer approximately 100 MB per satellite pass, per node. On the other hand, exploiting the vision depicted in Fig. 8, it will be possible to define a mission where the low-rate measurements are relayed to the scientists regularly, and only excerpts from high-rate data will be transfered. Given that the deployment period is long, it might also be possible that data can be gathered by use of data mules.

Figure 9: Deployed fish monitoring buoy. *Courtesy: Artur Zolich, `NTNU`.*

From this, we can draw the following information: The throughput requirements are greater than what is available today, or will be available through the `VDES` or Iridium `NEXT`. Since the installation will be static over a few years two alternatives can be considered. One is investigating the use of services like OneWeb if they are successful; the other alternative is to design a small satellite payload and launch a dedicated satellite to fit the needs of `CAMOS`. The measurement period will be comparable to the lifetime expectancy of a `SmallSat` in LEO. In order to enable transfer of the low-rate data as well as parts of the high-rate data, a link with, for example, 2 - 10 Mbps should be considered. Final requirements with regard to data throughput and number of buoys are not yet finalized; however, tentative specifications are listed in Table 2.

Tracking dynamic ocean phenomenon: Natural & anthropogenic

Oceanographic fronts are boundary layers in the vertical or horizontal planes which are at the intersection of two (or more) dissimilar water bodies. They can often be found in most

Parameter	**Value/Range**
Data throughput per node	60 – 1000 Mbit / day
Data rate	2 – 10 Mbit/s
Data delay	depending on latitude
Responsiveness	< 24 t
Expected data from one node	$\sim$ 2.5 – 65 Mbit / hour
Number of nodes needed	1 – 20

Table 2: Possible payload characteristics for a fish monitoring system.

near-shore regions and are major sources of near-shore primary productivity as they foster congregation of micro-organisms (zoo and photo -plankton); fishermen, for example, often target fronts to obtain their catch. Fronts can be reasonably large spatially (occupying 10s of sq. km or more) and also dynamic. They can be observed in remote sensing images and also with near synoptic views.

With the use of space-based remote sensing however, detecting such zones especially off-shore is feasible (Fig. 11). If `SmallSat`'s carrying visible or SAR imagery could be used, in concert with in-situ assets, such a detection in near real-time, could aid and boost the localized targeting of such phenomenon. Further, such a scenario can also stand-in for dual-use methods of tracking man-made objects in the water-column.

Plumes are analogous to frontal zones in the ocean; with the unquenchable thirst for oil and increased access to the Arctic for exploration and transportation, contingent planning and

(a) Kuroshio frontal zone off of Taiwan. *Courtesy: Igor Belkin, URI*

(b) A front (arrows) observed from a manually controlled unmanned aerial vehicle (UAV) off of MBARI's R/V *Zephyr* (lower right) in September 2012 in Monterey Bay, California

(c) Tracking and spraying the oil plume from the Deepwater Horizon spill.

(d) Riverine plume from the Eel River, California. *Courtesy: Igor Belkin, URI*

Figure 10: Large scale dynamic and episodic phenomena in the ocean, which can be tracked in space and time with `SmallSat`'s.

execution of failure response in the light of spills is an important function every nation- state needs to provide. Early mitigation and response aided by remote sensing from `SmallSat`'s can focus response from policy makers and agencies; in particular the need to adaptively reposition one or more such space assets is far more viable than relying on transnational observation platforms. Equally, we envision in the near future, dynamic responses could include a rapid build-test-launch of sensor capability which can only be possible in the context of `SmallSat` payloads.

Equally important is tracking the long-term impacts of riverine plumes with anthropogenic runoff (fertilizers and/or pollutants) into the coastal ecosystem (see Fig. 10(d)). Typically coastal ecosystems are *copiotrophic* because of the complex mixing in near-shore waters. With plumes adding more nutrients they make for microorganism abundance and in turn make such ecosystems ripe for blooms, many of which tend to be toxic for human or animal consumption. However, the triggers associated with bloom initiation are often hard to detect and require space based assets – an area where `SmallSat`'s can provide significant leverage.

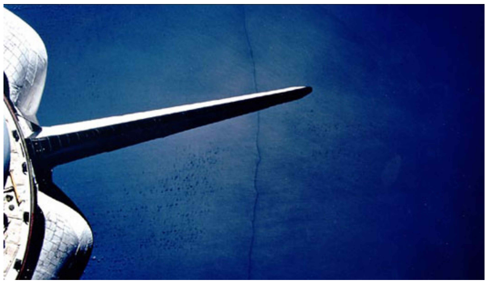

Figure 11: A frontal zone as visible from the Space Shuttle. From [44]

In such plume instances, `SmallSat`'s with appropriate sensors can provide not only a event-response capability, but given the spatial and temporal scales for plume migration, can help policy makers be situationally aware of the impacts of such phenomenon. Robotic platforms then can provide the ground-truth and further detail in higher resolution using coordinated observation capability and in-situ water sampling of the column; and do so cost-effectively.

A `SmallSat` Roadmap

`NTNU` and `AMOS`'s needs are focused on building cost effective tools, techniques and processes for observing the impact of the changing climate on the worlds oceans. Since existing robotic assets cover the aerial, surface and underwater domains, with `SmallSat`'s for coordinated observations (Fig. 3), a new paradigm of oceanographic observations will enable scientists to observe ocean processes across large as well as fine-scales spatio-temporally. To get to a point of enablement for `SmallSat`'s, a realistic roadmap is driven by operational needs. Typically, these needs will be driven by field experiments sometimes with purely engineering needs to test payloads, software, hardware or communication or other infrastructure, but more often science driven. For such experimentation key scientific hypothesis need to be formulated into actionable goals for technology development[6]. In the case of `SmallSat`'s this could involve payload development, orbit design as well as subsequent integration and test using proven concepts in system engineering.

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[6] See for example `http://sunfish.lsts.pt` or `http://rep15.lsts.pt`

When experiments are science driven, we expect the parallel development of the integration of an appropriate payload package with a commercial `SmallSat` bus and planned well in advance of the field operation.

We envision this initially, to be a 12 month (or more) process involving design/build/integrate/test/launch/operate activities, concurrent with the planning and execution of a hypothesis-driven science field experiment. In the recent past, these have typically included autonomous platforms, networked in a robust operational environment [45, 46, 47, 48, 49, 50, 24, 28] with infrastructure developed at `NTNU`, at international partners such as KTH and the Univ. of Porto, Portugal, and national collaborators NORUT Tromsø, NDRE (FFI), University in Tromsø, `SINTEF`, University Center in Svalbard, and industry such as the Kongberg Group and Maritime Robotics. In parallel, technology development for these platforms and their back-end data systems for Sampling and Control need to occur, targeting the specific scientific questions being asked (see `ODSS` [15, 51]). For example, for tracking ocean plumes, an appropriate Sampling methodology coupled with the experiment design would be developed and the proper mix of robotic assets and their payloads would be assembled and tasked with the job (Fig. 12). In turn, these experiments support a range of applications, from Oceanography to Maritime Domain Awareness (MDA), to Marine Search and Rescue. The addition of `SmallSat`'s, would add a dimension to cover larger spatio-temporal domain awareness and knowledge for such applications.

Our field experiments are yearly, and often more. Therefore, a key requirement is that, for `SmallSat`'s to be in support of such experimentation, one or more spacecraft with the appropriate sensors should be in orbit in support generating data products for ingest and assimilation into planning and ocean models. We envision initially, that such vehicles will be in ones and two's, but in subsequent iterations, we believe this technology can be scaled to ensure on-demand spacecraft in orbit, subject to a viable and cost-effective launch methodology. Equally, when ramped up, a constellation or a "train" might be more appropriate to

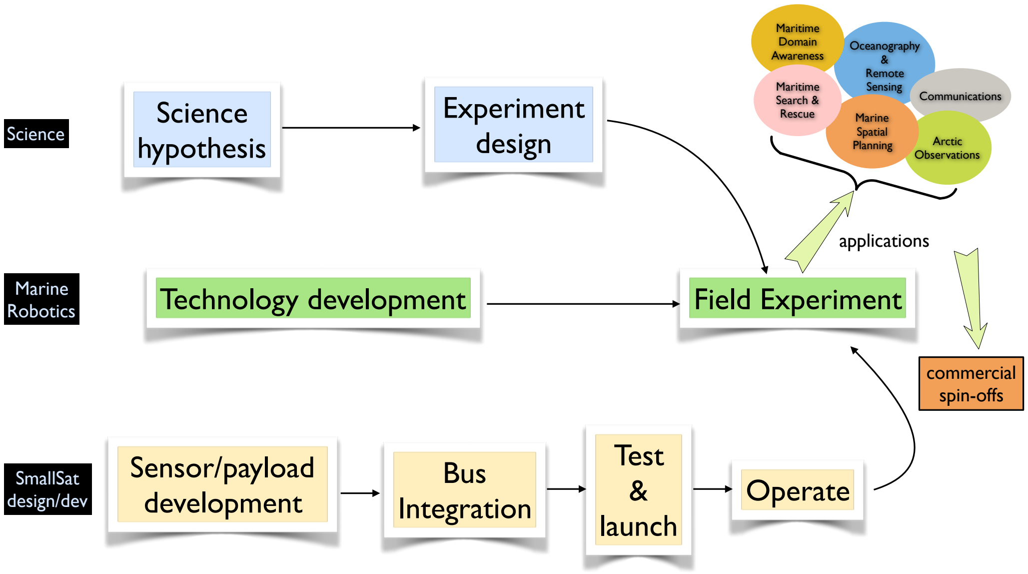


Figure 12: A proposed generalized process for `SmallSat` development for ocean observation.

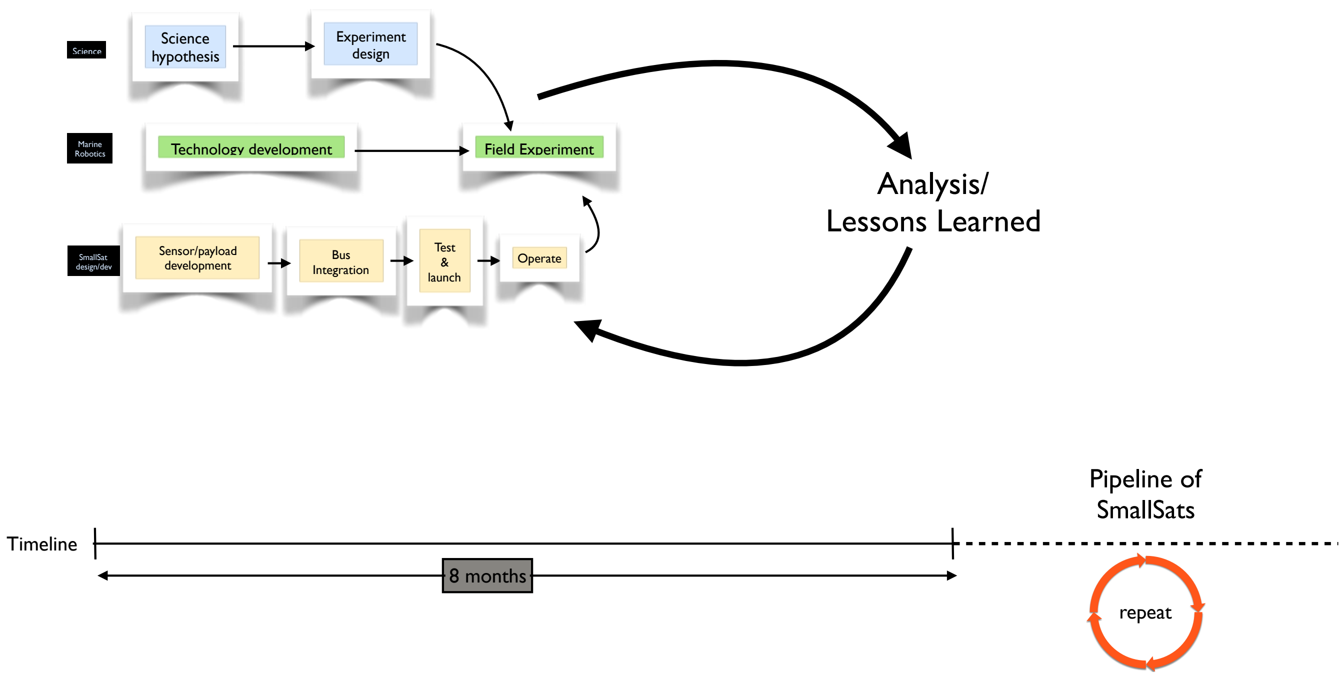


Figure 13: Using the motivation to deploy and operate a single `SmallSat` as in Fig. 12, we envision a continuous *pipeline* of vehicles being operated in orbit after due consideration of lessons learned from previous flight missions.

build and operate especially to meet the need of near real-time data for any of the applications above.

Equally, what this also entails, is that we intend to have a *continuous pipeline* of spacecraft in an ongoing process of development, test and operation. This is a radically different concept of a program, both for a university and in general for any `SmallSat` program anywhere. This also implies a clear understanding of how to not just initiate, but to find the financial, technical and logistical support for such an ambition beyond the initial startup efforts. To enable this, we envision a process of continuous production, learning from the inevitable failures and factoring the lessons-learned into new designs, methodologies and processes to design/build/test/launch/fly as shown in Fig. 13 and to do so rapidly.

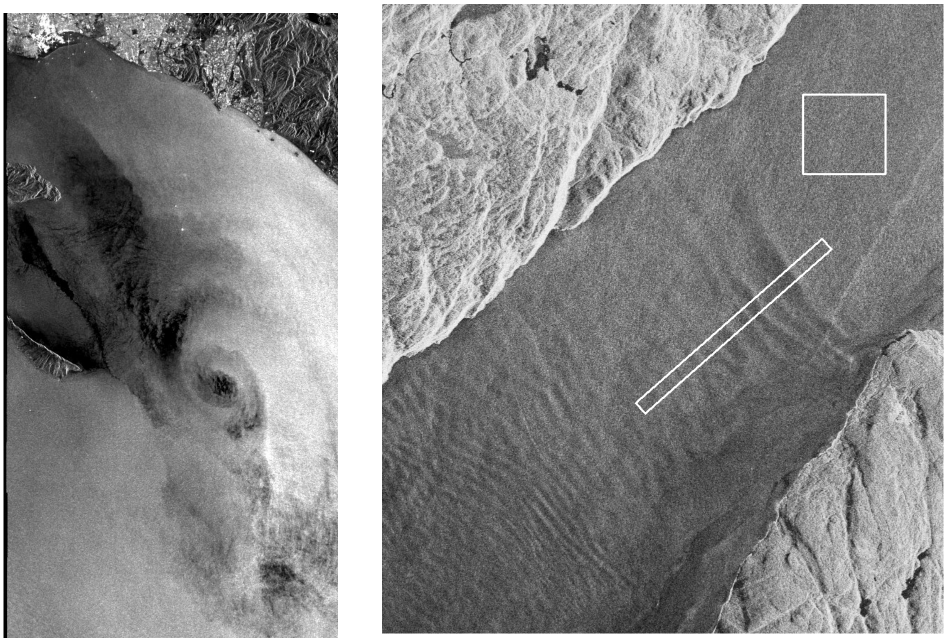
The case for sensors

With a `SmallSat` essentially being a bus for one (or more) sensors, the way to conceptualize and make such a vision operational is to focus on sensor development. While the maritime applications will determine what type(s) of sensors are likely to be useful, from a broad array of capabilities surveyed in [5] from optical (including hyper and multi-spectral) cameras, to altimetry and gravimetry, ocean color, winds and sea surface temperature (SST) and salinity, can be designed and built to `SmallSat` specifications today. In of itself, having any of these capabilities, especially for ocean modeling and prediction, is of substantial help. One end goal however, that might still be a stretch-goal, is radar based (especially Synthetic Apperture

Radar (SAR)) sensors.

The ability to see thru earth's weather engenders a range of application scenarios especially in MDA. Correlating ship traffic with AIS data provides a level of situational awareness that is available in few areas of the global ocean, but with operational limitations due to infrequent availability of SAR images. Clearly, increasing the frequency of available SAR images would be a important objective of `SmallSat`'s. Recent SAR use, interestingly has also been widely used in oceanography to study eddies, plumes, bathymetry, internal waves and to track large cetaceans [52, 53, 54, 55, 56]. Fig 14 shows eddies and internal waves clearly across a large spatial scale. [57, 54] in particular and work derived thereof, is a novel and exciting way to determine coastal bathymetry by processing SAR imagery.

Fig. 15 shows an ambitious yet systematic roadmap for sensor development across disciplinary lines. It starts with the focused development of a sensor that will have immediate applicability for field driven science. Lessons learned will be continuously brought into how efficiently to streamline the design/build/test/integrate process. Simultaneously, we will explore launch possibilities which are opportunistic and cost-effective for such a university run enterprise, including partnering with `NASA`, `ESA` and the Indian space agency `ISRO` using standard spacecraft interfaces now available as open source knowledge. With each launch we expect to have a dedicated team of students and faculty monitoring the spacecraft and systematically logging and dealing with off-nominal conditions. Data systems will be lever-



(a) an ENVISAT SAR image of an eddy in the Ensenada frontal zone off the coast of Southern California

(b) SAR image of internal waves in Trondheimsfjord from May 10th, 2012

Figure 14: SAR imagery providing synoptic views of oceanographic phenomenon of interest.*Courtesy: Jose da Silva, CIIMAR & the Univ. of Porto*

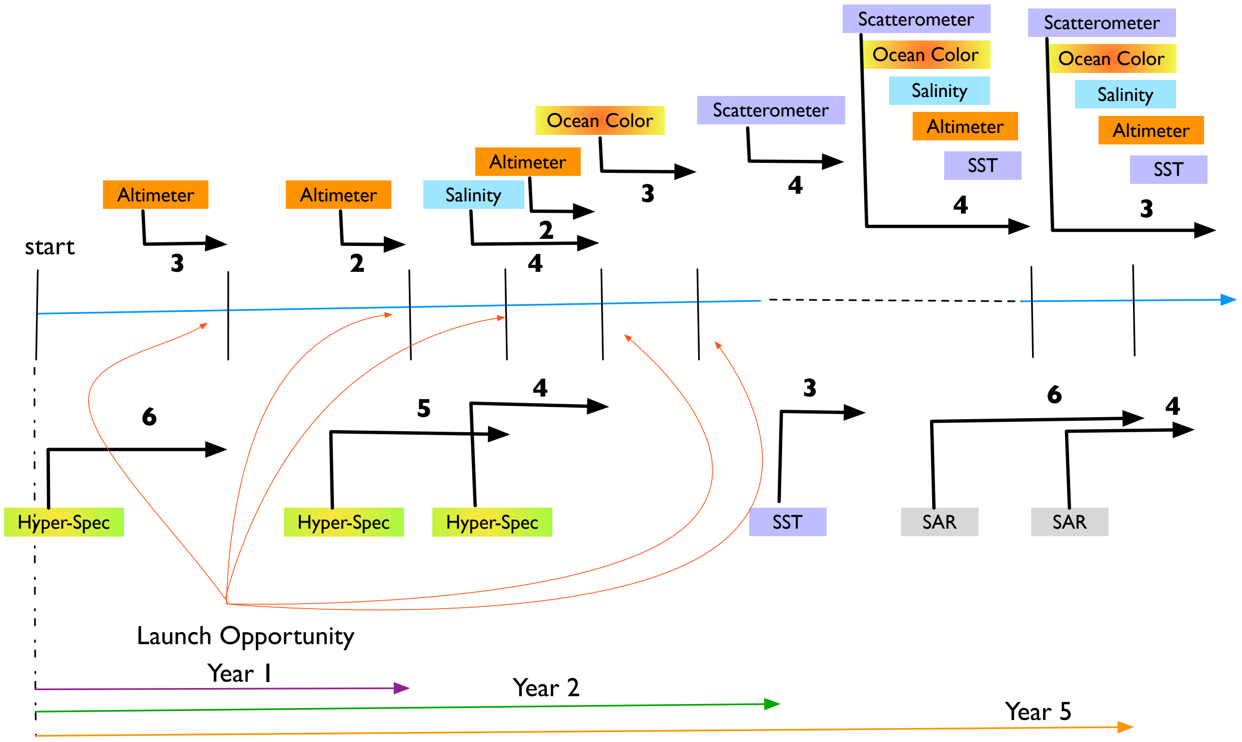


Figure 15: A coupled roadmap for sensor development. The numbers indicate months of development/test/refinement starting with payloads which are easier to build and potentially deploy. As we gather more experience and lessons learned, we expect not only do development times shrink, but so do simultaneous sensor development for a veritable pipeline of `SmallSat`'s.

aged and built upon using open source methods (e.g. `MBARI`'s `ODSS`[7] or `SOCIB`'s `DAPP`[8]) and back-end systems will be built with student-led and faculty mentored projects, especially those on the critical path. While we envision, a skeletal permanent staff deeply involved and overseeing all parts of the build proces, we expect to have a methodical handover of one mission to another of data, systems and processes, so there no loss of knowledge with a transient student population.

Immediate use cases

Opportunistic goals often arise in long-duration space mission planning. As a result, we articulate the need for three sensor packages for near-term deployment on a potential `SmallSat` mission. These packages are grounded on science-based needs with the intent their data be used in field experiments in Norway or with collaborative partners for ocean observation. The two *immediate* use cases pertain to a light-weight hyper-spectral imager and the ability to fly a communications package for communicating with buoys in sparsely monitored Arctic waters. The third, revolves around the persistent need to have all-weather radar imagery over the ocean with a dual-use capability for detecting fronts, plumes, internal waves as well as

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[7] `http://odss.mbari.org/odss/`

[8] `http://apps.socib.es/dapp/`

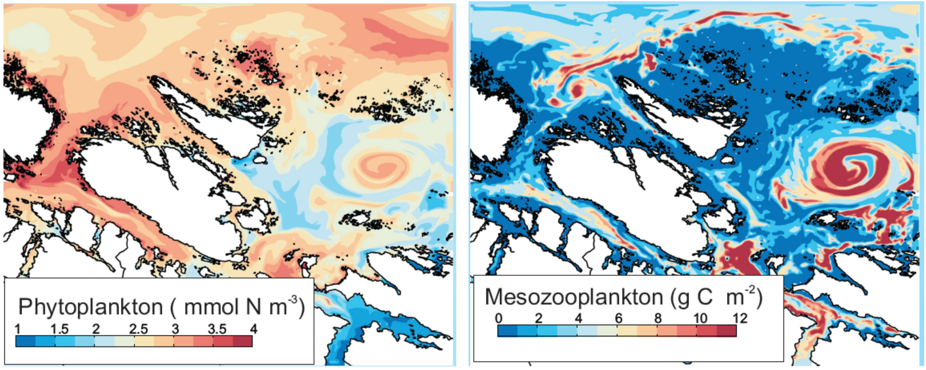
for monitoring for oil slicks and ships. The complication arises from the power and antenna requirements for such a system in a small form-factor adequate to fit into a `SmallSat`.

Hyper Spectral Imaging

Research Council Norway (RCN) has recently funded a coupled modeling-Sampling project (`ENTiCE` – ENabling Technology providing knowledge of structure, function and production in a complex Coastal Ecosystem) which targets algal blooms off the Frøan archipelago which has an unusual resonant characteristic. Multi and hyper-spectral imagers (HSI) are ideal instruments to measure the summer bloom extant *synoptically* and additionally provide fine-scale measurements of surface bloom properties including possible extant of the mixing of differing dinoflagellate types based on coloration. Such an imager could also identify possible anthropogenic influences where present, and help scientists build a more comprehensive ecosystem model in software (e.g. SINMOD). Finally, in the domain of fisheries research, which has a special resonance in Norway, off-shore fish farms are constantly in need of monitoring equipment to ensure that the ecology of their farms is not impacted by undue anthropological influences (e.g. nutrient runoff from nearby land-based farms) nor naturally occurring blooms. In all such cases, data from such HSI imagery can be used by policy makers to determine the likely impacts and look for mitigatory influences, which are critical for the health of the environment, as well as for the burgeoning commerce and industry.

In addition to `ENTiCE`, the RCN funded research projects `Arctic ABC` (started 2016 for 4 years) and the `Arctic ABC-D` (started 2016, to last for 10 years) and, the large Arctic marine ecosystem program Nansen Legacy[9] with a tentative start in 2018, will greatly benefit from such HSI imagers. Possible requirements for such an imager would likely be to:

In the light of the above, possible requirements for such an imager would likely be to:



(a) (b)

Figure 16: Primary productivity as modeled in `SINMOD` at 160m resolution for the mid-Norwegian coast for the `ENTiCE` project's bloom measurement and modeling; phytoplankton in 16(a) and zooplankton in 16(b). Authenticated data via a hyper-spectral imager on a `SmallSat` would help validate such model results leading to better predictive capabilities. *Courtesy: Ingrid Ellingsen, SINTEF.*

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[9] `https://site.uit.no/nansenlegacy/`

1. As high spatial resolution as possible (300 m per pixel or better) to track phytoplankton bloom dynamics
2. Spectral window: Minimum requirements: 400-700 nm), if data in IR - that will help for temperature measurements
3. measure Chl a (phytoplankton biomass)
4. measure cDOM (coloured Dissolved Organic Matter)
5. measure TSM (total Suspended matter)
6. identify, map and monitor different pigment groups of phytoplankton (bio-optical taxonomy)

Preliminary Payload Specifications and Requirements Two different models of the HSI camera can be considered; the smaller of the two and the most likely to be used, is shown in Fig. 17. The payload will consist of the imager (optics, mechanics and camera) as well as an payload processing unit. A typical data series would require around 2 minutes of sampling (example: HD resolution, 30 fps). With a pessimistic estimate of compression rate, this will result in around 500 MB per data series. Assuming one data series per pass, this calls for a downlink capable of a datarate of around 10 Mbps.

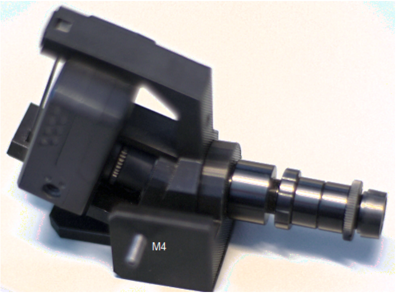

Figure 17: A prototype Hyper-Spectral imager being evaluated on `NTNU`'s UAV's and capable for `SmallSat` integration (120 grams). *Courtesy: Fred Sigernes, UniS*

- Mass: 500 g
- Power 5 W - 10 W (including processor unit)
- Downlink: 500 MB per pass
- Downlink datarate: 10 Mbps
- Placement on bus: NADIR pointing

Onboard processing would include both compression and data analysis based on mutivariate statistical methods [58, 59].

Arctic Communications with Buoys

As shown in previous sections, there is a need for communication services in the Arctic neither in play today nor currently planned. In order to gain experience with customized payloads and missions, we need to consider a step-wise approach leading up to the final communication payload usable for, for example the Arctic ABC program.

Research Steps

1. To align with other research in Norway, specifically the VDES and the NORSat-series of satellites, the first step can be setting up a test environment based on VDES to evaluate how VDES can be used to give direct satellite connectivity to buoys in the Arctic including dealing with QoS (throughput, delay, prioritizing) of data.
2. To make any communications system using a limited number of satellites scale better, investigate how coverage and throughput can be improved using multiple satellites including investigating swarms, constellations, exploiting simultaneous coverage from multiple satellites, MIMO etc.
3. On the longer term, evaluate how a multitude of satellite systems, (VDES, small-sat swarms and commercial constellations as OneWeb) can be integrated and used in parallel.

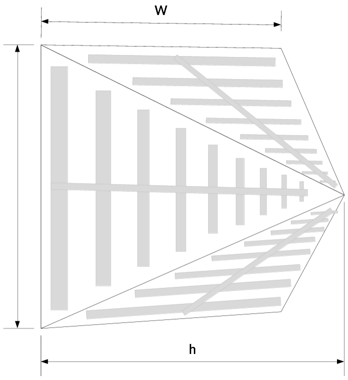

Figure 18: Sketch of an LPDA antenna. *Courtesy: Egil Eide, NTNU.*

Research Payload for NORSat or other small satellites Communications are crucial for reaching the goals of scientific programs in the Arctic; we therefore propose to launch a flexible communication payload for research and test purposes. This payload could be a re-programmable software designed radio (SDR) where it is easy to change the payload specifications in frequency, power, bandwidth, modulation, wave-forms or link-protocol. The payload should support a broad range of frequencies, for example from 433 or 800 MHz to 6 GHz. The broadband properties can be achieved by means of a single broad band antenna covering the entire frequency band from 433/800 MHz to 6 GHz. A typical design could either be a printed dual polarized Log-Periodic Dipole Array (LPDA) arranged in a pyramidal structure or a conical spiral antenna. By careful design, it is possible to achieve an antenna gain around 10 - 12 dBi over the whole frequency range. A dual polarized LPDA is shown in Fig. 18 while typical dimensions for different low-frequency cut off is listed in Table 3. It is also possible to build a planar circular polarized spiral antenna that covers the same frequency band but with somewhat lower antenna gain.

Low freq. [MHz]	**W [mm]**	**h [mm]**
1300	100	140
700	215	300
400	350	400

Table 3: LPDA specifications.

The RF front-end can be implemented using a broad-band LNA in combination with a bandpass filter bank if necessary to avoid receiver saturation. The payload must be bi-directional; this can be achieved either by mounting two antennas or switch between RX and TX mode. The purpose of such a payload will be to experiment with communication in several bands and to test a multitude of link-layer and higher order protocols. In addition to communication research, the payload can be used as additional down-link for the HSI-imager (if launched on the same satellite) as well as being the communication link between for example the Arctic ABC buoys. However, should the two payloads be placed together on the same bus, we would ensure redundancy so the HSI imager would not depend on the communications payload in its entirety.

Proposed Budget

To realize the vision described in this document, and to build a viable long-term capacity needed in Norway to strategically exploit the expanding opportunities of `SmallSat` we estimate a dedicated budget of $250 - 500$ MNOK over an $8 - 10$ year period as shown in Table 4.

The low budget indicates a *minimum* program with emphasis on the research and education part of the program, while the high budget is a recommended target providing significantly higher outcomes related to test flights, innovations and advanced payload systems and technology.

Item	**Low Budget**	**High Budget**
$5 - 10$ kg vehicle launch/year	50	100
Hardware, testing, facilities	75	150
Pedagogical, PhD and educational program	75	100
Researchers, operations, outreach, innovation program	50	150
Total	250	500

Table 4: Proposed budget in MNOK

In addition to the numbers in Table 4, internal direct funding from `NTNU/AMOS` in collaboration with `NDRE/FFI` and others could target 10%, of the funding i.e. $25 - 50$ MNOK. Yet another 10% of the budget could be targeted via competitive grants on top of the indicated budget.

Conclusions & Take Home

`SmallSat`'s have made substantial inroads in how we see operational assets in near earth orbits. More recently deep space missions including one to Mars [10] are being contemplated. Our aim at `NTNU` is to design/build/test/operate `SmallSat`'s for operational oceanography, to democratize the concept further with direct impact to a major societal challenge facing us in the form of climate change. And in the process build knowledge in Norway to exploit this new and still latent technology for a seaward facing nation. Besides oceanography, we expect to directly make a sizable impact to learning and pedagogy, environmental science, robotic control for autonomy, sensor development and material science to build and test new materials for long-lasting space structures. Side-effects of such a technology will impact the fields of Marine Spatial Planning, Arctic observations and communications and for dual-use capabilities for Maritime Domain Awareness and national and alliance security. And do so by propagating valuable systems engineering skills for the workforce.

The time is now for such an investment; Norway can take the lead in cost-effective advanced technologies for monitoring the environment and understanding our planets rapidly changing ecosystem. As an Arctic nation, it is well placed to observe, record, anticipate and study the changes and impacts of the loss of ice cover and in the process pull together researchers from different fields to tackle **the** major challenge of our time. `SmallSat`'s are quickly emerging as a more mature and game changing technology that can and should be developed at the national level rather than at the international level such as ESA. Beyond the importance for science and economy, national autonomy enabled by `SmallSat`'s should be considered as a strategically important factor.

In this white paper we articulate a vision for a long-term sustainable program to be hosted at `NTNU` with a strong inter-disciplinary flavor which will build on current capabilities in `SmallSat`'s, marine robotics and oceanography, and conceive a pipeline of spacecraft for operational needs, built and operated by students under faculty supervision. In doing so, together with national industry, existing competences, stakeholders and international collaborators, we expect to build a skills-based capability with an outlet for commercialization of technology garnered as a consequence.

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[10] `http://www.jpl.nasa.gov/cubesat/missions/marco.php`

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