

## On small satellites for oceanography: A survey



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### ABSTRACT

The recent explosive growth of small satellite operations driven primarily from an academic or pedagogical need, has demonstrated the viability of commercial-off-the-shelf technologies in space. They have also leveraged and shown the need for development of compatible sensors primarily aimed for Earth observation tasks including monitoring terrestrial domains, communications and engineering tests. However, one domain that these platforms have not yet made substantial inroads into, is in the ocean sciences. Remote sensing has long been within the repertoire of tools for oceanographers to study dynamic large scale physical phenomena, such as gyres and fronts, bio-geochemical process transport, primary productivity and process studies in the coastal ocean. We argue that the time has come for micro and nano-satellites (with mass smaller than 100 kg and 2–3 year development times) designed, built, tested and flown by academic departments, for coordinated observations with robotic assets *in situ*. We do so primarily by surveying SmallSat missions oriented towards ocean observations in the recent past, and in doing so, we update the current knowledge about what is feasible in the rapidly evolving field of platforms and sensors for this domain. We conclude by proposing a set of candidate ocean observing missions with an emphasis on radar-based observations, with a focus on Synthetic Aperture Radar.

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## 1. Introduction

Starting with **Sputnik's** launch in 1957, more than 7000 spacecraft have been launched, most for communication or military purposes. Nevertheless, the scientific potential of satellites was perceived early on, and even though **Sputnik** did not have any instruments, the radio beacon it had was used to determine electron density on the ionosphere [1,2]. A small percentage of the satellites were, and still are, dedicated to research (see Fig. 1). In particular, we focus on Earth observation and remote sensing satellites, as they have changed the way we perceive and understand our planet. This transformation started with the first dedicated weather satellite, **TIROS** (Television Infrared Observing Satellite) 1, launched 3 years after **Sputnik 1** [1].

Although the first satellites had mass smaller than 200 kg, consistent demand on performance led to a natural growth in spacecraft mass, with direct consequences to their complexity, design, test, launch, operation and cost. This reached a peak of 7.9 tonnes with ESA's **EnviSat** mission in 2002 [4]. With launch costs to low Earth orbit (LEO) being on average 21 k€/kg, and for geostationary Earth orbits (GEO) 29 k€/kg, for conventional satellites, the missions were mainly developed by national institutions or multi-national partnerships involving substantial investment [5]. However, several engineering problems arose from having different instruments (with different features and requirements) within the confines of a single spacecraft. Consequently, this rise in mass has stopped and spacecraft of about 1 tonne, with fewer instruments have been preferred by the European Space Agency (ESA) and the American National Aeronautics and Space Administration (NASA) in the last few years.

The cost of a spacecraft is not only linked to the launch, but also

to its development time, so as to account for mission complexity, production and operation during its life-span [6]. Moreover, their design, development and subsequent operation require a substantial infrastructure to provide the end user with the desired data. Furthermore, project, planning and execution demands years of investment prior to a successful launch.

The revolution of very-large-scale integration, in 1970, opened the possibility of integrating sophisticated functions into small volumes, with low mass and power, which paved the way for the modern small satellite [5]. This concept was initially demonstrated in 1961 with the Orbiting Satellite Carrying Amateur Radio (**OSCAR**) 1, and kept growing in sophistication until **OSCAR-8**, at the end of the 1970s (although still without an on-board computer). In 1981, the launch of the **UoSAT-OSCAR-9** (**UoSAT-1**), of the University of Surrey, changed this, as it was the first small satellite with in-orbit re-programmable computers.

In this context, the recent evolution of small satellite (or SmallSats) designs have proved to be promising for operational remote sensing. Typically these platforms have come to be classified as small, micro, and nano satellites. According to the International Academy of Astronautics (IAA) a satellite is considered small if its mass is smaller than 1000 kg [7]. Small satellites comprise five sub-classes: mini satellites have mass between 100 and 1000 kg; micro satellites, whose mass range from 10 to 100 kg; nano satellites, with mass smaller than 10 kg; and satellites with mass smaller than 1 kg are referred to as pico satellites [8]. In this work, we will refer to SmallSats as encompassing all of the above categories.

For each class of mass, there is an expected value for the total cost (which accounts for the satellite cost, usually 70% of the total cost, launch cost, about 20%, and orbital operations, 10% [5]) and

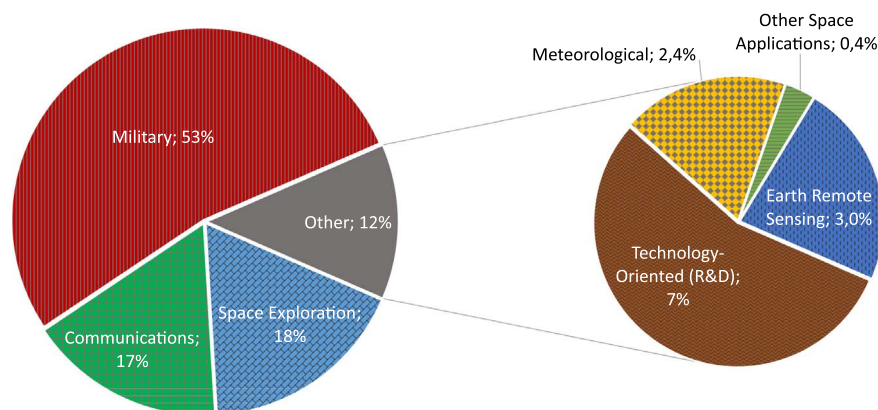


Fig. 1. Distribution of the 7472 spacecraft, launched from 1957 to 2013, according to their mission objectives (from [3]).

**Table 1**  
Spacecraft classification according to mass [8], cost [5], and development time [10].

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

developing time, as shown in Table 1. Typically, these platforms have been demonstrated in low to medium Earth orbits, and are launched as secondary payloads from launch vehicles. Due to this piggyback launch, sometimes is not the mass of the spacecraft that determines the launch cost, but the integration with the launcher [9].

### 1.1. Advantages of SmallSats

While lower costs are one relevant consideration, SmallSats have other inherent advantages. With developing times of less than 6 years (substantially less than larger platforms), SmallSats have more frequent mission opportunities, and thus, faster scientific and data return. Consequently, a larger number of missions can be designed, with a greater diversity of potential users [7]. In particular, lower costs makes the mission inherently flexible, and less susceptible to be affected by a single failure [11]. Furthermore, newer technologies, can iteratively be applied. This is particularly pertinent for the adoption of commercial-off-the-shelf (COTS) microelectronic technologies (i.e. without being space qualified), and Micro-Electro-Mechanical Systems (MEMS) technology, that had a powerful impact on the power and sophistication of SmallSats [5]. Another important feature of SmallSats is their capability to link *in situ* experiments with manned ground stations. As they usually have lower orbits, the power required for communication is less demanding and there is no need for high gain antennas, on neither the vehicles nor the ground control station. Finally, small satellites open the possibility of more involvement of local and small industries [7]. These factors combined, make such platforms complementary to traditional satellites.

There are however some disadvantages associated with small satellites. The two most conspicuous are the small space and modest power available for the payload. Both of these have a particular impact on the instrumentation the spacecraft can carry and the tasks it can perform. As most of small satellites are launched as secondary payloads, taking advantage of the excess launch capacity of the launcher, they, most often, do not have any control over launch schedule and target orbit [12].

Lower cost, greater flexibility, reduced mission complexity and associated managing costs, make small satellites a particularly interesting tool for the pedagogical purposes, with a number of platforms often designed, tested and operated by students (taking the operations of the spacecraft to the university or even department level) [5]. Actually, small satellites projects have had a substantial educational impact even at the undergraduate student level. A number of universities over the world, have launched satellite programmes, and the first launch took place in 1981 (the already mentioned **UoSAT-1**) [13]. Rather unfortunately, these small satellite missions were so different in kind, in terms of mass, size, power and other features, that by the turn of the century a series of failures brought the student satellite missions, especially in the United States, nearly to a halt. This led to the introduction of a standardisation effort, that took shape via the CubeSat.

In 1999 Stanford University and the California Polytechnic State

**Table 2**  
Standard classes for CubeSats [14].

Class	Size [cm]	Mass [kg]
1U	10 × 10 × 11.35	<1.33
1.5U	10 × 10 × 17	<2
2U	10 × 10 × 22.7	<2.66
3U	10 × 10 × 34	<4
3U+	10 × 10 × 37.6	<4

University developed the CubeSat standard, and with it the Poly Picosatellite Orbital Deployer (POD) for deployment of CubeSats [14]. The CubeSat (1U) corresponds to a cube of 10 cm side (with a height of 11.35 cm) and mass up to 1.33 kg, even though other sizes are admitted as a standard (see Table 2). The hardware cost of a CubeSat can vary between €50, 000–200, 000.

### 1.2. Ocean observation

Spacecraft have become an indispensable tool for Earth Observation given their capability to monitor on regional or global scales, and with high spatial and temporal resolution over long periods of time [15]. Several missions have covered and widely influenced the Earth sciences, from meteorology and oceanography, to geology and biology [16]. SmallSats (in particular micro and nano satellites) however, have had little to no impact thus far on oceanography. We intend to make a case for such a focus.

About 70% of Earth's surface is covered by the oceans, which are a fundamental component of the Earth's biosphere. Variations on the oceans properties range from: temperature to salinity [17]; the formation or dissolution of episodic phenomenon such as blooms, fronts or anoxic zones; and anthropogenic events, such as human induced chemical plumes from oil rigs, ships or agricultural runoff. Other anthropogenic changes, including increased pressure on fishing, extended ship traffic due to expanded global trade, drug and human trafficking and the recent uptick in maritime disputed boundaries, further call for increased surveillance of the oceans. One should also point out that the above causes have a significant impact on the coastal ecosystem, inhabited by about 44% of the human population. Traditional methods for monitoring and observation have involved static assets such as moorings with sensors fixed to the ocean floor, Lagrangian drifters or subsampling by manned ships or boats. Understanding the change of ocean features has generated the need for *synoptic* measurements with observations over larger spatial and temporal scales, critical to deal with subsampled point measurements. More recently, robotic platforms such as autonomous underwater vehicles (AUVs), including slower moving gliders, have extended the reach of such traditional methods. As a consequence, scientists are now able to characterise a wider swath of a survey area in less time and more cost effectively. While an advance, they are not considered to be spatio-temporally synoptic, since they do not match the mesoscale (> 50 km<sup>2</sup>) observation capability, necessary to digest the evolving bio-geochemistry or for process studies, especially in the coastal ocean.

On the other hand, synthetic ocean models to provide means for prediction also come with their own limitations. Their *skill level*, in particular, is often poor given the complexity of mixing in near shore waters. Therefore, observation prediction continues to be a challenge hampering a better understanding of the global oceans. Such a need is demonstrably important in situations like oil spill response, such as the Macando event in the Gulf of Mexico.

With recent advances in unmanned aerial vehicles (UAVs), payload sensors, and their cost-effectiveness in field operations, these platforms offer a tantalising hope of further extending the

reach of oceanographers. Nevertheless, ship-based or robotic-based observation and surveillance methods have yet to provide that level of scale, maturity or robustness (or all of the above) appropriate for providing rapid maritime domain and situation awareness.

For all these reasons, satellite remote sensing continues to be a valuable tool, providing a range of high-resolution data including imagery. More recently, radar imagery, from LIDAR (Light Detection and Ranging) to SAR (Synthetic Aperture Radar), have been a boon for maritime authorities, as well as policy makers, with their clear all-weather capability to observe the oceans. The costs and complexity to provide such capabilities however is a significant shortcoming, especially in the study of the changing ocean.

### 1.3. SmallSats and ocean observations

Our thesis is that micro and nano satellites are a key element in the (near) future needs of oceanography. Besides the cost and more modest operational requirements, increasingly smaller form-factor sensors are being designed and built for autonomous robotic (terrestrial, aerial and underwater) platforms, which can be leveraged for SmallSats. Furthermore, as sensors become increasingly affordable, we can envision *multiple* SmallSats in a constellation with identical sensors, pointing Earthwards, to provide near real-time coverage to any part of the planet, especially the remote oceans. Launch costs associated with a single SmallSat are unlikely to be substantially reduced from multiple launched vehicles. In other words, we envisage that multiple SmallSats carrying appropriate sensors in the same orbital plane, can and should become an extension of oceanographic sensing. While such platforms cannot provide *in situ* sampling capability, their synoptic observations can be used to intelligently provide such a capability to ensure robotic elements are “at the right place and right time”, to obtain data especially of episodic phenomenon.

Thus, combining the robotic capabilities of autonomous underwater vehicles (AUVs), autonomous surface vehicles (ASVs), and unmanned aerial vehicles (UAVs), with dedicated small satellites will considerably boost the study of the oceans, provide synoptic views potentially close to real-time, and yield an unprecedented view of our evolving ecosystem on Earth, characterised by the large mass of the ocean. SmallSats, AUVs, ASVs and UAVs are then elements in a strategy to provide *coordinated observation* data. Another key objective of our work, is to show that such a capability, along with novel methods of multi-vehicle control, can provide a new observational capacity, that combines both hardware and software so to make data more accessible to the oceanographer, at whatever scales one wishes to select. These can be from small temporal scales of observing evolving Harmful Algal Blooms (HABs), to large spatial scales of movement of coherent Lagrangian structures [18]. Together with new methods in data science and analytics, trends can be examined in more detail, with point measurements giving way to near continuous observations of the ocean surface and potentially upper water-column. And to be able to do so in a cost-effective manner.

Our objective in this survey paper is to provide a timely and comprehensive view, with a wide perspective, of what SmallSats capabilities are currently available, and in many cases previously proposed. And in surveying the field rigorously, we attempt to provide a perspective of the use of such technologies now, and in the near future, for oceanographic measurements. Our intended audience is scientists and engineers typically in the ocean sciences, and students in engineering with interests in making ocean measurements and ocean engineering, especially marine robotics.

This paper is organised as a survey of SmallSat missions for oceanography cited in the literature, coupled with current methods in robotic oceanographic observations, and SmallSat

characteristics, to make a strong case for their focus on this domain. The organisation of this paper is as follows: in [Section 2](#), we motivate the use of SmallSats with *in situ* robotic platforms; in [Section 3](#), we survey prominent examples of micro and nano satellites and, in particular, those designed for oceanographic studies or monitoring; in [Section 4](#), we discuss the main building blocks of SmallSats; and in [Section 5](#), we present a common set of sensors useful for oceanography. Finally, in [Section 6](#) we conclude with a discussion and our conclusions and perspectives.

## 2. Motivation: coordinated observations with autonomous platforms

Observing the ocean synoptically in space and time is an increasingly important goal facing oceanographers. The changing climate has become a major societal problem to tackle, and with an emphasis on the ocean as the primary sink for greenhouse gases, ocean science and the study of the changing climate has become critical to understanding our planet. However, much has been made of the lack of data and the need to analyse oceanographic phenomena at large scales, not approachable with current observation tools and methodologies, that often rely on traditional ship-based methods. To study phenomena and processes in the ocean which can spatially and temporally range from minutes to months, ship-based methods are neither cost-effective nor sustainable in the long run. Further such measurements do not provide a continuous scale of change in either space or time necessary to understand natural variability.

Recent advances in robotic vehicles have made a dent in more sustainable ocean observation, with the use of autonomous and semiautonomous platforms to observe at such varying spatio-temporal scales. While this is a good start, we are at the infancy of systematic observations using the current generation of robotic hardware. The principal challenge is to observe a water column not just with point-based observations, but across the mediums of air and water, and the air/water interface, and doing so continuously. Such observations need not only to be synoptic, but also to be coordinated across space and time to observe the same patch of the ocean at the same time. Its enabling requires coordination and control of a range of robots with appropriate sensors, across the space, aerial, surface and underwater domains ([Fig. 2](#)).

This necessitates the use of multi-platform systems to observe a patch of the ocean in the meso-scale ( $> 50 \text{ km}^2$ ), and to follow targeted phenomena of interest such as blooms, plumes, anoxic zones, fronts over a period of days, weeks or longer. Recent experiments [19–23] have led to the conclusion that multiple vehicles, operating in different operational domains, are critical for such observational needs. Detection of the targeted features however require observation over larger scales, with the consequent need for remote sensing data to drive robotic assets *in situ*.

Current generation of Earth (and ocean) observing spacecraft provide a rich trove of remote sensing data, and have been credited with understanding the anthropogenic impact on our environment [24]. These systems have been complex, expensive and years in the making for design, build, test and launch operations, and typically undertaken by governmental agencies or multinational institutions.

The advent of the smartphone has resulted in a revolution in sensor technology with a corresponding surge in applications for robotics. This surge has also seeped into satellite technology, with SmallSats being produced as student projects, and operated in a far more affordable way. SmallSats provide just such a novel approach to augmenting ocean observation methods. Their coordination with Earth bound robotic platforms, with all-weather



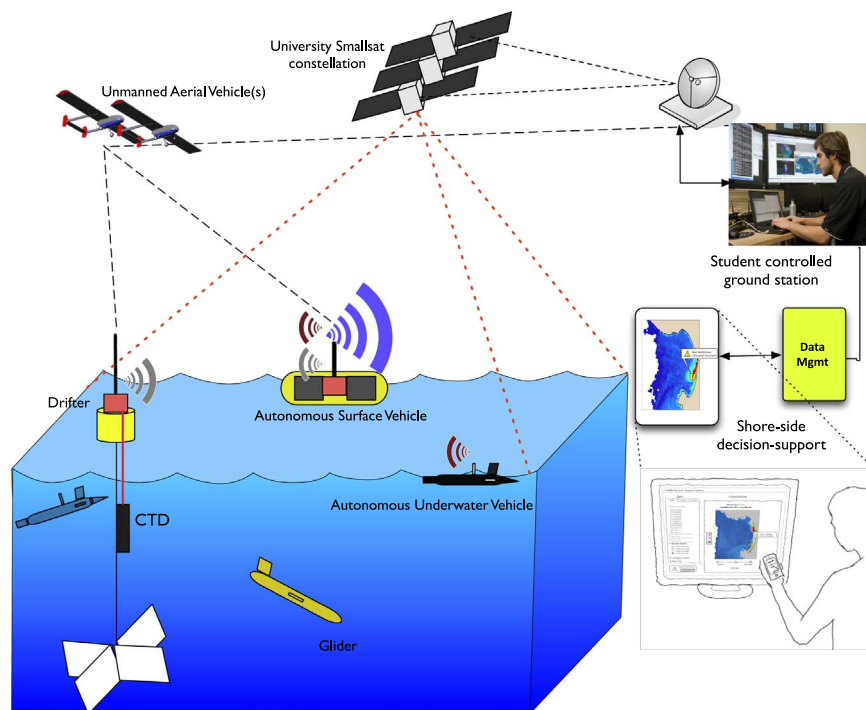


Fig. 2. Networked robotic platforms for synoptic oceanographic observations.

radar imagery, will allow for localising features or targets (in security scenarios) for the ensemble of vehicles in the open ocean. Such experiments have already commenced [21,22], albeit without the space component.<sup>1</sup> A range of applications, starting with upper water-column observations targeting HABs, plumes, anoxic zones and frontal zones, will provide a rich trove of experience and equally importantly, scientific data. Developments along these lines, will push the state of the art, and practice, in both engineering methods in marine robotics as well as in ocean science. Moreover, the technology is dual-use and has clear applications to maritime security and defence.

Equally important, SmallSats are increasingly viable as student-led projects. Not only do they provide a vehicle for student involvement, for a successful operation, such projects provide students with a strong background in systems engineering and collaborative work in teams across various disciplines, including electronics, material science, physics and control systems to name a few.

We call for an increased focus in SmallSats, both as a technological push, and for obtaining new and sustained methods of observation and data collection, as also as pedagogical tools for students in inter-disciplinary science and engineering. Student-led missions, with help from various departments, will be required to design materials, sensors and software to be embedded within these space-borne assets. Such platforms can then be part of a robotic ensemble, which can be controlled for purposes of making sustained coordinated measurements in offshore environments.

### 3. Survey of ocean observing SmallSats

We focus now on a survey of SmallSats in the context of observing the oceans. In this and following sections, we categorise SmallSats in terms of micro, nano or CubeSats. The survey covers those in design stages, successfully operating, as well as those

which were unsuccessful in meeting their operational requirements. This survey is up to date until around Fall 2015.

Some of the fields where SmallSats (especially below 100 kg) have proved useful are ocean imaging, data storage and relay, and traffic monitoring (e.g. through the Automatic Identification System, AIS, as explained in Section 3.3). While not all the surveyed examples involve oceanographic variables per se, they have relevant bearing on oceanography. We also consider missions where a constellation of SmallSats is employed.

The SmallSat's described here were referenced through available online databases (the Earth Observation Portal,<sup>2</sup> the Union of Concerned Scientist satellite database,<sup>3</sup> and the Nanosatellite Database<sup>4</sup>), and via a wider survey of the literature as well as the web. Whenever possible, references of the different missions were used, although some information comes from the databases. Table 3 summarises the spacecraft discussed here, with mass, power, mission and payload (related to oceanography), and launch date (past and future).

#### 3.1. Ocean imaging

While a number of imaging nano and micro satellites have been flown, and although some of the SmallSat imagery could be used for oceanographic studies, only a few are actually focused on ocean observation. No CubeSats were found that were equipped with ocean imaging systems [4], although in 2013 **COPPER** was about to be the first. Among micro satellites, only two were found that have already been launched: one for commercial purposes (**WINISAT-1**); the other (**QSat-EOS**) for monitoring ocean health, using data acquired for other purposes.

**RISESat**. The Rapid International Scientific Experiment Satellite (**RISESat**) is being developed under an international cooperation

<sup>2</sup> <https://directory.eoportal.org/web/eoportal/satellite-missions>

<sup>3</sup> <http://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database.html>

<sup>4</sup> <http://www.nanosats.eu/>

<sup>1</sup> See <http://rep13.lsts.pt/>, <http://rep15.lsts.pt/> and <http://sunfish.lsts.pt/>.

**Table 3**

Summary of Ocean Observing SmallSats (Operational if not stated otherwise).

Satellite	Mass [kg]	Power [W]	Size [cm] <sup>a</sup>	Mission <sup>b</sup>	Payload <sup>b</sup>	Launch
ZACube-2 <sup>c</sup>	4	–	10 × 10 × 34	Vessel tracking and ocean colour	AIS and imager	–
RISESat <sup>c</sup>	60	100	50 × 50 × 50	Fisheries and environment studies	Multi-band camera	2016
M3MSat <sup>c</sup>	85	80	80 × 60 × 60	Augmenting maritime surveillance capabilities	AIS	2016
AAUSat5	0.88	1.15	10 × 10 × 11	Vessel tracking	AIS	2015
LambdaSat <sup>d</sup>	1.5	1.5	10 × 10 × 11	Vessel tracking	AIS	2015
LAPAN-A2	68	32	50 × 47 × 36	AIS payload for the equatorial region	AIS	2015
AlSat	14	15	10 × 10 × 11	Helical antenna technology demonstration	AIS	2014
QSat-EOS	50	70	50 × 50 × 50	Ocean eutrophication	VIS and NIR camera <sup>e</sup>	2014
AAUSat3 <sup>d</sup>	0.8	1.15	10 × 10 × 11	Vessel tracking	AIS	2013
COPPER <sup>f</sup>	1.3	2.5	10 × 10 × 11	Infrared Earth images	Uncooled Microbolometer Array	2013
WNISAT-1	10	12.6	27 × 27 × 27	Monitoring Arctic Sea state	VIS and NIR cameras <sup>e</sup>	2013
Aeneas	3	2	10 × 10 × 34	Track cargo containers	Antenna and corresponding electronics	2012
VesselSat 2	29	–	30 × 30 × 30	Collect space-borne AIS message data	AIS	2012
SDS-4	50	60	50 × 50 × 45	Demonstrate space-based AIS	AIS	2012
exactView 1	98	–	63 × 63 × 60	Commercial constellation of AIS spacecraft	AIS	2012
exactView 6/5R/12/11/13	13	15	25 × 25 × 25	Commercial constellation of AIS spacecraft	AIS	2011/13/14
VesselSat 1	29	–	30 × 30 × 30	Collect space-borne AIS message data	AIS	2011
AlSSat-1	6.5	0.97	20 × 20 × 20	Assess feasibility of situational awareness service	AIS	2010
NTS/CanX-6 <sup>d</sup>	6.5	5.6	20 × 20 × 20	Demonstrate AIS detection technology	AIS	2008
WEOS	50	14.5	52 × 52 × 45	Data relay from cetacean probes	UHF Antenna	2002

<sup>a</sup> Size of the main structure (not accounting for deployed mechanisms, e.g. antennas).<sup>b</sup> Related to oceanography.<sup>c</sup> To be launched.<sup>d</sup> Concluded operations.<sup>e</sup> Visible (VIS) and near infrared (NIR).<sup>f</sup> Mission failed.

led by Tohoku University, within the Japanese programme FIRST (Funding Program for World-Leading Innovative R&D on Science and Technology) [25]. With a launch planned for 2016, the objectives are two fold: technological – to demonstrate the platform performance, as it is planned to be a common bus for future missions; and scientific – through the integration of scientific payloads from different countries, mainly focused on the Earth and its environments (to a total mass of about 10 kg) [26].

The spacecraft bus, the Advanced Orbital Bus Architecture (AOBA), is intended to be versatile, cost effective, and with a short development schedule, to be compatible (and competitive) for future scientific missions. The size of the bus is expected to be smaller than 50 × 50 × 50 cm, with a maximum mass equal to 60 kg (but typical less than 55 kg). The main structure has a central squared pillar, with one side extended to connect to the outer panels (increasing the mounting surface and resulting in a more stable satellite). The outer panels are made of aluminium isogrid.

Attitude and orbit determination is performed through the use of two star sensors, a 3-axis fibre optic gyroscope, a 3-axis magnetometer, a GPS receiver, and coarse and accurate sun sensors (covering 4 $\pi$ ). Control is achieved with four reaction wheels and 3-axis magnetic torque rods. To achieve a high reliability, some sensors and actuators are designed with redundancy.

Power is supplied by gallium arsenide (GaAs) multi-junction cells, divided in two deployable panels and a body-mounted one, generating more than 100 W. The enhanced amount of electric power, around double the power consumption (expected to be more than 50 W), allows for long period and multi instrument observations. A power control unit (PCU) provides each subsystem supply lines, although, some more demanding components (in terms of power) are also directly connected to the PCU. Nickel-metal hydride (NiMH) type batteries are also installed.

Three different bands are used for communications. The UHF is used for command uplinks, and a S-band for housekeeping downlink. As large amounts of scientific data are expected to be generated, a X-band downlink system was added [26].

Furthermore, a de-orbit mechanism will be installed, so to

make the spacecraft re-enter Earth in about 25 years, following the standards for the maximum re-entry time after the mission completion [27,28]. Six microcameras will also be installed to monitor the satellite's structure and deployment, and to view the Earth and where the instruments are pointing.

The payloads include a High Precision Telescope, a Dual-band Optical Transient Camera, an Ocean Observation Camera (OOC), a Three-dimensional Telescope, a Space Radiation micro-Tracker, a micro-Magnetometer, a Very Small Optical Transponder, and a Data Packet Decoder.

The only focused in ocean observation, the OOC is a multi-band camera, with about 100 m spatial resolution, and a wide field of view (swath width of approximately 65 km) [25]. Although the system will work in a continuous acquisition mode, the region of interest is around Japan and Taiwan. The resulting data will mainly be used for fisheries and environmental studies. The instrument is compatible with Space Plug & Play technology, and has a mass of about 1 kg [26]. Furthermore, it has a power consumption of less than 3 W (5 V), and uses a Watec CCD (charge-coupled device) with 659 × 494 pixels (square pitch size of 7.4  $\mu$ m), for each of the three F/1.4 lens.

**QSat – EOS.** Graduate students of Kyushu University, in Japan, started developing a spacecraft for space science. However, the main objective of the mission was shifted to Earth Observation, in particular to disaster monitoring, due to funding requirements [29]. Other objectives include monitoring of Earth's magnetic field, detection of micro debris, and observation of water vapour in the upper atmosphere [30]. Data acquired also supports other studies, namely agricultural pest control, red tide (harmful algal bloom) detection, and ocean eutrophication (pollution due to excess of nutrients [31]). Launched in 2014, data is currently being gathered by this SmallSat.

**COPPER.** The Close Orbiting Propellant Plume and Elemental Recognition CubeSat was an experimental mission to study the ability of commercially available compact uncooled microbolometer detector arrays to take infrared images, besides providing space situational awareness [32]. Additionally, it was

intended to improve models of radiation effects on electronic devices in space. This SmallSat was part of the Argus programme, a proposed flight programme of a few CubeSat spacecraft spanning over many years, of which **COPPER** was the pathfinder mission [33]. It was launched in November 2013, but communications were unable to be established.

**WNISAT – 1.** One of the largest weather companies, Weathernews Inc. of Tokyo, funded the sea monitoring mission **WNISAT-1** (Weathernews Inc. Satellite-1), which was launched in 2013 [34]. The objective was to provide data on the Arctic Sea state, in particular ice coverage, to shipping customers operating in that area [35]. The micro satellite was designed by a university venture company, AXELSPACE. The aim was to use a simple architecture and, when possible, COTS devices, with a compact design, simple operational support, and minimum redundancies. This SmallSat continues to be operational.

### 3.2. Data relay SmallSats

There are various missions that do not have payloads designed specifically for oceanographic studies, but even so they perform or support work in oceanography, as data relay spacecraft. Some receive data from *in situ* experiments (e.g. buoys), and transmit the data received when a ground station is in view. This alleviates the need for a human operator to monitor an experiment, and to get the acquired data. A prominent example is the Whale Ecology Observation Satellite (**WEOS**) of the Chiba Institute of Technology in Japan.

Other examples within the realm of data relay SmallSats are the **ParkinsonSat** [36], the **TUBSAT-N** and **N1** nano spacecraft (which were launched from a submarine) [37], the twin **CONASAT** 8.2 kg spacecraft [38], and the **FedSat** (Federation Satellite) [39].

The submarine launch, the first commercially, was made from a Russian vessel, using a converted ballistic missile, in 1998. Such submarine-based launches open up the possibility of sending a spacecraft to any orbit inclination, without requiring any space manoeuvres. Clearly, form-factors are critical, since only small spacecraft can be launched in this manner, due to size and rocket power constraints.

**WEOS.** Launched in 2002 to a Sun-synchronous orbit of about 800 km, the **WEOS** spacecraft was designed, built and operated by students of the Chiba Institute of Technology, in Japan. The goal was to track signals emitted by probes attached to whales, while studying their migration routes. The probe transmitted GPS position, diving depth, and sea temperature using the UHF band [40]. Although the spacecraft is still operational, scientists were unable to attach the probes to whales, and only tests with ocean buoys were made.

### 3.3. Tracking and AIS

Maritime domain awareness and security is a key need for governments and policy makers worldwide. This includes protection of critical maritime infrastructures, enforcement of the freedom of navigation, deterrence, preventing and countering of unlawful activities [41]. A number of countries are paying special attention to this problem. One example is Canada, where 1600 ships transect its extended continental shelf per day [42]. Japan, Norway and Indonesia are other examples of countries paying attention to maritime traffic, given that their exclusive maritime economic zones are substantial [43–45].

To have an effective Maritime Domain Awareness (MDA), a number of information sources are available, even though most maritime infrastructure still lack a thorough response to the current necessities [46]. Most ship monitoring is currently performed using maritime radars, vessel patrolling, and by ground based

Automatic Identification System (AIS) [47,48]. A significant part of the time is spent in identifying unknown targets, collected from a variety of Intelligence, Surveillance, and Reconnaissance (ISR) sensors. An efficient process to perform this sorting, and to correlate information with other ISR data, is critical. A possibility, suggested by many, is the combination of AIS with SAR imagery. In some cases this has already been initiated, for instance, by operations of the Norwegian Coast Guard [43].

AIS is a ship-to-ship and ship-to-shore system used primarily to avoid collisions, and to provide MDA and traffic control [48,49]. It is mandatory for all vessels with more than 300 tonnes and all passenger ships in international waters, as also for ships with more than 500 tonnes in most national waters [43].

AIS works by sending a VHF signal providing the Maritime Mobile Service Identity (i.e. position, heading, time, rate of turn, and cargo) [42]. It has a typical range between 50 km and 100 km, making it only practical nearshore and in maritime choke points. However, due to this limited range, the system can be simpler, using a self-organised time division multiple access scheme (i.e. each transmitter within 100 km can self-organise and transmit its information without interfering with messages sent from other ships in the same cell) [49].

When an AIS receiver is placed in space, a global view of maritime traffic, with a number of applications can be achieved. These include not only traffic awareness (with capabilities for national security tasks and shipping), but also for search and rescue, and environmental studies. In the fourth revision of the recommendations for the system, AIS has been suggested as a means to promote ship-to-space communication [43]. However, in doing so, signal jamming problems arise, due to the wider FOV (field of view) of a space-based platform (normally more than the 100 km), specially in high traffic areas [43]. Furthermore, because the signal has to travel a longer distance (than the normal maximum 100 km) it is weaker. Another problem is the high relative velocity of the spacecraft, which induces Doppler shifts [44]. Moreover, the ionosphere induces a Faraday rotation of the polarisation plane of the signals (dependent on its frequency), decreasing the signal power received by the satellite (due to the discrepancy between the signal and the antennas), a problem also present with other remote sensing measurements.

Several spacecraft have carried AIS systems, and much work in this area is still being performed [50]. For some, the literature is not detailed, besides some general data and the launch dates. For instance, **Triton 1** and **2** are two examples of 3U CubeSat spacecraft, from the UK, that intend to test advanced AIS receivers [51]. **TianTuo 1** is a Chinese nano satellite (9.3 kg) from the National University of Defense Technology (NUDT) that also performs tracking of AIS signals, in addition to other experiments [52]. Two others with less information available are **Perseus-M 1** and **2**. These spacecraft were built by Canopus Systems US, and follow the 6U CubeSat standard [53,54]. Finally, another example is the **DX 1** (Dauria Experimental 1), a 27 kg spacecraft, with a size of 40 × 40 × 30 cm, built by Dauria Aerospace [55]. Besides testing technology it also carries an AIS receiver.

**ZACube – 2.** The Cape Peninsula University of Technology (CPUT) created a programme to develop nano satellites in South Africa, of which the **ZACube-2** will be the second spacecraft [56]. Although still not launched, this spacecraft will serve as a technology demonstrator including a software defined radio (SDR), which will be used for tracking AIS signals, and a medium resolution imager, to perform ocean colour and fire monitoring.

**M3MSat.** The Canadian Department of National Defence (DND) wanted to expand the range of AIS farther than the maritime inner zone, and integrate AIS and ISR data to produce an improved Recognized Maritime Picture [42]. Building upon the experience of a previous mission, the Near Earth Object Surveillance Satellite, a

new satellite is scheduled to be launched in 2016, the **M3MSat** (Maritime Monitoring and Messaging Microsatellite). The main mission objectives are: to monitor ship AIS signals, utilised by the Canadian government and Exactearth (a commercial venture for tracking AIS data); serve as a platform demonstrator; and establish a flight heritage [42].

**AAUSat.** The Department of Electronic Systems of Aalborg University (AAU) created an educational programme where students could have access to many aspects of satellite design and development. From this programme three satellites were designed for tracking vessels with AIS systems, the **AAUSat3**, 4 and 5 [57]. Of these, **AAUSat3** has concluded its mission, **AAUSat5** was launched from the International Space Station (ISS) in October 2015, whereas **AAUSat4** is still being tested. With each spacecraft a new version of the AIS system is flown.

**LambdaSat.** A group of international students in Silicon Valley, California, have developed a spacecraft with three main objectives: space qualification of graphene under direct solar radiation and space exposure; demonstration of an AIS system; and space qualification of three-fault tolerant spacecraft [46]. The SmallSat was deployed in March 2015 from the ISS [58]. About 30 days later, the mission was concluded and the spacecraft re-entered the atmosphere in May 2015.

**LAPAN – A2.** The Indonesian space agency (LAPAN) propelled by the training of its own engineers in the Technical University of Berlin, during the design and building of **LAPAN-TUBSAT** or **A1**, developed the **LAPAN-A2** [59]. It was launched in 2015, for Earth observation, disaster mitigation, and implementation of an AIS system [45].

**AISat.** The Automatic Identification System Satellite (**AISat**) was designed by the German Aerospace Center (DLR) to monitor AIS signals. Launched in 2014, it is currently operational. In particular, the Institute of Space Systems is responsible for adapting the Clavis bus (an adaptation of the CubeSat platform by DLR) to this mission, while the Institute of Composite Structures and Adaptive Systems developed the helical antenna for the AIS payload [60]. Two companies (The Schütze Company and Joachims) and the Bremen University of Applied Sciences were also partners in the project. The difference between this mission and others described here, is in the use of a helical antenna.

**Aeneas.** The **Aeneas** nano satellite was designed to track cargo containers (equipped with a 1 W Wifi type transceiver) around the world [61]. It was developed by students of the University of Southern California, Space Engineering Research Center in partnership with iControl Inc. (the primary payload provider) and was launched in 2012 [62]. The orbit is an ellipse with a periapsis of about 480 km.

**VesselSat.** LuxSpace Sarl owns and operates two micro satellites, the **VesselSat 1** (launched in 2011) and 2 (in 2012), to monitor maritime traffic with a space-based AIS system [63]. Both continue to be operational. These spacecraft were built upon the experience gained in flying the **Rubin 7**, 8 and 9 non-separable payloads, flown before on the upper stage of the Polar Satellite Launch Vehicle [64].

**SDS – 4.** The Japan Aerospace Exploration Agency (JAXA) created the Small Demonstration Satellite programme in 2006, in order to test the next generation space technologies and, at the same time, to create a standard 50 kg bus for future missions [44]. Within this programme, the Small Demonstration Satellite 4 (**SDS-4**) is the second satellite, and one of its objectives, apart from demonstrating high performance and small bus technology, is to validate a space-based AIS system [50]. Launched in 2012, it remains operational, even after completing its designed life time [65].

**AISSat – 1.** Launched in 2010 (to a 630 km altitude Sun-synchronous polar orbit), **AISSat-1** is the first dedicated satellite build

for space-based monitoring of AIS signals by Norway, in partnership with the University of Toronto, Institute for Aerospace Studies/Space Flight Laboratory (UTIAS/SFL) [43,47]. The objective is to enhance MDA in Norwegian waters, which amounts to more than 2 million square kilometres. Due to continuing success of the **AISSat-1** mission (still operational in late 2015), two more spacecraft, the **AISSat-2** and 3, were built (**AISSat-2** was launched in 2014, and **AISSat-3** is expected to be launched in 2016).

**NTS/CanX – 6.** In 2007/2008 cooperation between the University of Toronto, Institute for Aerospace Studies/Space Flight Laboratory (UTIAS/SFL) and COM DEV Ltd. designed, produced and launched a nano satellite, in less than seven months, to perform experiments in the reception of AIS signals, the Nanosatellite Tracking Ships (**NTS**) [49]. While the platform is based on SFL **CanX-2** nano satellite and the Generic Nanosatellite Bus (GNB), the AIS payload was developed by COM DEV. A top-down approach was performed, based on the mission requirements (lifetime, data throughput, attitude, schedule, and resources), balanced with a bottom-up analysis, which accounted for hardware limitations (on-board memory, downlink rate, power, volume, and others), maturity and readiness. Even though the spacecraft is still in orbit, and keeps regular contact with the ground stations, it is no longer considered operational.

### 3.4. Constellations

Constellations can be considered as a category of their own. They are primarily used to combine several observations of the same target, performed by different platforms, and to obtain scientific data that could not be acquired using a single spacecraft. Another usage concept for a constellations is to achieve a permanent global coverage, like the GPS constellation, or **Iridium** for communications. An example of such a constellation, and of particularly relevance for this work, is the **exactView** discussed below.

**SOCON.** The **SOCON** (Sustained Ocean Observation from Nanosatellites) project, intends to develop the **SeaHawk** 3U CubeSats spacecraft [66]. Two prototypes are expected to be launched in 2017, and will act as forerunners for a constellation of ten SmallSats. The objective is to measuring ocean colour, using HawkEye Ocean Colour Sensors. The associated cost is expected to be about eight times less, with a resolution from seven to 15 times better, than its predecessor, the single mini **OrbView-2** satellite (previously named SeaStar).

**CYGNSS.** Each **CYGNSS** (Cyclone Global Navigation Satellite System) satellite has a mass of 25 kg, and the constellation has eight identical satellites weighting in total 200 kg [67]. This constellation, expected to be launched in 2016 on a single launch vehicle, will serve to relate ocean surface properties (retrieved from reflected GPS signals), atmospheric conditions, radiation and convective dynamics, with tropical cyclone formation [68].

**exactView.** The **exactView** spacecraft/payloads are part of the exactEarth company constellation of currently seven AIS systems [69]. With this constellation exactEarth expects to have a global revisit time (gap between subsequent detection of individual ships) of around 90 minutes, giving their customers a comprehensive view of traffic in an area of interest.

The first satellite was the experimental **NTS (EV0)**, discussed above, which is considered by exactEarth to be retired. In 2011, came the **EV2**, an AIS payload aboard the **ResourceSat 2** satellite, and **EV6** and **5R** satellites (which were named **AprizeSat-6** and 7) produced by SpaceQuest and transferred to exactEarth. The fifth satellite, launched in 2012, is **exactView1 (EV1)**. **AprizeSat 8** was commissioned and became **EV12** in 2013. More recently, in 2014, **EV11** and 13 (**AprizeSat 9** and 10) started operations. Three more AIS systems are expected to be added to the constellation, the **EV9** spacecraft (launched in September 2015), the **EV8** (which is part of



the payload of the Spanish **Paz** satellite), and the **M3MSat** satellite discussed above (considered by exactEarth to be **EV7**) [70].

The AprizeSat constellation goes beyond the 6 to 10 that passed onto exactEarth. About 64 satellites are planned, so as to build a global system of data communication, tracking and monitoring of assets, and in some cases AIS payloads [71].

#### 4. SmallSat features

For completeness, we now present some features of a typical spacecraft, while highlighting some specifics that are of importance for ocean observation SmallSats. These platforms share most of the characteristics of large spacecraft, adapted to the microcosm of a SmallSat, and thus the information gathered here was obtained from [4–6,72,73].

Any spacecraft design is based on a *bus*, which includes all subsystems essential to its operation and to support the *payload*, its useful mission specific component. Some authors also consider the booster adapter as an element to be part of the spacecraft [6]. For the purpose of this paper, the payload is the assembly of hardware (and software) that senses or interacts with the object under observation, in this case, the Earth's oceans. This is the focus of Section 5.

The bus performs the crucial functions of carrying the payload to the right orbit and maintaining it there, pointing the payload in the right direction, providing a structure to support its mass, stabilising its temperature, supplying power, communications and data storage if necessary, and handling commands and telemetry. The bus is the physical infrastructure on which everything else is mounted in hardware, or run in software. These functions are usually divided into seven subsystems:

1. Structure and Mechanisms;
2. Propulsion systems;
3. Attitude Determination & Control System (or guidance, navigation & control) – ADCS;
4. Power (or electric power) system – EPS;
5. Thermal (or environmental) control system;
6. Command & Data Handling (or spacecraft processor) – C&DH;
7. Communications (or tracking, telemetry and command) – Comms.

In many cases, the bus is a standard design adaptable with only minor adjustments to a range of missions, each with a different payload. This does not mean that any bus is adequate for any payload. The aim of this section is to give a brief description of a standard bus, while keeping the focus towards an oceanography oriented SmallSat. In each part a brief description of the subsystem is provided together with some limitations to be dealt with when considering micro and nano satellites. Some of the subsystems are crucial for oceanographic SmallSats, as their features will limit scientific objectives. A schematic of these subsystems, with their essential components, is shown in Fig. 3.

##### 4.1. Structure and mechanisms

The structure and mechanisms subsystem is the skeleton of the spacecraft, determining the overall configuration. It carries and supports all the equipment, and protects (during launch) the components to be deployed in orbit. The structural architecture is designed based on the attitude control requirements, and typically its mass range between 10% and 15% of the dry mass of the spacecraft.

For many SmallSats, the basic shape of the satellite is a cuboid (for 3-axis stabilised spacecraft), with usually five lightweight

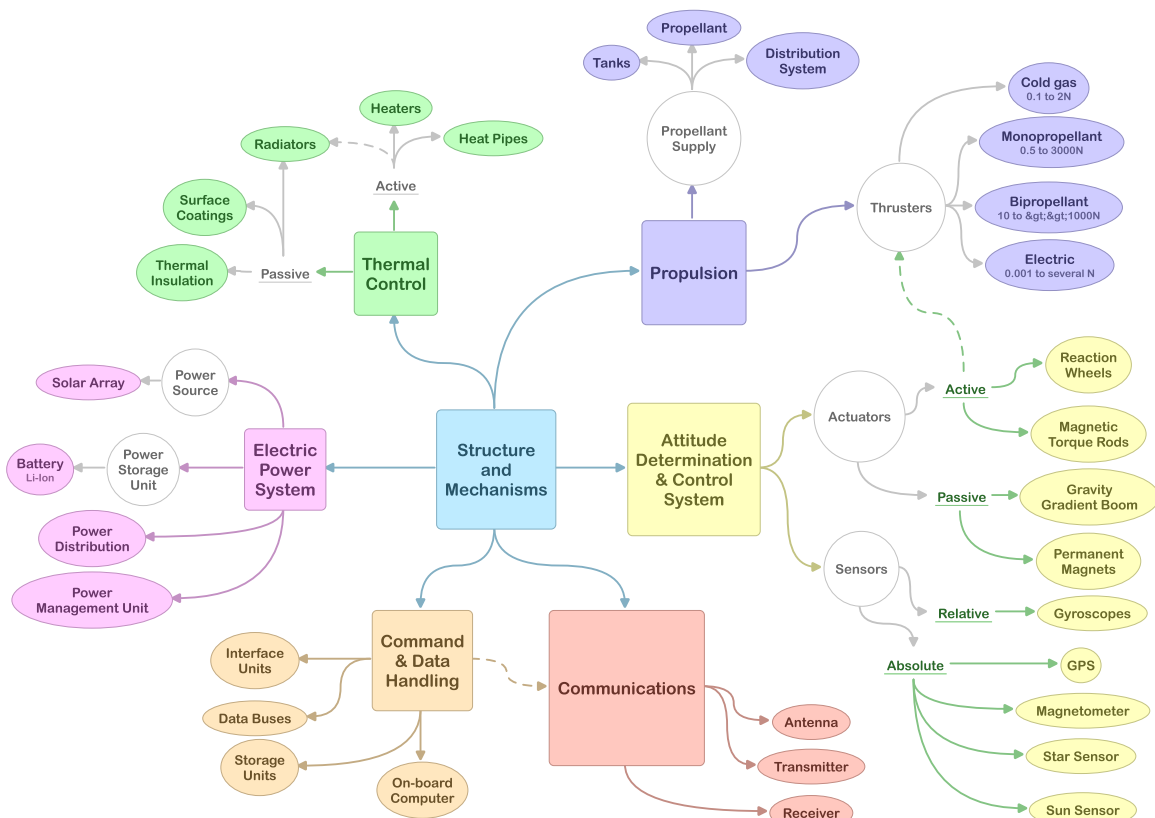


Fig. 3. Schematic of a spacecraft subsystems (squares), with respective components (ellipses).

sides and a more massive structure which supports the link to the launch vehicle. The spacecraft components (including payload) are linked to the inner side of the exterior panels. Conversely, CubeSats have four pillars (trusses or stiff rods) at the corners that support the structure, and face plates (closed or open).

The University of Surrey, which is at the forefront of designing small satellite platforms, also uses the CubeSat modular approach [5]. Thus each subsystem is machined in identical boxes, which are stacked on top of each other, and held together by tie-rods, to form the main body, and to where other instruments and solar panels are mounted onto.

Although in most missions the structure adapts to the payloads that will be installed, there are some that work the other way around, i.e. structure dimensions, and internal configuration, constrain the payloads the satellite can carry. Payload restrictions are more evident in CubeSats, since there is a standard for dimensions (and mass) to be followed.

#### 4.2. Propulsion systems

A propulsion system serves mostly to change or to fix the orbit of a spacecraft, including de-orbit manoeuvres at end of life, counteract drag forces, and sometimes to control its attitude and angular momentum. The most significant parameters of a propulsion system are the total impulse, and thruster characteristics (number, orientation, and thrust levels). Other important parameters are the total mass, power demand, reliability and mission lifetime.

Common propulsion methods cover, in ascending order of performance: cold gas, which can supply from 0.1 N to 2 N; monopropellant, with a capacity between 0.5 N and 3000 N; bi-propellant, yielding 10 N to much more than 1000 N; and finally electric, with forces of just 0.001 N to several N. Although more efficient, electric propulsion requires a larger power supply, than chemical propulsion, to produce thrust. Usually solar panels are used, for Earth orbiting missions. This has an inherent increase in mass (about 40 W/kg).

Even though a propulsion system is included in most spacecraft, especially if in geosynchronous orbit (where station-keeping manoeuvres are common), the simplest SmallSats *do not* have any thrust capability. Nevertheless, it has been installed in spacecraft as small as CubeSats, based on either chemical or electrical systems. An example, is the miniature cold gas system installed in the **SNAP-1**, a 6.5 kg nanospacecraft.

#### 4.3. Attitude determination and control system

The spacecraft's angular orientation (the direction it is pointing to) is controlled and sensed by the attitude determination and control subsystem (ADCS or ACS). In some cases, it also determines the satellite's orbit (and it may even control it if a propulsion system is present, as discussed in Section 4.2). Some references treat orbit determination and control as a different subsystem; we treat them together in this paper.

Characteristics and performance of the ADCS is determined by the mission, and in particular, payload requirements. These affect the accuracy (the difference between real-time and *post facto* attitude), the stability (the efficiency of keeping attitude rates), and the agility (the time needed to change between two desired attitudes). Other drivers include mass, power, cost, lifetime, reliability, and redundancy [73].

Some of the simplest spacecraft do not have any form of ADCS subsystem, and the attitude will continuously change (one of the oldest examples is the **Sputnik 1** itself). They can only have payloads that are omnidirectional, like antennas, and all facets need to have solar panels if powered by solar power. In other cases, specially if the mass requirements are stringent, some SmallSats

employ passive control methods [6]. More complex systems have controllers, actuators, and/or propulsion subsystems (to actively control attitude, velocity, or angular momentum), and sensing instruments to determine the attitude and orbit position [72].

There are several methods to determine the 3-axis attitude of a spacecraft but, typically, data of different sensors are combined. Common sensors include: star and sun sensors; magnetometers; gyroscopes; and GPS.

Attitude control can be achieved either passively or actively. Most common actuators are: permanent magnets; a gravity gradient boom; thrusters; magnetic torque rods; and reaction wheels.

For CubeSats, sensing accuracies of less than 2° have been achieved (which can be translated to a ground uncertainty of 14 km for a 400 km altitude orbit), while control accuracies are less than 5° [4]. These accuracies have to be improved for some oceanographic missions, although the estimated 0.02° of future CubeSats (a ground uncertainty of 140 m) will certainly be enough for most applications. Sun sensors with magnetometers are the preferred solution, combined with passive or active magnetic control. Reaction wheels have also been tested but are uncommon. Furthermore, advanced miniature GPS navigation devices have already been used in nano satellites for orbit determination.

A typical set of ADCS actuators for micro satellites, is a pack of reaction wheels with magnetic torque rods, as these are necessary for wheel unloading/desaturation, i.e. deceleration of the wheels. Nevertheless, some passive control using permanent magnets has also been used [5]. Usual sensors are a magnetometer, a gyroscope, sun sensors (using most times complementary metal-oxide-semiconductor, CMOS, detectors), and a GPS. Star trackers are not as usual, due to size, power and performance constraints, although there are some cases we have found in our literature survey.

#### 4.4. Electric power system

The electric power system (EPS) is another critical subsystem, of which micro and nano satellites have to take the maximum advantage of. The system needs to be autonomous and maintain the power supply whatever the failure conditions [72]. An EPS provides electric power for all other subsystems of the spacecraft, which influences its size. Not only nominal power requirements are important, but so is peak power consumption, and the orbit of the satellite (for some types of energy sources). Therefore, the EPS sizing limits the payloads carried by a spacecraft.

The basic system consist of a power source, a power storage unit, power distribution, and a power management unit (including conversion, conditioning, and charge and discharge). Due to degradation of the power source and storage, system dimensions must be made with end-of-life figures. Nevertheless, low mass and cost is always the primary criteria for SmallSats.

For Earth orbiting satellites, solar arrays equipped with photovoltaic cells are the most common power source. These are usually body-mounted, and/or in deployable rigid arrays, using multi junction GaAs triple junction cells.

With a solar array for power source, which is dependent on solar irradiation to generate power, the power storage unit takes special relevance. Furthermore, it will also support the bus when peak power is required (higher than what the solar array can supply). The typical means to storage energy is a battery. If the spacecraft is to survive more than a few weeks of mission life, batteries with charge capabilities are needed, usually with Li-ion (Lithium-ion), NiCd (nickel-cadmium), and NiMH sources.

#### 4.5. Thermal systems

One problem that is sometimes not dealt with appropriately, is thermal control, which can make a spacecraft inoperable. The

thermal subsystem is responsible to ensure that all components are kept within the temperature range needed for optimal operation, which in-turn determines its size.

A balance between heat loss and solar radiation received can be achieved passively, through physical arrangement of equipment, thermal insulation (e.g. thermal blankets) and surface coatings (e.g. paint). However, passive control may not be enough, and thus active techniques have to be implemented. These include heaters and heat pipes. Radiators, which have surfaces with high emissivity and low absorption, are also occasionally used actively or passively [73]. For micro and nano satellites, passive solutions are usually preferred due to mass saving and small space and size. In particular, heat sinks and optical tapes are common options for CubeSats [4]. Some active control (e.g. using joule heating on the battery) has already been used. Nevertheless, when photodiodes are present on a payload, active temperature control has to be employed (in most cases), since they have stringent thermal requirements.

#### 4.6. Command and data handling

Responsibility for distributing commands controlling other subsystems, handling sequenced or programmed events, and accumulation, storage and housekeeping for payload data, rests on the command and data handling system (C&DH). This subsystem is closely linked to the communication subsystem, to be discussed in Section 4.7. In particular, data rates influences the system parameters, together with data volume [6]. Other aspects to be addressed are performance, reliability, self-healing (i.e. the capacity to treat failures or anomalies), fault tolerance, the space environment requirements (e.g. radiation and temperature), and power and size (which is directly proportional to spacecraft complexity). Common units are a central processor, data buses, interface and storage units.

Usually, micro and nano satellites have a single on-board processor which controls all aspects of the spacecraft. Another trend is the increasing use of FPGA's (field-programmable gate array integrated circuits). Furthermore, to have high data processing capabilities, at the risk of less durability due to space radiation, COTS micro controllers are being increasingly used on micro and nano satellites, including commonly available ARM and PIC controllers.

#### 4.7. Communication systems

The communications subsystem assumes special relevance for micro and nano satellites, since limitations of power and size will limit the spacecraft's capability to transmit data. This subsystem links the spacecraft to the ground or in some special cases to other spacecraft. This is a critical system, since without communications a mission can be considered lost in practice, and hence, redundancy and as much as possible near spherical ( $4\pi$ ) coverage, must be implemented.

A receiver, a transmitter, and an antenna (which can be directional, hemispheric, or omnidirectional) are the basic components of a communication system. Each of these elements is selected and sized taking into account the desirable data rates, error rate allowance, communication path length, and radio frequency. The transmitting power, coding and modulation are also important factors. There are COTS components for each of these elements, with specific reliability characteristics. The communication bandwidth needed for a SmallSat is related to the power the spacecraft can generate, and correlated to the altitude at which the platform operates. Higher the altitude, less friction with the atmosphere, resulting in lower orbit decay rate, but it comes with a higher power requirement to communicate.

This survey of SmallSats confirms a trend found by other surveys, namely that 75% of CubeSats use UHF (ultra-high frequency) communications, with rates reaching 9.6 kbps, and 10% VHF (very high frequency), with similar data rates [4]. Only 15% have S-band systems, with maximum rates of 256 kbps (although in our survey the **NTS** SmallSat has the maximum rate, 32 kbps). The power required for communications can reach up to 1 W, although it is usually smaller. These small rates have a great impact on the science that can be performed.

For micro satellites S-band communications are the most common, and there are also cases of C, X and Ku bands. Typical values for data rates are around 1 Mbps, for S-band, but can reach 2.5 Mbps with the X-band (**RISESat**), or even an impressive 30 Mbps on the **QSat-EOS** spacecraft (using the Ku-band). Nevertheless, most SmallSats keep to UHF, although as more power becomes available, higher data rates can also be achieved; for instance the **VesselSat** has a UHF data rate of 512 kbps.

#### 4.8. Regulating SmallSat communications

With the growing interest of an increasing number of nations in developing their indigenous space capacity, there is a growing concern in the space community about the lack of adherence of CubeSat missions to international laws, regulations and procedures, as stated in the Prague declaration on Small Satellite Regulation and Communication Systems [74].

Developers and members of the SmallSat community have been asked, by the United Nations agency (the International Telecommunication Union, ITU), to re-evaluate current frequency notification procedures for registering SmallSats. Most users however, consider this procedure complex and unduly laborious, and not suitable for such low-cost missions. Consequently, the ITU has been asked to examine the procedures for notifying space networks, and consider possible modifications to enable SmallSat deployment and operation. Ideally, this should be done taking into account the short development and mission time, and unique orbital characteristics of such platforms.

In March 2015, preliminary results of a study showed that there are no specific characteristics that are relevant from a frequency management perspective [75]. Nevertheless, in April 2015, the UN Office for Outer Space Affairs (OOSA) and the ITU has issued a best practice guide [76]. It summarizes the laws and regulations that are applicable for launching small satellites, and include the following:

- Notification and recording of the radio frequencies used by a satellite at the ITU by its national authority;
- Consideration of space debris citation measures in the design and operation of SmallSats (to guarantee their re-entry in less than 25 years after the completion of the mission);
- After launch, registration of the spacecraft with the Secretary-General of the United Nations by its national authority.

Furthermore, SmallSat missions are under the Liability Convention resolution 2777 (XXVI), which establishes potential liabilities if a collision happens [77]. Consequently, a variety of countries are approving national space laws, including an obligatorily insurance to cover liabilities derived by collisions during the platforms life.

Finally, in November 2015, the Provisional Final Acts of the World Radiocommunication Conference recommends that frequencies used for telemetry, tracking and command communications, by satellites with missions lasting less than three years, should be preferably within the following ranges: 150.05–174 MHz and 400.15–420 MHz [78].

## 5. Sensors for oceanography

The use of remote sensing data has been an integral part of oceanography [79]. Typically, sea surface temperature, ocean colour, winds, and sea-state have been the traditional foci of such data collection. More recently, SAR has become a significant asset to both scientific and security related purposes. In oceanography, often remote sensing data allows for feeding synthetic ocean models (e.g. ROMS [80]), which in turn allows for predications, and can be used for sampling via manned or robotic assets [81,82].

Large spacecraft typically from NASA and the National Oceanographic and Atmospheric Administration (NOAA) or ESA have been a continuous source of data over a substantial span of time [83,84]. More recent trends show that SmallSats are being preferred over large conventional satellite missions [5]. Although this has not yet evolved to the use of micro or nano spacecraft, we believe that SmallSats will end up achieving more cost-effective ways to observe the global ocean.

In this section we describe the primary oceanographic features and the detectors that have been used in remote sensing. The main source for this discussion are [4,17,79,85–88].

### 5.1. Ocean colour

The coastal upper water-column is often a region of high primary productivity especially due to the presence of phytoplankton with chlorophyll [88]. Through measurement of ocean colour, one can infer the concentrations of sediments, organic material and phytoplankton, whose quantities and type influence colour. For example, anthropomorphic input primarily from sewage, fertiliser run off or commercial dumping has an impact on the number of organisms in the coastal ocean. Therefore, this influences productivity and in turn phytoplankton concentration, as determined by chlorophyll density. Consequently, remote sensing provides a wide-scale view in a cogent manner.

Other ocean phenomena that can be observed using ocean colour as a proxy include mesoscale eddies (circular currents on the ocean spanning 10 km to 500 km in diameter and that persist from a few days to months), fronts (boundaries between distinct water masses), upwelling (when deep cold water rises to the surface) and internal waves.

Ocean colour observations using spacecraft began in 1978 with the Coastal Zone Color Scanner (**NIMBUS-7**) [88]. However, only in 1996 other missions were launched: the Japanese Ocean Color and Temperature Sensor (**ADEOS-1**); and the German Modular Optical Scanner (on the **IRS-P3**). In that same year, the International Ocean-Colour Coordinating Group was established to support ocean colour technology and studies, backed by the Committee on Earth Observation Satellites (CEOS) [89]. It has brought together data providers, space agencies, and users, namely scientists and managers. Moreover, it sets the standards for calibration and validation of measurements.

A typical ocean colour sensor samples with a high spectral resolution in several bands, including ultraviolet, visible and near infrared. Two types of sensors exist: a multispectral radiometer, which has a limited number of narrow wavelengths to capture the structure of the incoming light; and an imaging spectrometer, which samples across the spectrum with a defined spectral resolution, generating substantially more data. The combination of different spectrum bands helps to distinguish the colour origin, and overcome some atmospheric interference. Nevertheless, precise measurements are difficult to perform due to shortcomings of the instruments (e.g. it demands a cloud free observation, and there are calibration and signal-to noise ratio difficulties in the blue and green regions of the spectrum), and accuracies are of about 50%.

**Table 4**

Ocean colour instruments.

Sensor (Satellite)	Figures of merit <sup>a</sup> (Past/Future)	COCTS [91] (HY-1B)	OCM-2 [90] (OceanSat-2)	HawkEye [92] (SeaHawk)
Spatial Resolution [km]	1.5/0.7	1.1	0.36	0.15–0.075
Swath [km]	1328/1474	2800	1420	750
Wavelength [μm]	0.404–5.42	0.402–0.885	0.404–0.885	–
Mass [kg]	122/242	50	78	–
Power [W]	99/206	29.3	134	–

<sup>a</sup> Average figures of merit of decommissioned and future sensors [79,86,89].

Large spacecraft with mass well above the small satellite limit of 1000 kg have flown with ocean colour sensors (e.g. **EnviSat**, **Aqua**, and **COMS-1**). There are only two examples of mini satellites, both carrying radiometers, the **OceanSat-2** of the Indian Space Research Organization (ISRO), which has 970 kg [90], and the Chinese **Haiyang-1B**, with 443 kg [91]. Resolution, swath and other instrument data of some ocean colour sensors are shown in Table 4. Nevertheless, it is perfectly possible to include a ocean colour sensor in a CubeSat, and two examples are described below.

As noted earlier, **SeaHawk** (of the **SOCN** constellation) and the **ZACube-2**, which are scheduled to be launched in 2016, will measure ocean colour using nano satellites. In particular, the **SOCN** project (a 3U CubeSat) will fly the HawkEye Ocean Colour instrument. This is expected to have a ground resolution of 75 m per pixel (for a 540 km orbit), and a total of  $4096 \times 10000$  pixels (each image), for a ground swath of  $300 \times 750$  km [92]. Measuring eight bands (similar to VIS and NIR of the SeaWiFS instrument), with eight linear CCDs, will generate a total of 4.6 Gb, to be aggregated to 655 Mb that must be downlinked [92].

### 5.2. Ocean altimetry

Altimetry has been used to retrieve surface topography (including sea level and wave height), ocean currents, and bathymetry (submarine topography). Additionally, it is one of the most reliable ways to observe mesoscale eddies, detected by small displacements of the sea surface elevation, and scalar wind speed. Thus, data acquired from altimeters have applications not only to oceanography, but also to worldwide weather and climate patterns.

The most common instruments for altimetry are nadir pointing (looking vertically downward) radar altimeters, sampling along the ground track. The instrument works by emitting short regular pulses, and recording the travel time, magnitude and shape of the returned signal. From the travel time one can get the range from the satellite to the sea surface, to which corrections due to the atmosphere and ionospheric free electrons, sea state effects, and instrument calibrations need to be considered. Combining this with other measurements, including precise gravity fields (from the model created by GRACE [93]), and orbit position using other instruments, the range is converted into the height of the sea surface relative to the reference ellipsoid. Sea surface roughness, for length scales of the radar wavelength (that is from a few millimetres to centimetres), and sea surface height variability, on the instrument footprint, can also be retrieved. These yield estimates for wave height and wind speed.

Accuracies of 1 cm can be achieved, with measurement precisions of  $6 \times 10^{-11}$  s, but most often are in the 2 cm to 3 cm range. However, the obtained accuracies are only for open ocean, since coastal waters induce other effects [94]. Altimeter constellations are deemed important, since they bring an increase in temporal resolution, and some ocean phenomenon can only be perceived if subject to an almost continuous observation. At the same time, a



higher revisit time represents an increase in spatial coverage and a finer spatial sampling grid, for a single altimetry sensor. Equally, sun synchronous orbits should be avoided, because of the errors associated with solar tidal effects.

The most successful missions are compact satellites (with low drag resistance), which are equipped with supporting sensors, to measure the necessary corrections and determine orbital position. These supporting sensors consist of: a radiometer – for atmospheric corrections; the Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) – a precise orbit determination instrument using ground beacons spread over the world; and a Laser Retroreflector Array – which provides a reference target for satellite laser ranging measurements. Although DORIS has been widely used, many spacecraft are replacing it by a Global Navigation Satellite Systems (GNSS) instrument (or adding to DORIS a GNSS sensor). Another measure that may be important is the inertial position.

Past missions equipped with altimeters oscillated between large spacecraft with more than 2000 kg mass (**SeaSat**, **ERS-1**, and **ERS-2**), and mini satellites with mass around 500 kg (**GEOS-3** and **GEOSAT**) [86]. Examples of recent altimetry missions, and which use dual frequency (C and Ku-band) with increased accuracy, are: **TOPEX/Poseidon** – with 2388 kg and active between 1992 and 2005; **Jason-1** – active from 2001 to 2013, with a mass of 500 kg [95]; and finally **EnviSat** – one of the heaviest so far, with a mass of 8140 kg, that was operational between 2003 and 2012, and was equipped with several instruments [96]. Currently, three mini satellites are dedicated to altimetry, namely **SARAL** (with Ka-band for which ionospheric delay corrections are substantially reduced) [97], **Jason-2** (C and Ku-bands) [98], and **CryoSat-2** (Ku-band with two antennas) [99].

Typically, an altimetry mission requires a payload mass of about 100 kg, a power consumption of 150 W, and one antenna with 1.1 m in diameter (averaging the values of the three currently flying mini satellite missions). Features from past, current and future altimeter instruments are presented in Table 5.

From the figures presented above, it appears to be challenging for altimetry to be performed with a SmallSat platform (nano satellites are obviously out of the question), if the same accuracy is required. Nevertheless, there has been some effort to miniaturise Ka-band radar altimeters. A study of a constellation of twelve small satellites (with an expected mass of less than 150 kg), **GENDER**, was made in 1999, but the objective was only to obtain significant wave height and wind speed (and not the full sea surface topography) [100,101]. In 2008, two institutes linked to the previous altimetry missions made a proposal of a micro satellite, with 45 kg and a power budget of 70 W, with errors of around 5.6 cm [102]. Another proposal, disclosed in 2012, was based on a 6U CubeSat (12 kg) [103].

Nevertheless, even with higher errors, more spatial measurements have the potential to increase the return on investment

[104]. Consequently, there are studies for nano satellites with altimeters. Making a scaling exercise from the **Jason-2** altimeter (70 W) to a nano satellite instrument consuming 1 W, the error would increase from 2 cm to a worst case scenario of 16.7 cm [104]. However, this is just for the altimeter and does not account for errors induced by orbit position determination, due to the lack of supporting sensors. The atmospheric corrections can nevertheless be introduced via suitable modelling (which have accuracies of about 1–3 cm).

### 5.3. Ocean surface winds

Ocean surface wind measurements have been performed since 1978, and have implications for atmospheric, ocean surface waves and circulation models. These measurements have also enhanced marine weather forecasting and climate prediction which have a direct impact on offshore oil operations, ship movement and routing.

Surface winds can be derived from surface waves distribution, and the most effective bands for wind speed retrieval are the microwave C, X, and Ku bands. Nevertheless, measurement accuracies are always dependent on the wind speed. There are two main methods used in satellites to retrieve surface wind speed and direction: passive microwave radiometers; and active radar instruments (including scatterometers and SAR). In most instruments there is a trade-off between spatial resolution and swath.

An effective sensor is the scatterometer, which is also the simplest type of radar for remote sensing. They work by emitting microwaves at incidence angles between 20° and 70°, and measuring the average backscatter of the signals reflected by the same patch of sea within a wide field of view. Each area has to be viewed several times, either from different directions or at different polarisations. Therefore, there are two types of scatterometers: fixed vertical fan beams pointing in a single direction, thus requiring several antennae; and focussed beam, which perform circular scans. Typically, some corrections have to be implemented to obtain valid data, such as noise, atmospheric attenuation, and ambiguities. The measurement then goes through a selected model to retrieve wind speed and direction.

Conversely, SAR measurements can only be used if the wind direction is previously known (so scatterometer backscatter models can be applied), since SAR views the ocean from only one direction, unlike scatterometers. We provide a detailed view on SAR in Section 5.7.

An alternative to active instruments, is a radiometer, which measures the microwave radiation emitted by the sea, passively. This radiation has a dependence on sea surface shape and orientation, besides water temperature and dielectric properties, allowing for wind speed retrieval. However, to retrieve wind direction, the radiometer that uses only vertical and horizontal polarisation must look twice at the same area. Whereas, fully polarimetric radiometers i.e. those that measure all four Stokes parameters (vertical and horizontal polarisation components, and the corresponding real and imaginary parts of the correlation between both polarisation components of the electric field) can retrieve the wind vector with a single look under some conditions (as the four parameters describe the properties of an arbitrarily polarised electromagnetic wave). The basic components of a typical mechanically scanning radiometer are: a single parabolic reflector; a cluster of feed horns; and microwave detectors and the corresponding gimbal. An alternative to the gimbal is to use an array of small antennae, and combine the inputs electrically, an approach used in the **SMOS** mission [105].

There were, and still are, many missions using these sensors to retrieve ocean surface winds. Many missions equipped with altimeters had launch mass higher than 2000 kg (e.g. **HY-2A**, **RA-DARSAT-2**, and **TRMM**), but some are of the SmallSat class:

**Table 5**  
Decommissioned, current and future altimeter parameters and supporting sensors.

Sensor (Satellite)	Figures of merit <sup>a</sup> (Past/Future)	Poseidon-3 <sup>b</sup> [98] (Jason-2)	AltiKa <sup>b</sup> [97] (SARAL)	Optimised [102] MicroSatellite
Spatial resolution [km]	~8.5	–	–	–
Swath [km]	13/68	30	8	–
Bands	Ku/C or Ka	Ku/C	Ka	Ku
Accuracy [cm]	6.1/2.4	2	1.8	2.5
Mass [kg]	108/142	70	40	13
Power [W]	134/329	78	75	24
Antenna [m]	1.2/2.5	1.2	1	0.4
Supporting sensors	Radiometer, GPS, DORIS, LRA <sup>c</sup>			GPS

<sup>a</sup> Average figures of merit of decommissioned and future sensors [79,86,87].

<sup>b</sup> These are representative of current capacities of mini satellites.

<sup>c</sup> SARAL does not have GPS and AltiKa also works as a radiometer.

**Table 6**  
Decommissioned and active instruments to measure ocean surface winds.

Sensor (Satellite)	Figures of merit <sup>a</sup> (Past)	SeaWinds <sup>b</sup> [106] (QuikScat)	WindSat <sup>c</sup> [108] (Coriolis)
Spatial Resolution [km]	50	50	25
Swath [km]	1000	1800	1000
Wind accuracy (Wind speed) [m/s]	2 (4–20)	2 (3–20)	2 (3–25)
Wind Direction Accuracy [deg]	20	20	20
Bands	Ku/C	Ku	C/X/K/Ka
Frequency [GHz]	13.9/5.3	13.4	6.8/10.7/18.7/23.8/37
Mass [kg]	230	205	341
Power [W]	197	250	350
Antenna [m]	1.7	1	1.8

<sup>a</sup> Average figures of merit of decommissioned sensors [79,86,88].

<sup>b</sup> The only currently active scatterometer in a mini satellite.

<sup>c</sup> An example of a currently active fully polarimetric radiometer in a mini satellite.

**QuikSCAT** [106] and **OceanSat-2** [90], both using active rotating scatterometers; and **DMSP** [107], **Jason 1** and **2** [95,98], and **Coriolis** [108], all with passive rotating radiometers. Furthermore, the altimeter on **SARAL** also works as a radiometer [97]. Relevant characteristics of scatterometers and radiometers flown or currently active are presented in Table 6.

Based on previous missions, an average radiometer would have a mass of 118 kg, a power consumption of 122 W, and a reflector of 116 cm. Conversely, for the scatterometer, this is a 238 kg instrument, consuming 221 W, and using a 120 cm antenna.

Consequently, a scatterometer would be extremely difficult (if not impossible) to fit on a nano satellite platform, due to mass and power requirements as well as mechanical constraints. Miniature radiometers have been suggested as viable options to be used on CubeSats, although with significant doubt on the utility of the measurements. For micro spacecraft, the average radiometer with the values presented above, would be more feasible, even though the mechanical needs could be difficult to accomplish. Without some in depth research, in principle, a scatterometer would not fit a SmallSat, since it has double of the mass of the platform.

#### 5.4. Sea surface temperature

The Global Climate Observing System has described sea surface temperature (SST), as an essential climate variable (together with sea surface salinity and ocean colour). With SST, one can retrieve information on current systems, eddies, jets, and upwelling regions, since these are closely linked to ocean circulation. Furthermore, SST moderates the global climate system, and influences atmospheric water vapour and heat fluxes, making it a critical boundary condition for many atmospheric models. Therefore, it is an essential part for global climate studies, such as the El Niño Southern Oscillation cycle, and it supports local climatology, including ship routing, and hurricane forecast. The sensor's accuracy requirements for most of the studied phenomenon are of at least 0.5 K, with short revisit time.

Typical satellite sensors for SST are closely related to those used in ocean colour, such as infrared systems, and for surface wind retrieval, such as passive microwave systems. While infrared payloads need a cloud free for observation, microwave instruments using appropriate channels can perform measurements through no rain induced cloud cover, with necessary atmospheric corrections. However, the microwave data cannot be used within 75 km of land, due to a reduction of signal to noise ratio (the noise coming from ground communications systems). The infrared sensor usually requires a black body of known

**Table 7**  
Decommissioned and currently active instruments to measure ocean surface temperature.

Sensor (Satellite)	Figures of merit <sup>a</sup> (Past/Future)	MVIRI [109] (Meteosat 1st)	ALI [110] (EO-1)	Hyperion [110]
Spatial Resolution [km]	15/0.9	5	0.03	0.03
Swath [km]	1030/2200	–	37	7.5
Accuracy [K]	0.65/0.35	1	–	–
Wavelength [μm]	0.6–12	0.5–12.5	0.48–2.35	0.4–2.5
Mass [kg]	190/196	63	106	49
Power [W]	205/173	17	100	78

<sup>a</sup> Average figures of merit of decommissioned and future sensors [79,85,86].

temperature for on-board calibration. Although temperature difference requirements are possible with current instruments, to achieve the needed revisit time (i.e. to have more readings of the temperature of a specific place), satellite data and data collected *in situ* (e.g. with buoys, AUVs and ships) is usually combined.

Typically, many of the spacecraft performing these measurements have mass over the 1000 kg limit of SmallSats (e.g. **EnviSat** and **Terra**). Within this limit there are only two mini satellites: **Meteosat-7** (with 696 kg) [109] and **EO-1** (572 kg) [110]. The first, has a high resolution 3-band (thermal infrared, water vapour absorption and visible range bands) passive radiometer, spinning with the platform. The normal data transmission rate of the sensor is about 330 kbps, but can reach 2.7 Mbps in burst mode. **EO-1** has two instruments that can be used to retrieve SST: the panchromatic and multi spectral imager ALI, which has a data rate of 300 Mbps; and the hyper spectral imager Hyperion, which uses two spectrometers, and creates multiple images per acquisition, each with 75 MB. Some figures of decommissioned, future and the two current mini satellites is shown in Table 7.

The described instruments could be adapted to fit a micro satellite, although the amount of data that they generate would be challenging to downlink. For CubeSats it is believed that microbolometers (an infrared sensor) can be a viable option to measure sea surface temperature. However, there are no recorded SmallSat missions with such an instrument.

#### 5.5. Ocean salinity

Ocean surface state has numerous effects on the climate of the planet, affecting the global hydrological cycle, on which differences in ocean salinity concentrations can have large repercussions. Together with temperature, salinity concentration has an impact on the density and stability of surface water, influencing ocean mixing and the water-mass formation processes, such as on the meridional overturning circulation [85,111]. Salinity measurements, therefore, would improve ocean modelling and analysis.

Passive microwave radiometers are used to obtain readings for the surface salinity from satellites. The most suitable frequency for this is 1.41 GHz, in the L-band. To acquire valid and relevant information, salinity should be determined with at least 0.2 psu.<sup>5</sup> Phenomena that require corrections include: sea surface roughness; ionospheric effects (inducing Faraday rotation); and heavy rain. Salinity can also be determined using brightness temperature (or radiance of microwave radiation) measurements, if the sea surface temperature is known. To accomplish that, the brightness temperature measurements accuracy must be about 0.1 K [88]. Typically, moored buoys also perform

<sup>5</sup> Seawater of 35 psu (precision salinity units), has a conductivity ratio of unity at 15 degrees Centigrade at 1 atmosphere, for 32.4356 g of KCl (potassium chloride) per kilogram of solution.

salinity measurements, and can be used to ground-truth satellite data.

Currently, two missions perform these measurements, the **SMOS** (a 670 kg spacecraft) [105], and the **SAC-D/Aquarius** Mission. **SMOS** is a SmallSat with only one payload, the Microwave Imaging Radiometer using Aperture Synthesis, which weighs 369 kg and has a power consumption of 375 W. This is a synthetic aperture radiometer, with 69 antenna/receiver modules distributed in a deployable three arm (each with a length of 8 m) structure, creating a sparsely populated antenna. The signals of each receiver is electronically combined, forming a two dimensional interferometer microwave image.

Currently, there are no radiometers that would fit on a nano satellite platform, and studies conducted raise doubts on the validity of measurements performed by a small instrument. Further research might allow for fitting a radiometer in a micro satellite. Finally, as stated above, there is a correlation between brightness temperature measurements and salinity, which could lead to microbolometers (that fit on micro or nano satellites) for measuring salinity. However, due to the low spectral resolution, this has still to be demonstrated.

### 5.6. GNSS reflectometry

As shown in the previous sections, most instruments used for oceanography have characteristics that makes them difficult to implement on micro and nano satellites. Additionally, many instruments suffer from limitations due to the frequency band in which they operate, which is often blocked by clouds and heavy rainfall conditions. However, a promising method to perform some of these measurements has been proposed, namely the use of Global Navigation Satellite Systems Reflectometry (GNSS-R). Although limited for some measurements, some of its advantages are the capability for operating in all precipitating conditions, as well as the availability of GNSS signals [68]. GNSS-R would work as a complement to other instruments and not as a substitute, since the expected accuracy is lower.

A smooth surface causes a specular point reflection of a signal (i.e. a mirror like reflection where the incoming signal is reflected in a single outgoing direction), whereas a rough surface causes a signal scattering. Measurement of this scattering allows for obtaining information of the surface, which for the case of the ocean gives information on the sea and wave height, and indirectly, about the near surface meteorological conditions. While most radars use this principle, they have to actively produce a signal to be reflected. As with radiometers, which passively measure the natural radiation emitted by the surface, the idea behind GNSS-R is to use GPS signals (or other navigation satellite constellations such as Galileo), to create an image of the scattering cross section in time and frequency; this is called the Delay Doppler Map [68]. This is achieved by combining the GNSS signal coming directly from the GNSS constellation, providing a coherent reference, as well as signals reflected from the ocean. By analysing both, a number of ocean parameters can be inferred with a centimetre scale accuracy [112,113].

The idea for using GNSS signals to perform ocean scatterometry (measuring ocean near-surface wind speed and direction) was proposed in 1988 [113]. In 1993, GNSS-R was also suggested as another means for altimeter measurements [112]. Moreover, ocean roughness data acquired through GNSS-R contributes to other areas of research, such as for ocean salinity, ocean circulation and sea ice studies (as well as some land studies) [68,114].

A mission was proposed in 2002 to fit a GNSS-R in a 12 kg micro satellite (and a 4.8 W orbit average power) [112]. The payload in this proposal was a GPS receiver (with a nadir pointing and another zenith pointing antenna) and a solid-state data recorder. There were also studies of a GNSS-R instrument to assist

radiometry for sea surface salinity. Even though it does not fit a CubeSat, it could work on a micro satellite [4,115]. In 2003, the GNSS sensing technique was tested in the **UK-DMC** satellite, even though only 20 s of data could be acquired each time [113,116]. In 2012, a proposal was made to employ GNSS for altimetry using twelve nano satellites in a non-polar orbit with the GNSS Ocean Wind and Altimetry mission [113]. This constellation would provide data with an accuracy between 7 cm and 20 cm, for ocean topography, and more than 70 m/s, for wind speed measurements. A spatial resolution of about 30 km, and a revisit time of less than two days, is also expected. Another proposed mission was a single 5.4 kg nano satellite, with an average power consumption of 5.5 W, and an expected payload data volume of 13.8 Mb/day, the **Cat-2** [117]. In 2014, a more robust and extensive test of this technique was performed with the GNSS-R payload (with a mass of around 1.5 kg and approximately 10 W power consumption) of the **TechDemoSat-1** [114]. Finally, the **CYGNSS** constellation (described in Section 3.4) will also use GNSS-R to perform ocean surface readings, and is expected to be launched in 2016 [68].

### 5.7. The case of (and for) SAR

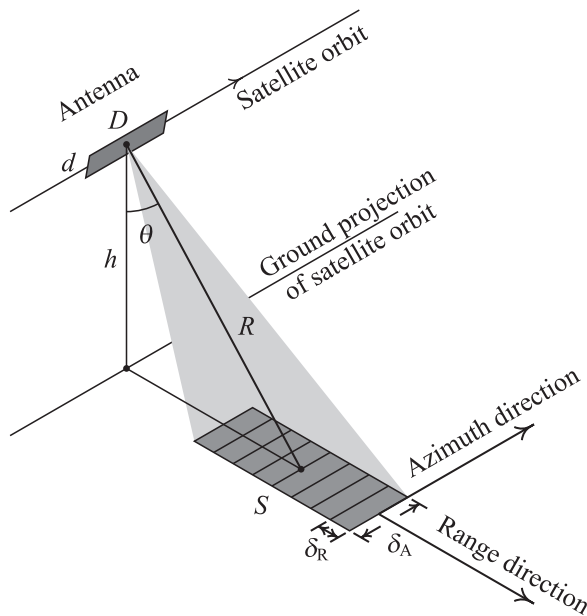
Synthetic Aperture Radar is a radar imaging system which has been increasingly used in a range of civil and security related applications. In particular, it has been critical for environmental monitoring and planning, especially in the context of maritime domain awareness (MDA) and marine spatial planning [118]. Furthermore, SAR can provide valuable information about the oceans, including surface and internal waves, shoals, sea ice, rainfall, and location of man-made platforms and large marine mammals [119,120]. One of the areas where SAR has been extremely successful is surface winds on coastal zones. Equally interesting is recent work in using SAR imagery to estimate local bathymetry, which has enormous implication for military applications worldwide [121]. Although, Doppler readings for currents has been used, it continues to be challenging from an algorithmic perspective [79].

Radar imaging systems (like SAR) use an antenna to send a sequence of short microwave pulses to the surface of the ocean. Their reflection is measured, usually using the same antenna, in the intervals when no pulses are being sent. The principle that distinguishes SAR from other radar systems, is that by combining several individual readings, while in view of a target, it synthesises a single image with high resolution. Since they are microwave based, the signal can penetrate clouds without major energy loss, allowing the system to work with cloud cover. Fig. 4 illustrates the working principle of SAR, which is discussed in more detail in the Appendix.

The first spacecraft carrying SAR, NASA's **SEASAT**, was launched in 1978. It was followed by other missions from several countries [122]. Table 8 shows the major spacecraft equipped with SAR, which are currently active. All are spacecraft with low, near polar, sun synchronous orbits with a period of about 100 minutes. The SAR instrument is usually turned on for approximately 10 minutes in each orbit due to its high energy demand.

Currently it is challenging to fulfil the user needs of SAR. That has led ESA to focus the use of their **Sentinel-1** spacecraft to view some regions of the globe they believe are of interest, since there is considerable lack of global coverage. Other SAR-based spacecraft still try to be open to scientist's requests for specific area observations. **TerraSAR-X**, for instance, makes some of the images available to the public. **RADARSAT 2** has better accuracy and resolution, but its images are less freely accessible.





**Fig. 4.** Illustration of a side looking imaging radar system on a space platform. All symbols are explained in the Appendix.

**Table 8**  
Earth observing spacecraft with SAR payloads.

Satellite	RADARSAT 2 [123]	TSX/ TDX [124]	COSMO- SkyMed [125]	KOMPSAT-5 [126]	Sentinel 1 [127]
Launch date	2007	2007	2007	2013	2014
Sat. Mass [kg] <sup>a</sup>	2200	1230/ 1340	1700	1400	2300
Sat. Altitude [km] <sup>a</sup>	798	514	620	550	693
SAR Mass [kg] <sup>a</sup>	750	394	–	520	945
Peak Power [W] <sup>a</sup>	1650	2260	–	1700	4075
Swath [km]	20–500	30–260	30–200	30–100	80–400
Resolution [m]	3–100	1.7–10	1–100	1–20	5–40
System Band	C	X	X	X	C

<sup>a</sup> Figures from [86].

### 5.8. The case for SmallSat SAR

The use of SAR in SmallSats poses some significant challenges. The spacecraft in Table 8 have masses ranging from about 1200 kg to 2300 kg. The SAR antennas used until recently have a length of 12 m, although more recent instruments use shorter antennas of around 5 meters. Israel's military satellite **TecSAR** uses a smaller deployable antenna, however, with an umbrella shape, with a mass of less than 0.5 kg [128]. Another challenge is how to generate the power needed to obtain a reasonable signal-to-noise ratio.

That said, we believe SAR is a potential SmallSat sensor, which can provide a significant boost for the use of SmallSats for oceanography and for studying the climate, while providing information to policy makers and for environmental monitoring. Coupled with *in situ* measurements that robotic platforms can make (Section 2), we believe that SAR can provide novel ways to observe the changing oceans systematically and persistently. In particular, for seaward facing nations such as Portugal, Spain and Norway, situational awareness in their territorial waters has been problematic, especially given significant increases in ship-borne traffic. With increasing access to the polar regions, for instance, where

search and rescue on-demand is challenging, MDA is critical to mitigate environmental pollution and loss of life. Portugal, for instance, should its ongoing application to the United Nations for the Extension of the Continental Shelf<sup>6</sup> prove to be successful, will need to cover a vast swath of the mid-Atlantic, over and beyond the Azorean archipelago, to monitor shipping. As a reflection of the complexity, should the extension be granted, it is estimated that upwards of 65% of all maritime traffic to the European Union will pass through waters under Portuguese jurisdiction. Ship or aircraft-based surveillance and monitoring is clearly not sustainable. Although they can be augmented with robotic vehicles, the sheer size of the area requires a space-borne all-weather radar asset that is affordable. In addition, the Azores and Madeira archipelagos provide a bellwether to understand our changing climate and, for instance, the impact it may have under extreme weather conditions. We believe that SAR on SmallSats is a technology that is viable for exploitation within the next 3 to 5 year time frame.<sup>7</sup>

## 6. Discussion and conclusions

The advantages of small satellites have been made clear throughout this paper: smaller costs and shorter development cycles allow for a greater flexibility. Indeed, there is a strong correlation between a satellite's size and its cost and time-to-launch. The shorter development cycle is enabled, in part, by the use of commercial-off-the-shelf components for some of the main subsystems. This allows not only for the exploitation of a greater number of mission opportunities, but also for the incorporation of newer technologies, either more advanced, cheaper, or both, in an agile development cycle.

There is another important benefit from the development of small satellites. The fact that they have been, and predictably will primarily be, built by small teams, makes university environments ideal for such projects. The cost structure allows for such a viable mode of operation. For example, at the University of Vigo we have recently launched our third SmallSat, opening a huge potential for future science oriented missions.

In addition to the lower costs and shorter design cycle, there is a critical pedagogical component. SmallSats can be designed, built, tested and potentially flown in space within the life-cycle of a graduate or undergraduate student's academic programme. And they have been operated predominantly by students when in flight. The life-cycle of the satellite provides a systematic view of how such complex systems can be built for young researchers, providing key life-long skills for a new generation of space engineers and scientists.

There are, however, still some important limitations for SmallSats and the range of their application, in the context of ocean observation. The examples listed in the survey on Section 3, fall into three main categories: Ocean Imaging, Data Relay and Tracking.

This last category is the most numerous, especially with the usage of space-borne ship-tracking systems like AIS, of great interest for many private and public institutions. The strategic and economical benefits are evident when considering the increase in ship traffic, due to the growth in global trade, the potential opening of new waterways, not to mention limitations and cost of land based solutions.

While not directly applicable to oceanography, some small satellites carrying communications and data relay payloads can be

<sup>6</sup> <http://www.emepc.pt/> in Portuguese.

<sup>7</sup> We note that the Norwegian Defense Establishment (FFI) is well advanced towards building a mini-SAR for use in UAVs (personal communication). We believe the transition to SmallSat operation could be a viable follow-up.



useful in the context of connecting sensors in the open ocean with land based facilities. Furthermore, as noted in Section 2, providing situational awareness and remote sensing data for oceanographic field experiments and persistent observations is a great asset.

It is also worth mentioning the significant potential of deploying small satellite constellations. These can be used to increase the capabilities, by combining different payloads that would otherwise be combined in a larger satellite, or the surface coverage. Some examples are already slated for launch as noted in Section 3.

The usage of imagers and other remote sensing payloads is still very limited in SmallSats. Some remote sensing satellites are among the heaviest and most complex ever launched. It is still unclear if and which remote sensing instruments can be adapted for use in small satellites, and when they will be available. Nevertheless, there is a substantial interest in the oceanographic community in increasing the availability and affordability of such instrumentation, with low(er) cost satellite operations.

For example, the measurement of ocean colour is quite relevant in coastal regions, where it can help to detect the presence and concentration of phytoplankton blooms or plumes, with scientific and economic ramifications. Section 5 discusses other examples of payloads that would be useful for oceanography.

The instrument that would, perhaps, have the greatest potential, would be radar-based and specifically SAR, as discussed in Section 5.7. This is primarily due to the wide range of applications that SAR has, from monitoring shipping, to ocean dynamics, to providing information on bathymetry for civil and military needs. Adding to the fact that SAR can work independent of cloud cover. Although there are significant technical challenges to overcome before a SAR can be installed in a SmallSat, the potential scientific, economic and security related benefits are substantial. This is especially true for countries with large territorial waters under their jurisdiction, that might necessitate the mobilisation of vast sea and airborne resources for effective monitoring and surveillance. We argue that using SmallSats instead could augment such needs with the use of radar based sensors and could potentially be achievable within the next 5–10 years.

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## Appendix

In this section, we briefly discuss the technicalities associated with SAR, which we believe will play a large and critical role in space-based oceanography, for civil and security applications, with SmallSats.

A typical side looking radar aboard a satellite is shown in Fig. 4, with the most relevant parameters. We represent the orbit of the spacecraft, its projection on the ground, and two extra directions, the range (perpendicular to the projection of the orbit on the ground) and the azimuth (parallel to the orbit projection), for convenience.

If the altitude of the satellite is  $h$ , its range,  $R$ , is the distance

from the spacecraft to the centre of the region on the ground illuminated by the antenna. As the figure represents a side looking radar, the imaging antenna points to the ground at an angle  $\theta$  with the vertical, the incident angle. As  $\theta > 0$ , the swath width,  $S$ , the width of the illuminated area in the range direction, is increased. Furthermore, the antenna's length in the direction of the spacecraft's motion,  $D$ , is usually bigger than the perpendicular length,  $d$ , as shown. Since the angle of the beam is inversely proportional to the length of the antenna, this also makes the illuminated region wider in the range, and narrower in the azimuth direction.

Consequently, different points along the range direction are characterised by different time delays between the emitted pulse and the return of the back-scattered signal to the antenna. A pulse reflected from a point with a distance  $R_r$  from the antenna, takes a time  $2 R_r/c$  to get back, where  $c$  is the speed of light. To distinguish two different points, the difference between their time delays must be larger than the time,  $\tau$ , that each pulse lasts. Therefore, the resolution distance,  $\delta_R$ , in the range direction is approximately

$$\delta_R \approx \frac{c\tau}{2}. \quad (1)$$

For the altitude of the spacecraft, typically a few hundreds of kilometres, very short pulses of a few nanoseconds are required to attain a resolution of the order of tens of meters. However, to give those short pulses the minimum energy to allow the reflected pulse to be distinguishable from the background noise, the peak intensity of the emitted pulse would need to be large. Thus, the required intensity would burn the antenna. The problem can be solved by sending a frequency-modulated (chirped) pulse, i.e. a pulse whose frequency decreases with time. The reflected pulse detected in the antenna is then filtered, delaying the higher frequencies. That shortens the time span,  $\tau$ , of the detected pulses, which turn them equal to  $1/B$ , where  $B$  is the bandwidth (that is, the difference between the higher and lower frequencies of the emitted pulse). The resolution in the range direction then becomes

$$\delta_R \approx \frac{c}{2B}. \quad (2)$$

The resolution in the azimuth direction,  $\delta_A$  in Fig. 4, depends only on the capability of the antenna to receive independent pulses from two points without interference, and it is approximately equal to

$$\delta_A \approx \frac{\lambda R}{D}, \quad (3)$$

where  $\lambda$  is the wavelength of the signal used.

An important parameter in radar systems is the signal-to-noise ratio (SNR). The expression for the SNR is usually called the radar equation. Various radar equations are found in the literature, specific to different types of images [129,130]. A general expression can be written as

$$SNR = \frac{P_t G_t G_r \lambda^2 A \sigma_0}{(4\pi)^3 R^4 k T B F_n L_s}, \quad (4)$$

where  $P_t$  is the average transmitted power,  $G_t$  and  $G_r$  are the gains of the transmitter and receiver antennas respectively (often equal since a single antenna is usually used),  $A$  is the area of the target and  $\sigma_0$  its normalised cross section (the fraction of the power of the radar radiation which is returned by the target in the direction of the receiver). In the denominator, we have Boltzmann's constant,  $k$ , the absolute temperature of the radar system,  $T$ , the receiver noise figure,  $F_n$ , and  $L_s$  that accounts for the system losses. As before,  $R$  is the range,  $\lambda$  the wavelength of the radar radiation, and  $B$  is the bandwidth of the emitted pulse.

For a typical radar, for instance, with a bandwidth of 15 MHz, a range resolution of 10 m can be attained, and the emitted pulse

can have a longer duration,  $\tau$ , of the order of tens of micro seconds. The bandwidth cannot be increased much further because it poses technical difficulties, and the possibility of getting off the range of frequencies allowed for microwave radars (without interfering with other telecommunication devices) [79].

Conversely, a wide antenna, with  $D = 10$  m, is not capable to achieve an azimuth resolution better than tens of meters. In fact, for microwaves, in order to get a reasonable image resolution, an antenna of several kilometres would be needed.

It is in this context, that SAR manages to outperform other radar systems. By taking advantage of the motion of the antenna relative to the target, a point in the ground reflects back the pulses to the antenna during the time that the satellite illuminates it. Meanwhile, the antenna moves a sizeable distance, receiving back-scattered pulses. Combining all signals, it is as if the antenna had the length of the distance that the satellite as moved while the target is still in view. In other words, the effective length of a SAR antenna,  $D_{\text{SAR}}$ , is of the order of the size of the illuminated region itself, yielding a much larger azimuth resolution. To distinguish pulses coming from different points along the azimuth direction, the Doppler shift of the received pulses is used [131].

To fully exploit SAR features we should then consider the minimum area of the antenna,  $A_{\text{min}} = \delta_R \delta_A / \sin \theta$ , and the “velocity”,  $v = D/\tau$ . Applying this to the radar equation, it follows the SAR equation

$$\text{SNR} = \frac{P_t G_r \lambda^3 \sigma_0 c}{128 \pi^3 R^3 k T B F_n L_s v \sin \theta}, \quad (5)$$

which exhibits the distinct  $1/R^3$  SAR factor.

From this equation it is clear that in order to improve SAR performance, one should either increase the signal or decrease the noise and losses (or both). The former asks for more power, more gain, and greater wavelengths. The latter can be achieved, in principle, by avoiding losses and increasing the velocity,  $v$ , which in turn requires shorter pulses and an upgraded discrimination of the incoming signal.

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