Ocean Observation: Monitoring, Control and Surveillance (MCS) Systems

Technological Challenges for the *Blue Economy*

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Aerospace Engineering

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The sea with an end can be Greek or Roman:
The endless sea is Portuguese

Mensagem, Fernando Pessoa

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Abstract

The ocean, both as a setting for global trade and commerce, and as a significant source of food, minerals and energy, has been taking on a more important role in our society each day. The European Union (EU) estimates that, by 2020, jobs under the "blue" economy could increase by 1.6 million and will have an added value of around €600 bn. Within this scenario it becomes critical to properly monitor and control ongoing projects, while providing the best conditions for a correct risk governance. On the other hand, Space assets and technologies are becoming ubiquitous and preferred sources of data and information for ocean Monitoring, Control and Surveillance (MCS).

This work, done in collaboration with DEIMOS Engenharia, intends to assess these MCS systems with particular focus on the Space component, and is organized in two parts.

The first part covers an extensive mapping of current and future MCS demands at Atlantic, European and national levels, the latter targeting Portugal's recent Exclusive Economic Zone (EEZ) expansion. Space technologies that address these oceanic MCS demands are then explored and evaluated through several filters, with the purpose of finding the most promising ones. Such analysis is made by giving special attention to solutions that capitalize on endogenous assets, but also take the most of EU's Copernicus and other initiatives under Horizon 2020.

The second part focuses on proposing a mission, capable of integrating these technologies (Sat-AIS and GNSS-R), and testing it with DEIMOS' GAT software tool.

The work is concluded with a discussion on how the covered topics can fit under Portugal's 2030 space strategy, and what is the current capacity of implementing them, having in mind the relation with initiatives from European Space Agency (ESA) and other international partners. Furthermore, this work displays the economical and technological opportunities in the value chain under the scope of this mission. It then provides recommendations to efficiently embrace those opportunities, building on the consolidation of Portugal as a key Atlantic player and innovative scientific nation.

Keywords

Aerospace; Atlantic Observation; Cubesats; GNSS-R; Sat-AIS, Space Strategy

Resumo

O papel dos oceanos na nossa sociedade tem ganho uma cada vez maior importância como cenário de comércio global e como fonte significativa de alimentos, minerais e energias. A UE estima que, em 2020, o emprego proveniente da "Economia Azul" possa gerar 1.6 M de novos postos de trabalho, e representar um valor agregado de €600 mM de euros para a economia europeia. É por isso fundamental garantir uma adequada monitorização e controlo dos oceanos. Por outro lado, as tecnologias espaciais têm alcançado uma importância e utilização cada vez maiores, como fontes de dados e informação, na monitorização de áreas vastas, como é o caso das zonas oceânicas.

Este trabalho, desenvolvido em colaboração com a DEIMOS Engenharia, foca-se na componente espacial destes sistemas de Monitorização, Controlo e Vigilância (MCS) e divide-se em duas partes.

A primeira parte cobre um mapeamento extensivo das necessidades de sistemas de MCS a nível Atlântico, Europeu e nacional, tendo o último foco na recente extensão da ZEE portuguesa. As tecnologias espaciais enquadradas nas necessidades de MCS são exploradas e avaliadas com recurso a diversos filtros e com o objectivo de identificar as que terão um maior potencial. Esta análise é feita dando ênfase às soluções que beneficiem de activos endógenos e que simultaneamente tirem partido dos programas europeus *Copernicus* e *Horizonte 2020*.

A segunda parte do trabalho propõe uma missão, capaz de integrar estas tecnologias (Sat-AIS e GNSS-R), testando-a com recurso ao *software* GAT da DEIMOS.

Concluí-se com uma análise à integração dos temas abordados no âmbito da Estratégia para o Espaço 2030, e à capacidade de implementação dos mesmos, tendo em conta a presente relação com iniciativas da ESA e parceiros internacionais. São ainda identificadas as oportunidades económicas e tecnológicas na cadeia valor, com potencial de serem exploradas no âmbito desta missão. Por fim apresenta recomendações quanto a modos de abordar estas oportunidades, apoiando a consolidação de Portugal como um interveniente-chave do espaço atlântico e nação científica inovadora.

Palavras Chave

Aeroespacial; Observação Atlântica; Cubesats; GNSS-R; Sat-AIS, Estratégia Espacial

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Abbreviations

ADS-B Automatic Dependent Surveillance-Broadcast

AIS Automatic Identification System

ALB Airborne Laser Bathymetric

ANPC Portuguese National Authority for Civil Protection

APA Portuguese Environment Agency

ATI Along-Track Interferometric

AUV Autonomous Underwater Vehicles

AVHRR Advanced Very High Resolution Radiometer

COTS Commercial Off-The-Shelf

DDM Delay Doppler Map

DGAM Portuguese Directorate General of Maritime Authority

DGRM Portuguese Directorate General for Maritime Natural Resources, Security and Services

EC European Commission

EEZ Exclusive Economic Zone

EMSA European Maritime Safety Agency

ESA European Space Agency

EU European Union

FCT Portuguese Foundation for Science and Technology

FIR Flight Information Region

FLIR Forward Looking Infra-red

GAT Geometry Analysis Tool

GEO Geostationary Earth Orbit

GNR Portuguese National Republican Guard

GNSS-R Global Navigation Satellite System-Reflectometry

GPS Global Positioning System

GSA European GNSS Agency

HALE High Altitude Long Endurance

IAA International Academy of Astronautics

IERS International Earth Rotation Service

IGSO Inclined Geosynchronous Orbit

IH Portuguese Hydrographic Institute

IPMA Portuguese Sea and Atmosphere Institute

IUU Illegal, Undeclared and Unreported

LEO Low Earth Orbit

LiDAR Light Detection And Ranging

LRIT Long Range Information and Tracking

MBES Multi Beam EchoSounder

MCS Monitoring, Control and Surveillance

MEO Medium Earth Orbit

MERIS MEdium Resolution Imaging Spectrometer

MIRAS Microwave Imaging Radiometer with Aperture Synthesis

MODIS Moderate Resolution Imaging Spectroradiometer

MONICAP Continuous Monitoring System for the Fishing Activity Inspection

MRCC Maritime Rescue Coordination Center

NASA National Aeronautics and Space Administration

NATO North Atlantic Treaty Organization

OLCI Ocean and Land Colour Instrument

P-POD Poly-PicoSatellite Orbital Deployer

PPS Purchasing Power Standard

RAAN Right Ascension of Ascending Node

ROV Remotely Operated Underwater Vehicles

SAR Synthetic Aperture Radar

SBES Single Beam EchoSounder

SCBA Social Cost-Benefit Analysis

SDB Satellite Derived Bathymetry

SeaWiFS Sea Viewing Wide Field-of-View Sensor

SIFICAP Portuguese Integrated System for the Surveillance, Taxation and Inspection of Fishing Activities

SIVICC Surveillance, Command and Control Integrated System

SLSTR Sea and Land Surface Temperature Radiometer

SME Small and Medium Enterprises

SMOS Soil Moisture and Ocean Salinity

SRAL SAR Radar Altimeter

SRR Search Rescue Region

SSMI Special Sensor Microwave Imager

SSS Sea Surface Salinity

SST Sea Surface Temperature

TEME True Equator Mean Equinox

TLE Two-Line Element

UAV Unmanned Aerial Vehicles

UCC Coastal Control Unit

UN United Nations

UTC Coordinated Universal Time

VHF Very High Frequency

VIIRS Visible Infra-red Imaging Radiometer Suite

VMS Vessel Monitoring System

VTS Vessel Tracking Service

1

Introduction

Contents

1.1 The Context

If one assesses all the economic activities depending on the sea, then the European Union (EU)'s blue economy represents 5.4 million jobs and a gross added value close to the €500 billions per year. These numbers are expected to increase to 7 million jobs and €600 bn respectively by 2020. [19]

A total of 75% of Europe's external trade and 37% of trade within the EU is seaborne, giving the sea a critical impact on EU's commercial relations [20]. Such an impact and growth require a proper monitoring of the current activities, as well as a competent assessment of the risks new enterprises may expect for the years to come.

This request for Monitoring, Control and Surveillance (MCS) systems is only matched by the constant and increasing development and innovation observed in both the monitoring industry and the solutions it offers. Examples of these fast-paced improvements on *in-situ* components are the recent advances in Autonomous Underwater Vehicles (AUV) [21, 22], gliders and buoys[23].

The other important branch of these systems, remote sensing, also experiences an innovative dynamic, not only on the upgrade of known instruments, with lighter and more accurate versions, but also with new paradigms. Concepts like the Nanosat, which enables space access to an all new different type of players and technologies, benefiting from a much higher launching frequency for a fraction of the cost [24] are thriving and gaining ground. This combined with the adaptation of proven technologies, such as Automatic Identification System (AIS), to the space-based environment, as seen in the case of Sat-AIS [25], supports the claim for limitless solutions. Moreover the assignment of some activities, previously attributed to satellites or local inspection, to Unmanned Aerial Vehicles (UAV), and consequent integration of the various systems, further contributes to a new reality and a source of technological development [26, 27].

Portugal with its wide maritime sovereignty, being its Exclusive Economic Zone (EEZ) the largest within Europe, the 3rd largest of the EU, and the 10th largest EEZ in the world, is a determinant player in this equation. The employment of these technologies is a requirement and a necessity not only resulting from a question of national sovereignty, but also from the country's North Atlantic Treaty Organization (NATO) and EU membership. This necessity opens an opportunity to the Portuguese industry, particularly the space-based one. The expertise and know-how arising from the increasing number of European Space Agency (ESA)-working Portuguese Small and Medium Enterprises (SME) [28], combined with the country's natural 3,877,408 km^2 maritime test bed and its decisive continental and insular position in the Atlantic, turns this matter into a critical strategic area for the country for the years to come.

1.2 Motivation

Portugal and the Sea are two inseparable realities. The famous Portuguese poet Fernando Pessoa, wrote *"Oh salty sea, so much of your salt is tears of Portugal."*, and in fact this relation between the two has marked the country throughout its history.

In the decades to come, the ocean and its resources are increasingly seen as indispensable in addressing the multiple challenges the planet will face. By 2050 enough food, jobs, energy, raw materials and economic growth will be required to sustain a population of 9.7 billion people, as expected by the United Nations (UN) [29]. Container traffic is expecting a very fast growth, with volumes tripling by 2030 and in capture fisheries, wild fish stocks are under great pressure, since that around a third of global fish stocks are over-exploited, depleted or recovering from depletion [30].

Bearing all these potentialities in mind, and knowing that the sea makes up to 97%! of the Portuguese territory [31], from a strategic point of view this "return to the sea" becomes critical for the Portuguese industry and innovation sectors.

The motivation for this work is, benefiting from Deimos Engenharia's expertise and through contacts with the industry, experts and stakeholders, to fully understand the Atlantic MCS reality, its struggles, shortages and trends in which the aerospace sector plays a decisive part. This is achieved with a thorough identification of every maritime activity and its monitoring requirements. This step is followed by a technological assessment, and a rational filtering in search of the most promising technologies, and the devices that allow their implementation , making sure that it takes the most of endogenous assets. From this combination of technologies and equipments to use, along with the monitoring requirements, a mission proposal is then made, appointing and defining a strategy for the years to come.

1.3 Blue Economy

More than 70 percent of Earth's surface is covered by water truly making our planet the "Blue Planet". Not only is water essential to life but it also provides resources that directly contribute to our society, ranging from sea transport to the production of raw materials, fisheries, leisure activities and others. The sea is an integral part of the European identity and of the continent's economy, being Portugal one of its more famous examples. Among the 28 Member States of the European Union, 23 have a coast and two thirds of the European frontiers are set by the sea.

These conditions, combined with current world trends, pose long term challenges to European countries. In 2025 it is expected that 2/3 of the world's population will live in Asia, which is likely to become the first producer and exporter of the world, as well as to surpass the EU and the US in the areas of research and industrial production. This Asian rise will change present commercial dynamics, originating tensions on food, energy, raw materials and water supplies. The EU, through its Europe 2020 strategy, opted as a response, for a smart, sustainable and inclusive economic and employment growth from the oceans, seas and coasts. [2]

The individual sectors of the blue economy are interdependent. They rely on common skills and shared infrastructure such as ports and electricity distribution networks. The actual state of the so-called "Blue Activities", can be seen in figures:1.2,1.3 and 1.4 [20].

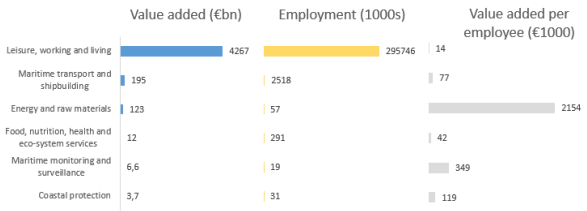

Figure 1.1: Current size of maritime economic activities in the EU

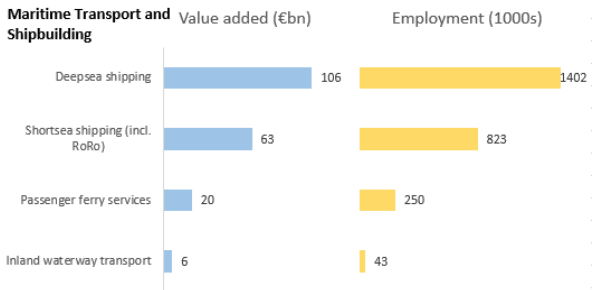

Figure 1.2: Characterization of the Maritime Transport and Shipbuilding sectors

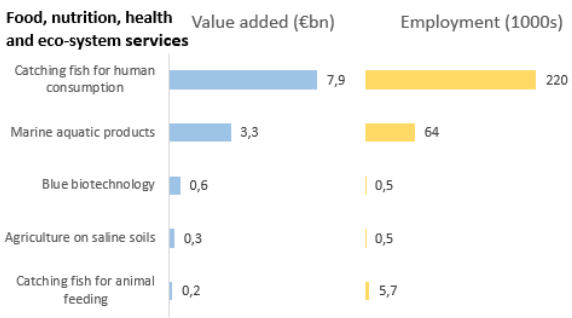

Figure 1.3: Characterization of food, nutrition, health and ecosystem-related services sectors

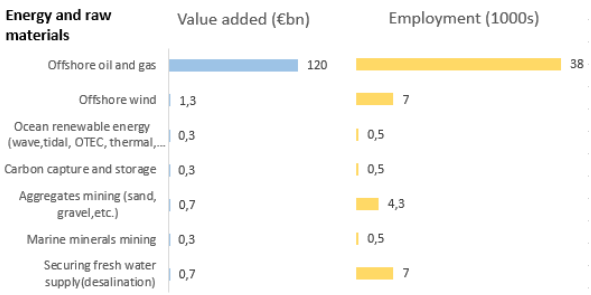

Figure 1.4: Characterization of the energy and raw materials sectors

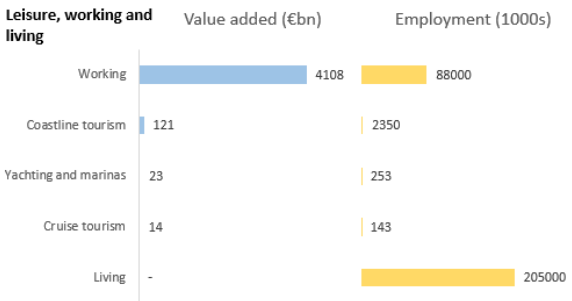

Figure 1.5: Characterization of the leisure, working and living sectors

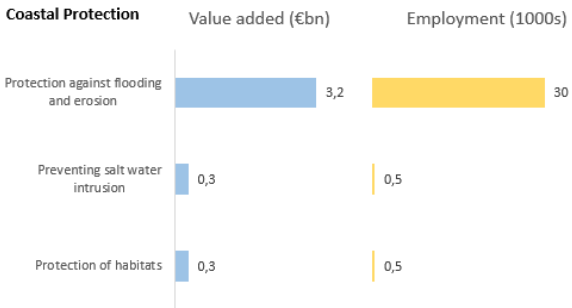

Figure 1.6: Characterization of the coastal protection sector

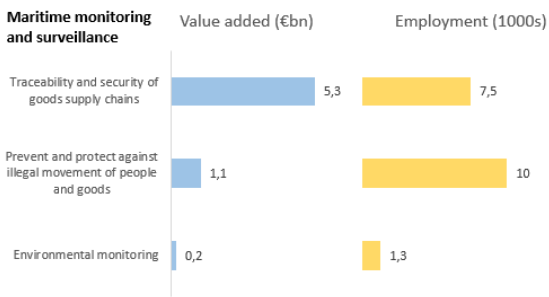

Figure 1.7: Characterization of the monitoring and surveillance sector

1.3.1 Technology and innovation

This economical snapshot, along with the mentioned tensions and demands that will define the years to come, enables the advent of a very wide range of technologies, being the following the most prominent:[32]

Advanced Materials Metallic, ceramic, polymeric and composite materials are increasing their usage and number of maritime applications due to their capacity to make stronger, tougher and more durable structures. As energy demands increase, offshore wind, as well as oil and gas, operations move increasingly into deeper water subjecting anchor, umbilical and power cables to tougher mechanical conditions. The use of composite materials, such as aramid polyester and kevlar in cables, or of high-density polyethylene for aquaculture cages are examples of these trends.

Nanotechnology Sometimes referred as a branch of materials science, Nanotechnology is starting to deserve undivided attention. Applications as self-diagnostic, self-healing or self-cleaning products in coatings, energy storage and nano-electronics are becoming determinant. These include the development of new biomolecules to obtain enhanced oil recovery, nano-scale surface corrosion protection materials and biocatalysts for bioremediation of oil. This preponderance is ultimately reflected in the number of filled patents, it grew from an average annual number of 300 during the 1990s, to a surprising 1800 during the last decade.

Biotechnology This technology, which includes genetics, experienced major improvements during the last decades and it will continue to have a decisive impact on most domains of the ocean economy. The development of new marine biochemical substances for pharmaceutical and cosmetic use, along with the progresses in breeding, vaccine and feeding that enable commercial scale aquaculture, support Biotechnology's increasing importance in fulfilling human needs.

Subsea Engineering The development of maritime industries as the already mentioned oil and gas, ocean renewable energy, offshore wind, aquaculture, seabed mining, carbon capture and storage, and their transition into deeper areas poses new technological challenges. These include underwater grid technology, power transmission to/from onshore, improving pipelines and develop new mooring and anchoring systems for stationary and floating devices. Being able to capture and

process all these raw materials and substances directly on the seabed and remotely controlled from the shore is the ultimate goal.

Sensors and imaging The recent search for low-power, low-cost devices for the measurement and display of the most different environments led to significant improvements in this area. During the last decade sensors able to monitor key micro-nutrients were developed, and the current trend is to reduce their power requirements and size in order to achieve micro-sensors capable of being carried by gliders, buoys and animals. New geophysical tools, as well as undersea remote sensing techniques that permit the visualization of the spatial extent and depth of important resources deposits, are some of these trends.

Satellites In recent years satellites have been essential to ocean-based activities and industries as means of communication, navigation, tracking and remote sensing. This tendency will continue during the next decades, as improvements are expected in optics, imagery, resolution of sensors and also in satellite coverage as more and more satellite systems are put into orbit. This rise on the number of deployed units is justified mostly by the advent of small, micro and nano-satellites, which allow for an increasingly tailored observation and tracking.

Computerisation and big data analytics Improvements in the number and quality of sensors and monitoring systems lead to increasingly larger amounts of data. This data in order to become meaningful and improve decision making in the different domains of the maritime economy needs proper treatment and analysis. As an example, a huge amount of data is collected during every step of an oil field exploration a: production, transport, refining and distribution. The capacity to interconnect and analyse these data is essential for business decisions and optimization of processes, and the same reasoning can be applied to every maritime activity. The multivariable optimization of wind-farm array layouts and the improvements in data processing and virtual imaging that make possible major progresses in reservoir monitoring and management can also be listed as examples.

Autonomous Systems As demands on safety, security and productivity increase, along with the progresses in miniaturisation, motion control and cognition systems, autonomous units are acquiring a fundamental role in this new paradigm. AUV, Remotely Operated Underwater Vehicles (ROV), drones, stationary data-collection and multi-purpose docking stations. Improvements in automation, intelligent algorithms to convert 2D images to 3D maps, and the new design possibilities brought by additive manufacturing (3D printing), which permits to dramatically reduce manufacturing costs, enabling otherwise prohibited geometries are among the tendencies. This choice for automation systems is also reflected on land-based operations since modern ports are already experiencing partial to full automation of cargo handling. As an example Rotterdam's Maasvlakte II terminal has no personnel inside its cargo-handling section.

These listed elements summarize some of the most important areas in terms of innovation and in response to some of the economical tensions, and opportunities, previously identified. Innovation is

moving fast in all these domains, travelling across and interconnecting them, which triggers yet further innovation. With these aspects in mind, one can say that monitoring systems present a dual condition, on the one hand they are one of these rising domains, on the other hand they are necessary to control and assure the correct functioning of each of the other systems. This emphasizes their fundamental role in both this economical area and the challenges it will face in a near future.

1.4 The Portuguese Context

The sea has been of determinant and strategic importance for Portugal and its people since the nation's foundation. In recent years this calling was rediscovered, bringing the ocean and its sustainable exploitation to the front row of scientific and political action, being a top priority in the goals outlined by the Portuguese President [33], his predecessor and the executive, with the creation of a Ministry fully devoted to this mission.

1.4.1 Territory

This national strategy does not come only from historical motives, in fact it is mostly a product of the country's assets and geographical situation.

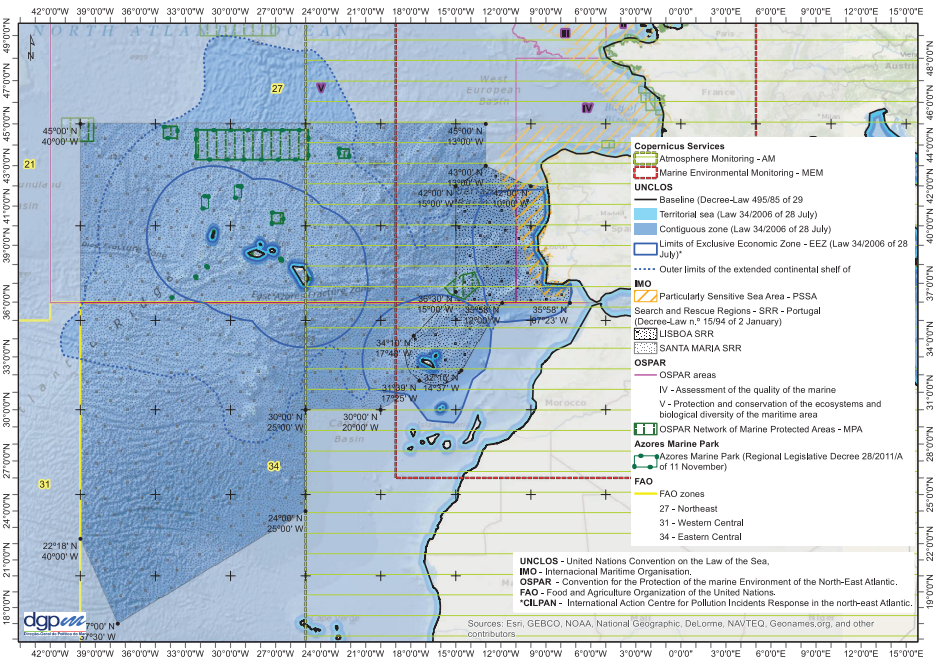

Figure 1.8: Portuguese territory and special zones resulting from national and international legislation, from DGPM

The EEZ is a sea zone prescribed by the United Nations Convention on the Law of the Sea over which a state has special rights regarding the exploration and use of marine resources, including energy production from water and wind [34].

The Portuguese EEZ consisted in a total area of 1,727,408 km^2, combining the areas of Continental Portugal, Azores and Madeira Islands. However in 2009 Portugal submitted a claim to extend its

jurisdiction over additional 2,150,000 km^2 of the neighboring continental shelf, resulting in an increase of almost 125% and a total area of 3,877,408 km^2, as visible in figure 1.8.

This expansion is leading the Portuguese EEZ to be the largest within Europe, 3rd largest of the EU and the 10th largest in the world.[35]

The Portuguese Search Rescue Region (SRR) is the largest in Europe, coinciding with Lisbon's and Santa Maria's Flight Information Region (FIR), with a total of more than five million square kilometres.

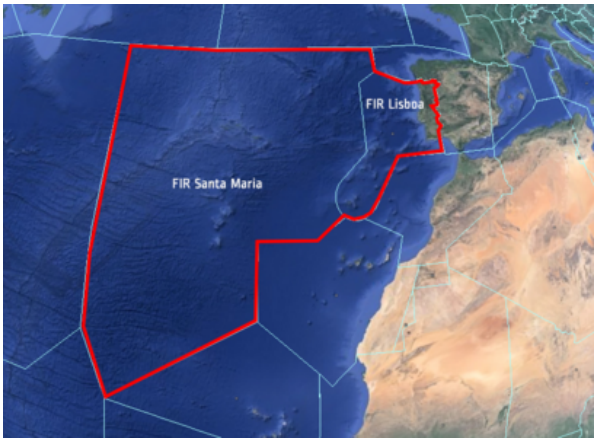

Figure 1.9: Portuguese SRR and FIR detail from Portuguese Air Force

Both Portuguese FIR are under NAV Portugal's responsibility and consist, for Lisbon's FIR, in a control centre as well as a control tower in the capital, accompanied by towers in Porto, Faro, Funchal and Porto Santo, being the latter two in the Madeira archipelago. The total area comprised, visible in figure 1.9, reaches almost 700.000 km^2.

Santa Maria's FIR, with a total area of more than 5 million km^2, has a control center and tower in the homonym island completed with the distribution of control towers in Flores, Horta and Ponta Delgada.

1.4.2 Bases and Monitoring Stations

Within the national territory there are numerous stations that are essential to the Portuguese monitoring and control system. Among these stations, two of them deserve particular attention as a result of their strategic importance. This relevance is not only a consequence of their strategic geographic position, but also a result of the international and institutional relations and cooperation already put into practice in these two places.

1.4.2.A Santa Maria Station

The Santa Maria S-band (defined by an IEEE standard for radio waves with frequencies that range from 2 to 4 GHz) station, also known as Monte das Flores (Hill of Flowers), is located 5 kms from the town of Vila do Porto on the Portuguese island of Santa Maria, in the Azores some 1500 km from Lisbon. Santa Maria is one of the first Estrack (European Space Tracking network) stations with launcher tracking capability and it is used to receive real-time telemetry from launches originating

from ESA's spaceport in Kourou, French Guiana. It is capable of tracking Ariane 5, and was first used to track the launch of ESA's Automated Transfer Vehicle Jules Verne in early 2008.

Location The coordinates of its 5.5-metre antenna are +36° 59' 50.10", -25° 08' 08.60". The antenna is sited at 276 metres above sea level with respect to the WGS-84 reference ellipsoid, a mathematically-defined reference surface that approximates the Earth's geoid surface.

Facilities and technology The station consists of a 5.5 meter antenna hard-wired on a stable concrete platform. It includes telecommunications equipment, a no-break power system, lightning protection and support infrastructure.

The station's tracking services also support Project CleanSeaNet, managed by European Maritime Safety Agency (EMSA) and providing satellite detection of oil slicks, as well as other programs endorsed by ESA.[36]

1.4.2.B Lajes Field

Lajes Field or Lajes air base is a multi-use airfield, home to the Portuguese Air Force air base number 4 and azores air zone command, it is also the headquarters of the United States Air Force's 65th Air Base Group, and a regional air passenger terminal.

Location The field is positioned near Lajes town, 15 km north-east of Angra do Heroismo on Terceira island in the Azores which is about 3,680 km east of New York City and about 1,600 km west of Lisbon, sitting in a strategic location midway between North America and Europe in the north Atlantic Ocean.

Facilities and users A joint facility for both Portuguese and American Air Forces, Lajes field houses the following units:

- Squadron 751 "Pumas" - search and rescue squadron flying AgustaWestland EH101 helicopters

The 65th Air Base Group is a group of the United States Air Force which provides base and en route support to the American Department of Defence [37], allied nations and other authorized aircraft in transit, its components are:

- 65th Civil Engineer Squadron
- 65th Communications Squadron
- 65th Logistics Readiness Squadron
- 65th Operations Support Squadron
- 65th Security Forces Squadron
- 65th Comptroller Flight
- 65th Force Support Flight

Over the last years USA's Department of Defence announced reductions in funding and personnel allocated to the base.[38] These reductions had a great economical impact on the island's population

and prompted the need for compensations, as well as new approaches and solutions for the base's facilities.

One of the outlined solutions intends to utilize these facilities for scientific investigations, mostly through protocols with American Universities.[39]

This search for new applications for the Lajes field gains special relevance in the context of this work since, as it was demonstrated in the previous sections, prospects concerning ocean-related activities for the years to come are very optimistic. The capability of benefiting from a highly strategical asset such as this air base, considering its determinant position on the Atlantic panorama and the close relationship with the USA it embodies, is simultaneously a major opportunity and challenge.

1.4.3 Portuguese Space Sector

This subsection intends to cast a glance over the Portuguese Space sector and the companies that are part of it. A brief contextualization of the area is given, followed by a mapping of both the players involved and their fields of expertise.

In the beginning of this century , Portugal became a member state of the European Space Agency, which enabled the full participation in ESA's technology and applications programmes. This successful presence in the European Union programmes, namely in FP7, Copernicus and Galileo has proven Portuguese companies and academia as both competitive and reliable partners in the European and international context.

Portugal contributes to several Space programmes, covering key domains of space applications, that range from satellite telecommunications, global navigation systems, Earth observation, space technology, space sciences and robotic exploration. The Portuguese Space Community is an active member of international networks, developing complex space technologies and participating in space science and exploration missions. It is also appointed that one of the success factors of the Portuguese Space Community is precisely the close links that exist between companies and academia.[28]

Recently the Portuguese Foundation for Science and Technology (FCT) along with the Trade and Investment Agency AICEP divided these players, according to their dimension and mission, as can be seen below in figure 1.10.

Figure 1.10: Main players in the Portuguese space community from FCT space catalogue

In addition to this, these companies can also be segmented in two different groups, for a more objective perception of their reality, based on the category of the products they provide:

- Hardware
- Software

Within the previous classification, a more detailed characterization is then applied regarding the destination segment of each application. In accordance with the Portuguese Space Catalogue [28] the chosen segments are:

- Space Segment
- Ground Segment
- Space-based Services

A company can provide both hardware and software products for all the three different segments, or just one type of service for a particular segment. The results of this survey are presented in figures 1.11 and 1.12.

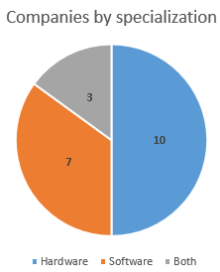

Figure 1.11: Distribution of companies according to the category of their products

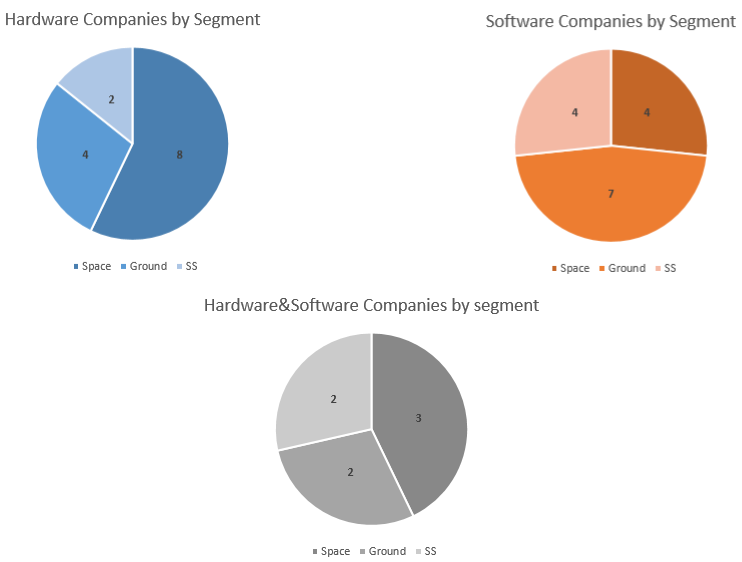

Figure 1.12: Product segmentation according to the area of expertise of each company

As one can see these players cover a wide range of solutions, acting in almost every segment of the space industry, being Portugal a global leader in some of these niches.[40] These expertises along with capabilities in the various segments and stages of space-based activities contributes to reaffirm the innovative and promising position of the Portuguese Space sector for the years to come, as well as the relevance and opportunities for the products it generates.

The importance of this industry is also sustained by the impact it creates in the national economy and in knowledge generation, as these facts demonstrate[40]:

- Every Euro invested in ESA has a return of 2 onto the national economy
- The value added per employee amounts to 4 times the national average
- The sector is a 100% exporter, without any imported intermediate inputs
- On account of the exclusiveness of its technology and the projects in which that technology constitutes the core element, it is the only sector where Portuguese companies - generally small ones - subcontract giants like Thales Alenia Space, Airbus Defence & Space among others

The Portuguese space sector also benefits from the traineeships in ESA, CERN and the European Southern Observatory, attended by young graduates. These trainees spend 1 or 2 years on-site training and return to Portugal to integrate the national industry, create SME or evolve in their academic and professional path. 284 trainees have been part of this program during the last twenty years with extremely positive results.[40]

EU's research and innovation programme, Horizon 2020, with nearly €80 billion of funding available between 2014 and 2020, is the biggest of its kind so far. It prioritises activities related to the existing two EU flagships: The earth observation programme Copernicus and global navigation system Galileo.

During the last European programme, the Seventh Framework Programme for Research and Technological Development (FP7 2007-2013), the Portuguese participants got €14 millions in contracts[1] being their distribution the one represented in figure 1.13.

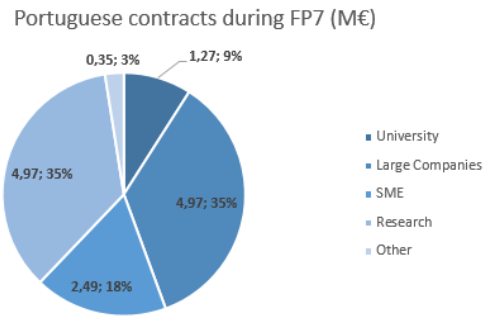

Figure 1.13: Portuguese contracts during FP7 by organisation type

Space sciences also have an important role in the development of the country, being an area of excellence within the international scientific panorama, as figure 1.14 attests:

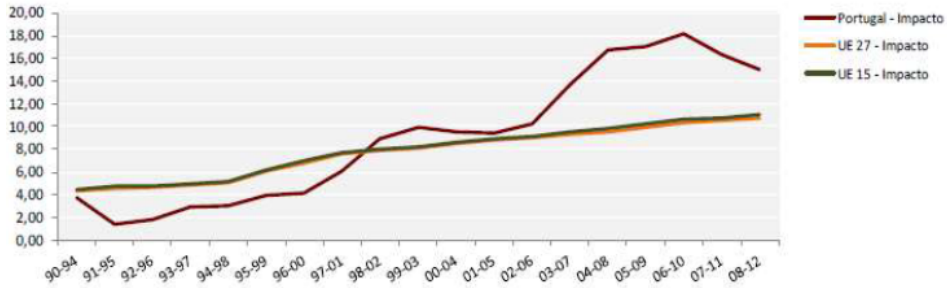

Figure 1.14: Impact per publication in space science (1990-2012)[1]

Another important indicator, regarding competitiveness, is the comparison of the returns across all the FP7 cooperation themes as can be seen in figure 1.15, where the space sector appears as the best theme.

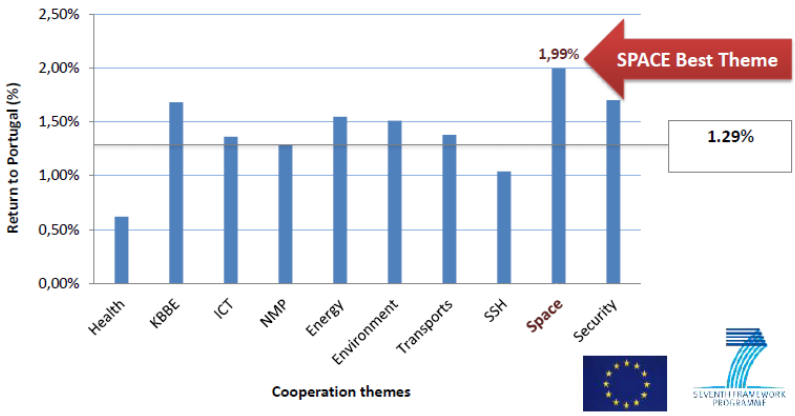

Figure 1.15: Comparison of the % return across all FP7 cooperation themes according to [1]

All these elements help to make the case for the Portuguese space sector, as a state of the art industry, where Portuguese engineers and academics can work with the best and contribute with high efficiency to the national economy, increasing knowledge and value in every step of the industrial chain.

1.5 Research Problem and Thesis's Outline

This thesis aims to identify relevant technologies, for the monitoring of the Atlantic space, and to propose guidelines for their configuration and implementation, all from an aerospace point-of-view.

This identification is oriented by two objectives:

- Address the opportunities arising from the growth of the ocean economy - attested by the increase in magnitude and relevance of the ocean-related activities for the global economy in the present time, as well as the very promising projections for a new future.
- Benefit the most from the use of Portuguese assets - taking advantage of the Portuguese qualities in terms of industrial, territorial, economical and scientific impact.

In Chapter 1 after presenting the context and motivation, a brief snapshot of the perspectives for the so-called *Blue Economy* is given in Section 1.3, identifying requirements and opportunities for the activities it comprises. In Section 1.4 the Portuguese situation is then presented, exploring the country's role, international obligations and opportunities arising from its strategical positioning and assets. The state of its aerospace sector is also explored, presenting significant players, their capabilities and making the case for this sector's role in both the national and international panoramas.

The technological assessment is explored throughout the Chapter 2, being the result of an extensive literature review on ocean-related monitoring activities and the technologies that are currently used to address them, as well as the ones expected to generate an impact for the years to come. Successive filters are then applied, aiming to achieve a solution that privileges both a significant operational impact and the Portuguese industrial and scientific reality. The final candidates are submitted, in Section 2.4, to a decision making map and chosen alongside DEIMOS Engenharia's experts, resulting in the selection of both Sat-AIS and GNSS-R.

A mission for these two technologies is drafted in Chapter 3 by analysing possible platforms and their associated advantages, followed by a deep assessment of cubesats and their subsystems. Section 3.3 explores different archetypes of satellite constellations, incorporates the DGRM's perspective on current monitoring requirements and presents GYNSS as a reference for the proposed mission. The option for small satellites is then tested by performing simulations in DEIMOS's GAT, comparing the receiver's capacity of detecting specular points and finally achieving an optimal configuration by maximizing the minimum specular point database that each inclination value is capable of providing.

Finally, in Chapter 4 the feasibility of this possible mission is studied under Portugal's 2030 space programme, along with an assessment of Portugal's capacity of implementing it. This is done by evaluating the country's relation with ESA during the last years and by benchmarking space priorities, for the years to come, among the state-members. This chapter also presents a value chain analysis of the sector, suggesting how the players mentioned in early sections could take part on it. Section 4.4 presents a methodology to be employed on the assessment of the projected impacts of the proposed mission and subsequent national space projects. The study is then concluded with discussion and recommendations for further work, with the purpose of contributing to capture the identified opportunities.

2

Monitoring, Control and Surveillance of the Atlantic Space

Contents

2.1 Introduction

Maritime monitoring and surveillance systems aim to improve the situational awareness of all activities at sea impacting on areas as diverse as maritime safety and security, border control, the marine environment, fisheries control, trade and economic interests of all the stakeholders involved, as well as general law enforcement and defence. [2]

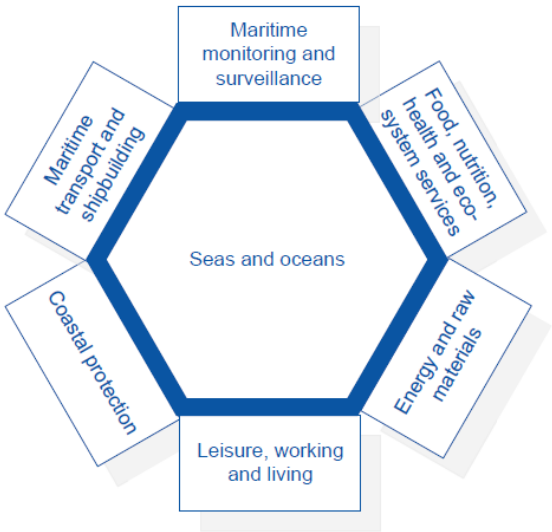

Figure 2.1: Global maritime core functions according to the EC's *Blue Growth* report [2]

The monitoring component is required for three main purposes[30]:

- Fundamental scientific understanding of the ocean, e.g. its properties and behaviour, its health, its role in climate change and how it is affected by those changes;
- Identification and follow-up of ocean resources such as food, energy, minerals or other materials enabling its effective and efficient use - e.g. assessment of fish stocks, location of potential oil and gas sources, as well as wave energy and offshore wind farm areas;
- Assessment of the impacts of ocean based activities such as shipping, resource extraction and coastal tourism, minimizing environmental and ecosystem degradation.

The two other components, control and surveillance, are required to prevent illicit activities as in the cases of piracy, as well as Illegal, Undeclared and Unreported (IUU) fishing [41]. These components are also used to enforce maritime laws regarding drug trafficking, migrant smuggling [42, 43] and environmental conditions including algae blooms [44] and oil spills [45].

In order to perform these tasks it is necessary a wide-range of both players and instruments. These can include UAV, ROV, research vessels, satellite remote sensing, submersible and fixed platforms and *in-situ* sensors, as it is the case of drifting buoys[46, 47]. These sensors are frequently assisted by modelling and computational infrastructures along with big data storage and management[30].

With the intensive growth of MCS systems, and of the needs they are meant to fulfil, the current trend in this area is to converge to an increasing cooperation between instruments, systems, entities and countries [46].

This section intends to assess both the user requirements, and the technologies that are driving and enabling this monitoring. The first part will comprise a detailed analysis of the areas and parameters to monitor, arising from national and international mandates. A brief description of the instruments and technologies utilized for this purpose is then made, along with an identification of challenges and opportunities for a near future.

2.2 User Requirements

MCS systems are required for a wide range of activities in the scope of both National and European directives, as attested by the Portuguese National Maritime Strategy [48] or the EC's integrated maritime policy [49]. For ease of comprehension these necessities are grouped under three main areas, according to their primary tracking function:

- Sea state;
- Ecosystem;
- Human Activity.

For each group a list of activities, the responsible entities, as well as their mandates and a brief description are presented.

2.2.1 Sea State Monitoring

The term Sea State is usually utilized to describe phenomena referring to the surface of a large area of open ocean, or sea, resulting from the combined effects of wind-generated waves, swells, and surface currents, at a given time and location [50]. In this work this concept is extended to incorporate all the physical parameters referring to the ocean itself, and its behaviour from the sea floor to the surface. These parameters, demanding monitoring, are:

- Bathymetry
- Annual and seasonal temperature profiles
- Velocity and direction of sea currents
- Wave characteristics (height, period and direction)
- Spatial and temporal distribution of salinity

All under Portuguese Environment Agency (APA)'s responsibility [51].

Other activities requiring MCS systems are:

- Meteorological, climatic, seismic and geophysical surveillance
- To support aerial and maritime navigation operations with adequate information on weather and sea state forecasts
- To provide meteorological data for national security operations

which are assured by the Portuguese Sea and Atmosphere Institute (IPMA) [52].

Some responsibilities are shared between different agencies, as it is the case of:

- Assessment and governance of risks related to earthquakes, tsunamis and other extreme meteorological events

assigned to IPMA and to the Portuguese National Authority for Civil Protection (ANPC) [53].

In addition to the previous mandates, the Portuguese Hydrographic Institute (IH), which is the Portuguese Navy's Laboratory of Ocean Sciences, is also responsible for the following tasks [54]:

- Marine Cartography Production
- To assure tide, wave, and sea current surveillance, as well as near real-time availability of data.
- Monitoring and characterization of the EEZ and other areas under national jurisdiction or interest.

2.2.2 Ecosystem Monitoring

Another important dimension is the health of the marine environment and its resources. The Maritime environment receives inputs of hazardous substances through riverine discharges, direct (end of pipe) inputs, and atmospheric deposition, being the ultimate repository for complex mixtures of persistent chemicals.

Consequently, organisms are exposed to a range of substances, many of which can cause metabolic disorders, and effects on wildlife populations through changes in growth, reproduction, or survival. This contamination along with IUU fishing is a major threat not only to our health and subsistence, but to the entire ecosystem.

The assessment of environmental quality, and the design and monitoring of measures to improve environmental quality, are best undertaken on the basis of combinations of appropriate sets of chemical and biological measurements, as mentioned in [55].

Phenomena requiring measurements are:

- Upwelling - Wind-driven motion of dense, cooler, and usually nutrient-rich water towards the ocean surface
- Spatial and temporal distribution of nutrients - Dissolved Inorganic Nitrogen (DIN), Total Nitrogen (TN), Dissolved Inorganic Phosphorus (DIP), Total Organic Carbon (TOC) and Oxygen.
- Profiles of pH, pCO2, or equivalent quantity to measure ocean acidification
- Habitat Characterization: structure and composition of seabed substrates, phytoplankton and zooplankton communities, including species and their seasonal and geographical variations

- Information regarding angiosperms (flowering plants), seaweed, and benthic invertebrates (organisms that live near the seabed), including species composition, biomass and annual/seasonal variations
- Characterization of fish populations regarding quantity, geographical distribution, age and size
- Description of marine mammals', reptiles' and birds' population dynamics, along with their natural and actual distribution areas
- Monitoring of chemical substances in biota (total collection of organisms of a geographic region or a time period) and its contamination, especially the one for human consumption

which are appointed to the APA [51].

Under the same topic, the Portuguese Directorate General for Maritime Natural Resources, Security and Services (DGRM) is mandated [56] to monitor and control fisheries, aquaculture, and other human related catches which have major ecological implications. However in this work these activities are analysed under the Human Activity subsection, in 2.2.3.

The IPMA activities [52] covering this subject are :

- To assure marine environment's state systematic evaluation and biodiversity preservation, with particular focus on protected areas
- To support the definition and operation of networks for monitoring the quality of both air and marine water

Combating maritime pollution is also extended to Portuguese Directorate General of Maritime Authority (DGAM)'s mission, as indicated by [57].

In agreement with reference [53], and when alerted by the DGAM, the ANPC is in charge of:

- Accidents involving biological agents, chemicals and hazardous materials
- Marine environmental pollution in conformity with "Plano Mar Limpo", a strategic program in line with the principles of the International Maritime Organisation's Convention on Oil Pollution Preparedness, Response and Co-operation [58]

While the IH is responsible for [54]:

- Assuring laboratory tests of the physical and chemical parameters necessary to its environmental monitoring

2.2.3 Human Activity Monitoring

As indicated in the previous subsection, 2.2.2, this area of activities comprises the ones directly related to the human presence in the oceans. Fisheries and aquaculture are examples of this, along with those related to law enforcement, as are the cases of drug trafficking or migrant smuggling.

Under DGRM's scope [56] one can find several duties:

- To program, coordinate and execute the surveillance and control of fishing activities and others related, namely those within the Portuguese Integrated System for the Surveillance, Taxation and Inspection of Fishing Activities (SIFICAP) and the Continuous Monitoring System for the Fishing Activity Inspection (MONICAP)
- To manage the fishing information system, including aquaculture, the processing industry and salt production, while also inspecting these industries.
- To manage fishing's statistical system and the National Fisheries Database
- To manage the Maritime Navigation National Database
- To coordinate and Operate the Marine Traffic services and monitoring and control systems
- To assign marine space user licenses
- To define fisheries' governance models and exploration strategies
- To assess recreational fishing's impact and propose adequate management measures
- To assure the inventory of the natural marine resources available in areas under national jurisdiction
- To operate the Continent's Marine Traffic Control Center and all the structures, systems and communications that constitute the Vessel Tracking Service (VTS) system
- To define, implement and operate the Portuguese component of EMSA's *SafeSeaNet* (AIS-based vessel tracking and monitoring system)
- To implement and operate the Long Range Information and Tracking (LRIT)'s (a satellite-based, real-time reporting mechanism) Portuguese component

Several mandates are also attributed to the Portuguese National Republican Guard (GNR)[59], mostly to its Coastal Control Unit (UCC). The UCC is the special unit responsible for the fulfilment of the GNR's mission in the entire coastal extension and territorial sea . It has specific surveillance, patrolling and interception competences, alongside with the task of managing and operating the Surveillance, Command and Control Integrated System (SIVICC) distributed along the shore.

This system covers the area from the shoreline to 24 nautical miles, 24 hours per day. It allows prevention and fight against threats in fiscal, customs, terrorist, drug trafficking, environmental catastrophes and migrant smuggling domains.

Regarding DGAM's mission [57], one can see that it is accountable for:

- Supervising, policing and securing navigation, people and goods.
- Rescue operations to sailors, ships and bathers.

The Port Authority, and the Maritime Police are both subsidiary units of DGAM, the latter having not infrequent overlapping tasks with the UCC or even the navy, sometimes resulting in an inefficient allocation of resources [60].

It is also important to mention the Maritime Rescue Coordination Center (MRCC), which was created precisely to overcome the situation previously described. Under the direct supervision of the Defence Minister and the Portuguese Navy, its purpose is to centralize all the fundamental entities in a response to a rescue situation. Combining efforts from entities as diverse as the Red Cross, the Portuguese Air Force, fire-fighters, the DGAM, or the GNR, is responsible for a 98% success rate in this kind of operation [61].

2.2.4 Classification

The activities explored in the previous sections can be grouped, according to the main origins of the acquired data,in the following categories:

In-situ *In-situ* monitoring consists in all the activities that involve a physical contact with the object, surface or phenomenon under investigation. Their ability to gather data under natural conditions, permits the determination of a variety of parameters under a broad range of conditions[62]. In the maritime environment *in-situ* monitoring is provided by manual field sampling or more efficient automated systems. The latter, using sensors in buoys, ROV, platforms or AUVs, enable periodic samples of places and times otherwise impossible to reach. It is also important to notice that since it requires direct contact with the object of study, this type data is the one utilized to calibrate and validate both models and satellite measurements. One of the drawbacks of this method however it is the difficulty to scale it and cover vast areas.

Models A model, in the most general sense of the word, can be any kind of representation of the real world. It can be physical, like a car model, or a theoretical construct that helps to explain some phenomenon. In this work, as in common ocean-related activities, one will address numerical, or computer, modelling. There are three main uses for this kind of monitoring. The first is scientific inquiry. Controlled experiments, varying one condition or parameter at a time, can be used to determine what physics are important and what assumptions are valid. In addition, "what if" kinds of experiments can be run to try to understand the behaviour of the ocean under varying parameters. The second use is to interpolate and interpret sparse data in a dynamically consistent way to produce a nowcast, or analysis. The third use for modelling is predictive. For example, if there is an oil spill at a location 50km off the coast now, where will the oil go, how it will behave? This makes it possible to anticipate scenarios and prepare responses to a variety of issues[63].

Although important for many predictions and to better understand the reality, models can never replace it totally, as numerical modelling of the ocean is not a perfect science.

There are always trade-offs to be made in terms of computational efficiency, spatial and temporal resolution, and sophistication of the physics and numerical schemes used, needing the ocean modeller to make appropriate choices and assumptions to solve a particular problem. In order to appropriately and effectively utilize the output the user must have an understanding of the choices that have been made through the development and implementation of a particular model[64].

Remote Sensing Earth Remote Sensing is primarily defined as the use of electromagnetic radiation to acquire information about the ocean, land and atmosphere without being in physical contact with the object of study.

Unlike shipboard measurements of quantities such as Sea Surface Temperature (SST) or wind speed, which are direct measurements made at a point by a thermometer or anemometer, remote sensing of such quantities covers broad areas and is indirect, as the quantity of interest is inferred from the properties of the reflected or emitted radiation.

This radiation has three principal sources: blackbody radiation emitted from the surface, reflected solar radiation, and, for the directed energy pulses transmitted by satellite radars, the backscattered energy received at the sensor[65].

A brief summary of these three methods is provided in table 2.1.

Category	Advantages	Disadvantages	Important Function
In-situ	Direct measurement of the quantity of interest	Difficult to scale for large areas	Used to complement, calibrate and validate other methods
Models	Low cost	Approximation of the discretized domain to reality vs. Computational Effort	Prediction and analysis of quantities and events
Remote Sensing	Large Scale monitoring	Spatial & Temporal resolutions vs. costs	Rapid data collection and dissemination

Table 2.1: Brief summary of the different monitoring categories

Most of the times the three categories (models, *in-situ* and remote sensing) are combined, which is expected since *in-situ* data is often used to calibrate and validate models and remote sensing instruments likewise. For the purpose of this work the criterion utilized to assess each activity is the quality of the data gathered from the correspondent category. The color code, utilized in table 2.2, is the following:

- **Green** - If the data generated from this source is relevant for the activity, and is obtained directly
- **Yellow** - If the data generated from this source has a significant input, but it isn't obtained directly
- **Red** - If the data generated from this source doesn't have relevance for the activity

Area	Organism	Activity	Models	In-situ	Remote Sensing
Sea-State	APA	Bathymetry			
		Annual and seasonal temperature profiles			
		Wave characteristics (height, period and direction)			
		Spatial and temporal distribution of salinity			
		Velocity and direction of sea currents			
	IPMA	Meteorological, climatic, seismic and geophysical surveillance			
		Support navigation with weather and s.s forecasts			
		Provide meteorological data for national security			
	ANPC	Risks related to extreme meteorological events			
	IH	Marine Cartography Production			
		Tide, wave, and sea current surveillance in NRT			
		Monit. and Charact. of the EEZ important areas			
Ecosystem	APA	Upwelling			
		Spatial and temporal distribution of nutrients			
		pH and pCO2 (acidification profiles)			
		Habitat Charact.			
		Flora Charact. (annual)			
		Fish population Charact.			
		Marine Mammals Charact.			
		Biota Monitoring			
	IPMA	Biodiversity preservation			
		Air and water quality monit.			
	ANPC	Accidents w/ biological, chemichals, hazardous materials			
		Marine pollution (Oil Spills)			
	DGAM	Combat and alert for Marine Pollution			
	IH	Laboratory test for phys/chem environ. Monit.			
Human Activity	DGRM	SIFICAP and MONICAP (fish. Surv. & Ctrl.)			
		Fish., Aquaculture, processing ind., Salt, inspection			
		Fisheries statistics and database			
		Maritime Navigation Database			
		Marine Traffic MCS			
		Marine space user licenses			
		Fisheries governance and explor. Strategies			
		Recreational Fishing manag.			
		VTS systems and communications operat.			
		SafeSeaNet implement. and Operat.			
		LRIT implement. and Operat.			
	UCC	SIVICC			
	DGAM	Supervise and secure navigation, people, goods			
		Rescue Operations			
	Navy	MRCC			
	IH	Support to rescue operations (Numerical Models)			
	NAV	Air Traffic Monitoring			

Table 2.2: Classification of the different activities according to their origin

2.3 Remote Sensing

Remote sensing, as presented in section 2.2.4, is the measurement of object properties on the earth's surface using data acquired from aircraft, satellites or other indirect sensor. Since one is not in contact with the object of interest, one must rely on propagated signals of some sort, for example optical, acoustical , or microwave [66]. This type of sensing, being derived from the utilization of aircraft and satellites, is then of great importance for the aerospace engineering, and therefore to this work.

Having this aerospace environment in mind, activities strongly based on models or *in-situ* data will be left out, enabling a deeper analysis of the space-related ones.

From table 2.2, in the previous sub-section 2.2.4, one can observe several activities that are classified with a yellow colour, meaning that their requirements are satisfied only after some significant data treatment or indirect measurement. For example upwelling areas can be characterized from satellite derived SST, color and wind data, both activities already listed in table 2.2.

This class of activities will thus be discarded in favour of the technologies that "feed" it, following one of the goals of this work, the identification and assessment of promising technologies. This option does not mean that an activity like upwelling will not be upgraded as a result of improvements in SST-gathering and processing technologies, on the contrary it aims for those results, but adopting a radical (aiming for the root of the problem) approach.

A list derived from the previous rationales is presented in table 2.3:

Area	Organism	Activity
Sea-State	APA	Bathymetry
		Annual and seasonal temperature profiles
		Wave characteristics (height, period and direction)
		Spatial and temporal distribution of salinity
	IH	Tide, wave, and sea current surveillance in NRT
Ecosystem	APA	Flora Charact. (annual)
	IPMA	Air and water quality monit.
	ANPC	Marine pollution (Oil Spills)
Human Activity	DGRM	SIFICAP and MONICAP (fish. Surv. & Ctrl.)
		Marine Traffic MCS
	UCC	SIVICC
	DGAM	Rescue Operations
	Navy	MRCC
	NAV	Air Traffic Monitoring

Table 2.3: Activities fulfilled with improvements in remote sensing technologies

In order to preform a proper analysis, a characterization of each activity and related technologies will be made in the next segment. A special attention is given to overlapping activities or mandates, focusing once more on possible technological breakouts.

Bathymetry Bathymetry is the science of determining the topography of the seafloor. Echosounding techniques have been classically used for accurate bathymetric mapping of the sea floor. The conventional Single Beam EchoSounder (SBES) is outdated by the Multi Beam EchoSounder (MBES) techniques, which have 100% coverage of the seafloor. However MBES bathymetry data collection of vast offshore domains for these purposes is a difficult task to achieve. In such circumstances, the synoptic characteristics of satellite radar altimetry and imagery could be utilized as an effective method for predicting bathymetry, which can be complementary to SBES and MBES bathymetry, as well as Airborne Laser Bathymetric (ALB) and Light Detection And Ranging (LiDAR) systems although very expensive, to create a reasonably accurate and complete coverage of sea floor bathymetry map of vast areas [67].

Satellite Derived Bathymetry (SDB) can be regarded as one of the most promising alternative tool to map the bathymetry of the ocean, because of its extensive coverage of the area, low cost and repeatability. The concept of SDB is that different wavelengths of light penetrate water to differing degrees. The smaller the wavelengths (e.g. blue and green light) penetrate water more than longer-wavelengths (e.g. near infrared, shortwave infrared). When water is clear and the seafloor bottom is bright (sandy for example) estimates of depth can be made by modeling the depth of light penetration based on the amount of reflectance measured by the satellite. And when multiple visible-wavelength spectral bands are used together, the effects of seafloor reflectance variability and water turbidity are lessened. In recent years, successful launches of remote sensing satellites such as Ikonos, QuickBird, and Worldview-2 offer imageries with both high spatial and spectral resolution, but all these images need to be procured commercially, which has been proved to be expensive for most countries. Landsat-8 imageries came to revolutionize the paradigm since they can be downloaded for free from the U.S. Geological Survey website and used to determine the bathymetry of the ocean [68].

Temperature Profile Ocean temperature is among the most important physical properties of the marine environment as it influences many physical, biological, geological and chemical aspects of the ocean.[69]

Although in situ measurements are the most exact method, they are also the most expensive and time-consuming one. This is aggravated with its inability to cover extensive areas of water regions in a short period of time.

To overcome these difficulties, throughout the years sensors were developed and launched into space as the likes of National Aeronautics and Space Administration (NASA)'s Advanced Very High Resolution Radiometer (AVHRR), Moderate Resolution Imaging Spectroradiometer (MODIS) and more recent Visible Infra-red Imaging Radiometer Suite (VIIRS). Its European counterpart

ESA most recent sensor is the Sea and Land Surface Temperature Radiometer (SLSTR), currently aboard Copernicus' Sentinel-3 mission, and with an accuracy up to 0.3 Kelvin.

Wave Characterization Winds blowing over the sea surface generate wind waves (also known as ocean surface waves), and the data on these waves are required for planning and designing facilities in the ocean. The major sources of wave data are in-situ measurements, voluntary observing ships data and satellite altimetry or remote sensing data. A number of satellite instruments such as the Scatterometer, the Special Sensor Microwave Imager (SSMI), Synthetic Aperture Radar (SAR) and the Radar Altimeter are available for the determination of wave height and wind speed and direction [70].

Examples of satellites hosting these sensors are the Eumetsat's MetOp-B with the scatterometer, SSMI under United States' Defence Meteorological Satellites, Sentinel-1 with the SAR and especially Sentinel-3 with its SAR Radar Altimeter (SRAL) instrument, intended to provide basic measurements of surface heights, sea wave heights and sea wind speed.

Also important to the wave and consequently ocean characterization is the using of Global Navigation Satellite System-Reflectometry (GNSS-R) technology, which relies on global constellations, providing high spatial and temporal coverages. This high-rate coverage enables proper sea surface height measurements, which are of great use in the monitoring and quick detection of tsunami waves. [71]

Salinity Distribution The variability in Sea Surface Salinity (SSS) ranges from daily to annual and inter-annual scales responding to processes as diverse as intense precipitation events, river plumes meandering, advection by eddies and currents, and large-scale changes in atmospheric conditions. Among other processes, salinity-induced stratification at lower latitudes can also control the mixed layer depth through barrier layer effects and therefore potentially regulate heat, gas and momentum exchanges between the ocean and the atmosphere. SSS is thus a useful proxy to monitor changes in the global hydrological cycle relevant to future climate variability and to identify changes in the global ocean circulation and associated changes in ocean density distribution.

Over the last 5 years, a revolution in observing SSS from space has taken place, with several satellite missions placed in orbit, including the first-ever satellite salinity mission, ESA's Soil Moisture and Ocean Salinity (SMOS), which has been providing global maps of SSS continuously every 3 days since 2009, thanks to its Microwave Imaging Radiometer with Aperture Synthesis (MIRAS). [72]

The US/Argentina Aquarius/SAC-D mission had been operational since 2011 but ceased functioning in early June 2015, being followed by NASA's Soil Moisture Active Passive mission, launched on 31 January 2015 and designed to combine radar and radiometer measurements. Six months after the launch, the radar stopped transmitting leaving the mission confined to its radiometer. Although it resulted in lower resolution data, it is still of great scientific relevance.[73]

Current Characterization Ocean currents influence the global heat transport, weather and climate, larval transport, drift of water pollutants, sediment transport, and marine transportation. Since currents influence so many marine-related activities and processes, meteorologists, oceanographers, ships, coastal and fisheries managers, and marine-related agencies need to have up-to-date information on ocean and coastal currents.

Over the past three decades shore-based high-frequency and microwave Doppler radar systems have been deployed to map currents and determine swell-wave parameters along the world's coasts with considerable accuracy. [74]

In an attempt to adapt a similar principle to satellites, the Along-Track Interferometric (ATI) technique was created. Originally developed in the 1980s at the Jet Propulsion Laboratory it requires two SAR antennas separated in flight (along-track) direction by a short distance. The two antennas acquire images of the same scene with a time lag on the order of milliseconds. Phase differences between the two complex images are proportional to the Doppler shift of the backscattered signal and thus to line of sight target velocities. This way, an ATI system permits high resolution imaging of surface current fields in the open ocean, coastal waters, and rivers, which is attractive for a variety of applications in the fields of oceanographic and hydrological research, operational monitoring, and offshore engineering. TanDEM-X and TerraSAR-X are examples of satellites that provide data using this technology. [75]

Flora Characterization There are two major concerns when one analyses the flora present in the ocean. The first one arises from photosynthesis , which ultimately leads to the conversion of inorganic carbon to organic carbon, providing an essential role in the carbon cycle, but mostly as the first step in the oceanic food chain.[76] The second crucial parameter revolves around the capability of properly detecting harmful algal blooms which can cause mortality of marine wildlife, threaten human health, and lead to significant economic losses.[77]

Having the necessity of addressing these problems, the estimation of the global phytoplankton (and then oceanic primary productivity) is a central goal of all ocean-color satellite missions which over the years included the likes of Sea Viewing Wide Field-of-View Sensor (SeaWiFS) and MODIS supported by NASA, and the MEdium Resolution Imaging Spectrometer (MERIS) supported by ESA. Large concentrations of algae or phytoplankton change the water's colouration and properties, enabling the detection and monitoring by the satellite's sensors. The Ocean and Land Colour Instrument (OLCI), recently launched into space as part of the Sentinel-3 mission, presents significant prospects in this area.[78]

Air and water quality Monitoring There are many different parameters that are used to monitor and assess water quality and these vary dependent upon the application of interest and the technology being employed. Regarding water quality, one control of major importance that remote sensing can provide is the previously mentioned harmful algal bloom, which refers to the increase in density of micro-algae leading to potentially or actual harmful effects. Dependent upon the species in question such events can affect human health, kill fish and/or result in the

closure of commercial shellfish beds.[79] Examples of some satellite missions designed to address this issue are also mentioned in the flora characterization section.

Air quality monitoring has evolved into a wealth of atmospheric composition satellite data with applications that have proven valuable to environmental professionals: nitrogen dioxide (NO2), sulfur dioxide(SO2), ammonia (NH3), carbon monoxide (CO), some volatile organic compounds, and also aerosol optical depth from which surface particulate matter, a key pollution parameter, may be inferred.[80]

Although these quantities can be provided by a series of satellites, one should highlight ESA's Sentinel-4 and 5 missions, totally devoted to atmospheric composition monitoring, being the number 4 in a geostationary orbit and the number 5 in a low Earth one. This geostationary mission consists in an Ultraviolet-Visible-Near Infrared Spectrometer that scans Europe in the East-West direction with a repeat cycle of 60 minutes, enabling the retrieval of the atmospheric trace gases. The Sentinel-5 will utilize the same instrument, being its global coverage the difference between the two.

Oil spills Marine oil spill pollution poses a serious threat to the ecology of the world's oceans. Thousands of tons of oil are spilled into the oceans every year due to both human causes, such as tanker accidents, rupture of rigs/pipelines or malfunctioning of oil extraction platforms, and natural events, such as natural seepage from seabed oil structures. However, the main contribution to oil pollution comes from illegal discharges of hydrocarbons intentionally released by ships cleaning their bilges underway to cut harbor costs. Some ESA reports estimate that 45% of global oil pollution comes from such malpractice.[81]

Oil spills dampen the sea waves, and since SAR data from airborne and satellite platforms are used widely for surface wave detection, they are a great tool for identifying and monitoring these spills. Other instruments used are the optical ones, as are the likes of the already mentioned MODIS, MERIS and OLCI. Laser fluorosensors can also be used in this process. These sensors are based on the phenomenon that aromatic compounds in petroleum oils absorb ultraviolet light and become electronically excited, this excitation is rapidly removed through the process of fluorescence emission, primarily in the visible region of the spectrum and since very few other compounds show this tendency, fluorescence is a strong indication of the presence of oil. Most laser fluorosensors used for oil spill detection employ a laser operating in the ultraviolet region of 308-355 nm.[82]

Fisheries Surveillance and Control SIFICAP, the integrated surveillance system for fisheries, combines efforts from the navy, the air force and GNR. It uses satellite-based technologies mostly for communications, however it also employs some remote sensing instruments as with the Forward Looking Infra-red (FLIR) integrated in SIFICAP's EH101 helicopters.

MONICAP is a monitoring system for fisheries inspection that utilizes Global Positioning System (GPS) and Inmarsat C for satellite communications between the fishing vessels and the terrestrial control center, enabling the transmission of the ship's position, direction and velocity.

Marine Traffic MCS A number of systems and standards currently exist for monitoring the position and activity of maritime vessels. The main MCS standards are: Vessel Monitoring System (VMS),AIS and LRIT.

Vessel monitoring services are offered commercially by many companies, as with the above mentioned MONICAP, and are based mainly on Inmarsat satellites (Geostationary Earth Orbit (GEO) orbit) or the ARGOS constellation (polar Low Earth Orbit (LEO) orbit). VMS securely transmits the location of a vessel and in some cases even extra information such as catch weight and species, through the satellite infrastructure, to the company that offers the service. VMS are also often integrated with communication services in order to provide added value to the crew and make it an attractive choice.[83]

The AIS standard was designed to assist in maritime traffic management. AIS uses Very High Frequency (VHF) to transmit location, course and speed to the authorities, as well as nearby vessels, in order to safeguard against collisions and assist in navigation. Although initially limited to coastal regions due to its terrestrial based receivers, this technology is now observing a change in paradigm as a consequence of its adaptation to satellite missions in Sat-AIS systems. This improvement in AIS has provided an unprecedented ability to monitor ship traffic on a global scale and the user feedback indicates that this space-based technology will gain even more relevance for the years to come. [25]

AIS data collection is therefore limited in coverage, spatially for terrestrial receivers and temporally for satellite receivers. AIS can also be detected by anyone in the neighbourhood of a vessel, increasing the vulnerability to security threats like piracy. For this reason, in low security areas, AIS can lawfully be switched off leading to incomplete or even missing tracks. A more secure vessel tracking system is the LRIT as it is based on point-to-point satellite communication, typically with a 6-hour reporting interval, rather than public broadcasting. [84] For this reason, LRIT offers the possibility to safely retrieve tracking information over areas affected by piracy. One drawback of LRIT derives from its reporting time being consistently lower than AIS's few seconds to minutes (when in range), however in wide areas this does not represent a serious limitation since usually merchant vessels do not often change course over ground.

SIVICC This surveillance system guarantees the permanent surveillance of an area up to 24 miles from the Portuguese coast, and it consists in 28 observation sites, being 20 permanent and 8 mobile. The technologies used in this system are high resolution daytime cameras, as well as thermal and infra-red night vision ones, complemented by radar technology.[85] All these components are centralized and managed in a central command center, enabling a rapid and efficient response to illegal activities.

Rescue Operations The response to the rescue situations in the Portuguese SRR area is provided by the 751 helicopter squadron. This squadron also employs EH101 helicopters with the already mentioned FLIR. Other remote sensing technologies seen as priorities are better communication systems and satellite imaging, as well as a proper integration of UAVs in this type of operation.[86]

Air Traffic Control Current surveillance systems suffer from a lack of availability in low altitude, remote and oceanic areas, and during extreme weather conditions. Some of these systems currently in use for surveillance are Primary Surveillance Radar (which relies on the reception of a reflected pulse), Secondary Surveillance Radar (receives pulses transmitted by the target, in response to interrogation pulses, such as the target's identity and altitude), Monopulse Secondary Surveillance Radar, Surface Movement Radar and MultiLATeration. The performance of these systems is however insufficient to satisfy the functional requirements of 4D (time being the fourth dimension) trajectory based operations, including high-performance situational awareness.[87]

Automatic Dependent Surveillance-Broadcast (ADS-B) is a surveillance technique which delivers the traffic surveillance and flight information by the air-air, air-ground data communication. The ADS-B communicates by the air-ground/air-air data link, and acquires the navigation data from the navigation systems and other airborne systems. Compared to the traditional radar surveillance techniques, ADS-B has the advantage of low cost, small accuracy error and strong surveillance capability. It can be applied in the non-radar-airspace surveillance service, the air traffic service of the high-density flight area, and airport surface surveillance service. [88]

The European ADS-B Implementing Rule mandates that new aircraft heavier than 5700 kg or faster than 250 knots must be equipped with ADS-B-Out since 2015, and for existing aircraft a retrofit from end of 2017 on. In 2020 ADS-B surveillance shall become operational. Similar mandates exist for some Asian regions and the U.S., whilst in Australia ADS-B-Out was required from end of 2012 on.[89]

In 2008 the German Aerospace Center started to investigate whether ADS-B signals broadcasted by aircraft can be received on board of LEO satellites. The studies and simulations lead to the "ADS-B over Satellite" project, which served for the development of a space-qualified ADS-B receiver and antenna system. As a result of this demonstration and similar ones, Aireon (a company owned by NAV Canada, Iridium, Irish Aviation Authority among others) is planning ADS-B receivers on each of the Iridium NEXT 66 LEO operational satellites constellation, expecting them to be operational by 2017.[90]

2.4 Choice of technologies

The technologies presented in the previous section are summarized in table 2.4 for ease of comprehension:

Area	Activity	Technology
Sea-State	Bathymetry	MBES
		LiDAR
	Annual and seasonal temperature profiles	VIIRS
		MODIS
		SLSTR
	Wave characteristics (height, period and direction)	SSMI
		Scatterometer
		SAR
		GNSS-R
	Spatial and temporal distribution of salinity	MIRAS
		SMAP
	Tide, wave, and sea current surveillance in NRT	ATI
Ecosystem	Flora Charact. (annual)	MERIS
		MODIS
		OLCI
	Air and water quality monit.	UVN-Spectrometer
	Marine pollution (Oil Spills)	MERIS
		MODIS
		OLCI
		SAR
Human Activity	SIFICAP and MONICAP (fish. Surv. & Ctrl.)	FLIR
		MONICAP
		SatCom
	Marine Traffic MCS	VMS
		AIS
		Sat-AIS
		LRIT
	SIVICC	Radar
		Thermal Camera
	Rescue Operations	FLIR
	Air Traffic Monitoring	ADS-B

Table 2.4: Relevant technologies and activities fulfilled by them

Having discriminated the activities and associated technologies, it is necessary to assess their relevance and possible impact, both essential to the funnelling process responsible for the focusing in one or two particular solutions.

2.4.1 Decision Making Map

This subsection presents the use of decision-making maps as data-collection instruments to support semi-structured interviews. A brief review of perceptual mapping and its uses in Marketing research is provided, since the idea to design decision-making maps for interpretive, interview-based research arises from this field. This is followed by a detailed explanation of the structure and process of the proposed data collection instrument according to the literature.

The literature [91] states that a research, such as this thesis, could benefit from the use of an instrument that, in the course of semi-structured interviews, would foster an environment where the ideas and meanings conveyed by all the players involved could be developed and further discussed in order to achieve a deeper understanding of the phenomenon under investigation. It also states that an instrument such as the perceptual map, with given proofs in Marketing, can also be successful in this

environment.

As mentioned above, the chosen approach is utilized mostly in interview environment, however it can also be used in the context of this work, considering it is developed under the orientation of industry experts, which results in a frequent quasi-interview environment. Perceptual maps are useful for this identification as they contribute for a broader visualisation of the available options, along with a judicious distribution, important in allowing the isolation of promising candidates and the discard of not so relevant ones.

Within Marketing research perceptual maps have been known as a powerful technique which is used for designing new products, advertising, determining good retail locations and developing several other marketing solutions and applications. All parameters that can be easily translated to technological identification processes.

The perceptual map, as used in Marketing research, includes three characteristics[91].

1. Axes that show the underlying dimensions that characterise how alternatives are differentiated by customers.
2. Pair-wise distances between alternatives that specify how close or far the products are in the mind of customers.
3. A vector on the map that indicates magnitude and direction in the geographical space of map.

The products of choice are then placed on this map, with their coordinates representing their value in a given axis. For example if the horizontal axis stood for sweetness, then on the right side of the map we would have chocolates or candy bars, and on the left side something sour, like a lemon. At the same time, if the vertical axis represented price, then one would have expensive chocolate brands on the top-right quadrant, and inexpensive lemons on the lower-left.

When applying the same principles to the technological assessment, the two axes of the map become the key characteristic to define, since both will set the criteria responsible for mapping the different options. If one considers each element as a circle on the map, it is then possible to add other two data elements to each candidate, one being the size of the circle and the other its color, totalling four different parameters of evaluation.

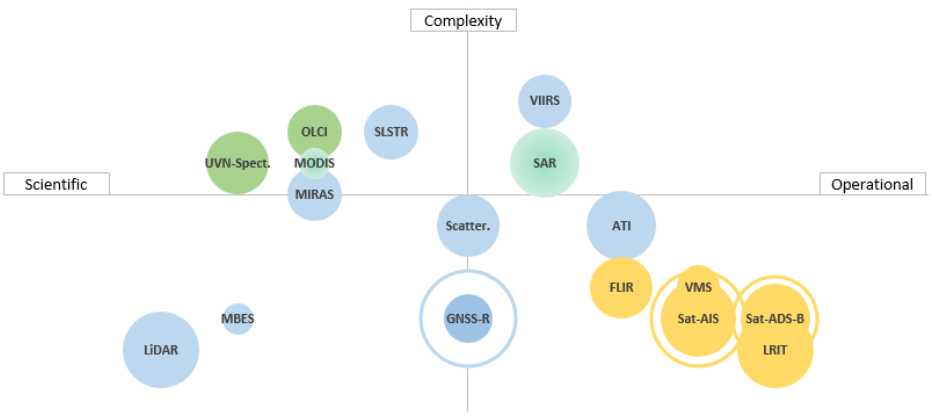

Figure 2.2: Perceptual map disposing technologies according to their complexity, level of operability and impact in a near future

Ocean related technologies, as with most technologies, can be distributed between two diametrically opposed poles, according to their purpose and use. These two ends of the spectrum are:

Scientific Instruments or missions considered as scientific are the ones that do not have direct correspondence with human activity, being used mostly for academic or R&D purposes. They usually do not require constant (or in near real time) monitoring, opting for a sporadic or regular approach instead. Most "ecosystem" and "sea-state" labelled activities fall under this side of the spectrum, and bathymetric measurements are a perfect example of this.

Operational On the opposite side, one can gather items that are closely linked with human activities and/or can impact them. Most of the time these technologies need permanent or short time interval monitoring, and some examples of highly operational ones are maritime rescues or vessel monitoring.

The other dimension, attributed to the vertical axis, evaluates each candidate according to its degree of complexity.

Complexity Though it may seem somehow vague, this term aggregates different dimensions of complexity such as monetary investment, knowledge, expertise, components and facilities necessary for the development, manufacture and implementation of each technology.

This map can also provide three more elements:

Area of the activity In agreement with the rationale presented in previous sections, which divided the activities requiring monitoring and surveillance in three different groups, the colour attributed to each item reflects this division. Orange indicates human-related activities, blue refers to sea-state, green to the ones focusing in the ecosystem, and sea green is applied in items which comprise two or more areas.

Impact in a near future This parameter is strictly based on experts' opinions, and reflects in a scale from 1 to 10, the impact that an investment in the technology will have in 5 to 10 years. This evaluation is reflected in the size of the represented circles, and it is proportional to different factors like the number of users that will benefit from it, the problems it will solve, the services it will provide and the economical impact it will have. As an example an outdated technology will have a very low value in this scale, while an emerging technology addressing necessities currently without response will score high.

Degree of completion This map can also differentiate technologies that are currently available from technologies which are still in concept or not fully operational. The former can benefit from improvements, variations or new missions, while the latter may have been proven but are not currently at use or with sufficient quality or maturity. This metric is represented in the map by the gaps between the inner and outer circles of the activities where this assessment is applicable.

Analysing the map, one should then define the criteria that will lead to the filtering and consequent focus on the most promising technologies. Attending to the Portuguese capacity in terms of economic

and industrial solutions, the option for the two lower quadrants (low complexity area) becomes evident, since that solutions in this spectrum enable the resolution of relevant issues, while being within the reach of the country's capabilities and aspirations.

The second relevant filter emerges naturally as the result of the expected impact in a near future, translated into the map as the size of the different elements. Although each contender has its merits and drawbacks, when opting for a new technology it is important to aim for the ones that are capable of generating the largest impact for a given effort, in order to capitalize from the chosen investment. Having this idea in mind, smaller area activities will be discarded in favour of larger ones.

Other important decision to make is related to the distribution along the horizontal axis, between scientific and operational-related activities. For this selection it is pertinent to distinguish two apparently similar factors, on the one hand the impact an improvement in the chosen technology is capable of generating in its field of application, and on the other hand the impact that the activity has in more absolute view.

As an example of the first situation one can examine LiDAR. The fact is that in the years to come advances in this technology are expected to occur, and investment in this direction will create returns in terms of the problems it solves and better conditions for bathymetric measurements. In spite of these improvements, the fact is that bathymetric measurements occur sporadically, preventing this technological impact of being more relevant in absolute terms, particularly when compared with more operational options. This rational will tend to highlight proposals on the right side of the map, which are more regular and present in the human everyday life.

A summary of the discussed reasons and the effects caused by them in the scope of the map can be the following:

- Low complexity
- High Impact
- Operational-oriented

These conditions result in a filtered version of the map, presented in figure 2.3

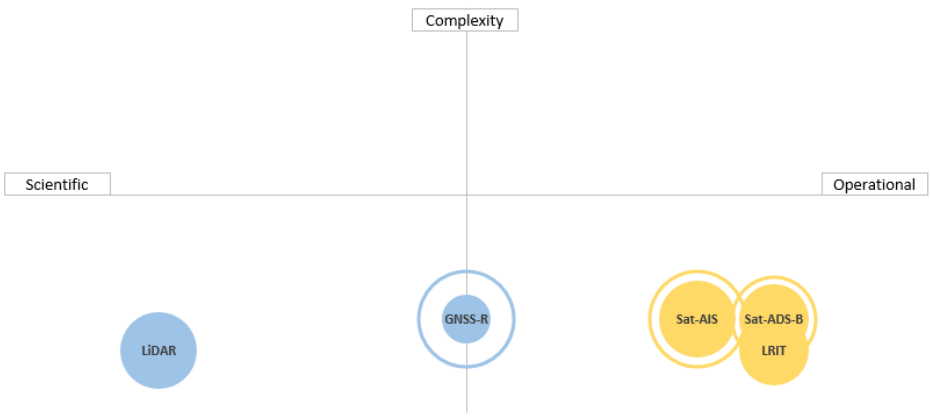

Figure 2.3: Perceptual map after the filtering

A final comment must be made regarding the non-completely filled activities (e.g., GNSS-R), that

is the ones that do not have yet a fully operational or functional system implemented. Fully-coloured technologies can be improved, or fulfilled in a more complete or efficient manner, for instance a SAR satellite with a revisit time of three days, can be improved with a daily-visit constellation, or with a better spatial resolution. However these solutions consist mostly on upgrades or refinements of systems that already exist. Oppositely the spaces to fill in the circles represent a myriad of new possibilities, as no full system is yet implemented (although some are currently being tested) or the technology is already proven.

As a result of this reasoning GNSS-R and Sat-AIS emerge as high potential candidates for development of a mission, to be explored in chapter 3. Sat-ADS-B also appears as an interesting technology to take into consideration. At the moment of the writing of this work, no system of this kind is implemented or functional, however Iridium-owned company Aireon predicts to have a global constellation fully-operational by 2018 [90]. NAV Portugal, the Portuguese air navigation systems provider, has already signed some memoranda with Aireon [92], as well as have other navigation providers. This solution withdraws some of the impact that addressing this technology could generate, losing some of the interest in incorporating it in a new mission.

Sea-State	Wave characteristics (height, period and direction)	GNSS-R
Human Activity	Marine Traffic MCS	Sat-AIS

Table 2.5: Technologies chosen to incorporate a possible mission

3

Mission Proposal

Contents

3.1 Introduction

This section intends to propose a mission that incorporates the technologies identified in 2.4.1, which are Sat-AIS and GNSS-R. One will start with a brief analysis on small satellites (SmallSats) and their role in the future of the Space industry, followed by a performance simulation of different configurations for SmallSats constellations using DEIMOS' software tool GAT. Finally the system's architecture of both technologies is presented and discussed with the purpose of integrating the outputs of this possible mission directly into the data supply chain and command centres of Portuguese and international authorities.

3.1.1 Platform overview

Having chosen the intended technologies, and being aware of their wide area of action, one should find the most appropriate device or mission that is both capable of enabling and getting the most out of them. UAVs, satellites and aeroplanes (figure 3.1) emerge as the natural candidates and, having all their merits in mind, the choice for one of them is once more based on the main objective of this work, the monitoring of the Atlantic space and the surveillance of its underlying wide areas.

Figure 3.1: Candidates for incorporating the chosen technologies: Satellites, Airplanes and Drones reprinted from [3]

UAVs (commonly known as drones) and satellites can be considered the two extremes of the monitoring spectre, when comparing altitude, prices, range, visit time or other characteristics. Satellites appear as a solution capable of monitoring large areas, enduring every weather condition but with large associated costs. On the other way drones emerge as a more tailored solution, better suited for specific operations, not requiring an around the clock monitoring and with much lower associated costs.

Aeroplanes appear somehow as a compromise between these two technologies, nonetheless they present a major downside since they require pilots for their operations. This makes it impossible to scale this option for the monitoring of large areas, like the Atlantic ocean, due to the associated monetary and practical difficulties this would impose.

A brief assessment of each candidate is presented in table 3.1:

Category	Advantages	Disadvantages
UAVs	Payload is retrieved and reused Inexpensive deployment and easy update	Unable to provide continuous coverage Medium area coverage
Satellites	Large area coverage More cost effective for large areas	Expensive launch Impossible to recover neither the spacecraft or payload
Aeroplanes	Compromise between the two previous candidates	Pilot required Very difficult to scale-up for large areas

Table 3.1: Brief summary of the different monitoring categories

During recent years both (satellites and drone) manufacturers have been trying to address their vulnerabilities. This resulted in the development of cheaper and smaller satellite solutions, commonly known as Smallsats, and simultaneously of High Altitude Long Endurance (HALE) drones, which have improved their area of coverage and autonomy[93].

This type of drones is gathering great levels of attention, as agencies like NASA and ESA, or big companies like Airbus, Google or Facebook, are investing on them as a replacement for satellites in communications, earth observation and ocean monitoring[94]. This thesis however, although the latter is also worthy of attention, will focus on satellite solutions, since those are the ones that capitalize the most on the environment and experts collaborating with this work.

3.2 Small Satellites

The world's first artificial satellite, *Sputnik*, was launched in 1957 and since then more than 7000 spacecraft were also sent to outer space[95]. The first satellites' mass was around 200kg, however performance requirements constantly increased this number throughout the years, until it reached a maximum of 7.9 tonnes with ESA's Envisat mission in 2004.

The rise on complexity, size and instruments was also reflected in price, meaning that satellite operation and manufacture was reserved only to space agencies or large companies. This constant growth, in order to be sustainable, required a new approach in the integration of so many (and also complex) systems, sensors and instruments. This issue was addressed for the first time by very-large-scale integration in 1970, which enabled the integration of sophisticated functions into small volumes, with low mass and power, being those the predecessors of small satellites[14].

According to International Academy of Astronautics (IAA), a satellite is considered small if its mass is less than 1000kg. Between the small satellite category there are also five sub-categories: Mini-satellites, ranging from 1000kg to 100kg; Micro-satellites, from 100kg to 10kg; Nano-satellites, under 10kg; and Pico-satellites if their mass is smaller than 1kg.

Each class of mass as associated expected costs and development time. The costs can be divided in satellite costs, launching costs and operational ones, which generally translate as approximately 70%, 20% and 10% of the total. These results are summarized in table 3.2.

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

Table 3.2: Mass, cost and development time for each class of satellites[14]

There are also two more relevant factors characterizing small satellites: their usual orbits and their launch into space. During the last years these satellites have been demonstrated in low to medium orbits, with particularly significant results achieved in LEO that will be analysed with more detail in the next subsection. Furthermore, their dimension allows them to be launched as secondary payloads of other space missions, often resulting in the cost of the mission depending more on the integration with the launcher, than on the satellite's mass[96].

3.2.1 Advantages and Disadvantages of Small Satellites

Table 3.2 presents the major differences between conventional and small satellites, with both mass and cost of the latter being in some cases up to one-hundred times smaller than conventional ones. Taking table 3.1 into consideration, one can conclude that this clearly addresses some of the main critiques stated against satellites: excessive manufacturing and launching costs.

Having much lower development times than conventional solutions grants small satellites more mission opportunities which result in faster data returns. This easiness in mission design makes possible to tailor a myriad of different missions appealing to a larger and more diverse number of potential users. Lower costs also liberate missions from some financial pressure, promoting the option for riskier proposals or proof of concepts, that otherwise would have remained only as ideas.

The advent of smart phones and of their associated instruments, combined with the modular integration of components, further contributes to this class of satellites, since it is possible to integrate Commercial Off-The-Shelf (COTS) microelectronic technologies (i.e. without being space-qualified). The integration of such instruments simultaneously expands the options for spacecraft configuration and areas of action, at a fraction of the traditional costs, thus resulting in a more rapid expansion of the technical and/or scientific knowledge base[14].

Their positioning in LEO, as mentioned above, provides additional advantages, as the power required for communication is less demanding and there is no need for high-gain antennas, on neither the ground control stations or platforms[14].

Previous missions have also shown that small satellites stimulate a greater involvement of local and small industry, replacing and providing alternatives to the traditional "big players". Their flexibility and comparative simplicity enable them to work as technical and managerial incubators for the education and training of scientists and engineers in space related skills, as they allow direct hands-on experience at all stages of a particular mission, including design, production, test, launch and orbital

operations[97].

Nonetheless all the flexibility and reduction in size, and costs, comes at a price. Little space and modest power available for the payload are usually appointed as the main downsides of small satellites, both limiting the instrumentation they can carry and the tasks they can perform. Another drawback affecting these platforms is their condition as secondary payloads. Although most of the time they take advantage of the additional capacity of launchers, in a considerable number of times they do not have any control over neither the launch schedule or the target orbit [14]. These limitations regarding their orbits, often result in orbits with an altitude no higher than LEO.

The summary of this discussion is presented below in table 3.3.

Advantages	Disadvantages
Low cost and frequent mission opportunities	Small space
Larger variety of missions and diversification of potential users	Little power provided to payloads
Rapid expansion of technical and scientific knowledge	Limited instrumentation and/or missions
Greater involvement of local and small industry	Does not control the launch schedule
No-need for high-gain antennas	Confined to LEO orbits

Table 3.3: Advantages and disadvantages of small satellites

3.2.2 Cubesats

One cannot finish this subsection without mentioning a platform which was essential during the last decade, and it is expected to play a decisive part on the one to come as well: the Cubesat.

Universities started their own small satellite projects as early as in the 1980s, in order to provide hands-on training for students in this interdisciplinary field of high technology. Despite the small satellite programs established at several universities (mainly in US and Europe) the results obtained were inconsistent as no standard was adopted at the time[98].

In 1999 the joint effort by professors Jordi Puig-Suari of California Polytechnic State University and Bob Twiggs of Stanford University gave birth to the CubeSat standard. This standard specified, originally, the requirements of a 1 kg, 10x10x10 cm3 nano satellite (1U). Satellites adhering to this standard are compatible with the Poly-PicoSatellite Orbital Deployer (P-POD), a standardized launch container developed, as well, at Stanford University. The P-POD is attached to the upper stage of a launch rocket, carries between one and three of such CubeSats (1U to 3U) and deploys them into orbit. The success of CubeSats is largely attributed to its standardized interface with respect to the launcher integration, which led to cheaper launch costs in the range of several tens of thousands of Euros and to the exponential increase on the number of potential launchers[98].

Figure 3.2: P-POD and Cubesat (1U) from Amsat UK

Their hardware cost can range between €50.000-200.000, and their classes are the following:

Class	Size[cm]	Mass[Kg]
1U	$10 \times 10 \times 11.35$	< 1.33
1.5U	$10 \times 10 \times 17$	< 2
2U	$10 \times 10 \times 22.7$	< 2.66
3U	$10 \times 10 \times 34$	< 4
3U+	$10 \times 10 \times 37.6$	< 4

Table 3.4: Standard classes for cubesats[14]

Having chosen the cubesat as the spacecraft of reference for this mission, the following step will be the definition of the subsystems required for its operation. An exhaustive optimization of each of the satellite's subsystems is outside the scope of this work, nevertheless a brief overview of the possibilities, along with a preliminary recommendation will be done and presented in the following sub-sections.

3.2.2.A Structures

Usually made from aluminum, Cubesat structure are responsible for mechanically supporting all the other subsystems and can also collaborate in thermal and radiation shielding of sensitive components. When deciding on the type of structure to deploy, one can go with custom built or to opt for an off-the-shelf structures, which can be provided by companies such as Pumpkin, ISIS or Radius Space[99].

The main advantage of off-the-shelf structures is their simplicity, and normalized operation in launching processes, while custom-made structures enable the tailoring to specific complex missions. Given the focus of this work in potentiating Portuguese endogenous space assets, one should opt for developing this component in collaboration with national hardware companies.

It should however be made the remark that independently of the chosen contractor, the final structure should be compatible with standard Cubesat design to ease its integration along the different phases of operations.

3.2.2.B Power

Cubesat's electrical power subsystem consists of a power source, energy storage, power distribution, regulation and control units.

The primary power source for this type of spacecraft are photovoltaic solar cells, which according to literature are capable of efficiencies in the order of the 30% [99]. These components can be either

body-mounted or deployable depending on specific mission power requirements.

Instrument peaks of power, or orbit eclipses, make the need for an on-board storage battery capable of continuing supplying energy to the payload and other subsystems. Types of batteries to be used include high energy density lithium ion and lithium polymer batteries that can be utilized as primary or secondary power source for CubeSat missions.

Following the rationale of building locally, and attending to the fact that power systems are often custom built by spacecraft designers based on their system requirements, the recommendation is to develop these batteries and systems locally leveraging the expertise of companies like Efacec, EvoLeo, Omnidea and others.

3.2.2.C Propulsion

Propulsion systems are vital in expanding CubeSat capabilities by enabling orbital manoeuvres, precise attitude control, formation flying as well as deorbiting capabilities at the end of the mission life in order to comply with orbital debris mitigation requirements. Still in an early maturity stage, this technology has been attracting a large share of interest and research in recent years.

Propulsion systems are usually divided into three categories: **Chemical**, **electric**, and **propellantless** propulsion systems. Chemical propulsion is known for achieving higher thrust levels although with limited specific impulse compared to electric propulsion systems. Propellantless systems, such as solar sails, do not make use of any propellant to produce thrust which results in simpler and lighter systems.

Over the last 5 years several CubeSat missions were launched carrying propulsion systems such as cold gas thruster, pulsed plasma thruster, vacuum arc thruster, electrospray, resistojet as well as solar sail.

Companies such as Busek Co. Inc., VACCO, Aerojet Rocketdyne, Accion Systems and Tethers Unlimited Inc. offer different types of propulsion systems for CubeSats with specific impulses ranging from about 40 s to 4000 s and the total impulse available for CubeSat class missions can reach over 3700 Ns, whereas, the thrust ranges from μ N to N levels[99].

FiberSensing and Omnidea are some of the players that could benefit from the local development of this component.

3.2.2.D Guidance, Navigation and Control

Guidance, Navigation and Control system is considered to be a combination of the Orbit Determination and Control Subsystem (ODCS), which measures and maintains the position of the satellite's center of mass as a function of time, and the Attitude Determination and Control Subsystem (ADCS), used to measure and maintain the satellite's orientation about its center of mass. For spacecraft position determination, these spacecrafts rely on GNSS systems, while in earth orbit, and on radio transponders for deep space navigation.

ADCS uses sensors such as star trackers, Sun sensors, Earth sensors, and magnetometers to determine spacecraft attitude and uses actuators such as reaction wheels, magnetorquers, and thrusters to

stabilize and orient spacecraft in the desired direction. CubeSat ADCS has dramatically improved over the last decade facilitated by the development of state of the art miniaturized star trackers capable of achieving precise 3-axis attitude determination with an arcsecond accuracy[99].

Due to the combined nature of these instruments several companies offer integrated units for precise 3-axis control, which combine different GNC components into a single package.

Examples of companies capable of collaborating in the development of this instrument are Deimos, GMV and Spinworks.

3.2.2.E Communications

CubeSat missions have been utilizing S-band communication systems, capable of achieving data rates of up to a few Mbps. These low rates put a limiting factor in the quality of Cubesat instruments since the payload will generate significantly more data than could possibly be downlinked at these rates, which discourages further technological advances.

CubeSat compatible high-speed Ka-band communication systems are gradually becoming available, which will improve CubeSat data rates by orders of magnitude in the near future. The next expected breakthrough in CubeSat communications will be the adoption of free-space optical communications technology. Laser communication has the potential to dramatically increase the data rates up to several Gbps thus potentially eliminating the currently experienced downlink constraints.

GMV, Lusospace and Tekever are examples of companies to involve in the development of these technologies.

3.2.2.F Command

Cubesat's command and data handling subsystem is responsible for receiving, validating, decoding, and distributing commands to other subsystems as well as gathering and storing housekeeping and mission data for downlink or onboard utilization. Last improvements in COTS microcontroller technologies enable high performance capabilities not without the downside of also presenting a higher vulnerability to space radiation.

Common on-board data handling systems for CubeSat include FPGAs, MSP and PIC microcontrollers, as well as microcontrollers based on high performance and power efficient ARM architecture. Recent developments have seen several open source hardware and software development platforms such as Arduino, BeagleBone, and Raspberry Pi gaining increasing interest among CubeSat developers. Thanks to its simple, effective and low-cost value proposition these platforms are expected to become very attractive to small satellite developers during the next years[99].

CubeSat onboard data storage can range from KBs to hundreds of GBs by taking advantage of commercial flash memory technologies. As mentioned in Subsection 3.2.2.E, the fundamental limiting factor for CubeSat is the bottleneck in the data downlink and not the onboard data storage. Overall, the CubeSat command and data handling subsystems are relatively mature field wide range of available options. There is however some expectation that the instruments evolve to increase their resistance to radiation, which will be required to extend the mission lifetime in LEO.

ActiveSpace, Critical Software and EvoLeo are some of the national companies capable of developing a solution for this mission.

3.2.2.G Thermal

Spacecraft's thermal budget is influenced by several factors including: external heat inputs from direct sunlight (the most important external heat source), sunlight reflected off the Earth or other planets and moons (albedo), infrared energy emitted from a surface or atmosphere of the central body and the heat internally generated by the components of the satellite.

To maintain optimal thermal conditions of operation, passive and active thermal control techniques must be integrated in the spacecraft. Passive thermal control has significant advantages such as reliability, low mass, volume and cost, which makes it a particularly appealing choice for CubeSats, given their constraints. Passive control is characterized by utilizing no power input and can be accomplished by a variety of techniques such as Multi-Layer Insulation (MLI), thermal coating, Sun shields, thermal straps, louvers, radiators and heat pipes[99].

In its turn, Active thermal control systems, that rely on power input for operation, may be needed for more efficient thermal control of missions requiring precise temperature ranges such as cryogenic cooling for optimal performance (e.g. high precision IR sensors).

Since the proposed mission does not require critical thermal conditions for its payload, the option will go to passive thermal solutions, a topic where several endogenous companies such as Activeaerogels, Activespace, HPS, ISQ among others have deep expertise and know-how on topic, and should engage on the development of these components.

3.2.3 Sat-AIS

Sat-AIS is responsible for major benefits in maritime traffic monitoring, as one previously explored in Section 2.3.

The International Maritime Organization requires that ships of 300 tonnes or more in international voyages, cargo ships of 500 tonnes or more in local waters and all passenger ships, regardless of size, carry AIS on board. Sat-AIS overcomes AIS's horizontal range limitation of 74 km from the shore (due to the Earth's curvature limits) since the satellites directly record and decode the ship's identity, sending it then to ground stations for further processing and distribution.

ESA is currently addressing this technology in three complementary areas:

- The Novel SAT-AIS receiver (NAIS)
- SAT-AIS microsatellites (E-SAIL)
- The Platform for Advanced SAT-AIS Maritime Applications (PLASMA)

Thanks to their comparatively lower costs, small and microsatellites do also have a lower time of operation and consequently larger substitution rate. From a Portuguese point-of-view the challenge is to learn from others (as the likes of Norway) and take part in this value chain, contributing with one or more exemplars for this network.

E-SAIL is ESA's ship-tracking satellite program provided by Luxspace as the satellite prime contractor and is planned to enhance exactEarth's current SAT-AIS satellite constellation. ExactEarth will be responsible for the launch (targeted for 2018) and the ground segment to command the satellites, and process the AIS data. E-SAIL characteristics are presented below in table 3.5

Altitude	550-750 km
Power Consumption	100 W
Weight	100 kg
Size	600 x 600 x 700 mm
Antennas	2x2 up to 4x2
Downlink (data rate)	C-band (up to 100Mbit/s)

Table 3.5: E-SAIL specifications

E-SAIL's microsatellites are designed within the 100 kg and 100 W class in order to handle large amounts of AIS messages and data while staying suitable for cost-effective shared launch opportunities.

The Novel SAT-AIS Receiver (NAIS) is a SAT-AIS payload on the Norwegian Space Centre's NORSAT-1 satellite developed by Kongsberg Seatex of Norway under an ESA contract[100]. Its characteristics are presented below in table 3.6.

Dynamic Range	>80 dB (additional 30 dB via built-in step attenuator)
Noise Figure	<1.7 dB
Altitude	550-650 km
Power Consumption	<5 W
Weight	<1.5 kg
Size	51 x 140 x 168 mm
Antennas	2 or 4 per unit
AIS Channels	• 1 and 2, long range 3 and 4 • ASM 1 to 2 • With upgrades: VDE plus built-in 156-162 MHz spectrum analyser

Table 3.6: NAIS specifications

NORSAT and NAIS are relevant as they could be easily used as reference platforms and sensors for the ones explored in future Portuguese solutions, especially due to NORSAT's total launch mass (including separation system) being lower than 30 kg, supporting the adequacy of a similar solution to the national economical context.

3.2.4 GNSS-R

The GNSS-Reflectometry, already mentioned in section 2.3, has been introduced to the science community more than two decades ago[101], where it has been shown that the GNSS signals of the available GPS satellites could be used as opportunistic signals to derive quantities others than the original ones they were designed for (position determination, among others). GNSS-R applications

explore the usually undesired GNSS multipath to obtain several geophysical measurements, such as soil moisture content, above ground biomass, wave height, wind speed and snow depth, being ocean altimetry the most prominent field of application. The concept behind GNSS-R is the same as the one behind bi-static radar where the receiver and the transmitter are at different locations. In the case of GNSS-R, the role of the transmitter is played by the GNSS satellites and the receiver is the GNSS-R instrument.

The left side of the figure below illustrates this process. The direct GPS signal is transmitted from the orbiting GPS satellite and received by a right-hand circular polarization (RHCP) receive antenna on the zenith (i.e. top) side of the spacecraft that provides a coherent reference for the coded GPS transmit signal. The signal scattered from the ocean surface is received by a downward looking lefthand circular polarization (LHCP) antenna on the nadir side of the spacecraft. The scattered signal contains detailed information about the ocean surface roughness statistics, from which local wind speed can be retrieved.

The image on the right below shows scattering cross section as measured by UK-DMC-1. This type of scattering image is referred to as a Delay Doppler Map (DDM). A DDM exhibits a typical horseshoe-like shape, which is linked to the space-to-DD coordinate transformation and consequent reshape of the spatial scattered power. The position of the spacecraft is determined from the direct GPS signal; the surface winds are determined by the indirect signal scattered off the ocean surface. Combining the position and scattering information allows for the creation of DDM, from which ocean surface wind speeds can be inferred [4].

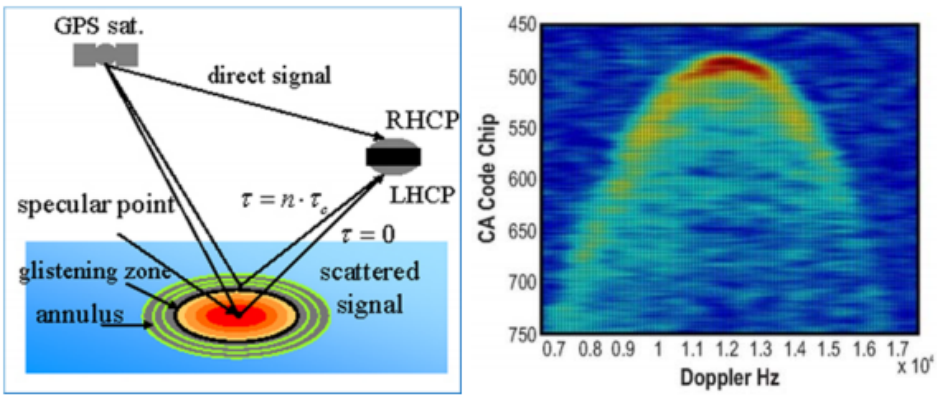

Figure 3.3: Illustration of GNSS-R principle and Delay Doppler Map, from [4]

A recent example of deployment of GNSS-R satellites was the launch of constellation CYGNSS. The CYGNSS Project will implement a spaceborne earth observation mission designed to collect measurements of ocean surface winds through variations in the direct vs. reflected GPS signals. The observatory portion of this mission consists of a constellation of eight satellites. The CYGNSS mission will provide new information about ocean surface winds in Tropical Cyclones, enabling advances in the knowledge of their genesis and intensification.

Due to its size, orbit and mission scenario, satellites from the CYGNSS constellation can be considered a good proxy for the parameters and key information necessary for GNSS-R simulations. Its

characteristics are the following[102],[103],[104]:

Altitude	510 km
Power Consumption	38.3 W
Weight	25 kg
Size	510 x 640 x 280 mm
Antennas	2x2
Antenna Beam Width	37
Downlink (data rate)	S-band (up to 4Mbit/s)
Number of satellites	8

Table 3.7: CYGNSS specifications

3.3 Constellation definition

Having decided in the previous sections the type of spacecraft in which to implement the selected technologies, it becomes necessary to define the constellation archetype that is more appropriate to extract more value from these technologies.

This is done by exploring the different patterns and selecting the more suitable solution, resulting from a compromise between what the literature recommends for cubesats, and the type of technology one has at hand. This choice also incorporates the inputs from the interview with DGRM's Eng. Nelson Marques, specially when considering AIS needs and the interactions with EMSA.

3.3.1 Constellation patterns

The distribution of satellites in a constellation can present many forms, depending on the mission objective or operational constraints face by the project.

The list below briefly characterizes the most common ones[105]:

- Geosynchronous - three to five satellites in GEO providing worldwide coverage
- Streets of Coverage - polar or near polar orbits with satellite right ascensions of ascending node (RAAN) spread evenly across one hemisphere of the earth
- Walker - satellites in individual rotationally symmetric orbital planes with identical altitudes and inclinations, the ascending nodes of the orbital planes are uniformly distributed around the equator and the satellites are uniformly distributed within the orbital planes
- Elliptical orbital patterns - provide additional free parameters to optimize the constellation. However satellites must be designed with greater complexity to work at varying altitudes (variations in range, angular size of the Earth's disk, in-track velocity, and relative position for satellites in the same orbit)
- Polar Non-symmetric - satellites in polar orbits with varying rotational spacing designed to optimize coverage over a specific region
- String of Pearls (A-Train) - multiple satellites in same orbital plane

Economies of scale and simplicity in the manufacturing process imply that the satellites should be identical. To assess the more appropriate orbits, Marinan explores the least optimal condition for the

subsystems discussed in 3.2.2 and match the design to maintain the performance metrics even in these situations [5].

After assessing the elements that meet the requirements, the author presents a performance matrix defined by the satellite altitude and inclination, which is depicted below in figure

Maximum number of subsystem whose design requirements are met

Minimum number of subsystems whose design requirements are met

Satellite Altitude (Km) \ Satellite Inclination (degrees)	0°	30°	42°	60°	90°	98°
300 km	Power Thermal Radiation	Comm Power Thermal Radiation	Comm Power Thermal Radiation	Comm Power Radiation	Comm Radiation	Comm Radiation
400 km	Comm Power Thermal Radiation	Comm Power Thermal Radiation	Comm Power Thermal Radiation	Comm Power Radiation	Comm Radiation	Comm Radiation
500 km	Power Lifetime Thermal Radiation	Comm Power Lifetime Thermal Radiation	Comm Power Lifetime Radiation	Comm Power Lifetime Radiation	Comm Lifetime Radiation	Comm Lifetime Radiation
600 km	Power Lifetime Thermal Radiation	Comm Power Lifetime Thermal Radiation	Comm Power Lifetime Radiation	Comm Power Lifetime Radiation	Comm Lifetime Radiation	Comm Lifetime
700 km	Power Thermal Radiation	Comm Power Thermal Radiation	Comm Power Thermal Radiation	Comm Power	Comm	Comm

Figure 3.4: Summary of cubesat expected performance across the orbital design space. Color code varies w/ number of subsystems meeting the design requirements, from [5]

From the matrix it is clear that the altitude should be kept between **500-600km** (as the majority of the literature recommends [99])and inclination in the range **30-60 degrees**, in a preliminary approach.

3.3.2 AIS considerations

The interview with Eng. Nelson Marques allowed one to deepen his knowledge about the Portuguese maritime sector, current MCS needs, and interactions with EMSA and other European agencies/departments.

Eng. Marques' inputs enabled to guarantee that the constellation design addressed all DGRM requirements in terms of monitoring, and helped to assess the initial hypothesis one had regarding the impact of this project.

One will start by listing the initial hypothesis, followed by the main takeaways from the meeting with DGRM and conclude with the impact that those had in recalibrating the project's design.

Initial Hypothesis	Takeaways from the interview	Implications for mission design
There are areas of the Portuguese EEZ with non-existing or very little Sat-AIS coverage which should be prioritized when defining the Cubesat orbits	All the zones under the responsibility of Portuguese authorities have fully Sat-AIS coverage and reasonable visiting times. Additional coverage is always welcomed as it provides shorter revisits and more data collection opportunities in high density traffic situations	Not having a specific area, or corridor, dramatically requiring Sat-AIS coverage enables the mission to shift its design more in function of the other selected technology (GNSS-R) while still providing additional instruments and positive redundancy for current AIS operations
Development of own capabilities in Sat-AIS could have a big economical impact in increase of revenue and reduction of costs alike. The first would be a consequence of the money injected in Portuguese space sector (award of contracts to Portuguese SMEs and future exports of the technology to third-party countries/companies once it is matured). The reduction would be achieved as a result of the stoppage of payments to EMSA for accessing AIS data, due to the new state of self-sufficiency	Premisses on the revenue generating side were confirmed, since vessel monitoring is an area requiring almost real-time tracking and the lifespan of its associated spacecrafts implicates high-levels of satellite/cubesat replacement. Hypothesis on the cost side however were not corroborated due to high level of centralization of operations under EMSA's responsibility. Presently every MCS activity is reported to EMSA who then shares the processed data, free of charge, with every member state's responsible department (i.e DGRM in the Portuguese case)through its IMDate website.	The expected revenues for the Portuguese space sector, the transfer of knowledge associated with it, and the opening of new potential markets for national space companies help to make the case for the constellation development in partnership with aligned international players. The generation of new sources of data, will not result in any tangible savings for Portuguese MCS operations, it can result however in a more detailed worldwide monitoring and control of the maritime space, especially if this mission is developed in collaboration with non-european players incorporating their additional sources of data
Reduction of revisit periods and solutions for treating non-cooperative vessels are important for DGRM in the near-future	Near real-time AIS monitoring combined with good resolution SAR imagery could be decisive in combating pollution and potentially illegal non-cooperative vessels. Higher resolution imagery and machine learning algorithms could play a big part on these so-called "unknown shadow patterns"	SAR and other radar-imagery instruments should be incorporated in the future into this mission. This could be done as a future combined payload to be integrated in a second-generation of the constellation, or in collaborative cubesats in a future satellite federation

Table 3.8: Initial hypothesis, takeaways and impact of interview with Eng. Nelson Marques

This centralization of AIS signal processing in EMSA and the inability to have access to structured AIS data, with the objective of evaluating the constellation's performance in signal covering, led to adjustments in the simulations. These adjustments resulted in a shifting of focus to GNSS-R as the main technology of concern for the orbital simulations in GAT software.

3.3.3 The CYGNSS Example

Following the discussion from the previous subsection, and the need to find a satellite pattern favourable to both Sat-AIS and GNSS-R, one should dwell in a high-revisit rate orbit, with a large focus on the Atlantic Ocean as the primordial zone of interest.

CYGNSS satellite constellation, already presented as an illustrative example in Subsection 3.2.4 could be an important model for defining the constellation pattern.

The CYGNSS Satellite Constellation operates in a non-synchronous near-circular orbit with all spacecraft deployed into the same orbital plane, orbiting 510 Kilometers above the Earth at an inclination of 35 degrees to either side of the equator[106], which correspond exactly to the criteria range recommended by 3.4.

The orbital inclination was selected to optimize the revisit time for the tropics and mid-latitudes where the vast majority of events occur that are of interest to the mission, in particular hurricanes and other tropical storms. Selecting a 35 degree inclination increases the dwell time for latitudes at the maritime area of interest. When the desired distribution of the eight satellites at 45 degrees in their single orbital plane is achieved, the constellation can achieve a mean revisit time of six hours.[107]

CYGNSS ground tracks at the end of 90 minutes and 24 hours respectively, are shown in Figure 3.5.

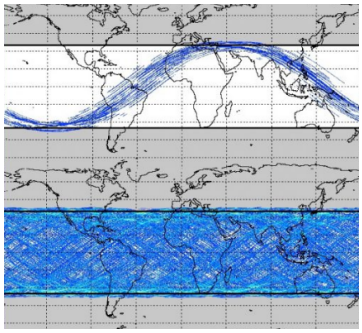

Figure 3.5: CYGNSS ground tracks at for 90 minutes (top) and 24 hours (bottom), from [6]

Another particularity regarding CYGNSS micro-satellites gives respect to their launch and posterior manoeuvres into their mission orbits. The air-launched vehicle was carried aloft by Orbital's modified aircraft, "Stargazer," which took off from a runway at Cape Canaveral Air Force Station in Florida and deployed the three-stage Pegasus XL rocket at a predetermined drop point of about 12 km above the Atlantic Ocean [106].

This solution is of great interest to this work given the fact that alternative low-cost launchers/launching systems are a large trend in the space sector, and Portugal 2030 space strategy emphasizes the technology's important role for the potential azorean space hub, as it will be explored in more detail in Section 4.1.

Orbital manoeuvres are also interesting due to their low-cost approach, which enabled each of the constellation parts to reach its correct orbital position based solely on differential drag. These systems use active attitude control methods and deployable surfaces to alter the projected area of the satellite and therefore drag profile to achieve minor differences in semi-major axis, which in its turn enables the separation of the satellites within the plane[108].

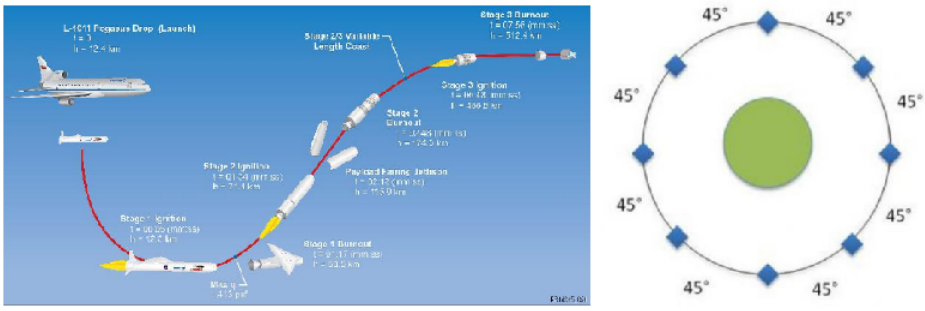

Figure 3.6: Launching system and final constellation spacing, credit: Orbital ATK

3.4 Geometry Analysis Tool

Having discussed some of the possible platforms for this mission, it becomes relevant to study and project possible orbits, simulating the monitoring conditions and efficiency.

This section begins by contextualizing GNSS systems, as well as the theoretical basis supporting both the GNSS-R and Sat-AIS technologies. It then continues with a brief summary on the GAT software, its functionalities, operation, required inputs and possible outputs.

The SARGO-Geometry Analysis Tool (GAT) is a generic Geometry Analysis Tool for GNSS-R missions, developed at Deimos Engenharia.

The purpose of the tool is to perform a geometric determination of the ground coverage footprints for a GNSS-R system, based on the analysis of specular points over the region covered by a specific GNSS receiver. The tool supports the following types of platforms where the GNSS receiver may be deployed:

- Ground-based: The receiver is at a fixed point on the ground
- Airborne: The receiver is on-board an airborne vehicle (e.g. Drone)
- Spaceborne: The receiver is on a spatial vehicle (e.g. satellite)

In this work one will opt for spaceborne vehicles, as a result of subsection's 3.1.1 discussion.

The GAT supports mission analysis and field campaigns preparation, including the following features:

1. Determine the position of the specular points on the WGS84 ellipsoid (an Earth-centered, Earth-fixed terrestrial reference system and geodetic datum) for all available GPS and Galileo satellites in the time-space interval selected
2. Having defined the antenna's beam angle, determine the antenna footprint on the WGS84 ellipsoid
3. Perform the visualisation of the specular points positions over the time in the world map, as well as displaying the antenna's beam footprint onto the Earth's surface;

This GNSS-R software will also be utilized for the sat-AIS analysis. Despite some differences between both technologies, the physical principles behind GNSS-R's simulation can be interpolated and applied to sat-AIS, requiring only small adaptations on the antenna parameters.

3.4.1 GNSS systems

GNSS systems are the basis of GNSS-R technology and therefore deserve a succinct overview. Although they all have identical usage and functions, each of these systems has its own singularities, as it is expected given their differences in the countries of origin and the start of operation.

Despite these differences, all the systems are usually divided in three segments:

- Space Segment - Composed of the satellites
- Ground Segment - Reference Ground Stations and Processing which provides navigation info encoded in the signal and reference data
- User Segment - consists in the user receivers and their main function is to receive the system signal to compute accurately position and time.

Beidou The BeiDou Navigation Satellite System, also known as BeiDou-2, is China's second-generation satellite navigation system. By 2020, the space segment will consist of a constellation of 35 satellites, which include 5 GEO satellites and 30 non-GSO satellites; 27 in Medium Earth Orbit (MEO) and 3 in Inclined Geosynchronous Orbit (IGSO) (one per plane). The intersection node is 118E and the MEOs are deployed as a Walker constellation: 24 MEOs in 3 planes plus 3 spares. Beidou's orbital parameters are presented below in table 3.9

Orbit parmts.	GEO	IGSO	MEO
Semi-Major Axis (Km)	42164	42164	27878
Eccentricity	0	0	0
Inclination (deg)	0	55	55
# Sats	5	3	27
# Planes	1	3	3
Frequencies (MHz)	1561.098, 1207.140, 1268.52		

Table 3.9: Beidou's orbital parameters[15]

The constellation has been designed in order to provide positioning, navigation, and timing services to users on a continuous worldwide basis.

Galileo Europe also has its own global satellite-based navigation system, designed to provide a number of guaranteed services to users equipped with Galileo-compatible receivers.

Its specifications are the following:

Orbit parmts.	MEO
Semi-Major Axis (Km)	23 222
Eccentricity	0
Inclination (deg)	56
# Sats	30
# Planes	3 (equally spaced)
# Operational Sats	8 equally spaced in each plane
# Spare Sats	2 spare satellite (also transmitting) in each plane
Mass	700kg class satellite
Frequencies (MHz)	1575.42, 1278.75, 1191.795

Table 3.10: Galileos's orbital parameters [16]

With this structure, there is a very high probability (more than 90%) that anyone, anywhere in the world will always be in sight of at least four satellites and hence will be able to determine their position from the ranging signals broadcast by the satellites.

From most locations, six to eight satellites will always be visible, allowing positions to be determined very accurately, to within a few centimetres. Even in high rise cities, there will be a good chance that a road user will have sufficient satellites overhead for taking a position, especially as the Galileo system is interoperable with the US system of 24 GPS satellites. Having this interoperability in mind, the inclination of the orbits was also chosen to ensure good coverage of polar latitudes, which are poorly served by the US GPS system[16].

GLONASS GLONASS is Russia's take on GNSS. Initially developed in the 1980's, the system suffered some drawbacks, namely the collapse of the Soviet Union in 1991, and the economic crisis between 1989-1999 which resulted in the space program's funding being cut by 80%, and a consequently minimum of only six operational satellites. Vladimir Putin's high priority investment restored the full constellation in 2011.

Orbit parmts.	MEO
Semi-Major Axis (Km)	19 100
Eccentricity	0
Inclination (deg)	64.8
# Sats	24
# Planes	3 (equally spaced)
Mass	750kg class satellite
Frequencies (MHz)	1246.0, 1602.0

Table 3.11: GLONASS's orbital parameters [17]

GPS The United States began the GPS project in 1973, to overcome the limitations of previous navigation systems, becoming fully operational in 1995 with the original 24 satellites. At the moment, in 2016, there are 31 satellites in use. The additional satellites improve the system's precision by providing redundant measurements. About nine satellites are visible from any point

on the ground at any one time, providing a considerable redundancy over the minimum four satellites needed for a position.

Orbit parmts.	MEO
Semi-Major Axis (Km)	26 560
Eccentricity	0.02
Inclination (deg)	55
# Sats	31
# Planes	6 (equally spaced)
Mass	1630kg class satellite
Frequencies (MHz)	1575.42, 1227.6, 1176.45

Table 3.12: GPS's orbital parameters [18]

3.4.2 GAT's Timeline Definition

A clear understanding and definition of the timeline in use during the simulations is essential, since it drives the processing epochs. This requires the input data to cover this time arc, otherwise it may result in computational errors or meaningless values.

In a computing context, an epoch is the date and time relative to which a computer's clock and timestamp values are determined. The epoch traditionally corresponds to 0 hours, 0 minutes, and 0 seconds (00:00:00) Coordinated Universal Time (UTC) on a specific date, which varies from system to system [109].

The relevant time systems for this work are briefly presented below:

Universal Time (UT1) UT1 is a time reference that conforms, within a close approximation, to the mean diurnal motion of the Earth. It is determined from observations of the diurnal motions of the stars, and then corrected for the shift in the longitude of the observing stations caused by the polar motion. It is also typically used as time reference for orbit state vectors.

Coordinated Universal Time(UTC) UTC is the time system generally used for all products dating. The UTC is piecewise, uniform and continuous, i.e. the time difference between UTC and TAI is equal to an integer number of seconds and is constant, except for occasional jumps from inserted integer leap seconds. The leap seconds are inserted to cause UTC to follow the rotation of the Earth, which is expressed by means of the non uniform time reference Universal Time UT1. If UT1 is predicted to lag behind UTC by more than 0.9 seconds, a leap second is inserted. The message is distributed in a Special Bulletin C by the International Earth Rotation Service (IERS). ΔT1 = UT1 - UTC is the increment to be applied to UTC to give UT1 (expressed with a precision of 0.1 seconds) which is broadcasted, and any change announced in a Bulletin D by the IERS. DUT1 is the predicted value of ΔUT1. Predictions of UT1 - UTC daily up to ninety days, and at monthly intervals up to a year in advance, are included in a Bulletin A which is published weekly by the IERS.

GPS Time (GPST) GPST is an atomic clock time similar to, but not the same as, UTC time. It is synchronised to UTC but the main difference relies in the fact that GPS time does not introduce

any leap second. Thus, the introduction of UTC leap second causes the GPS time and UTC time to differ by a known integer number of cumulative leap seconds; i.e. the leap seconds that have been accumulated since GPS epoch in midnight January 5, 1980. GPS Time is the time system in GPS products like SP3 orbits.

Galileo System Time (GST) GST is the Galileo System reference time. Similar to GPST, GST is obtained from the atomic clocks in the Galileo satellites and the Galileo ground control stations. Knowing the GST is important to accurately estimate the Galileo satellite positions. The selected approach uses GPST and GGTO "GPS to Galileo System Time Conversion and Parameters" to determine GST.

International Atomic Time (IAT) IAT represents the mean of readings of several atomic clocks, and its fundamental unit is exactly one SI second at mean sea level and is, therefore, constant and continuous. Δ TAI = TAI - UTC is the increment to be applied to UTC to give TAI.

All these time relations are depicted in figure 3.7

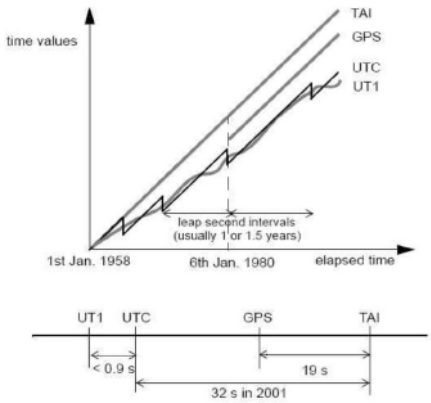

Figure 3.7: Relations between the different time systems from DEIMOS

GAT's main function is to perform the geolocation of the specular points. As a consequence, an Earth-Fixed frame is the natural reference frame to use, end-to-end. On the other hand, accurate conversion between inertial and earth-fixed frames happens only when polar motion data is available, more precisely when the time relations are initialized with an IERS Bulletin. Therefore, when polar motion data is not available, the user would need to initialize Orbit files with Earth-Fixed frame data (orbit state vectors), and to compute geolocation information in Earth-Fixed.

Not following these directives results in slightly inaccurate computations and should be avoided unless ignoring polar motion is acceptable.

In order to get consistent results, time relations and Earth orientation parameters shall be provided the IERS Bulletin B, together with the initialization of EOCFI TimeId. Being EOCFI a collection of precompiled C libraries for timing, coordinate conversions, orbit propagation, satellite pointing calculations, and target visibility calculations, provided by ESA.

3.4.3 Receiver Trajectory

As mentioned before in 3.1.1 the receiver platforms chosen for this work will be small satellites. This option has the following possible trajectory inputs, presented in table 3.13:

Orbit Format.	Description
SP3	In this case the receiver trajectory will be retrieved similarly to the GNSS orbits computation.
TLE	In this case the receiver trajectory will be retrieved similarly to the GNSS orbits computation.
Orbit State Vector file(EECFI OSV)	The Orbit State Vector OSV file is a standard file of EECFI containing the positions and velocities that shall be used to make the OrbitId initialization. The trajectory values in the timeline epochs are computed interpolating the input data.
Orbit Scenario File(EECFI OSF)	The Orbit Scenario File contains orbital parameters that are used typically to characterize Earth observation satellites (e.g. longitude of ascending no, repeat cycle, etc). The orbit computation is performed using EECFI mean Kepler propagation.

Table 3.13: Possible trajectory input files for GAT software

As referred in Subsection 3.3.3 CYGNSS orbit could be a good starting point for this mission's orbit and the chosen format will be Two-Line Element (TLE) as a result of its high popularity and ease of use.

3.4.3.A Keplerian Elements

An orbit can be defined as the gravitationally curved trajectory of an object, resulting from the attractive forces between two celestial objects. If one only considers the attractive force between two masses, the motion of mass m_1 relative to another mass m_2 is defined by the following differential equation:

$$\frac{d^2r}{dt^2} + \frac{G(m_1 + m_2)r}{r^3} = 0 \tag{3.1}$$

For the case of an artificial satellite we can consider earth's mass as m_1 and the satellite's mass as m_2. Due to large disparity between the two masses, one can assume that satellite's mass does not affect the motion of m_1, which will be represented as M. This simplifies Equation 3.1 into the following[110]:

$$\frac{d^2r}{dt^2} + \frac{GMr}{r^3} = 0 \tag{3.2}$$

The integration of Equation 3.2 yields six constants of integration, which are usually known as orbital elements. These elements are illustrated in Figure 3.8:

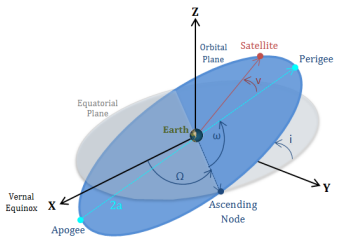

Figure 3.8: Keplerian elements from [7]

The six Keplerian elements are presented below, based on [7]:

a**: Semi-major axis of orbital ellipse** is the semi-major axis of the ellipse defining the orbit

e**: Numerical eccentricity** of the orbit is the eccentricity of the orbital ellipse. Eccentricity is a measure of how an orbit deviates from circular. A perfectly circular orbit has an eccentricity of zero; higher numbers indicate more elliptical orbits

i**: Inclination of orbital plane** is the angle between the orbital plane and the equator

Ω**:Right Ascension of Ascending Node (RAAN)** defines the relative angular phasing between the orbital plane and the Vernal Equinox, which is the point of intersection between the Sun's trajectory and the Earth's equatorial plane

ω**: Argument of perigee** is the angle between the ascending node and perigee directions, measured along the orbital plane. The perigee is the point of closest approach of the satellite to the centre of mass of the earth. The most distant position is the Apogee. Both are in the orbital ellipse semi-major axis direction

v**: True anomaly** is the geocentric angle between perigee direction and satellite direction. The sum of the True Anomaly and the Argument of Perigee defines the "Argument of Latitude". For a circular orbit ($e = 0$) the Argument of Perigee and the True Anomaly are undefined. The satellite position, however, can be specified by the Argument of Latitude.

These elements are essential for orbit characterization and are components of the TLE file, explained in detail in the next subsection.

3.4.3.B Two-Line Elements

Originally used by NASA and by the North American Aerospace Defence Command, TLE present the most comprehensive and up-to-date source of Earth-orbiting objects and are key in many monitoring and analysis activities [111]. The earth-centered inertial frame used for the NORAD two-line elements is sometimes called True Equator Mean Equinox (TEME), although it does not use the conventional mean equinox. Figure 3.9 presents below the breakdown of TLE format:

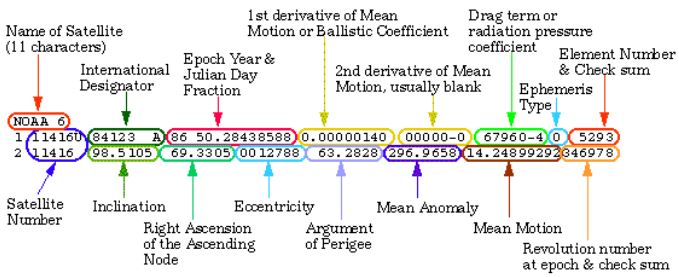

Figure 3.9: Definition of Two-line Element Set Coordinate System, from [8]

A brief description of the various components is the following:

Inclination, RAAN, Eccentricity, Argument of perigee and Mean Anomaly were already described in the previous subsection

Name of Satellite Name associated with the satellite, as the cases of "Mir" or "ISS"

International Designator (84 123A) The 84 indicates launch year was in 1984, while the 123 tallies the 124th launch of the year, and "A" shows it was the first object resulting from this launch

Epoch Date and Julian Date Fraction The Julian day fraction is the number of days passed in the particular year. For example, the date above shows "86" as the epoch year (1986) and 50.28438588 as the Julian day fraction meaning a little over 50 days after January 1, 1986

Ballistic Coefficient (0.00000140) Also called the first derivative of mean motion, the ballistic coefficient is the daily rate of change in the number of revs the object completes each day, divided by 2. Units are revs/day.

Second Derivative of Mean Motion (00000-0 = 0.00000) The second derivative of mean motion is a second order drag term in the SGP4 predictor used to model terminal orbit decay. It measures the second time derivative in daily mean motion, divided by 6.

Drag Term (67960-4 = 0.000067960) Also called the radiation pressure coefficient (or BSTAR), the parameter is another drag term in the SGP4 predictor.

Element Set Number and Check Sum (5293) The element set number is a running count of all 2 line element sets generated by USSPACECOM for this object (in this example, 529). Since multiple agencies perform this function, numbers are skipped on occasion to avoid ambiguities. The counter should always increase with time until it exceeds 999, when it reverts to 1. The last number of the line is the check sum of line 1.

Satellite Number (11416) This is the catalog number USSPACECOM has designated for this object. A "U" indicates an unclassified object.

Mean Motion (14.24899292) The value is the mean number of orbits per day the object completes. There are 8 digits after the decimal, leaving no trailing space(s) when the following element exceeds 9999.

Revolution Number and Check Sum (346978) The orbit number at Epoch Time. This time is chosen very near the time of true ascending node passage as a matter of routine. The last digit is the check sum for line 2.

Making use of a website such as Celestrak [112], one can find an open-source repository of TLE for satellites with scientific and educational purpose.

TLE elements for the CYGNSS constellation are displayed in Table 3.14:

CYGNSS Constellation TLE parameters
CYGFM01
1 41887U 16078D 17293.52754163 .00000577 00000-0 33026-4 0 9992
2 41887 34.9540 327.6877 0016580 19.5856 340.5489 15.13713221 46840
CYGFM02
1 41886U 16078C 17293.53108753 .00000576 00000-0 32718-4 0 9996
2 41886 34.9597 326.8948 0015280 18.0840 342.0413 15.14051779 46853
CYGFM03
1 41891U 16078H 17293.51770490 .00000611 00000-0 34269-4 0 9996
2 41891 34.9561 325.7507 0013262 17.9843 342.1335 15.14394321 46855
CYGFM04
1 41885U 16078B 17293.50218908 .00000603 00000-0 33998-4 0 9998
2 41885 34.9505 326.4461 0014556 18.8309 341.2938 15.14192325 46856
CYGFM05
1 41884U 16078A 17293.51986428 .00000582 00000-0 33329-4 0 9991
2 41884 34.9573 327.6997 0016206 18.6460 341.4842 15.13731206 46848
CYGFM06
1 41889U 16078F 17293.54238246 .00002288 00000-0 12357-3 0 9999
2 41889 34.9590 326.0217 0013999 16.9883 343.1295 15.14334387 46858
CYGFM07
1 41890U 16078G 17293.52317732 .00000614 00000-0 34411-4 0 9994
2 41890 34.9529 325.7220 0013770 18.3534 341.7672 15.14390490 46858
CYGFM08
1 41888U 16078E 17293.49454920 .00000666 00000-0 37672-4 0 9997
2 41888 34.9511 327.3490 0015709 19.3990 340.7317 15.13920376 46838

Table 3.14: CYGNSS Constellation TLE parameters

3.4.4 Analysis of the results

GAT simulator requires several parameter inputs, being the more critical the TLE files for the GNSS constellations and our proposed platforms.

For the GNSS, one considered a combination of BeiDou, Galileo, Glonass and GPS, which translates in all the major GNSS systems. For further simulations one can consider the further incorporation of the Japanese our Indian constellation as a mean of widening the available data-sources.

For the deployed platform one considered the parameters defined in Table 3.14, which follow recommendations from Section 3.3.1, specially regarding the 35 degree inclination, defined due to technical constraints intervals and the case example of CYGNSS.

In order to provide a proper assessment the simulations must however be submitted to a sensitivity analysis regarding the specular points covered per epoch as a function of the constellation's inclination. To achieve this, TLE parameter files, similar to Table 3.3.1 were created, for each 1 degree variation

of inclination, ranging +-5 degrees, translating into a range between 30 and 40 degrees.

The results obtained are presented below in Figures 3.10,3.11 and 3.12

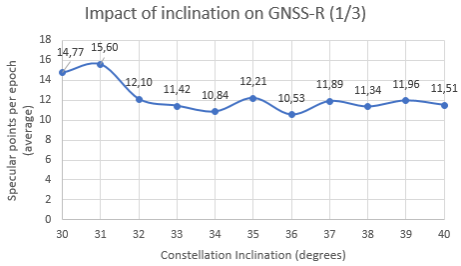

Figure 3.10: Average Specular Points per Epoch vs. inclination

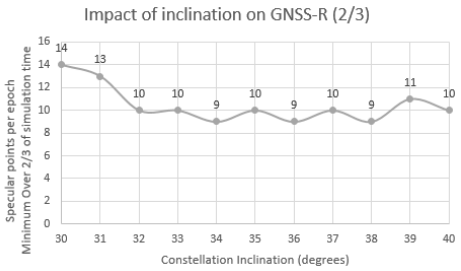

Figure 3.11: Average Specular Points per Epoch during 2/3 of mission

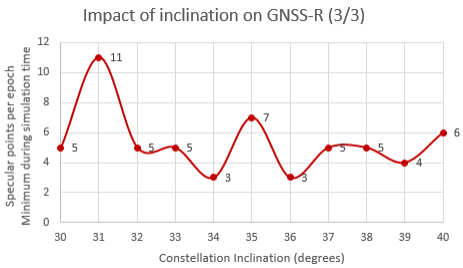

Figure 3.12: Minimum Specular Points per Epoch during the mission

As GNSS-R's data quality is directly proportional to the number of specular points, an optimal configuration would be the one presenting the best indicators for the three dimensions of specular point detection:

Average of specular points detected Employed to translate the inclination that is capable of providing the most data points on an overall basis

Minimum specular points over 2/3 of simulation time Used to detect outliers capable of achieving good averages due to a combination of "high-visibility" periods and undesired "blackouts"

Minimum specular points detected in absolute Chosen to assess the reliability of each inclination as way of ensuring that the data points would never go below a given threshold

From the previous figures it is visible that the optimal inclination would be at 31 degrees. At this degree of inclination the constellation is capable of achieving the highest average of specular points

per epoch while ranking second in the minimum number of specular points over 2/3 of the mission period (i.e. over 2/3 of the mission, for 31 degrees, the constellation will always detect 13 or more specular points). Absolute minimum of detected specular points can be used as a tiebreaker criterion from where the 31 degree configuration emerges as an obvious leader with more than 50% of the second classified (35 degrees).

Summarizing all the recommendations and constraints listed on this chapter it results that the constellation should have the following parameters:

Proposed Constellation TLE parameters
CONST01
1 41887U 16078D 17294.18709196 .00000586 00000-0 33540-4 0 9992
2 41887 30.9540 323.5964 0016506 25.5521 334.6003 15.13714104 46940
CONST02
1 41886U 16078C 17294.19049007 .00000583 00000-0 33066-4 0 9990
2 41886 30.9596 322.8025 0015205 24.0424 336.0995 15.14052620 46957
CONST03
1 41891U 16078H 17293.51770490 .00000611 00000-0 34269-4 0 9996
2 41891 30.9561 325.7507 0013262 17.9843 342.1335 15.14394321 46851
CONST04
1 41885U 16078B 17293.50218908 .00000603 00000-0 33998-4 0 9998
2 41885 30.9505 326.4461 0014556 18.8309 341.2938 15.14192325 46852
CONST05
1 41884U 16078A 17294.17940681 .00000593 00000-0 33909-4 0 9991
2 41884 30.9573 323.6084 0016129 24.6085 335.5393 15.13732119 46941
CONST06
1 41889U 16078F 17293.54238246 .00002288 00000-0 12357-3 0 9999
2 41889 30.9590 326.0217 0013999 16.9883 343.1295 15.14334387 46854
CONST07
1 41890U 16078G 17294.18243148 .00000627 00000-0 35123-4 0 9991
2 41890 30.9529 321.6282 0013700 24.3231 335.8125 15.14391427 46950
CONST08
1 41888U 16078E 17293.49454920 .00000666 00000-0 37672-4 0 9997
2 41888 30.9511 327.3490 0015709 19.3990 340.7317 15.13920376 46834

Table 3.15: Proposed Constellation TLE parameters

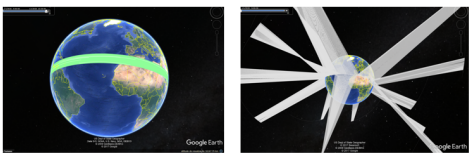

Figure 3.13: GAT's simulation Kmz output of satellite swath for 35 degree inclination and output of satellite and GALILEO swaths for 35 degree inclination

4

Assessment of Opportunities

Contents

4.1 Cubesats and Portugal's 2030 space strategy

Portuguese space-related activities, which includes satellite operations, are usually developed under ESA banner or in strict cooperation with its member states. In this way, ESA centralizes budgets and efforts for pursuing the common goals of its 22 member states. Despite following this common strategy, each of these members, has its own governance structures and strategic priorities as a result of its national context and geopolitical aspirations.

The development of a space strategy, which maps the policies and activities of interest for the years to come, reveals itself of extreme importance. With this instrument the country is not only more capable of steering and influencing ESA with its contributions but also of finding external partners who share the same interests and specificities, as way of benefiting from synergies and closer cooperation.

The objective of this section is to explore the Portuguese Government 2030 space strategy's objectives and make the case for cubesats as MCS agents, framing it as a critical project to develop and a mean to achieve the proposed strategic goals.

4.1.1 Strategic Objectives

The referred programme [113] intends to present the paths capable of generating the most value from future investments in space activities, both in economical terms and building of capabilities for young Portuguese engineers, scientists and entrepreneurs.

Its three main strategic objectives are the following:

- To stimulate economic growth and creation of skilled jobs through market uptake and exploitation of satellite data and signals
- To foster generation of satellite data through new space technologies, space-related infrastructures in Portugal and international technological partnerships
- To contribute to the development of Portugal and to strengthen its diplomatic relationships and international cooperation, leveraging its geographic location as well as its historical and economical ties

These three objectives are then translated into three major axes which are presented below. These axes and the actions to be developed under the framework are fully detailed in [113], however in this work one will focus in the ones that apply to Cubesats as a solution for ocean monitoring, supporting its role as the flagship technology for the Portuguese space sector.

4.1.2 Strategic Actions

The previously mentioned actions are the following:

1. **Exploit space data through space-based and space-enabled services and applications**
   - Promote a set of demonstrator activities in Portugal supported in partnerships and considering specific projects with the European Commission and its executive agencies, including EMSA for maritime surveillance and European GNSS Agency (GSA) for satellite navigation
   - Stimulate the participation of Portugal in areas such as governmental satellite communications ("GovSatCom") and space surveillance and tracking, at both European and international level
   - Encourage further technology and knowledge transfer initiatives between space and non-space, supporting both spin-in and spin-off activities aligned with the increasing use of COTS components in space systems
2. **Build and operate space infrastructure and data generation services, with emphasis in small satellites, launcher services and potential space port; extend also existing satellite monitoring and tracking services**
   - Foster innovative and environmentally responsible launching technologies, enabling the growth of the small-satellite markets and envisaging disruptive operation approaches, including the attempt to promote an "open spaceport" in a way to leverage international cooperation with a wide range of space value-chain actors
   - Development and construction of miniaturised satellite platforms, with an increasing use of COTS components, flexible multi-purpose sensors and state-of-the-art energy and orbit management technologies
   - Deployment of large inter-connected constellations in domains such as Earth observation and satellite navigation
   - Hosting strategic ground-based infrastructures that enable the operation of current and future spacecrafts, improving access to satellite data and signals
     - Development of a "new-generation" spaceport in the Azorean archipelago, or the potential installation of a sea launching facility in the Portuguese EEZ
     - Promote the installation of a 15m-antenna in the Island of Santa Maria, Azores, by the end of 2017, in close cooperation with ESA
     - Install other major antennas for satellite tracking and reception of Earth observation data

This programme will be fulfilled by leveraging the following international partnerships, being some of them already in motion:

- **Spain** - Through a partnership in the area of launchers
- **France** - Through cooperation in developing a micro-satellite for communications
- **United Kingdom** - Through a partnership to develop a nano-satellite constellation

- **Germany** - Through cooperation in the fields of supporting entrepreneurship, attracting private funding, satellite surveillance & tracking and launchers
- **USA** - Through partnerships in developing micro-satellite series, launchers and data science
- **Brazil** - To play a part in the development of the micro-satellite series
- **China** - To involve in the development of the micro-satellite series
- **South Korea** - Through a partnership for the development of nano-satellites

3. **Build national capabilities and skills allowing for the long-term sustainability of space infrastructure, services and applications**
   - Promoting a "Collaborative Laboratory" in satellite and space applications, facilitating a risk sharing partnership involving private and public institutions
   - Promoting the involvement of universities to foster space applications and related technologies, namely through of a series of "Hackaton-type" events

Despite the large number of countries already enrolled in these partnerships, it should also be sought the coordination and involvement of the following additional players in nano-satellite and micro-satellite constellations. This dialogue should be pursued mostly due to these countries' natural condition of key maritime players (as figure 4.1 suggests), but it should also take into account their geographic location, which can divide them into two categories:

- Countries to involve in a future "Atlantic Space Hub/ Atlantic International Research Center" - **Canada, Denmark, France, Ireland Mexico, Norway**
- Countries to involve in global MCS nano and micro-satellite constellations and ocean-related space activities- **Australia, Chile, Indonesia, Japan, New Zealand, Russia**

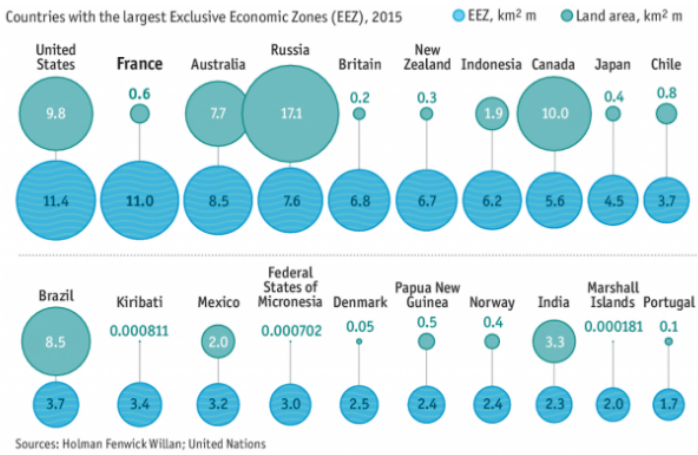

Figure 4.1: Countries with the largest EEZ (2015), from [9]

4.2 Strategy Implementation

To put the strategy addressed in Section 4.1 into practice, it is of interest to assess two essential topics, which will be detailed in Section 4.2.2:

1. Portugal's capacity of influencing ESA projects and strategy
2. Fit between the Portuguese and other ESA countries space strategies

The first topic will dwell on comparing the Portuguese contribution to ESA's budget, and the number of nationals employed in the agency, to Portugal's peers. This comparison will be used as a proxy for the country's commitment with the agency and capacity of implementing its own agenda.

The second topic will be focused in comparing space governance and strategic priorities of ESA state members, according to Sagath's methodology and with a special focus on the agency's smaller members (based on their annual contributions), a group of countries that includes Portugal.

4.2.1 Portugal's capacity of influencing ESA projects and strategy

Portuguese contribution to ESA budget can be examined in two dimensions: In absolute terms and as a percentage of GDP. One can consider that the former translates into a *de facto* influence factor over the direction an organization can follow, much like a major shareholder has control over the destiny of its company. Countries' contributions as percentage of GDP result in a very good approximation of each country's commitment with a project, since that even if the contribution appears to be small, when compared to economically stronger countries, it still is a product of a country's effort, investment and support for a given cause.

As figure 4.2 illustrates Portugal's contribution to ESA funding, for the year of 2017, represents a mere 0,5% of total members contribution, corresponding to 17M Euro.

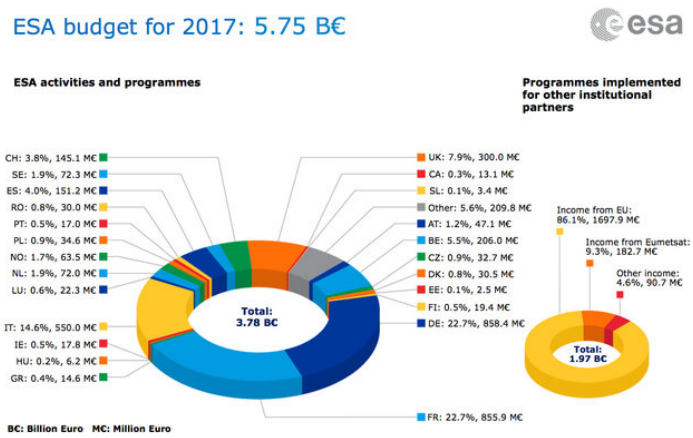

Figure 4.2: ESA 2017 budget, segmented by source of funding [10]

It is relevant to notice that the only EU countries that rank below the Portuguese contribution are Hungary, Greece, Slovenia and Estonia. This fact can be justified by the recent crisis and adjustment processes that recently affected the country, however it also suggests that if the country is willing to use space as a flagship sector for innovation and capability building, this is a factor to take into account.

One can deep-dive in this topic by exploring the national contribution as percentage of GDP, adjusted to Purchasing Power Standard (PPS), which converts GDP into artificial common currency values. Figure 4.3 is calculated based on 2017 member funding divided by its 2016 PPS-adjusted GDP.

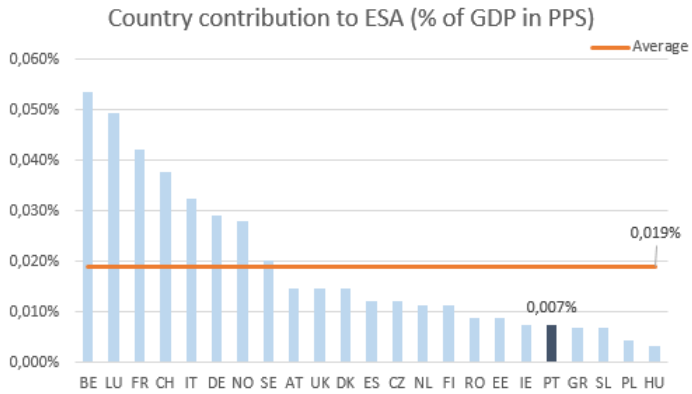

Figure 4.3: Country contribution to ESA 2017 budget, % of PPS adjusted GDP from Eurostat

Once again the 0.007% of 2016 GDP are well below the values paid by its peers, being the average percentage of contribution almost three times higher. Once again the financial crisis affecting the country can somehow explain these values, as it is demonstrated, in Figure 4.4, by the progressive increase in investment in the sector since 2012, one year after the intervention of the Troika institutions.

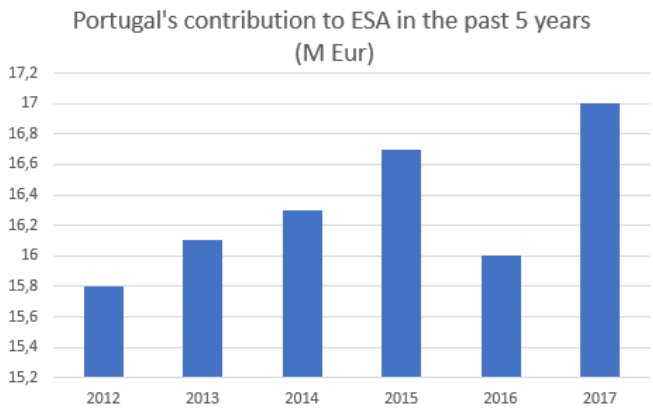

Figure 4.4: Portuguese annual contribution to ESA from 2012-17, source ESA

The exception is made with the momentary decrease experienced in 2016, but recent declarations of the Minister responsible by the sector exhibit signs of return to the sustainable growth path, with promises of increasing the contribution up to 19 M€[114]. This fact is important not only in the perspective of having space as a flagship for innovation, technological development and high-skilled job creation, but also, as mentioned before in Section 1.4.3, due to the fact that **every Euro invested in ESA generates a return of 2 onto the national economy**.

Another relevant metric resides on the formation of high-raking scientists and engineers currently working at ESA. The space agency presently employs around **2,300 employees** from the various member states, including a total of **28 Portuguese nationals**. The number of employees per M€of contribution to ESA is presented in Figure 4.5.

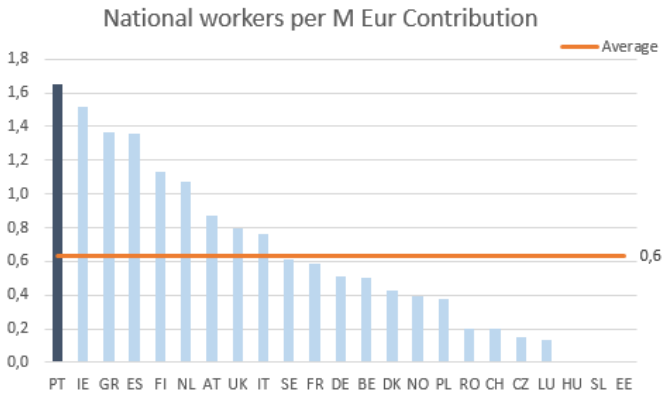

Figure 4.5: National workers for M €of investment in ESA, [11]

Unexpectedly Portugal leads the ranking with 1.6 national collaborators at ESA for every million Euro of contribution, a value three times higher than the European average.

This over-representation of Portuguese scientists and engineers provides the following takeaways:

- Incorporating more skilled workers into ESA ranks should be expected to be accompanied by an increase in Portugal's contribution, as the European organizations tend to prevent representation imbalances
- Portuguese space-skilled workers are as capable or more than their European counterparts, which should encourage the investment in this sector from the government but also from the private sector, especially in hiring this talent to leading roles in their companies and projects.
- The large number of current ESA Portuguese employees and also *alumni*, suggests that there is the know-how and capabilities to implement and lead proposed projects like the Azorean space-port or the Atlantic International Research Center.

4.2.2 Fit between the Portuguese and ESA countries space strategies

During the last years ESA experienced an increase in its number of members, a result of the entrance of Estonia in 2016 as the 21st member and Hungary as the 22nd state to sign the Accession Agreement. These adhesions impelled newcomers to define their space strategy and policy, as well as their space governance. Simultaneously this constant-changing European space landscape may lead to other states having to consider to revise their established strategy, policy and governance alike.

Sagath focus his work in the comparison between ESA's 11 smaller states space strategies and the member state group as whole[115]. In this thesis one will build upon his work and implement this methodology to assess Portugal's Space 2030 directives. In the outcome of this exercise it will be possible to identify which Portuguese aspirations fall under ESA scope and strategy, which should be pursued in cooperation with Atlantic or other non-European partners, and also possible recommendations to be attached to the 2030 strategy.

Essential areas considered for benchmarking are:

- Ministry responsible for space
- Priorities for space in technology domains

- Priorities for space in areas of sustainability
- Motivations for space

For ease of understanding in each figure policies followed by Portugal will be marked with the value corresponding to all ESA members, that is 22 states. In this way the more a Portuguese policy is followed by other members, the closer it is from the Portuguese line. In cases where a policy is followed by every state member then the marks will coincide. On the other side, the more a Portuguese policy is isolated the more distant will be respective lines.

4.2.2.A Ministry responsible for space

Most countries opt for attribute space affairs to the Ministries responsible for Science, Research or Education, as it is the case of Portugal, where the responsibility falls under the Ministry of Science, Technology and Higher Education as exhibited in Figure 4.6.

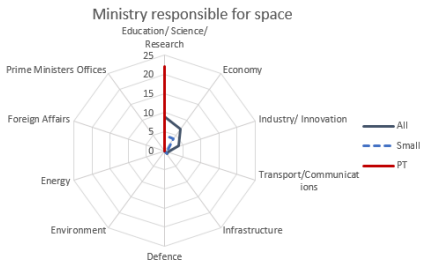

Figure 4.6: Ministry responsible for space in every ESA member state

Some recent trends include a change in the responsible Ministry, which can enable the restructuring of the strategic priorities of a given state. That was the case of Luxembourg which shifted its space sector from its Ministry of Education into the Ministry of Economy. This new approach brought a new dynamic for the Luxembourgian space strategy and policy via the so called SpaceResource.lu Initiative. The new objectives set by the Ministry of the Economy favoured the focus on the exploration and commercial utilization of resources from Near Earth Objects through the establishment of an appropriate legal and regulatory framework for private entities to endeavour in space resource exploitation[115]. This example is relevant for Portugal as result of the recent boom experienced in its start-up ecosystem, from which the hosting of WebSummit is an example. The exponential growing in Cubesat's and other space downstream applications could benefit dramatically from interactions and joint projects with the entrepreneurial and developer communities, usually under the Secretary of State for Industry and respective Ministry of Economy.

This trend is supported by an increasing involvement of other ministries in the definition and implementation of space strategy, policy and programme, in virtue of the rise of downstream space sector interests, such as the technology and applications for agriculture, energy, transport, telecommunications, environment, security and defence, etc.

Another trend that confirms the path being pursued in the 2030 Space strategy is the creation of space agencies by several state members during the last couple of years. Countries such as Austria(ALR), France(CNES), Germany(DLR), Italy(ASI), Romania(ROSA) and UK(UKSA) were joined

by the likes of Luxembourg (Luxinnovation in 2017) and Poland(POLSA which became operational in 2015)[115]. The option for a space agency, with its enlarged scope, promoter role and capability to perform in-house research endows the country with the resources to seize the emerging opportunities in the new space sector paradigm.

4.2.2.B Priorities for space in technology domains

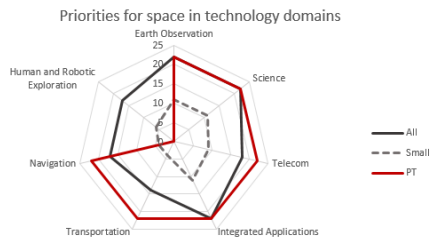

Figure 4.7: Priorities for space in technology domains for every ESA member state

Figure 4.7 demonstrates clearly that a Cubesat mission incorporating Sat-AIS and GNSS-R is fully aligned with Space 2030 objectives and general state-member strategy, given the support for Earth Observation, navigation and transportation. The smaller number of countries pursuing transportation application is justified with the geographic location of some countries, probably with reduced borders and areas of land and sea. However this result should hint Portuguese space authorities into cooperating with international partners who share the same challenges and objectives for this specific topic.

Furthermore it is important to note the support by all member-states of Earth Observation, Science and Integrated Application, probably a result of the expected potential of the development of the downstream space sector.

Human and Robotic Exploration is not actively followed by Portugal or the majority of smaller states as its fully deployment requires large investments of which these countries are not capable of. Nonetheless this area should be further explored as it could present important opportunities for Portuguese collaboration due to the relevant Robotic scientific community, know-how and expertise already existing in the country.

4.2.2.C Priorities for space in areas of sustainability

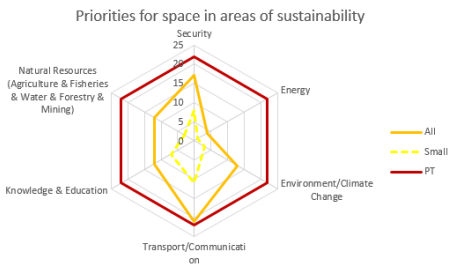

Figure 4.8: Priorities for space in areas of sustainability for every ESA member state

This metric will be the more affected by each country specificities in terms of historical, geopolitical, economical, geographical, financial and political position and outlook. Countries with considerable natural resources will tend to support policies capable of serving these interests, and as mentioned in the previous sub-section, States with long borders, will attribute more relevance to the topic of security, as an area to which space can contribute.

The field of transport and communications is flagged as a critical area to benefit from space operations, once again reinforcing the case for a Sat-AIS Cubesat constellation.

One should also refer that Small Member States show substantially less interest in two areas: energy and environment. Among these, Portugal appears as the sole member interested in space applicabilities for the energy sector in the hope of developing solutions for monitoring wind farms. The also diminished number of supporters of space-based energy solutions among the overall organization suggests that this is an also an area in which Portugal can benefit from developing strategic close partnerships with leading satellite and wind-energy European players (as it is the case of Germany) or non-European (from which the United States and China are leading examples).

It is also important to note that the Portuguese government presents all the six dimensions as ”priorities” to be addressed in the 2030 space framework. Being this a strategic document, it should narrow its focus to a reduced number of first-level true priority objectives, converting the remaining into secondary ones.

The fact that a MCS constellation of Cubesats could be a valuable instrument for the most addressed areas: Security, Transport and Environmental, reinforces its possible role as a flagship project for the 2030 strategy.

4.2.2.D Motivations for space

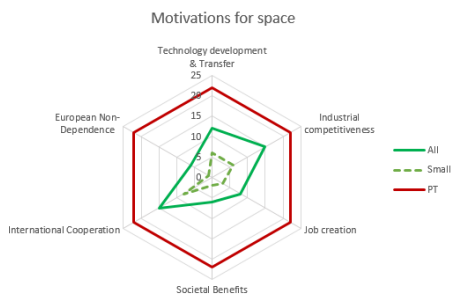

Figure 4.9: Principal motivations for space for every ESA member state

According to [115] most common motives for engaging in space activities are busting industrial competitiveness, engagement in international cooperation, technology development and transfer, job creation, European non dependence, and societal benefits. As illustrated by Figure 4.9, developing the industrial competitiveness is the principal objective of the member-nations, with the desire to promote and foster international cooperation achieving the second place. Investments in space are seen by countries as means to enhance the competitiveness of their respective space and space related industries and skilled workforce. Closely linked to the objective of industrial competitiveness is the potential for technology transfer from space into terrestrial commercial applications . European non-dependence is

also an important rationale for public investments in space, especially for the larger Member States, willing to access independently to critical satellite technology in navigation, communications and earth observation for decision making.

By examining Figure 4.9 it is clear that Portugal's Space 2030 and the proposed Cubesat mission target the major motives and benefits of space explanation. Due to its high-cooperative, and simultaneously state-of-the-art/Off-the shelf nature, it could be a privileged mean of International cooperation, Technology transfer and development, increase in industrial competitiveness and creation of highly-skilled jobs.

4.3 Value Chain Analysis

The satellite industry ultimate objective is to supply government agencies, commercial companies and increasingly the everyday consumer with solutions for a wide range of fields (e.g. climate, navigation, medical, communication...). Technology improvements, reliance on COTS technology, and freely accessible data have all contributed to increasingly specialized functions within the commercial satellite sector. The entity that launches, operates, and collects satellite imagery may be different from the entity that analyses the data, which may be different from the entity that stores the information and processing power.

The several levels of the satellite value chain are depicted below in Figure 4.10.

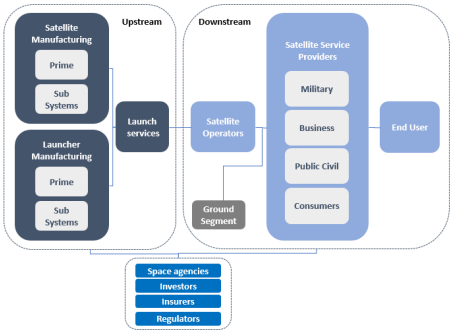

Figure 4.10: Value chain of the satellite industry

Government agencies In charge of funding space technology R& D for their own uses, along with developing the space policy and strategy and the management of procurement contracts

Space industry upstream A level until recently reserved to a limited number of players, with the funds and know-how to design and manufacture this type of space systems and their launch vehicles. With the recent developments in lower cost solutions this range of candidates was widened, enabling the entrance of new disruptive players

Satellite operators Own the satellite systems and market their capacities to the service providers (downstream) who deliver communications, navigation and geographic information services to the final users by integrating the satellite signal into packaged solutions

Ground segment and terminal suppliers Design and deliver a large variety of software and equipment for both the management of satellite infrastructure, and for the access to services by the users. Customers stand along the value chain.

Satellite service providers The final users, whether governmental (civil/military) or commercial (business or customer), do not ask for the satellite technology per se but for solutions tailored to their needs. For this mission this will be the ship location provided by the Sat-AIS technology and sea altimetry and other relevant variables of interest supplied by the GNSS-R instrument

The global satellite industry has been growing fast in the last 5 years and presents the following key financial figures:

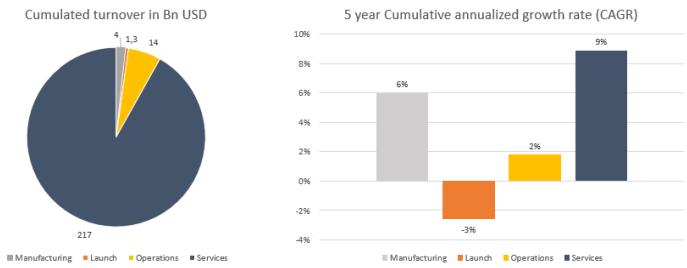

Figure 4.11: 2012-16 Cumulative turnover and CAGR for the different levels of Satellite value chain, source Euroconsult

These results displayed illustrate three main conclusions:

- **Services are the dominant source of revenue** which is a good indicator for Portugal and a segment to leverage regarding the recent boom in the country's Start-Up ecosystem [116]
- **Manufacturing and services have been thriving during the last 5 years** which supports the claims of the space sector as a sector in expansion and capable of generating economical and technological benefits
- **Launcher segment has been decreasing during the last years** which can present an opportunity for low-cost solutions, such as the ones Portugal is planning to explore in Azores

Manufacturing challenges for the satellite and its subsystems were already explored in Section 3.2.2. Launching systems on their turn are currently experiencing a disruptive moment, presenting various low-cost opportunities of entering this level of the chain.

Some of these launching technological challenges[117] are presented below:

- Heavy/Medium launchers
  - Adapters - such as ESPA, a payload adapter ring for launching secondary payloads
  - Space Tugs - which are a type of spacecraft used to transfer payloads from LEO to higher-energy orbits
- Dedicated Launchers
  - Air Launcher - Multi-stage rockets to be launched from modified aircraft, acting as airborne launch pads, to increase performance[118] (e.g. Virgin's Launcher One, SOAR)
  - Small Launcher - Launchers specifically designed to carry Cubesats, launching a fraction of the normal weight for a fraction of the regular cost, vs. current piggy-back solutions. These

launches are usually done in private-built and owned launching sites, permitting a more frequent access to space. Examples of this are Rocket Lab's Electron and Firefly's Alpha

Portuguese and international companies, in close collaboration with investigation centres and agencies could work on some, or a combination, of the listed launching solutions for the Azores. An alternative launching pad, enables an independent access to new orbits at a much faster pace and benefiting from the high demand for smallsatellite launches for the new future. As an example, Rocket Lab's private-owned launching complex is licensed to conduct a launch as frequently as every 72 hours. According to the CEO, however, the company expects to carry out a launch about four to five times per month, which is still a dramatic improvement in launching frequency[119].

4.4 Economical and Strategical Impacts

The purpose of this chapter is to recommend a methodology to assess not only this mission's economical and strategical impact, but also the impact of projects to be developed by the future Portuguese Space Agency, based on extensive literature research.

Investments in space generate a wide range of impacts across industries and companies, either directly or indirectly. Space research has been responsible for developing innovative materials and technologies throughout the years and with a multitude of uses: in consumer products, manufacturing industries, intelligence and defence.

Space activities are also responsible for generating high amounts of knowledge, responsible responsible for increasing the pace of innovation, decreasing production costs and constituting an asset for further utilization. 4.12 summarizes the logical flow of investments, outputs and impacts for this sector.

A correct assessment of these effects is then extremely important to validate the several options taken to implement a space strategy. It can also be used to evaluate and compare competitor applications for a given project, across multiple dimensions and to rank them in terms of impact and feasibility.

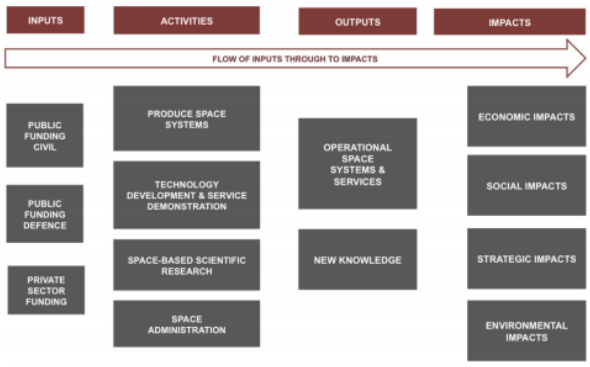

Figure 4.12: Space sector flow of impact, from [12]

According to the literature [13] the first classification to be taken into account is the difference between quantifiable and unquantifiable effects (i.e. the ones which can be measured and the ones which cannot). The majority of economical effects fall under the quantifiable category (e.g. jobs, units produced), while pride or discontentment fall under the unquantifiable category.

Ways of assessing and quantifying unquantifiable effects usually pose the biggest challenge in these assessments, and require extensive work to identify and select appropriate proxy indicators. Once these become available, and are considered reliable, can be moved into the quantifiable category.

4.4.1 Quantifiable effects

Quantifiable effects can be segmented in the following categories:

Direct effects Comprises all effects on the space sector itself, including investment and additional production. Within the space industry, these effects can be distributed along upstream or downstream operations, as explored in Section 4.3

Indirect effects Indirect effects are also caused by the investment and additional production in the space sector, but arise as additional investment and production in other sectors. The size of the indirect effects depends, besides the size of the investment or additional production, on the extent of the linkages between the space sector and the other sectors influenced by it. These indirect effects can also be subdivided in the following categories

- Backward Linkages - Consists in inputs or half products required by the space sector
- Forward Linkages - Comprises deliveries from the space sector to other sectors
- Induced effects - Additional household spending in the local economy. For example the spending done by employees who work on a satellite project, which leads to higher turnover, employment and profits in the involving area

4.4.2 Unquantifiable effects

Unquantifiable effects on their turn can be segmented in the following categories:

Strategic effects Although they cannot be quantified, strategy takes an important role in the effects of the investment. The main strategical focus used to be defence, however in Europe strategic effects are currently more directed towards influence in international politics and science, being space exploration a critical venue for countries to cooperate

Competitiveness and reputation take an important part in the strategic effects, resulting in long term effects on the political position of a given country. These long term effects include:

- Effects on innovation such as new production methods, better capital goods or better consumer goods
- Effects on labour productivity and capital intensity
- Effects on the competitive position of sectors among countries
- Effects on the standing of countries in Europe and in the world - e.g. The Apollo programme increased the scientific and technological reputation of the government, and also the levels of internal confidence in the government [13]

These effects are important in the space industry, as it provides and develops innovation and knowledge intensively. They can be further maximized with development of clusters (e.g. Aerospace valley in Toulouse, or the Portuguese Aeronautic cluster in Evora) which develop a positive feedback reinforcement between companies' economic and knowledge development

Societal effects These effects address the quality of life of individuals, based on indicators such as health or happiness. Space being a key vector of globalization, international deregulation and integration of peripheral areas. All these effects are very difficult to quantify, however their importance to today's society is determinant and must be taken into account when assessing different types of programmes, investments and projects.

Great efforts are made to find proxies to help quantifying strategical and societal effects, which by being quantified can be compared and integrated in broader analyses. Some examples of mechanisms used to achieve this goal are the use of Quality-adjusted-life-years as a proxy for health effects, or the utilization of willingness-to-pay of citizens to prevent pollution for the value of natural resources. The application of these techniques enables the scope of economic methodologies to be enlarged and more relevant to space policies.

4.4.3 Suggested Methodology

Scientific literature segments the type of methodology to use into Monetary and Non-monetary methodologies. Monetary methodologies include computable general equilibrium analysis, cost effectiveness analysis, cost benefit analysis and social return on investment, whereas non-monetary consist of impact assessment and multi criteria analysis [12].

The detailed assessment of each of these methodologies, including the advantages, disadvantages and outcomes they present, it is not part of the scope of this work. As result of this, one will base this subchapter in the conclusions of Simmonds [12], detailing his proposed methodology and applying it into the Portuguese context.

His recommendation is that the best method to assess the impacts of space investments is a combination Social Cost-Benefit Analysis (SCBA) and multi-criteria analysis, which they name "SCBA-plus". The plus represents the effects that are hard to monetize or measure, like the previously mentioned strategical and societal effects. In short, the SCBA part intends to objectively weigh effects where possible, while the "plus" part provides the needed flexibility through multi-criteria analyses.

4.4.3.A SCBA-Plus

This methodology, adapted to the Portuguese context, consists on the following steps:

1. Identify the assessment criteria: costs, possible effects and other criteria, including the actors involved;
2. Quantify and score the effects
3. Calculate outcomes
4. Perform sensitivity analysis
5. Present the results
6. Evaluate

For each investment one lists the outcome effects, and for each of these effects it is assessed whether objective measurement and money valuation is possible. In the cases where both are possible, the effect is evaluated using regular SCBA methodology. In the cases where one of the mentioned conditions is

not met, then the effect is valued according to a multi-criteria analysis. For some of the effects, it may be necessary to introduce indicators, and score them subjectively, using all the available data with the final objective of make these scores as relevant as possible.

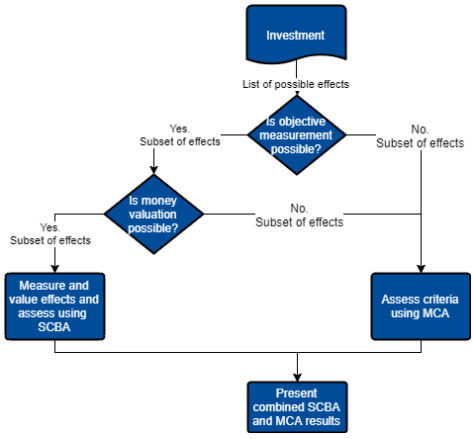

Figure 4.13: Flowchart illustrating SCBA-Plus methodology, according to [13]

After scoring the effects, it is necessary to weigh them accordingly to their importance. For the effects calculated with SCBA methodology this will reside on their net present value, for the MCA ones it should be defined with support from groups of experts. Due to the subjectivity associated with the MCA analysis, both in the given scores and weights used, one should run a sensitivity analysis on these values, and observe its effect on the outcomes. This is particularly important for the scores where the criteria used are the least objective. A table summarizing both analysis and selected indicators is displayed below:

SCBA-part	Measurement
Investment costs	Identify and estimate related investments
Reduced costs in space sector	Estimate the cost reductions through changes observed over time and/or surveys
Increased revenues in space sector	Estimate net revenues (profits) by subtracting costs of labour, capital etc. From gross revenues. Correct for cost reduction above to avoid double-counting
Increased profits in other sectors	Estimate cost reductions transferred to other sectors, depending on market conditions. Correct for double-counting
MCA-part	
Rating on knowledge spillovers	Compute additional patent citations and scientific publications, compute trends in education and knowledge related to the space sector and use these as inputs for judgements of (panels of) experts
Rating on competition effect	Use judgements of (panels of) experts
Rating on reputation effect	Use judgements of (panels of) experts
Score on(un)employment impact (happiness)	Compute additional jobs and correct for long term equilibrium effects. One should assess the figures with (panels of) experts to gather their inputs regarding the rating of happiness effects
Score on distribution impact	Compute effects for (groups of) stakeholders. Compute an inequality index. Translate this to a scale of 1 to 10

Table 4.1: Summary of indicators and measurements according to citesimmonds and SEO Economic Research Investments

Given the subjectivity of the MCA-part, and the preponderance of the panels of experts in this part of the assessment, the panel's composition acquires a major relevance in the process. It is recommended

that these panels are appointed by an independent task-force and composed by independent academic and governmental agents, with accredited competences in their topics of expertise.

Each project will generate a SCBA-plus evaluative card, resulting from Table 4.1, which can be compared among other prospective projects, enabling the choice and implementation of the project that is capable of delivering more impact in economic and capability-building terms.

4.5 Further Work

The work developed in this thesis can be given continuity in three main axes:

The first one should focus on the Cubesats subsystems detailed on Subsection 3.2.2. Each of these subsystems (e.g. structures, thermal, power systems) should be allocated to a leading Portuguese Engineering School (i.e. IST, FEUP, University of Coimbra, University of Aveiro, UBI) to develop a group of work and possibly a doctoral or master thesis in each of the topics. These groups of work should be accompanied and work in close collaboration with the expert space companies identified in section 3.2.2, in their areas of knowledge, through mentoring programs or joint teams.

This close collaboration would enable companies to benefit from state-of-the-art academic research and highly motivated and capable students while simultaneously providing the know-how, technology, environment and approach of an industrial and commercial player.

The work to be developed by each of these groups should include:

- Complete survey of the technologies with interest for the given subsystem and recent trends
- Assessment of each technology according to the relevance to the topic and ability to develop capabilities in the subject, given the university/company expertise background
- Mapping and performance assessment of current COTS components and/or other solutions in the market, and identification of opportunities for improvement or for developing alternative technologies
- Setting a roadmap for the internal development of the technology of choice, defining: timeline; required activities, capabilities and inputs; potential international partners; potential international customers; estimation of costs

Furthermore these work groups should actively seek international partnerships with investigation centres knowledgeable in the subsystems of interest and the smallsat and cubesat environment.

All these activities should be developed under a central coordination team responsible for leading the project, integrating its different components and monitoring its execution.

Additionally, establishing international research grants to attract renowned scientists could not only provide support these groups in their work, but also provide a necessary boost for the development and establishment of the desired Atlantic Research Centre in the Azores.

The proper implementation of these activities will make possible the achievement of the 2030 space programme goals through international collaboration, know-how transfer between industry and academia, and viable commercial production of high-technological systems and components.

The second axis should consist on obtaining detailed AIS data of the movements of the vessels on the Atlantic space from EMSA, since this was not possible in this work, and use them to refine the constellation's orbits by assessing the coverage of these signals at Atlantic and international levels. The evaluation of the signal's coverage and quality, should feed future adjustments in the orbital parameters, capable of ensuring satellites with increasingly smaller revisiting periods.

Additionally one should access SAR data in the same space-time conditions of the AIS, from Sentinel-1 or other SAR sources. The AIS and SAR datasets should then be compiled and compared, with the objective of identifying non-matching shadow patterns, that is, SAR patterns that do not correspond to AIS signals, identifying in this way non-collaborative vessels or pollution

Another relevant topic to pursue could be the development and optimization of SAR components, especially miniaturized instruments. This expected increase in the definition and quantity of generated data, should be accompanied by improvements in satellite data transmission subsystems, and optimization of antennas and control towers to increment their capacity of receiving more data.

From all these activities results a critical task, which is processing all the generated big data and using it to feed machine learning systems to constantly refine the detection algorithms of illegal vessels, pollution etc. This is probably the most relevant task to accomplish in a near future. Exponential increase in generated data will happen either one takes part in it or not, the ability of processing it, extracting value and insights from it is what will be truly distinctive and game-changing.

The last axis of suggested further work dwells in the Technological assessment methodology. Following the methodology presented in Chapter 2, a similar survey of technologies with applications for Atlantic MCS and Portuguese EEZ should be produced on an annual or biennial basis. For the various areas associated with MCS, this would consist on, assessing the state of the art, how they are evolving and which of those in a space of five years may be of interest to address on a commercial level.

Furthermore the technologies that one considers that potentially might have academic or commercial interest, should also be attributed to the associated universities (as suggested in this section's axis number 1), to follow the same group of work approach. By periodically analysing possibilities of impactful technological development in a methodical manner, one will be able of systematically identifying opportunities in the space sector, grabbing the ones that could capitalize on our endogenous specificities.

The responsibility of monitoring fishing, vessels, sea state, among others, will always exist. Exploring opportunities for building technology and capabilities by pilot-testing solutions for these areas could help Portugal to become a leading reference in the maritime MCS sector, producing and exporting high-skilled solutions and workforce to the immense maritime global market.

A final comment should be made regarding the Portuguese 2030 space strategy. Despite the still embryonic phase of the document, efforts into drafting a more detailed and concrete version of it should be made. This should be achieved by defining two or three national priorities and associated actions, and convert them into flagship projects to be developed with two different types of partners. The first being ESA and its state members, while others should be developed with Atlantic partners or international maritime partners (e.g. China, India, Japan).

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