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Study and design of a Business Model that explore the complementarity of VLEO platforms for Vessels Tracking

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Abstract

Throughout this study, the application of satellites in a Very Low Earth Orbit (VLEO) is analyzed to complement the already existing technologies used for vessels tracking. This study is part of the DISCOVERER project, which focuses on the research and development of VLEO technologies to apply them in Earth Observation (EO). Within the team, the UPC focuses on market analysis and the study of business opportunities for VLEO technologies.

A value proposition is developed following the Canvas model, this being the strategy used to offer a service to a specific client. For the development of the value proposition, the study focuses on optimizing vessels tracking for maritime transport companies. A market study is carried out previously, to analyse how could the value proposition fit in it.

The analysis determines that the optimal methodology and technologies to complement the platforms currently used for vessels tracking with an AIS system (Automatic Identification System) installed, is through Data Integration. This method refers to the combination of the data obtained by different platforms (satellites with different technologies and in different orbits complementing both, aerial and terrestrial platforms) once received in the ground station. For the tracking of those ships exempt from carrying an AIS transponder or those that do not want to be tracked, the optimal tracking method would be the combination of data between different platforms before being received on the ground station (System Integration).

Resumen

A lo largo de este estudio, se analiza la aplicación de satélites en una órbita terrestre muy baja (Very Low Earth Orbit (VLEO)) para complememtar a las tecnologías ya existentes empleadas para el rastreo de buques. El estudio forma parte del proyecto DISCOVERER, el cual tiene como objetivo investigar y desarrollar las tecnologías VLEO para aplicarlas en Earth Observation (EO). Dentro de este gran equipo, la UPC se enfoca en el análisis del mercado y el estudio de las oportunidades de negocio para las tecnologías VLEO.

Se desarrolla una propuesta de valor según el modelo Canvas, siendo esta la estrategia empleada para ofrecer un servicio a un cliente específico. Para el desarrollo de la propuesta de valor, el estudio se centra en optimizar el rastreo de buques para las compañías de transporte marítimo. Previamente, se realiza un estudio de mercado para analizar cómo podría encajar la propuesta de valor en él.

El análisis determina que la metodología y las tecnologías óptimas para complementar a las plataformas actualmente empleadas para el rastreo de buques con el sistema AIS (Sistema de identificación automática) instalado, es mediante la Integración de Datos. Este método hace referencia a la combinación de datos obtenidos por diferentes plataformas (satélites con diferentes tecnologías y en diferentes órbitas junto con plataformas tanto aéreas como terrestres) una vez recibidos en tierra. Para el rastreo de barcos exentos de la instalación del AIS o aquellos que no quieran ser rastreados, el método óptimo de rastreo sería mediante la combinación de datos entre diferentes plataformas previamente a ser recibidos en tierra (Integración de Sistemas).

Acknowledgments

First of all, I would like to thank the UPC DISCOVERER team for giving me the opportunity to participate in this program and for the support received during these months, specially from the directors of the thesis: Silvia Rodriguez-Donaire and Daniel Garcia-Almiñana. Their feedback and the way they clarified my doubts in each meeting was crucial, and the interest they showed for my thesis made me feel really motivated. I was able to learn lots of things from their seminars and the one by Miquel Sureda Anfres.

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Last but not least, the biggest appreciation goes to my parents: Gustavo and Isabel. They supported and encouraged me whenever I felt a bit down and gave me strength with a hug every time I needed it, not only during the final thesis but during the whole bachelor's degree.

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List of Abbreviations

ABEP Atmosphere-Breathing Electric Propulsion. 12, 25, 53

AI Artificial Intelligence. 38

AIS Automatic Identification System. 11

AMARO Autonomous Real-Time Detection of Moving Maritime Objects. 30

B2B Business-To-Business. 38

B2G Business-To-Government. 38

CAGR Compound Annual Growth Rate. 37

EMSA European Maritime Safety Agency. 28, 33

EO Earth Observation. 1, 2, 9, 11, 12

FOV Field Of View. 22

GEO Geosynchronous Equatorial Orbit. 15

GLONASS Global'naya Navigatsionnaya Sputnikovaya Sistema. 15

GNSS Global Navigation Satellite System. 22

GNSS-R Global Navigation Satellite System Reflectometry. 22

GPS Global Positioning System. 11

GSD Ground Sample Distance. 13

HAPS High Altitude Pseudo-Satellites. 17

IoT Internet of Things. 38

LEO Low Earth Orbit. 15

LiDAR Light Detection and Ranging. 21

MEO Medium Earth Orbit. 15

ML Machine Learning. 38

MMSI Maritime Mobile Service Identity. 29

MS Maritime Surveillance. 20

ODARIS On-board Data Analysis and Real-time Information System. 30

RPAS Remotely Piloted Aircraft Systems. 33

SAR Synthetic-Aperture Radar. 20

SAT-AIS Satellite-Based Automatic Identification System. 19

SNR Signal-to-noise ratio. 18

SSO Sun-Synchronous Orbit. 23

UAV Unmanned Aerial Vehicles. 16

VHF Very high Frequency. 19

VLEO Very Low Earth Orbit. 1, 2, 9, 10, 11, 15

VMS Vessel Monitoring System. 18

1 Introduction

1.1 Aim

The aim of the thesis is to do a proper research about Very Low Earth Orbit (VLEO) technologies to study how they could enhance the results obtained in the Earth Observation (EO) field. An explanation of VLEO technologies will be carried out, as well as the unique advantages and challenges they would offer.
In order to get familiar with these new technologies and to analyse how they would fit into the actual market, a particular case of VLEO application for EO purposes will be studied: the impact that complementarity VLEO technology platforms could have in the Maritime Surveillance field, in this case to track vessels with an increased accuracy than when tracked by a higher orbit satellite. Afterwards, a Value Proposition Canvas of this particular case will be done.

1.2 Scope

In order to fulfill all the above stated, this thesis will cover the following points:

- Development of the state of the art of the complementarity of VLEO technology platforms applied to the maritime surveillance field in order to analyze current competitors.

- Do a general research about VLEO technology to understand how it works and what contributes to the EO field .

- Learn about the platforms and technologies used for EO to clearly understand how VLEO technology could complement actual platforms.

- Description of remote sensing applications in the maritime surveillance field.

- Analyze which are the strengths and the weaknesses of applying the complementarity of this technology specially on Maritime Surveillance.

- A Value Proposition Canvas will be developed. The following aspects will be covered:

    1. Definition of the customer profile and identification of his needs in order to build the customer side.
    2. Build the product side.
    3. Fit both customer and product side.

- Final discussion of the study.

- Calculation of the estimated cost of this project's development (budget).

- Carry out an environmental study to see the footprint the implementation of the complementarity of VLEO platforms would leave.
- Conclusions reached in the thesis.

Leaving the following aspects **out of scope**:

- Implementation of the study.
- Study of the Whole Canvas Business Model.
- Other cases study different than the Oceanic & Continental one.
- Technical aspects, performance or production of VLEO technology platforms.
- Calculation of the satellite's orbits and the forces applied to it.

1.3 Requirements

- Follow Monerris' final thesis methodology.
- Act in accordance with the DISCOVERER outlines and purposes, as part of one of their research groups.
- Be compliant with UPC's final degree thesis regulations.
- Study the complementarity of VLEO technology platforms for the case study selected.
- Develop a Value Proposition Canvas.

1.4 Justification

VLEO technologies are arising to get the best out of EO. Even though they may have some disadvantages, using these satellites at a lower altitude would lead to great improvements in the EO sector.

One of the main reasons to take into account this technology is the cost difference between launching a satellite at a higher orbit and launching it at a lower one, considering the same payload.
On the other hand, some cases of unreliable forecasting were noticed. It is specially important in marine navigation for the ship's officer to know the accurate vessel's position. While at sea, accurate position, speed, and heading are needed to ensure the vessel reaches its destination in the safest, most economical and in the shortest time possible. While the vessel is in port, the need of a precise position is even higher as maneuvering becomes more difficult and the risk of accidents increases [31].
In December 2019, irregular Automatic Identification System (AIS) data was received. The vessels were navigating in circles, which is not the common pattern for a ship. The duration of the circling pattern goes from less than an hour to as much as two weeks. As mentioned in *Skytruth's* article:
"*SkyTruth reported on a number of locations on the Chinese coast (mostly oil terminals) where ship tracking positions from the AIS became scrambled as soon as ships approached within a few miles of a point on shore[7].*"
By checking another source of GPS data (Strava's heat map of fitness trackers), it was discovered that it was not an AIS malfunction but a Global Positioning System (GPS) disruption.
During these years the number of shipments done by sea has increased, therefore high traffic areas have grown too, having a negative impact in the AIS data.

Maritime surveillance is key to be aware of what happens in the sea: irregular migration/border control, maritime security, anti-piracy, oil pollution, navigational hazard location and mapping [32]. It is also utilized for analyzing the quality of the water and its vegetation indicator.
GPS is also used by fishing fleets to go towards the optimum fishing locations, to track fish migrations, and to ensure compliance with regulations. Also, nautical charts that alert mariners to changing water depths and underwater hazards, are achieved thanks to survey vessels, which use GPS positions (combined with sonar depth soundings). Offshore oil rigs and bridges over water are also designed considering accurate hydrographic GPS data [31].

As seen, lots of applications in the marine surveillance field require accurate satellite data. VLEO satellites would improve data in this sector, which directly affects to other sectors (such as fishing,building or commerce). A higher precision technology such as this one could definitely mean an improvement in this field and related ones.

1.5 The DISCOVERER project

The DISCOVERER project is a Horizon 2020 project that aims to enable sustained and commercially viable operation of spacecraft in VLEO (satellites located at less than 450km high), principally for EO applications [11].
This could be achieved combining new aerodynamic materials, aerodynamic control and atmosphere-breathing electric propulsion for drag-compensation. The result would lead to smaller, lighter and cheaper to launch satellites, while the data accuracy is maintained or even improved. The implementation of these platforms would be significant as the cost of European programmes for maritime surveillance, intelligence and security, precision agriculture and food security, land management and disaster monitoring would be reduced. Also, Europe would be way ahead of the upgrade of the technologies used in all these fields [41].
The DISCOVERER project is developing novel concepts for spacecraft that could operate in very low Earth orbits. These designs include drag-reducing materials, novel Atmosphere-Breathing Electric Propulsion (ABEP) systems (which use the residual atmospheric gas to propel the satellite and provide effective drag-compensation without the limitation of propellant storage), and aerodynamic control surfaces. Once these designs are developed, the data and services that those satellites will provide will be provided at a lower cost, which makes easier to access to satellite information globally and resulting in an optimistic alternative to the current proposals in this field [11].

This project has received funding from the European Union's Horizon 2020.

The DISCOVERER consortium is formed by the following institutions [33]:

- THE UNIVERSITY OF MANCHESTER (UNIMAN)
- ELECNOR DEIMOS ENIGINEERING AND SYSTEMS (DEIMOS)
- GOMSPACE APS (GS)
- UNIVERSITY OF STUTTGART (USTUTT)
- UNIVERSITAT POLITÈCNICA DE CATALUNYA (UPC)
- UNIVERSITY COLLEGE LONDON (UCL)
- EUROCONSULT (ECONSULT)
- CONCENTRIS RESEARCH MANAGEMENT GMBH (CONCENTRIS)

The UPC research group will focus on studying the implications that implementing VLEO satellites combined with the current available platforms would have and analyse different applications and business models for it.

2 Background

This study does not focus on the replacement of the current technologies used for EO, but on how VLEO technologies can cooperate with the existing platforms in order to improve the results. This would optimize the exploitation of multi-staged platforms that integrate different technologies used for EO, getting the best out of each one.

In order to understand how VLEO technologies would help in the EO field, the extraction of data and measurements through EO platforms (remote sensing) must be explained first. Charged particles vibrating with different wavelengths and frequencies produce electromagnetic energy, which is detected by instruments to extract several data. Wavelengths are key to make a distinction between elements, as some wavelengths are not able to pass through some molecules while others can. For instance, microwave energy can go through clouds, being this the reason why this wavelengths are used for meteorological satellites so clouds are not an obstacle to observation.
When differentiating particles, albedo is key. It describes the ability of a surface to reflect radiation. The part which is not reflected, will either pass through the surface or be absorbed by it. This is useful to determine the components of the atmosphere or in the water for example (among several other applications) and a higher resolution means more accurate data, leading to solid conclusions and results.

2.1 Remote sensing applied to Earth Observation

2.1.1 Resolution types

- **Radiometric**: The set of digital levels that represent the data the sensor collects. Those would determine the brightness, intensity and colour level. How sensitive is the equipment and how intense is the signal will define radiometric performance. A higher radiometric resolution means a better distinction.

- **Spatial**: Relationship between the size of each pixel within a digital image and the surface area represented. Spatial resolution can be measured in several ways; one of the most common is the Ground Sample Distance (GSD), which calculates the spacing between projections of adjacent pixel centers. A higher distance between pixel centers shows a lower resolution. For instance, a satellite with a resolution up to 30 m show an image with pixels that represent an area of 30x30m in the ground [61].

Figure 1: Sentinel-2(ESA) image with a 10m resolution (medium resolution) (left) vs. satellite Pléyades (Airbus) image with a 50cm resolution (high resolution) (right) [61]

- **Temporal**: The amount of time needed to revisit and acquire data for the exact same location. When applied to remote sensing, this amount of time depends on the orbital characteristics of the sensor platform as well as sensor characteristics. As geostationary satellites have daily periods, the temporal resolution is very good (30 seconds - 1 minute). However, temporal resolution for satellites in polar orbit can go from 1 to 16 days. [35]

- **Spectral**: The ability of a sensor to define fine wavelength intervals. The finer the spectral resolution, the narrower the wavelength range for a particular channel or band. Many remote sensing systems record energy over several separate wavelength ranges at various spectral resolutions. These are referred to as multi-spectral sensors. Advanced multi-spectral sensors called hyper-spectral sensors, detect hundreds of very narrow spectral bands throughout the visible, near-infrared, and mid-infrared portions of the electromagnetic spectrum. Their very high spectral resolution facilitates fine discrimination between different targets based on their spectral response in each of the narrow bands [51]. The narrower the wavelength range for a given band, the finer the spectral resolution, allowing to distinguish between rocks or vegetation types.

The study area is divided in cells, so the spatial coverage can be determined. The number of cells analysed during a time interval is calculated. A smaller size requires more time to be analysed. If the target is a region where things are changing rapidly (e.g. hurricanes or another natural disaster), short timescales will be needed, losing spatial resolution at the same time.

This research will investigate how with the combination of different platforms could be obtained the highest resolution possible of each type.

2.1.2 Space platforms and orbits used in EO

The platforms and orbits that currently exist in EO are presented below, in order to take into account the different solutions that could be complemented by VLEO satellites.

Typical types of orbits depending on the altitude: Orbits can be distinguished according to their altitude. The typical ones are the following:

- **Geosynchronous Equatorial Orbit (GEO)** (35,786 km) are frequently used for fixed communications (e.g. broadcasting) and observations (e.g. weather) due to their synchronised rotation with the Earth and ability to achieve global coverage with only a small number of spacecraft. At this altitude, the satellite has the same angular velocity as the Earth with an orbital period of 24 hours [11]. Therefore, these satellites always remain fixed on the same point projected on the surface and provide a constant view of almost an entire hemisphere due to its altitude, but reducing spatial resolution. On this orbits can be found the satellites that provide internet and other data to several regions.

- **Medium Earth Orbit (MEO)** (2 000 km-35 786 km) are popular for navigation constellations such as GPS, Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS) and Galileo, that require a balance between global coverage and diversity (number of satellites visible from the ground at the same time) [11]. MEO orbits offer lower resolutions than LEO but longer visibility time, they are therefore a type of orbit mostly used for navigation rather than for EO. A satellite at this altitude takes 12 hours to complete one orbit approximately, so the satellite crosses the same two points on the equator every day.

- **Low Earth Orbit (LEO)** (400km-2 000 km) are the preferred for observation missions due to their proximity to the Earth's surface, as they can obtain higher resolution images. On this orbit it cannot be monitored the same area all the time because the angular velocity is higher than the Earth's. Recently, LEO has also become popular for communications constellations due to increased bandwidth and reduced latency and power requirements. Unlike satellites in GEO that must always orbit along the Earth's equator, LEO satellites do not always have to follow the same projected path. Their plane can be inclined, meaning that more that one route can be offered. This type of orbit is ideal for EO, as the resolution is higher and also it can fly through the same point several times per day.
  LEO orbits require a launch at a lower altitude,reducing provisioning and launching cost [35].

- **Very Low Earth Orbit (VLEO)** (100 km-450 km). There is a certain region between HAPS and LEO, located between 100km and 450km that is unexploited and a potential candidate for EO, as drag effect is still perceptible but not as much as in lower layers. This region is called VLEO. A new hybrid platform in this region would require a propulsion system to defeat drag, as well as an aerodynamic design that reduces its effects. This is because eventually, drag causes orbit degradation, leading towards the end of the mission. Also, special materials would need to be used to ensure the satellite is appropriate to resist the atmospheric gas particles in that region.

The altitude of the satellite impacts its operation. At higher altitudes not propulsion is needed (just sometimes to correct the orbit in case it is slightly deviated), as the satellites orbits the Earth following orbital mechanics. Therefore, the mission can be longer and have a wider range. All this is achieved at a higher cost.
On the other hand, at less altitude the drag effect is significant and thrust is needed to correct the orbit. The resolution is better and the cost to launch the satellites is lower, although the coverage is reduced.

Different platforms used for EO: There are different types of platforms depending on their field of operation.

- **Ground-based**: reduced coverage range but more accurate data due to its short distance to the subject. An example of these are maritime platforms.
- **Aerial**: reduce costs and facilitate operation, but regulations and their low payload capacity currently limit their range of activity.
  - **Unmanned Aerial Vehicles (UAV)**: also known as drones; these are aircraft piloted by remote control or on board computers. As drones are smaller than satellites and unmanned, this technology is a good alternative and a cheaper one. It has a wide range of operation and allows lots of manoeuvres, as well as a high resolution due to the possibility to get close to the target. There are fields in which drones cannot replace satellites, but those two platforms are good complementing each other: if any disruption is detected via satellite, a drone could be used to take a closer look to the area. Drones also depend on meteorological conditions, and for some of them the battery duration is also an issue.
    Unmanned solar aircraft are a special type of UAV vehicle under development. They are designed to operate in the stratosphere and they will offer services at a low cost. The mission's duration is increased and they offer a better performance and mobility compared to satellites.
  - **Planes and helicopters**: a good alternative to satellites to obtain higher precision. Airplanes are preferred to helicopters as vibration is lower and stability is higher. Installing a small platform in commercial aircraft would be a good way to take advantage of the huge amount of trips that are completed in a day.

– **Balloons and High Altitude Pseudo-Satellites (HAPS)**: balloons do not require power and are stable, but maneuvering is not easy with them. Another advantage is that balloons can stay at high altitudes during a long period, while other platforms cannot. Those balloons operating at high altitudes are the stratospheric ones, also known as space balloons, and are divided into three groups: tied, free and electric. Tying the balloon is an easy way to keep the balloon in the same area, but this reduces significantly the range. The altitude reached with the free ones is higher that with the tied ones. As those balloons would be located in a VLEO or a LEO, the data obtained would be near the space (e.g of cosmic radiation, northern lights,etc.). As no fuel is required to lift balloons (even though power may be needed for the components in it) the mission lifetime can be long [35].

  HAPS operate at 20km-50km high, in the stratosphere. They could be high-altitude free-floating balloons, airships, or powered fixed-wing aircraft that use either solar power or an on-board energy source. All systems are unmanned.
  As they are at a lower altitude than satellites, HAPS platforms can project smaller beams onto the ground from a directional antenna, increasing the capacity delivered per unit area, hence the level of detail. However, the aircraft must consume significant energy to remain airborne, whilst also providing sufficient residual energy to power its payload [22]. The environmental impact is drastically reduced compared to other platforms.
  An example of HAPS would be the *Google Loon* balloons. Project Loon proposed using high-altitude balloons in the stratosphere at an altitude of 18-25 km, to create an aerial wireless network and deliver the Internet to remote and rural communities through 'floating cell towers'. However, while the technology apparently worked as intended, the business case was never properly figured out. In January 2021 it was announced the end of the project after nine years in development,as a way to lower costs enough to build a long-term, sustainable business was not found [53].

- **Space**: satellites allow true and reliable global coverage, providing several observations over the same area, but at the expense of a higher cost of technology implementation [35].

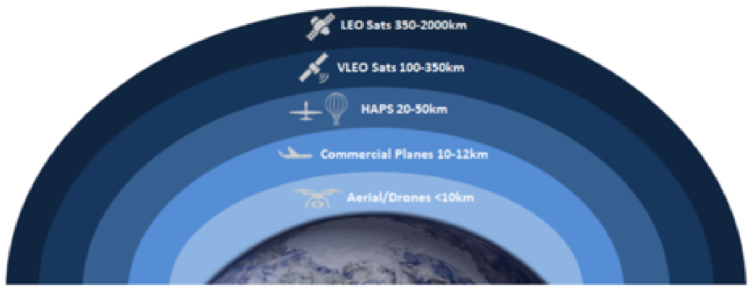


Figure 2: Main Aerial and Space platforms for Earth Observation by range and field of operation [35]

2.1.3 Remote sensing in the maritime field

There are several applications of EO in the oceanic and continental waters field, and for each of them an explicit accuracy is required. A low resolution is required to study large oceanic areas but a very high precision would be needed to geolocalize vessels, to analyze the quality of the water or the thickness of ice layers. It is true that in-situ surveillance (ground-based data) provides a higher precision than satellite data, but the coverage is drastically reduced. Using remote sensing to complement ground-based data would increase the coverage, allowing to study several parameters with the accuracy required in a large area.
The mapping of water bodies and hazardous elements in the sea is not an easy task for remote sensing, as just a little part of the energy coming out of the water's surface gets to the sensor due to its very low reflectance and also due to several interference in the atmosphere.
To conclude, integrating VLEO in this field as a complement could improve the result obtained as radiometric resolution and Signal-to-noise ratio (SNR)(the level of a desired signal compared to the level of background noise) are enhanced [35].

Vessels tracking:

The Vessel Monitoring System (VMS) is a satellite-based monitoring system specifically for fishing vessels which provides information about the vessels' position and activity [5]. Most of the monitoring is done with the help of the Global Positioning System (GPS), which calculates the position of the unit and sends a data report to ground stations. It is mostly used for monitoring vessels in compliance with their area and time. Furthermore, due to encryption of the VMS signals, only the government agencies can access the data. It will be not considered as an option for this case study as the interval data transmission is higher (from 10 min to 4 hours), the cost of the system is high, the accessibility is low and it is more dedicated to fisheries [10].

On the other hand, AIS is a digital Very high Frequency (VHF)-based radio system that relies upon an open, standardized, internationally adopted, non-proprietary communication protocol that allows two-way exchange of information between ships and ship-to-shore in a continuous, autonomous, and dependent on the information being transmitted, near real-time (2 sec.–6 min.) [23]. AIS transponders on board vessels include a GPS (Global Positioning System) receiver, which collects position and movement details. It also includes a VHF transmitter, which periodically transmits this information and makes the data available to the public domain [5].
For the tracking of vessels, the Automatic Identification System (AIS) is mandated by the International Maritime Organization for all vessels over 300 tons. This becomes an issue while tracking vessels of less than 300 tons.
AIS transponders automatically send signals at regular intervals, which are received either by other ship's AIS or land-based systems. The VHF-based AIS has a low horizontal range on the order of 40 nautical miles (74 km), meaning it is only effective within coastal zones and on a ship-to-ship basis. But AIS propagates much further vertically, all the way up to Earth orbit, allowing to cover the current AIS blind spots in the open ocean, provided useful data can be extracted from overlapping signals [6].
Also, AIS becomes saturated in areas with a high concentration of ships due to the high number of users, reducing the report of the tracking of all the vessels.

A common practice for fishing vessels is to deactivate AIS equipment when they are about to make catches, so that nearby vessels and monitoring stations cannot know their exact location (known as Dark Vessels). This avoids revealing information about fishing grounds and fishing zones to their competitors, as the information transmitted by AIS is not encrypted and can be received by all members of the network. In today's maritime traffic, it is estimated that about 47% of vessels sail in waters out of range of AIS transponders [24].

Some vessels need to spend a long time in remote areas in the sea, far away from land or other ships, so ground-based AIS systems are not reliable in those cases. Satellite-Based Automatic Identification System (SAT-AIS) improve vessel tracking and location. Sat-AIS and VDES (VHF Data Exchange System) help overcome terrestrial coverage limitations with the potential to provide global AIS services.

Space-Based technologies used for MS applications:

In order to decide the technology and orbit type of the VLEO satellites, first a study needs to be carried out.

Starting with sensors, there are two type of them to detect the reflective energy by a surface: passive and active. The passive ones are those that measure the energy reflected by the Sun, whilst active sensors use their on light source.

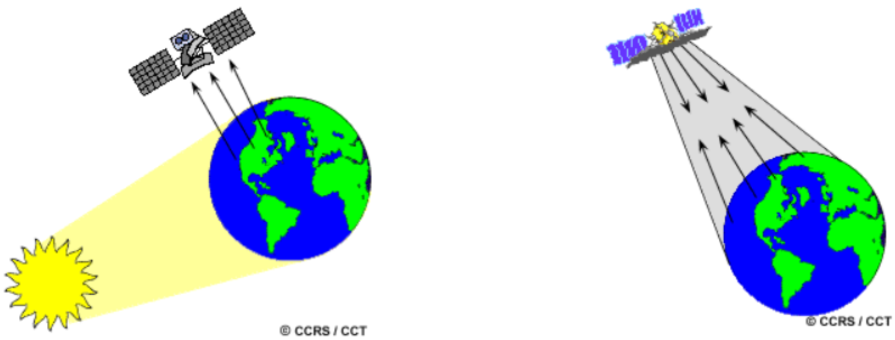


Figure 3: Passive sensor (left) vs. active sensor (right) [43]

Passive sensors can only be used to detect energy when the naturally occurring energy is available. For all reflected energy, this can only take place during the time when the Sun is illuminating the Earth [43].
On the other hand, active sensors do not have the limitation of the Sun's radiation dependence. A transmitter sends a specific electromagnetic signal and a sensor receives the response of the interaction of the signal with the target.

Some of the technologies used for MS are explained below:

- Optical imaging: In optical imaging, electromagnetic energy of the Sun, which is reflected by the Earth, is received and measured. It is a passive remote sensing technique, so it collects data only in daytime. The incoming energy from earth is separated into several spectral components that are sensed independently. The light wave is directed from the grating through a prism that split the energy into different wavelengths like UV, visible and near infra-red. Depending upon the number of bands it can be multispectral (MSP) or hyperspectral (HSP), the last ones being separated into a higher number of spectral bands.
  Image with this technique is acquired only in clear weather, not being able to penetrate through clouds.

- Synthetic-Aperture Radar (SAR): It is an active microwave remote sensing technology. The process involves transmitting the pulses of microwave in the direction of interest and record the reflection which contains strength and position of the object. The presence of a dedicated transmitter enables a monitoring capability that does not depend on sunlight illumination and allows for effective sensing regardless of weather, as microwaves undergo a much weaker scattering and absorption from the atmosphere. For a given wavelength, the longer the sensor's antenna, the higher the spatial resolution. From a satellite in space operating at

a wavelength of about 5 cm, in order to get a spatial resolution of 10 m, a radar antenna about 4 250 m long would be needed. An antenna of that size is not practical for a satellite sensor in space. The synthetic aperture is able to achieve from a shorter antenna the higher resolution that would be obtained with a much larger antenna [21].
SAR systems typically operate in a monostatic geometry, where the receiving antenna is co-located with the transmitting one [49]. That way, the energy reflected in the backscattering direction is collected to then be processed and form a 2D array of columns and rows of picture element (pixel). Each pixel represents a small area of the earth surface, which gives a complex number having amplitude and phase information of the backscattered field of the microwave. Grey levels in the SAR image show the properties of the object. High intensity back-scattering is represented as the brighter tones while low intensity back-scattering appears as the dark tone of the grey-scale. Rows represent the azimuth resolution and column represents the range resolution [3].

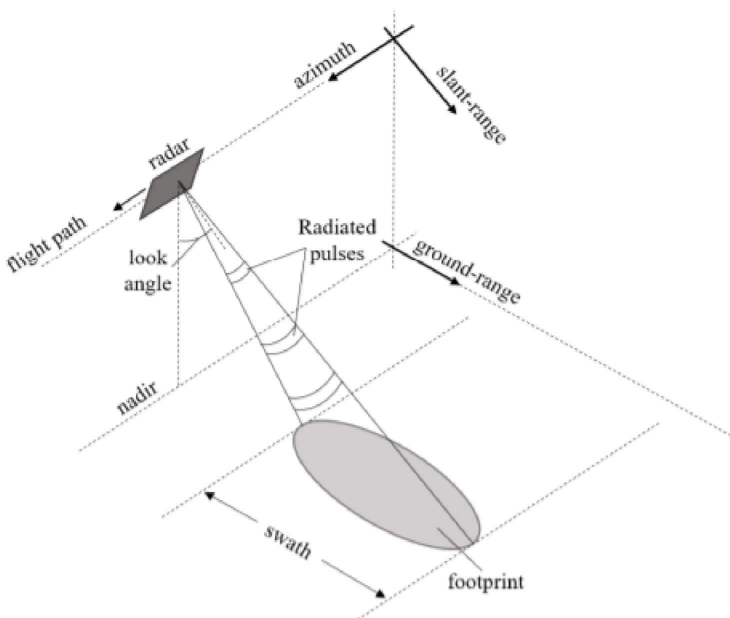


Figure 4: SAR technology [3].

- Light Detection and Ranging (LiDAR): LiDAR systems use the same principle as SAR but using a laser that impacts a surface and allows to calculate the distance between the laser source and the surface [35]. The instrument measures the time delay of the pulse and thus extracts the elevation data. The elevation can be extracted because distance between transmitter and reflector can be calculated by using the travel time of laser beam as it travels at the speed of light . It does not provide continuous coverage of an area [3].

Scanning should be performed in cloud free condition. LiDAR scanning is generally performed for the generation of the three dimensional (3D) profile of the terrain.

- Sat-AIS: This technique refers to satellites mounting AIS transponders on-board, allowing reception of AIS signals within the Field Of View (FOV) of the receiving satellite antenna, increasing the detection range of traditional land-based stations and enable the exploitation of AIS worldwide. A satellite AIS transponder in a 600 km altitude orbit exhibits a range to the horizon as large as 1 440 nautical miles (2 111.28 km), compared to the 40 miles (74 km) that terrestrial AIS transponders can cover. It is worth noting that the larger the FOV, the higher the probability of message collisions [49].

- GNSS-R: This technique shows the complementarity of platforms (GEO+LEO). Global Navigation Satellite System Reflectometry (GNSS-R) is a satellite remote sensing technique that uses surface-reflected Global Navigation Satellite System (GNSS) signals to infer information about the Earth's surface. The reflected GNSS signals act as radar with the reflected signal power responding to changing surface conditions. Reflected GNSS signals can be received on-board a low Earth orbiting satellite and used to estimate environmental conditions over ocean, land and sea ice [18].

Here is a summary of all the technologies mentioned above. A high spatial resolution and coverage regardless bad weather conditions are needed to track vessels, so some of these technologies are not valid for this case study.

Technology	Advantages	Drawbacks
Sat-AIS	Accurate ship information Very high update rate (up to 2 seconds) Global coverage of AIS services Compact, low-power, light-weight and cheap	Vulnerable (e.g. spoofing) Limited to ships with AIS Limited to cooperative ships Limited to ship detection/tracking
SAR	All-weather, all-time sensing capabilities Very high spatial resolution (down to 1 m) Polarimetric diversity	Large size Imagery difficult to visually and manually interpret Affected by speckle noise
MSP	Imagery easy to interpret Very high spatial resolution (down to 0.3 m)	Sensitive to cloud and sunlight conditions Limited revisit time Limited areas covered during each acquisition
HSP	Very high spectral resolution (down to 1 nm) Anti-camouflage capabilities Suited to accurate classification	Low spatial resolution Large computational burden Sensitive to cloud and sunlight conditions
GNSS-R	All-weather, all-time sensing capabilities Compact, low-power, light-weight and cheap Seamless global coverage 100+ GNSS satellites available	Low spatial resolution Very low power density Poor performance in standard configuration Predetermined waveform

Figure 5: Comparative between EO technologies [3].

Orbits:

The most common orbit used for EO satellites is the Sun-Synchronous Orbit (SSO), a particular kind of polar orbit (those orbits in LEO with an inclination close to 90º) in LEO. Satellites in SSO, travelling over the polar regions, are synchronous with the Sun. This means they are synchronised to always be in the same 'fixed' position relative to the Sun, so the satellite always visits the same spot at the same local time [55].

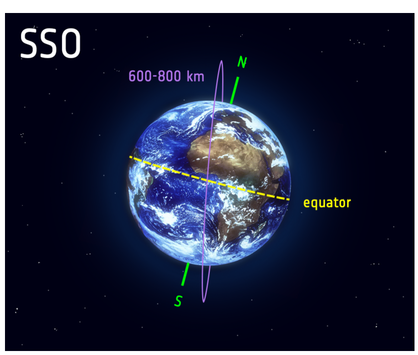


Figure 6: Polar and Sun-synchronous orbit [55].

Due to the rotation of the Earth, a point near the equator will rotate out of the swath of an AIS satellite in Sun-synchronous orbit after four overpasses, and be re-acquired half a day later. This results in gaps of the order of 9h at equatorial latitudes. As the circumference of the parallels gets smaller at higher latitude the number of overpasses increases to 15 per day at the poles. A few AIS satellites are in equatorial orbit, meaning that they cover an area near the equator at any time with a revisit time of approximately 90 minutes; hence the time of the overpass varies from day to day, and areas high north and south are not covered at all. Some satellites have orbits in between polar and equatorial, called inclined orbits; also these have overpasses that vary from day to day [14]. Revisit time could be significantly reduced launching a constellation of several satellites [49].

2.2 VLEO advantages/disadvantages

As mentioned in section 2.1, resolution can be divided into four groups: spatial, radiometric, temporal and spectral. The spectral one is the only type of resolution that will not be impacted by changing the altitude of the satellite, as it depends on the specifications of the payload. The other three types vary with the distance to the target. Placing the satellite in a VLEO, would improve spatial and radiometric resolution, as well as the accuracy while geopositioning the target. Even though the distance to the target is shorter providing a smaller coverage area, as spatial resolution is increased the effective footprint area would be bigger.
If the equipment is closer to the target, the intensity of it will be higher, leading to a better radiometric resolution.
Also, being closer implies the signal has to travel a shorter path, leading to a reduction of interference on the way.
Regarding the mapping and geopositioning accuracy, reducing the altitude will also decrease the error between the measured position and the current position of the target.

Another fact is that being at that altitude favors natural de-orbitation due to drag force, making it happen earlier than satellites at a higher altitude. Just to get into situation, a CubeSat (nanosatellite) at 800km (LEO) would need up to 150 years to naturally de-orbit, while in VLEO would take no more than 25 years. Currently, space debris is a topic that has astronomers en scientists preoccupied. All the satellites that are being placed now, will have to fall back into the Earth, and the fact of a small particle could impact with any part of the satellite, a disaster could occur. As VLEO is not as crowded as other regions, the risk of collision decreases significantly.

Another important aspect to remark is that launching the platform at a lower altitude means reducing fuel consumption, so satellites could be more compact and increase its performance.

The last remarkable benefit of VLEO is that, due to the density of the atmosphere is higher there than in higher regions, the harmful particles will be less present than in higher layers, as they are absorbed by the Earth's atmosphere.

It is true that all these benefits come at some costs, such as the aerodynamic resistance in that region. The useful life of a satellite without propeller in VLEO is much shorter than if it was in LEO.

Another negative point is the corrosive environment due to the high density of the atmosphere there. The residual atmosphere in low altitude orbits is also rich in highly-reactive atomic oxygen. In combination with the high orbital velocity and thermospheric temperatures, this atomic oxygen can damage the external surfaces of spacecraft through erosion. Sensitive optics, solar arrays, and antennas can also be adversely affected, reducing the mission performance and lifetime of the spacecraft [11]. As an example, the atomic oxygen concentration would be five times higher at 300km (VLEO) than at 500km (LEO). Electronic equipment can also be altered due to ionized particles.
It must be noted that the satellite and ground synchronization is badly affected by the altitude reduction, as satellites' velocity is higher and there is less time available to download the data leading to a reduction in the volume of data transferred, so the windows communication is reduced.

Changes in density and flow direction in the atmosphere at VLEO altitude could cause disruptions and impact satellite's stability. Those can be compensated with attitude control systems, but as altitude decreases, more control power is required to compensate for the rest of the forces. Thanks to the conditions of this region propulsion systems that collect the surrounding atmospheric gas and use it as a propellant for an electric drive can be used. So, the atmosphere produces the drag but then is used to feed the propulsion system allowing to compensate for it. This would not be possible without a high gas density, and thanks to this system the payload could be reduced. Atmosphere-Breathing Electric Propulsion (ABEP) is the system that would ensure this function. Gas is collected from the atmosphere and then fed to an electric plasma propellant, which ionizes and accelerates these particles in order to provide thrust while expelled [35].

To conclude, operating in VLEO would lead to a better overall performance regarding accuracy and resolution compared to higher altitudes, taking into account the same equipment is used. Also, if not that level of accuracy and performance is required, to obtain the same performance than a satellite in higher orbits, the lenses, antennas and apertures could be smaller and lighter, leading to cost savings in the end. On the other hand, the materials used for these satellites should be really prepared for that environment and the shape needs to be aerodynamic to reduce the effect of the drag force.

3 Complementarity of VLEO technology platforms

VLEO satellites can be used as an intermediate platform to link air and space platforms, getting the best out of both [35].

As seen, lots of platforms are available for EO purposes, but what if some of them are combined in order to get a better performance?

The two solutions proposed to complement different platforms are exposed below.

3.1 Data integration between different platforms

Data of different resolutions of each type (see section 2.1) is collected in order to enhance specially spatial and radiometric resolutions, which would allow a higher quality image. An effective method to do this is adding layer by layer of precision until the accuracy needed is obtained. If more resolution is needed, more details provided by lower altitude platforms will be added.
VLEO platform should be used to complement other platforms that obtain medium and low resolution images, as VLEO would help to increase its resolution and the results would be significantly improved.

3.2 System integration between different platforms

Combining systems and resources of several platforms used for EO in order to use them simultaneously instead of combining the data once received in the ground would be the second option. The platforms at different altitudes could even communicate between them to avoid irrelevant data collection and to enhance its performance.

Figure 7: Data Integration scheme (left) vs. System Integration scheme (right) [35].

So the question that will be answered is the following: which is the best option for integrating VLEO platforms in the EO field, adding the data obtained by satellites at VLEO to other platforms' data or obtaining data directly from combined platforms?

4 State of the art

Currently, the use of nanosatellites in the EO sector is arising rapidly. A nanosatellite is any satellite with a mass from 1 kg to 10 kg [29]. Normally, nanosatellites follow a polar orbit (in the direction of the Earth's meridians) and they are normally located at 400 km – 650 km of altitude and travel at a speed of 8 $\frac{km}{s}$. The time they take to complete an entire orbit is 90 minutes, being able to complete from 14 to 16 orbits per day. The main advantage of these satellites is that they cost much less to launch, due to their smaill size, as one rocket can carry several nanosatellites. They can complement current networks by providing complex logistic management solutions.[47].
Nowadays, the production and deployment of nanosatellites are led by private industry, but the cost reduction of nanosatellites is allowing institutions outside of traditional space agencies like NASA and the European Space Agency (ESA) to play a role in the new age of space exploration [29].

4.1 Platforms used for the tracking of vessels

- **Balloons:**
  MarineTraffic (a provider of ship tracking and maritime intelligence) successfully attached an AIS receiver to a high-altitude meteorological balloon launched from the mountains of the Peloponnese in Greece. This project was called *Ballooney Project*, and its aim was to offer a cheaper alternative to satellite data and complement their land based receivers. The balloon was operative for two hours at an altitude of 26 535m before the balloon burst, collecting in this time about 99 000 vessel position reports from a very wide area [56].

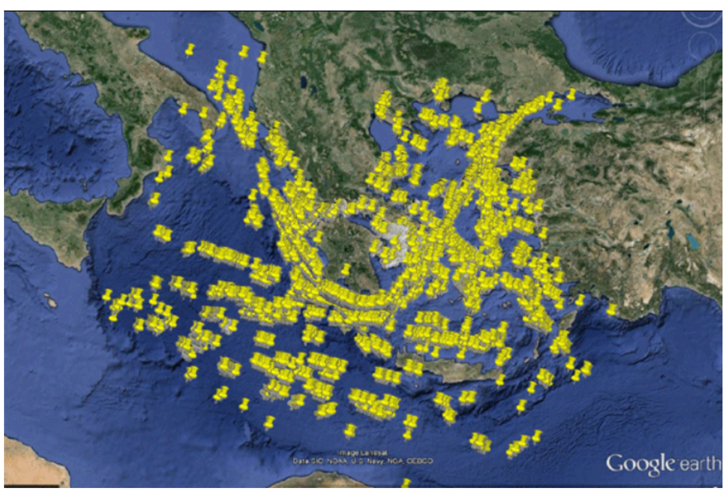


Figure 8: AIS data obtained during the 2 hours *Ballooney Project* [56].

Another example of balloons used to receive AIS data was prototype of AAUSAT3, a Cubesat from Aalborg University. The balloon was launched in the northern part of Sweden and Finland during the autumn of 2009, in order to evaluate AIS reception in Arctic regions. The results of the analysis show that, assuming a similar ship distribution, it is feasible to monitor the ship traffic around Greenland from space with a satisfactory result [1].

- **UAVs:**
  European Maritime Safety Agency (EMSA) developed remotely piloted aircraft to enhance general maritime surveillance. The mid-sized RPAS craft can stay in the air for more than 6 hours, reach a cruise velocity of 55 knots (about 100 km/h), have a maximum payload of 50kg and a range up to 200km [20]. All RPAS are equipped with AIS sensors to have a complete picture of vessel movements and distress sensors to be able to react in emergencies [13]. The main barrier identified for the deployment of RPAS in the maritime domain is the current lack of a mature pan-European legal framework with respect to the regulatory aspects to achieve flight approval for RPAS and operating RPAS in non-segregated airspace [45]. The RPAS uses its radar, optical and IR sensors to detect vessels and objects on the sea. After the information from the vessel is forwarded to EMSA, possible suspect vessels are identified and forwarded to EMSA/user. As a complementary task to maritime patrolling, the long-range cameras on the RPAS allow for illegal activities to be detected on vessel deck. Furthermore, the RPAS speed and high altitude allows the user to monitor and identify the behaviour on board the vessel while keeping the aircraft undetectable. The RPAS can track a target, for as long as its endurance allows [39].

Figure 9: EMSA RPAS [13].

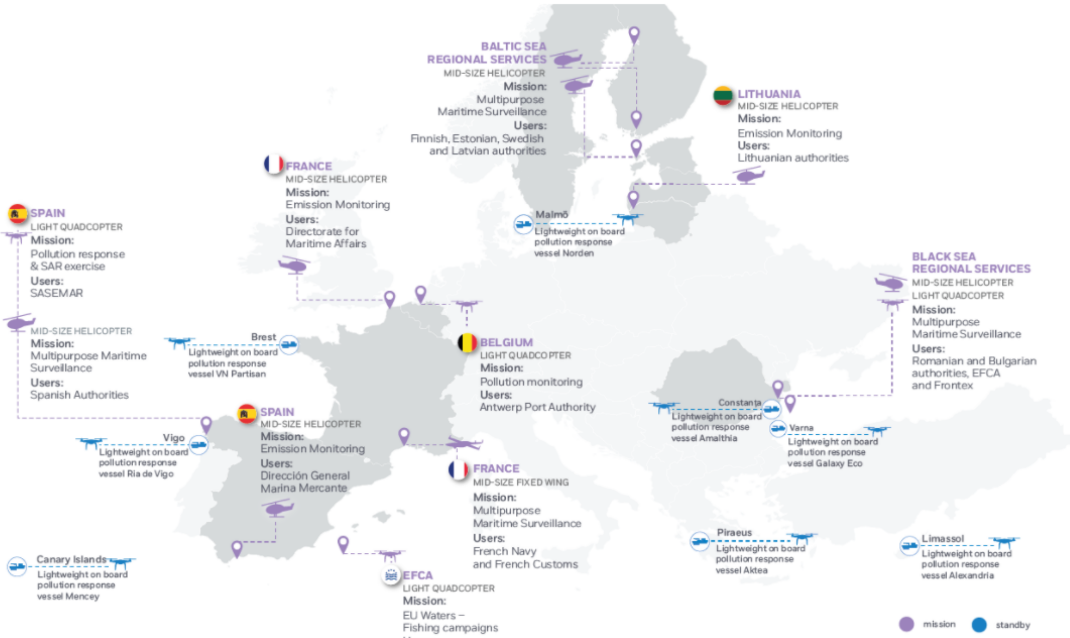


Figure 10: Maritime surveillance missions and stand-by missions that used EMSA RPAS in 2021 [45].

- **VLEO:**
  Columbus AIS (COLAIS) is an experiment hosted by ESA's Columbus module on the International Space Station, located at an altitude of 350–460 km. Two AIS receivers , NorAIS (Norwegian Automatic Identification System) and LuxAIS (LuxSpace AIS), were integrated into the Columbus module of ISS in September 2009. It had a viewing range of $\sim$ 4000 km covering the ocean areas between 68º north and 68º south several times per day, not providing global coverage [34].
  The results of the experiment showed that ,on a good day, approximately 400,000 ship position reports were received from more than 22 000 different ship identification numbers (Maritime Mobile Service Identity (MMSI)). In a summary made in Oct. 2011, the total number of position reports received exceeded 110 million messages from more than 82 000 different MMSI numbers. 10 days of near-real-time data show that 80 percent of the messages collected in the period could be delivered through the station's communications network with data latency significantly less than 1 hour [50].
  The NORAIS Receiver was commissioned 1st of June 2010 and was operated almost continuously until 1st of February 2015, when it was de-activated.
  The noise floor of the NORAIS Receiver system was significantly high due to the amount of equipment installed on the ISS. As the ISS orbit is lower, the field of view is reduced. A study about the tracking capability of space-based AIS systems compared 3 AIS receivers: 2 located at LEO (AISSat-1 and 2, at 634km) and the other one at VLEO (NORAIS, ISS-400km). The analysis proved that in

high ship density areas the re-detection probability is improved in a lower orbit [37].

- **HAPS:**
Airbus Zephyr Solar is a great candidate for maritime surveillance in the future. Filling the gap between ground towers, conventional aircraft and satellites, Zephyr is positioned perfectly to complement and enhance existing infrastructure. It achieved 36 days of stratospheric flight, across two 2021 flights. Zephyr uses sunlight to fly and recharge its batteries, using no fuel and producing no carbon emissions. Flying in the stratosphere, the plane has direct exposure to sunlight, which it harnesses to power its solar cells. With its ability to remain in the stratosphere for months at a time, Zephyr could bring new connect capabilities to both commercial and military customers [4]. Zephyr has wide visual payload coverage of 20km by 30km footprint, enabling it to provide a range of continuous surveillance to meet mission requirements as well as high resolution imagery and video capture for intelligence gathering. Zephyr is close enough to ground stations to have little latency and offer a near real-time service [60].

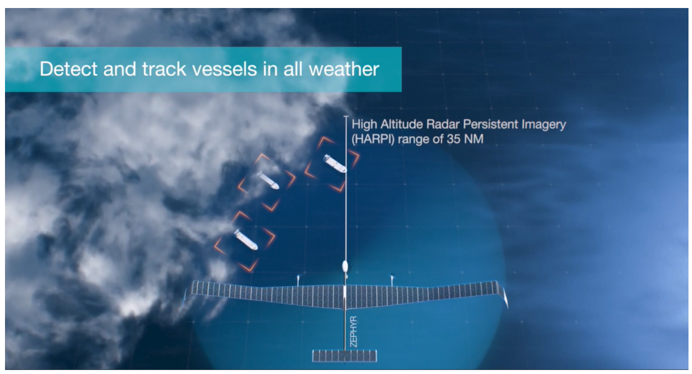


Figure 11: Zephyr vessels detection [60].

- **Airplanes:**
DLR is the Federal Republic of Germany's research centre for aeronautics and space. They developed a system called On-board Data Analysis and Real-time Information System (ODARIS), which uses an EO platform to obtain AIS data and process it on-board to send it afterwards to an existing satellite communication services (like ORBCOMM or Iridium) for transmission of the result to users on ground. Product information can be communicated to any device on ground with a connection to the internet, independent of the location of carrier platform and user.
The first demonstration of the on-board data analysis and real-time information system was done within the Autonomous Real-Time Detection of Moving Maritime Objects (AMARO) project. An AIS receiver, AIS antenna and communication hardware were placed in an airplane. The flight experiment over the

North Sea took place in April 2018. The results were successful: more than 84% of the user queries were answered in less than five minutes with an average of less than two minutes [38].

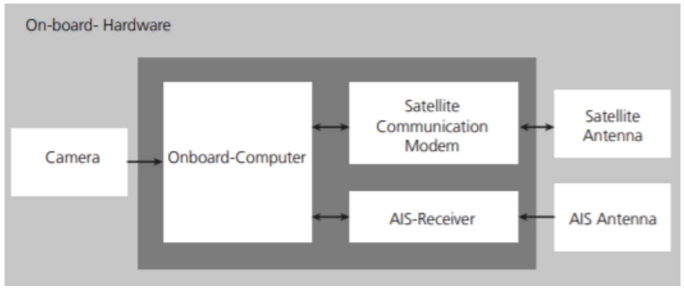


Figure 12: On-board hardware of ODARIS

4.2 Competitors analysis

Some companies that develop satellites that can be used to track vessels and are in similar conditions to the ones of this case study are summarized below, with its main characteristics and added values.

- **Alén space** :

  Figure 13: Alén Space logo

  This startup has the goal of developing economic, fast and small satellites in order to allow small companies to get into space observation offering a global service that can be accessed 24 hours a day, following the *New Space* principle. Its satellites are located in LEO.

  Alén Space offers the development of a satellite in less than eight months.

- **Skeyeon**:

  Figure 14: Skeyeon logo.

  This company bets for a VLEO satellite located at 250 km high. At end of life, the Skeyeon space craft will deorbit and burn up within weeks, leaving no space debris and minimizing any potential collision risk . Its lens telescope has a 1-meter resolution in a small form factor and reducing the volume of the telescope by 25x. Also the cost is reduced about 10-50 times when compared to other space telescopes of similar performance. Skeyeon has developed a patented low drag and atomic oxygen resistant. The company also patented a radio link system that leverages existing cell phone tower infrastructure to facilitate real-time downloads, resulting in direct-to-consumer, low latency image delivery. Skeyeon's design philosophy is to make the form factor and power consumption as low as possible in order to reduce the weight of the vehicle and minimize launch costs [36].

- **exactEarth**:

Figure 15: exactEarth logo

This company was founded in 2009 and it is a provider of global maritime vessel data for ship tracking and maritime surveillance using satellite AIS. They have 60 satellites launched in LEO, which receive the AIS data that vessels transmit, to send it afterwards to the ground stations in order to elaborate these data [12]. They offer global average revisit under one minute, customer data latency lower than 60s, and the tracking of fishing boats and small commercial vessels with AIS Class B type receivers [40].

- **Planet**:

Figure 16: Planet logo

PlanetScope is one of the satellite constellation operated by Planet. It consists of more than 130 small satellites called Doves. Each Dove satellite is a CubeSat made of three cubic units, measuring 10 cm x 10 cm x 30 cm. The satellites are launched in groups at an altitude of 475 km [2], which constantly improves mission's characteristics such as revisit times, spatial and spectral resolutions.

- **ORBCOMM**:

Figure 17: ORBCOMM logo

ORBCOMM is an American company that offers services designed to track, monitor, and control fixed and mobile assets. They provide near real-time vessel monitoring, ocean buoy tracking and AIS ship tracking for commercial fishing boats and merchant fleets travelling global waters. Its satellites can monitor vessels beyond coastal regions and enhance maritime safety [28], combining both terrestrial AIS from leading partners and satellite AIS data from their own constellation. With 16 satellites combined with terrestrial AIS data, ORBCOMM is now processing 30 million messages daily, from over 240,000 vessels. They offer IsatData Pro , a low-data rate satellite communications service that can provide a latency as low as less than 15s for 100 bytes [8].

- **EMSA**:

Figure 18: EMSA logo

The European Maritime Safety Agency (EMSA) is a decentralised agency of the EU, based in Lisbon, Portugal. Next, two platforms used by EMSA for maritime surveillance are exposed:

  - *Satellite-based services*: Copernicus Maritime Surveillance service is used for maritime safety and security and fisheries control, among others. Data from Copernicus obtained from satellites in a LEO is then combined with other data (either from EMSA or external) to obtain accurate results. [46].
  - *Remotely Piloted Aircraft Systems (RPAS)*: Used as a complementary tool for surveillance purposes (including satellite imagery, vessel positioning information and surveillance by manned maritime patrol aircraft and vessels). The RPAS Data Centre (DC) service provides different users to have access to the video and the data archived or collected in real-time.

- **LuxSpace**:

Figure 19: LuxSpace logo

The microsatellite ESAIL, from LuxSpace, is located at an altitude of 515 km. They developed ESAIL, a satellite that forms part of the exactEarth satellite constellation, which will monitor ships using its automatic identification system [30]. ESAIL captured more than two million messages from 70 000 different ships in a single day, representing 15% to 20% better detection rate than previous satellites [15].

- **ESA**:

Figure 20: ESA logo

ESA developed a series of next-generation Earth observation missions, on behalf of the joint ESA/European Commission initiative Copernicus. Copernicus SENTINEL-1's SAR mission supports ship monitoring. SENTINEL-1 is an imaging radar mission providing continuous all-weather, day-and-night imagery at C-band. The SENTINEL-1 constellation is located at 693 km high and follows a SSO [9]. SENTINEL-1 has a primary operational mode over land and another over open ocean The main operational mode features a wide swath (250 km) with high geometric (typically 20 m) [42].

- **ICEYE**:

Figure 21: ICEYE logo

ICEYE satellite SAR data enables users to precisely and timely detect vessels operating in the area of interest, by combining with external AIS data [27]. ICEYE has developed an innovative radar technology for under 100 kg satellites to better meet the needs of commercial and government customers. SAR technology and optimal resolution choices enable dramatically improved cost-effectiveness over traditional large-size radar satellites. The resolution can be of 0.25 m, 3 m or 15 m.By mid-2021 ICEYE has launched 14 satellites in orbit. The company aims to expand its constellation to more than eighteen satellites in 2022 [26]. The satellites follow a polar SSO located at an altitude between 560km and 580 km [25].

- **Spire Global**:

Figure 22: Spire logo

Spire is a space-to-cloud data company that specializes in the tracking of global data sets powered by a large constellation of nanosatellites (more than 110 satellites at 500 km (LEO)), providing a spatial coverage of 90 N, -90 S, -180 W, 180 E and an orbit period of 95 minutes [52].

- **DLR**:

Figure 23: DLR logo

The German Aerospace center derives information products from optical remote sensing data and combine them with data from other sources, such as AIS (Automatic Identification System) for ship tracking. Data from various satellite missions are used to extract information relevant for maritime safety [54].

5 Value propositions of multi-staged EO space platforms for vessels tracking

5.1 Proposals generation

As VLEO satellites are still in a development phase and they are not deeply introduced yet, the impact of the complementarity of VLEO will be studied in the value proposition of multi-staged EO business models. To perform this analysis, the Value Proposition Canvas methodology will be used. It is a methodology developed by Alexander Osterwalder, which has the purpose of defining the value offered by a company and analysing its impact on the customers, in order to guarantee there is a correspondence between the product/service offered and the market. Before developing the proposal, a market research needs to be carried out, to understand if the service offered will fit in the current market. Then, the customer and his needs and expectations will be analysed to, finally, see how the product would have an impact on his life.

5.1.1 Target segment

The main goal of this project is to study the complementarity of VLEO for EO purposes, comparing the two integration alternatives proposed in the previous section. In order to make the proposal successful, it cannot be focused on several applications at the same time. This is why it has been selected a concrete application of remote sensing applied to EO: vessels tracking. This is an application that is currently in continuous growth due to the dramatic rise in e-commerce, increasing drastically the number of worldwide shipments. This causes the need of a higher accuracy while tracking vessels, as the traffic will be higher. That is the reason for considering the integration of VLEO for this specific application, as it can improve the resolution of the data obtained.

5.1.2 Market and potential customers

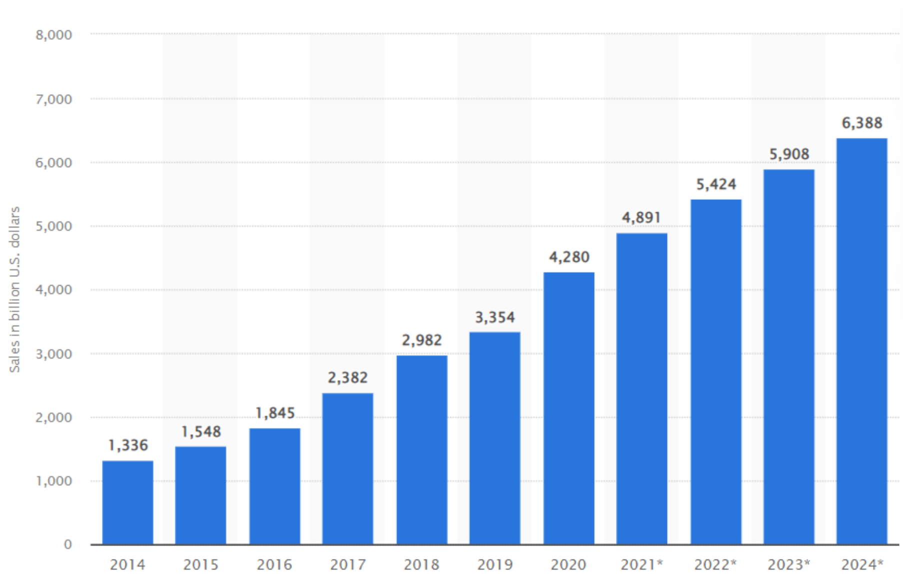


Figure 24: Retail e-commerce sales worldwide from 2014 to 2024 (trillions) [44]

As shown in figure 24, e-commerce market is expected to rise even more during the following years. As an example, the revenues of the company *Spire* from September 2020 and same month on the 2021 are shown:

Spire reported $9.6 million in revenue for the third quarter ended September 30, a 33 percent jump from the same period in 2020. During the quarter, Spire's earnings from annual recurring revenue customers grew to $45.2 million, a 51 percent spike from a year earlier.

Another example from *exactEarth*'s revenues:

ExactEarth revenues for the third quarter of 2021, ending July 31, were $6 million, a 26 percent increase from the $4.8 million reported for the third quarter of 2020.

The global vessel tracking system market stood at a value of USD 740.2 (651.49 EUR) million in 2020. The market is further expected to grow at a Compound Annual Growth Rate (CAGR) ,which refers to mean annual growth of an investment over a specific duration, of 11.35% in the forecast period of 2022-2027 to attain a value of USD 1410.9 (1241.80 EUR) million by 2026. The high demand on this sector is due to rising trade activities and the evolution of international trade routes. In the forecast period, it is expected a higher growth as governments are rising capital expenditures in the maritime industry. Furthermore, the rapid technological advancements, such as 5G technology

and the Internet of Things (IoT), along with Artificial Intelligence (AI) and Machine Learning (ML), are projected to propel the industry growth during the following years [19].
To conclude, there is a vast potential market for space data [57]. It is expected a high commercial demand for vessel tracking systems.

The proposals would fit for two different clients:

1. **Business-To-Business (B2B) → Maritime transport companies:** focused on transport companies that deploy a large number of cargo ships per day and require a high accuracy while tracking them. It will be supposed that all the vessels from this company are vessels of a gross tonnage equal to or exceeding 300 tonnes, requiring Class A transponders, which provide the following information:

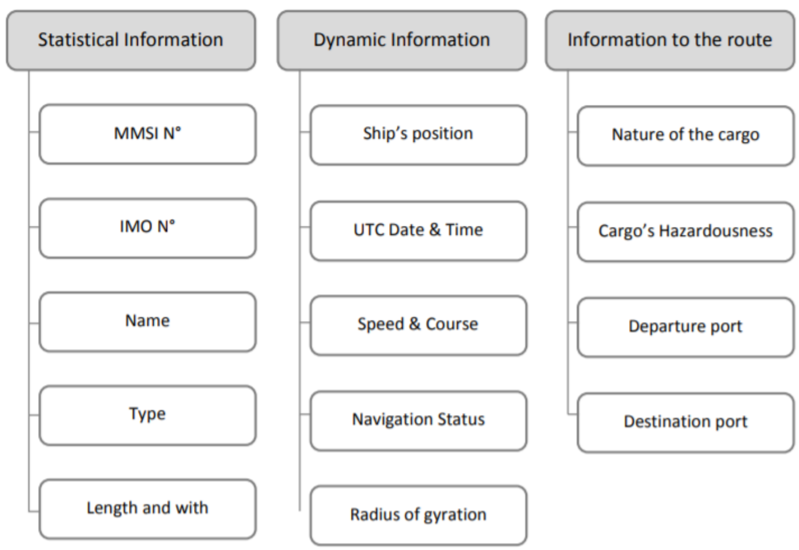


Figure 25: Nature of AIS data [48]

2. **Business-To-Government (B2G) → Government and state security agencies:** regulatory and governmental entities require to acknowledge the position of the vessels continuously in order to avoid vessels navigate in forbidden areas of a country's EEZ, illegal fishing, piracy, immigration, trafficking or Search and Rescue (S.A.R) services. In this case, not only vessels with AIS transponders installed will be tracked. Using AIS is limited to cooperative ships and large ships mounting properly-working AIS facilities on-board. Moreover, AIS lacks authentication and encryption, and is hence vulnerable to hacking or spoofing. Also, even in high traffic areas all the vessels need to be localized with a high accuracy. The information needs to be updated rapidly and a regular monitoring of all the zones surveyed is required. Almost a real-time communication between

the client and the satellite is a must, as well as a high resolution image of the area. The need to contrast information with another data in case of discrepancy is also a requirement. Data needs to be received during all day and night, no matter the weather conditions and sunlight. Another determining factor requested is the easiness of access, manipulation and interpretation of the information provided by the service. It is also mandatory the incorporation of alarms that in case of emergency are sent to the client at the moment, allowing him to take action as soon as possible.

Both clients have different purposes and budgets, but also different coverage and data integration requirements. Hence, two completely different value propositions with different satellites and orbits would be needed. In both cases, though, data would need to be received regardless weather condition. This is the main reason to choose the combination of Sat-AIS and SAR technology for the satellites of this case study, allowing to achieve both a high resolution and continuous coverage of an area.

In this project, it has been decided to focus only on the B2B proposal (**maritime transport companies**), as it would offer a global coverage and not just a regional one. Also, due to the rise of e-commerce it can be predicted that the maritime transport sector will be in a continuous growth during the following years.
However, it is worth mentioning that the study of the complementarity of VLEO for the Coast Guard of any country would be really interesting for further projects, as in the coastal areas is where AIS data is more inconsistent and lost and suffers more interference due to the high amount of signals being sent at the same time, as the traffic is really high. This fact makes SAR satellites + Sat-AIS + AIS ground platforms in a VLEO a promising proposal to enhance the tracking of every vessel in a country's territorial waters and ensure not only a few vessels are tracked.

5.1.3 Problems, needs and requirements

The client requires a high accuracy while tracking his vessels and the ones approaching to them.
As all the company's vessels will have AIS transponders installed, the main source to track the vessels will be AIS data from the satellite's receiver. This is due to the reduction on AIS gaps owing to on purpose turned-off AIS transponders. The vast majority of missing AIS data provides from those ships that do not want to be tracked for several reasons, such as illegal goods shipping or illegal fisheries, so given the fact that VLEO satellites can receive a stronger signal than higher-orbit satellites, AIS gaps would be significantly reduced. However, there are other reasons why a vessel could go dark. This can go from unintentionally reasons like equipment failure or being outside of satellite coverage, to intentionally turned-off AIS transponders for transshipping activities, fishing in protected areas or avoiding coast guard controls and

trade sanctions. In the case of a maritime transport company, it is more common an unintentional failure but for safety reasons all the options must be considered, even though an intentionally turned-off AIS system. Incorrect position of vessels are also a current problem to solve. If the latitude and longitude of a vessel is being transmitted out of range of the satellite, it can be flagged as an area of potential spoofing. Therefore, in case of inconsistent or missing data due to AIS gaps, the client will be able to request for SAR images support to contrast different sources to obtain even more precise information. All these services need to be offered at a competitive cost.

5.1.4 Buyer persona definition

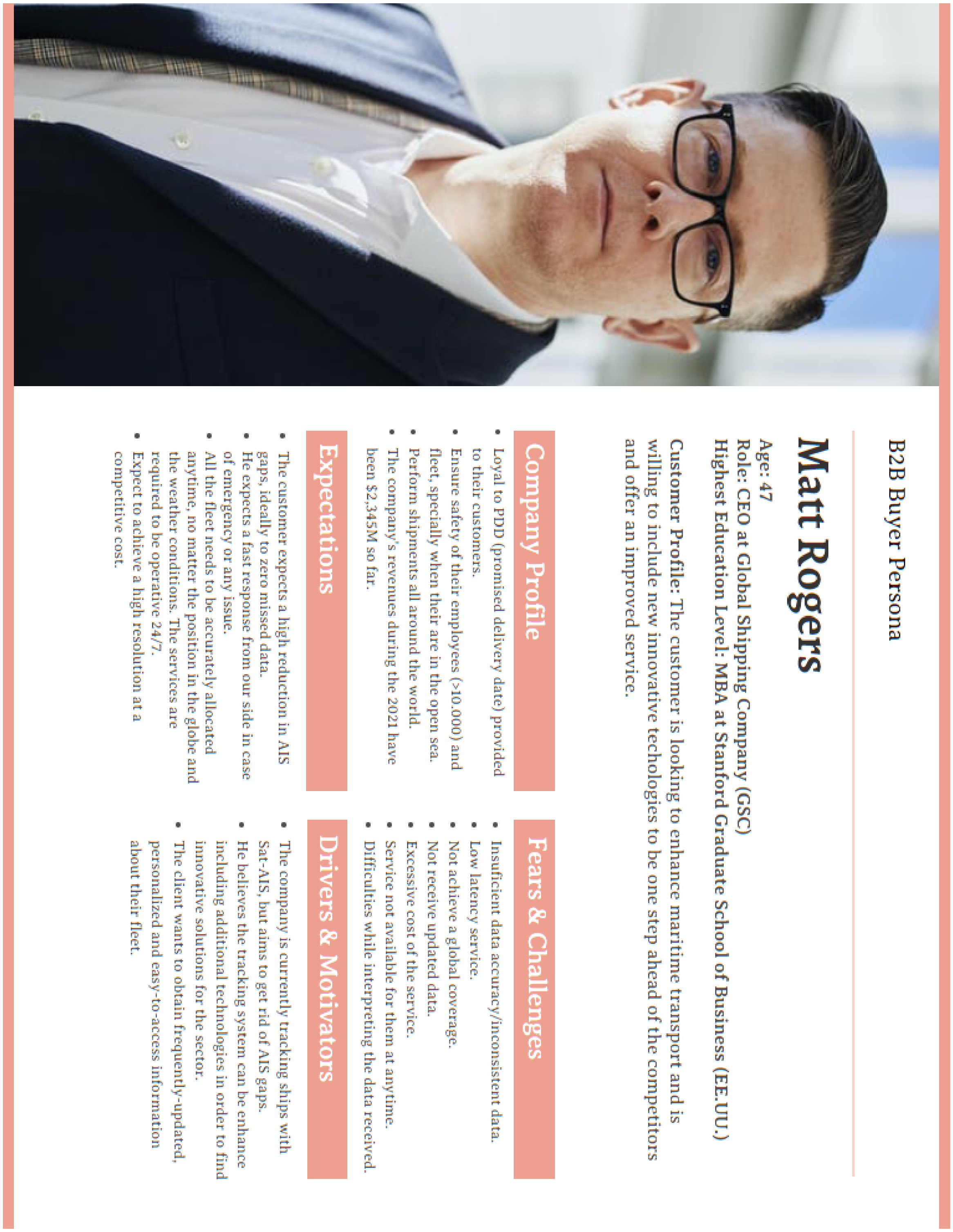


Figure 26: B2B buyer persona

5.1.5 Scope

The proposals generated will be EO space multi-platforms for satellite remote sensing in VLEO and LEO orbits, to provide tracking services to a maritime transport company. The proposal will be created to be the owner of the satellites and will collect, interpret and analyse the data. Not only a tracking service will be offered, but a complete surveillance service instead: from collecting data from satellites to extract the information required and map it with additional features available to provide it to the customer. Alerts will be sent to the user as soon as possible whenever a suspicious practice is detected.

5.1.6 Empathy map

Figure 27: Empathy map.

5.1.7 Solution and benefits

"Several active observation satellites placed in a VLEO will offer vessels data available 24/7 and anywhere in the globe, combining data from different resources once received in the ground station."

Active imaging systems, especially Synthetic-Aperture Radar, can penetrate clouds and does not require sunlight to provide reliable remote sensing data.

In this practical case, even though data could be combined using to different methods (Data Integration and System Integration) as explained in section 2, only Data Integration will be considered. This is due to the clients' requirements, as combining the data before receiving it would mean a continuous contrast of information between AIS receiver and SAR images, which is not needed for maritime transport companies as SAR images would act as a support source. Anyway, it is worth mentioning that system integration would be really interesting for the B2G kind of client, as the probability of having dark vessels in the area and not only cargo vessels is really high.
The constellation of satellites would achieve a global coverage, at least in terms of maritime transport. That means that all the areas where a ship can travel through will be covered. As SAR imagery will be a complementary data to contrast the information obtained by AIS receivers, not all the satellites launched will include SAR sensors. The constellation will be formed by more than 90 nanosatellites, but only a few of them (between 20-30) will carry out SAR sensors. Sat-AIS satellites will only weight about 5kg, in contrast with the few SAR+AIS satellites that can weight up to 90kg. The main source to detect vessels will be Sat-AIS, but in case of discrepancy SAR images will be consulted.

The satellites would be launched in VLEO. Communication via satellite begins when the satellite is positioned in the desired orbital position. Ground stations can communicate with satellites only when the satellite is in their visibility region. The visibility region is in fact the horizon plane. Because of natural barriers or too high buildings in urban areas, practical horizon plane differs from the ideal one. The duration of the visibility and so the communication duration varies for each satellite pass at the ground station, specifically for VLEO satellites which do move too fast over the Earth and suffer from high latency in making contact with their satellites, due to geographic sparsity of the required ground stations.
Given that VLEO has the drawback of a slower download time and an difficult synchronization, there is less available link time (reduced windows communication). As the resolution obtained by VLEO platforms is higher, the data is heavier. So a direct communication between ground stations and the satellites is not feasible for this case study; lots of ground stations would be needed to make this direct communication feasible. This is the main reason to reject VLEO satellite-ground station direct communication system.

A solution has been found for this issue: sending the data from VLEO to geostationary relay satellites, this ones being directly linked to the ground station. Those satellites only offer restricted bandwidth, which is not enough to send continuously raw data from the sensor to the ground-station, but the data that the user requires fast consist in small data such as position, velocity, heading, type and status of the shift. If the data is processed on the EO platform before sending it to the EO satellites, the information required by the user would be extracted fast and sent via satellite communication services [59]. Due to the large FOV of GEO satellites, just with two geostationary data relays continuous real-time access to VLEO satellites could be provided. These data would then be transferred to a ground station by the GEO repeater, leading to a continuous communication between the satellites and the ground stations.

Even though the combination of these two systems would allow the detection of most vessels, there is still an AIS gap remaining: high traffic areas, specially coastal zones. In this case, some of AIS data can still be missed and we could only trust in SAR imagery to detect vessels. This is not what the client expects. He expects to have a secondary source to contrast the information anywhere and anytime. This is why in coastal areas an extra platform will be deployed to increase even more the accuracy of the vessels position: UAVs or tied balloons if the country's regulations allow it, ships with an AIS receiver in case those are not allowed in that area. This last platform deployment would allow a truly global and anytime coverage for maritime transport companies vessels.
The data obtained from the drones would be directly sent to the nearest ground station to combine it, once received, with the SAR images and the AIS data. Therefore, data from different platforms will be integrated once received in the ground station, as the contrast of the information acquired will not be required in all cases.

The main added values compared to other space remote sensing services offered in this sector are the higher precision and resolution achieved thanks to the decrease in the satellite's orbit, the continuous tracking of vessels (no matter the traffic condition and the location in the globe) and the possibility to track vessels without an AIS transponder on-board in case any suspicious activity is taking place.

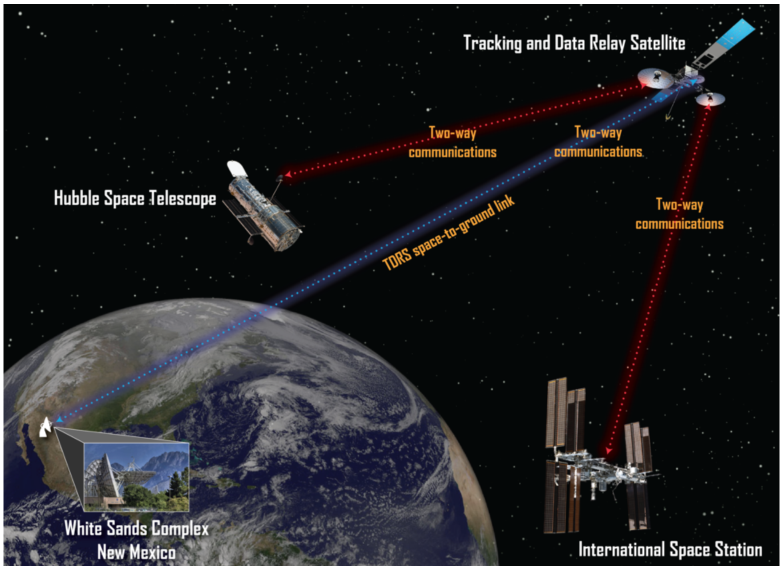


Figure 28: Tracking and Data Relay Satellite communications between the ground and space [58].

This proposal has been selected due to the different platforms that can be used depending on the traffic situation and the reliability on the first source chosen to obtain the data (in this case, Sat-AIS).

5.2 Value Proposition Canvas

The analysis is divided in two blocks: customer side and product side:

5.3 Customer side

This will form the right part of the Value Proposition Canvas. In order to develop the value proposition, the client must be studied first: his problems, behaviour and requirements will be analysed so his needs can be accomplished.
Afterwards, the customer jobs, pains and gains will be defined. The aim is to find the client's problems which deserve to be solved.

First of all, the buyer persona will be defined.

- Customer jobs: activities that the client develops to solve a labour/personal situation. In this section the focus will be the problem the client founds while developing a certain task or activity, the motivation to perform this task/activity and the needs for carrying it out.
- Pains: frustrating/disgusting situations that the client experiences while developing a task. The challenges and difficulties that the client finds in his personal or

labour life, that would be the non-desired aspects of developing a specific activity, the obstacles and the risks while developing it.

- Gains: positive results, happiness and benefits the client experiences once the situations mentioned above are solved. The benefits the clients obtained can be classified as follows:

    1. Minimum → the proposition is not accomplishing the goal.
    2. Expected → the benefits accomplish the minimum ones expected by the client.
    3. Desired → the ones the client wants to obtain when they purchase the service.
    4. Unexpected → benefits the client didn't expect but mean a pleasant surprise.

5.4 Product side

This will be the left side of the Value Proposition Canvas. After studying the customer side, the product will be focused on offering a solution to the client that relieves his frustrations and pains and brings him good results and satisfaction.

- Pain relievers: how can the product help the client to relieve his annoyances. Analysing the "Pains" section from the client side, an effective solution shall be offered.
- Products & Services: definition of each of the products and services offered, designed to solve the client's problems.
- Gain Creators: clear explanation of the benefits the product or service will offer to the client, taking into account his expectations [17].

5.5 Product-Market fit

The goal of the Value Proposition Canvas is to assist in the design of a great value proposition that matches the Customer's needs and jobs-to-be-done and helps him solve his problems. This is what the start-up scene calls product-market fit or problem-solution fit.

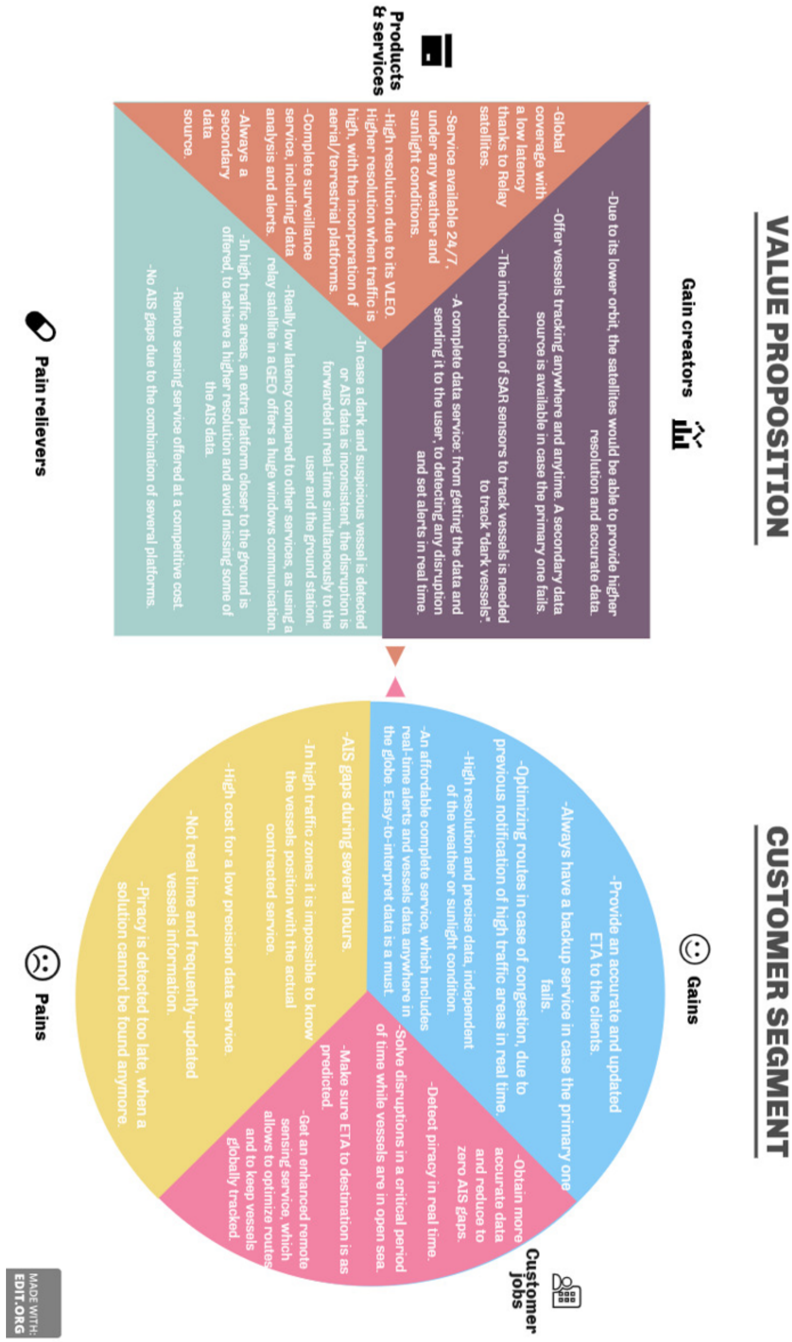
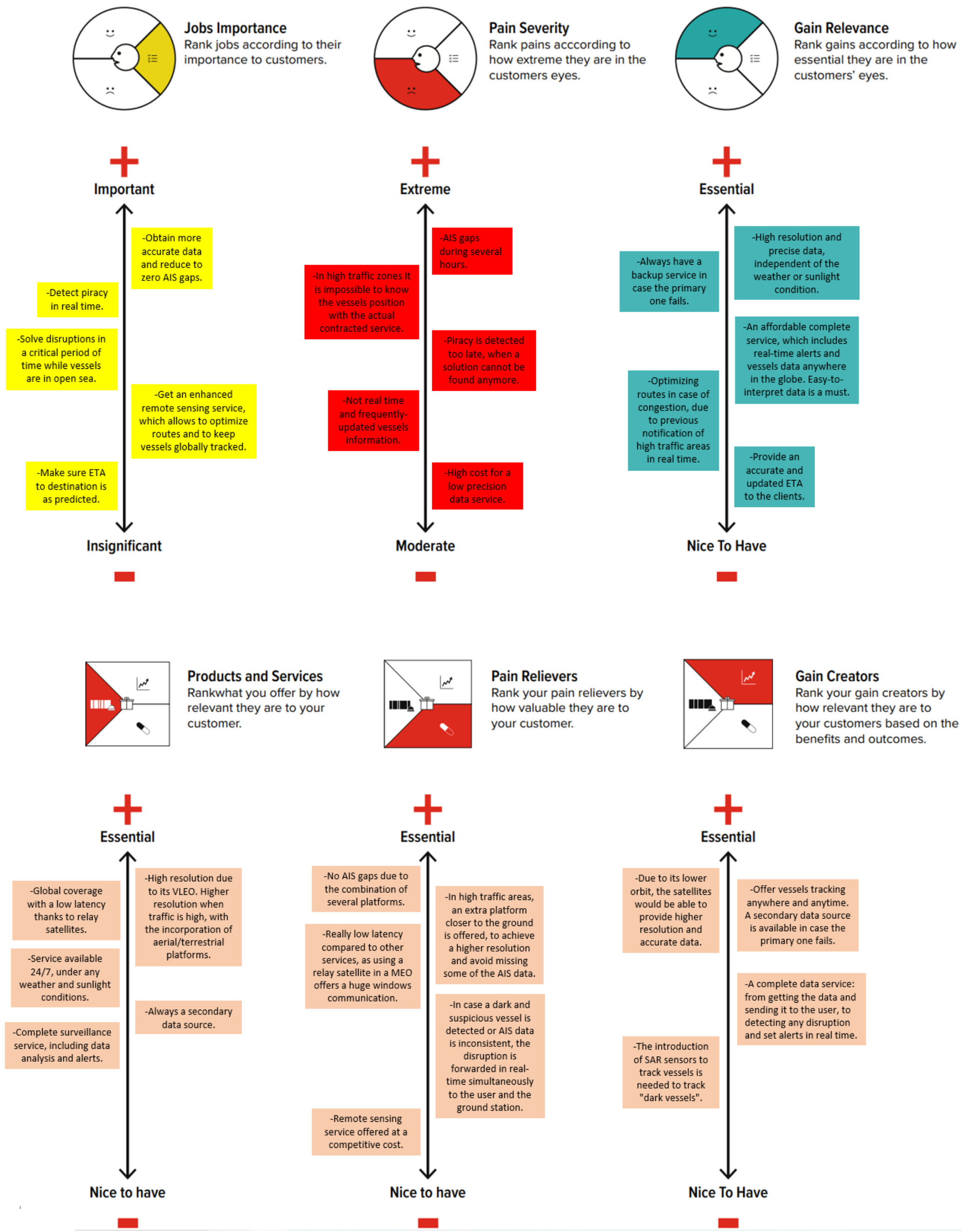


Figure 29: Value proposition Canvas.

Once this is done, the customer jobs, pains and gains will be prioritized; from less significant to more significant. The same will be done with the products and services, pain killers and gain creators on the product side.



Afterwards, the product-market fit can be discussed:

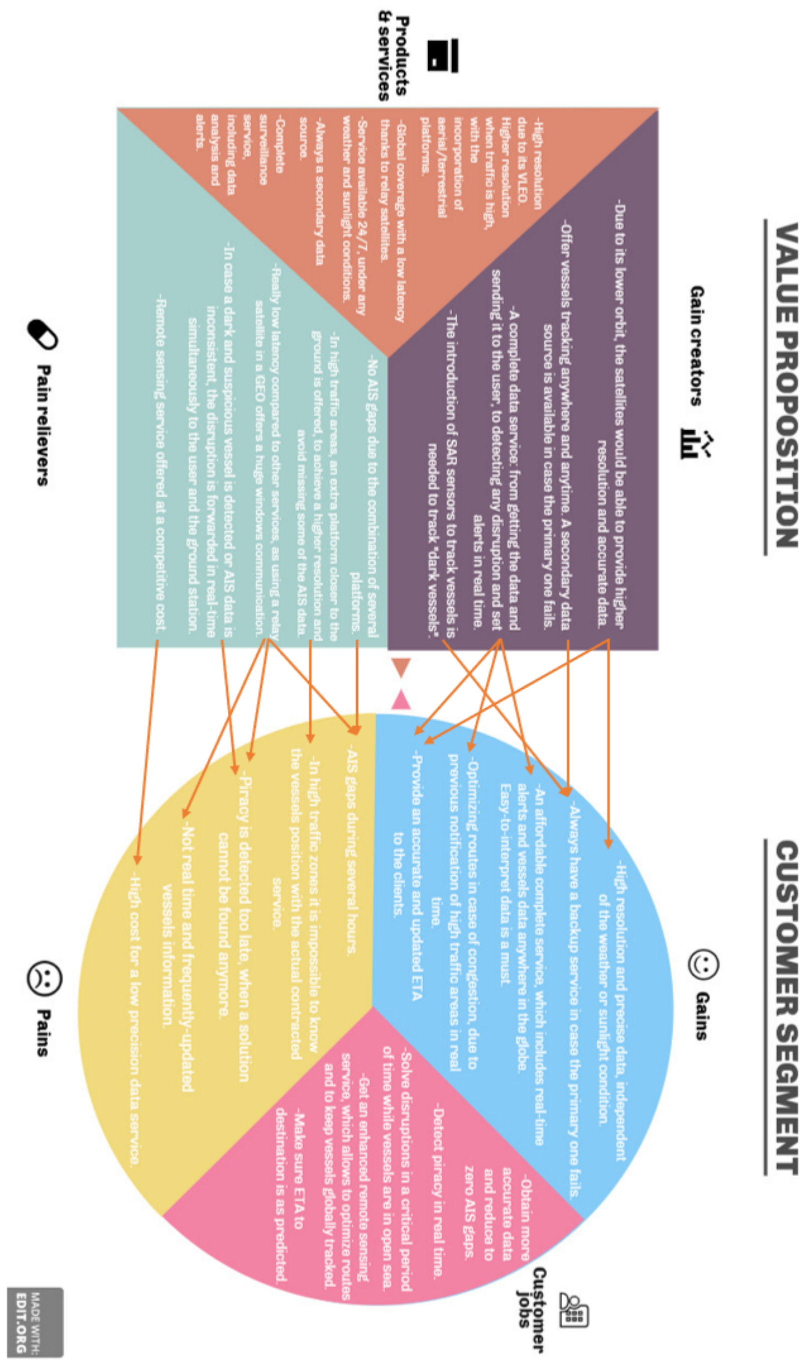


Figure 30: Value proposition Canvas: Product- Market fit.

As seen above, all the gains the customer expects to achieve and the pains he wants to defeat, are covered by the service offered. So the service is considered to fit in the market.

6 Final discussion

Now the incorporation of VLEO satellites to complement EO platforms in the maritime surveillance field has been studied and exposed, some points need to be remarked.
First of all, as mentioned in previous sections, VLEO satellites are still in a preliminary phase. This means that several ways to complement the current EO platforms available are still to be studied and discovered. Before developing VLEO satellites, several challenges such as aerodynamic resistance due to residual atmosphere, corrosive environment and reduced windows communication would need to be overcome. Once this is achieved, the benefits VLEO could bring to the maritime surveillance field are a lot.
As seen in the Value Proposition Canvas of the model, the requirements of a typical leading maritime surveillance company are all fulfilled with the VLEO complementarity proposal. This could hardly be achieved with only using higher orbit platforms, as the accuracy needed to know the exact position of vessels is really high, so the better the resolution the most data from the vessels the ground station will be able to connect.
The use of several platforms to fulfill all or most of the needs of the mission, is a huge progress in EO applications; the data does not depend only in one platform type and its resolution and characteristics, as deficient or improvable parameters of a platform can be improved with a different one. In this case study, the low resolution problem is solved with VLEO or aerial platforms, whilst the reduced windows communication issue is sorted out sending the data to a satellite in a Medium Earth Orbit. In different cases study the problems to solve may be different, and another platforms combination may be used. This is why space market in the EO field is really promising: with the correct platforms combination, a solution to each problem can be found and not necessarily at a high cost.

To reduce costs, several satellites will be able to be launched at the same time with the same rocket, as all the satellites will be nanosatellites. Nowadays, several companies offer a reduced cost for launching small satellites as a secondary payload. Also, some materials can reduce the cost of the satellites.

Thanks to nanosatellites, not only exclusive companies have access to space and also with VLEO satellites the exploitation of it could be accessible to small companies with not necessarily a huge fund.

The proposal is validated to be successful for this case study, leaving also the door opened for the B2G customer as the tracking of dark vessels is even more required and critical for them. The accuracy needed to track vessels is really high, so the higher the resolution the better for this case study. VLEO and aerial platforms are really helpful in this field. In is truth that aerial platforms offer the best resolution, so it may be a good solution for B2G clients that only need to survey a specific region. But just with aerial platforms, a global coverage is not feasible as a lot of platforms would be needed,

and the current regulations for them are strict. This is why VLEO satellites combined with different platforms are selected to be the solution for the high precision needed to track vessels, considering that the maritime transport market is expected to be in a rise in the following years and more and more accurate data will be needed.
The need of a secondary data source is a must, as it is not permitted to have any manned vessel or carrying hazardous goods out of track for several hours due to an AIS system malfunction or a satellite's communication failure.

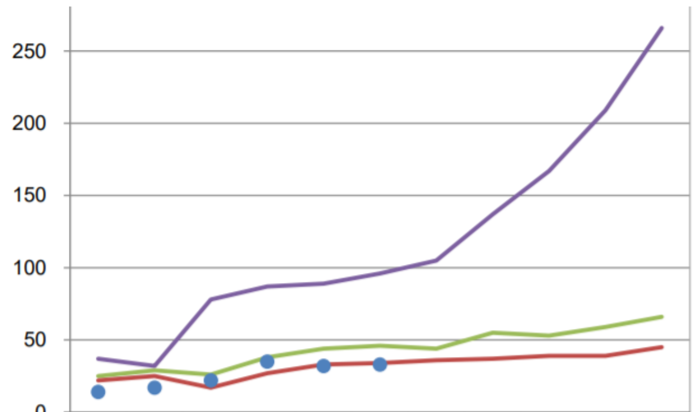
Data Integration shall be used when only data from vessels with AIS transponders on-board is needed (e.g. Maritime transport companies). On the other hand, System Integration can be used when a continuous track of small vessels or not registered ones is needed (government and state security agencies).

7 Environmental study

Introducing VLEO platforms in the current market would significantly reduce the environmental impact due to the natural de-orbitation satellites can achieve at this altitude. It is at this low altitude where the residual atmosphere is dense enough so aerodynamic forces are relevant enough to cause natural de-orbitation of the satellites. Drag causes the satellites to "loose" the orbit faster that in higher altitudes, so in case no thrust is provided, the satellite does not have to develop any manoeuvre to decay from its orbit back to the atmosphere, where the major part of the equipment decomposes due to the high temperatures caused by friction. For example, a LEO satellite at an altitude of 800 km would take 100 to 150 years to naturally de-orbit, while below 500 km it would be fulfilled naturally in less than 25 established years [35].
Space debris is an actual matter that has lots of scientist and astronomers concerned, and introducing VLEO technology would allow to reduce it from now on.

Another significant environmental impact that satellites have is the pollution caused by its launch. This can be reduced by both, launching small satellites and launching them at a very low altitude orbit. This allows the fuel consumption to be reduced, therefore leading to a lower weight to be launched. Several satellites could be launched at the same time using the same launch vehicle, consequently reducing the pollution derived from the burning of fuels and their obtainment.
The number of launches could also be reduced achieving the collaboration between all the companies and individuals that own satellites already in orbit: no satellite with the same purpose and characteristics that another one already in orbit should be launched, as this would mean increasing space debris just for a matter of competition.
VLEO satellites can complement other satellites in a higher orbit in order to achieve the resolution requirements without the need to launch another satellite at a higher orbit, as both would be communicated and the information could be combined and sent to the ground station.

The environmental impact can also be reduced using biodegradable materials and rockets that can be reused.
Also, the pollution can be reduced thanks to the introduction of Atmosphere-Breathing Electric Propulsion (ABEP) systems. At very low altitudes, where the atmosphere is source of aerodynamic drag on the spacecraft, an efficient propulsion system is required. One solution is ABEP that collects atmospheric particles to be used as propellant for an electric thruster. This system would also allow to reduce the weight of the fuel needed.
Nowadays, space industry is in a continuous growth; several companies are interested in the exploitation of the space in order to understand it beyond our planet and also for Earth Observation purposes. This creates a huge concern about environmental contamination and space debris in the future, so the need to focus on new proposals that reduce the environmental impact is becoming greater and greater.



	FY2015	FY2016	FY2017	FY2018	FY2019	FY2020	FY2021	FY2022	FY2023	FY2024	FY2025
Actual	14	17	22	35	32	33					
Forecast High	25	29	26	38	44	46	44	55	53	59	66
Forecast Low	22	25	17	27	33	34	36	37	39	39	45
Industry Forecast	37	32	78	87	89	96	105	137	167	209	266

Figure 31: Number of FAA Licensed and Permitted Operations by Fiscal Year, World-wide [16]

To conclude this section, it is worth mentioning that currently all is about competition. This increases space debris and causes a huge waste of money, as some satellites are redundant because another company's constellation is placed in space for exactly the same purpose. Using a satellite already in orbit should be normalized an prioritized to launching a new one. Cooperation between companies is a must to avoid redundant satellites.

8 Conclusions

Once the study has been carried out, several conclusions can be extracted from this analysis:

- Both space market and e-commerce are in a continuous growth, meaning that maritime surveillance field will need even more accurate solutions during the following years. In terms of achieving a high resolution and global coverage, VLEO satellites are a really good option to consider, as they offer an intermediate solution between aerial and space platforms, maintaining the satellites' characteristics and offering improvements mainly in spatial and spectral resolution.

- The periods of time vessels are not able to be tracked by AIS system are called AIS gaps. This is due to the reduced window communication of the satellites in a low orbit as the time they are linked to the ground station is really low or due to any AIS system malfunction. To definitely solve this issue, the data needs to be forwarded to a relay satellite in a GEO to send the data to the ground station afterwards. That way, VLEO satellites and ground stations will be continuously linked thanks to relay satellites and its huge FOV. Otherwise, a vast amount of ground stations would be needed to directly link the VLEO satellite with the ground station.
  Also a secondary data source is needed in case of AIS malfunction; in this case study, SAR imagery is the most appropriate one thanks to its all-weather coverage.

- In coastal areas is where most AIS gaps are found. This is why an extra data source is added in high traffic zones: UAVs, balloons or ships (depending on the country's regulations) with an AIS receiver to avoid any lost AIS message. This data will be directly sent to the nearest ground station in the area.

- The main source to detect vessels will be Sat-AIS but, in case of discrepancy, SAR images will be consulted. Whenever a suspicious event is taking place (i.e. a non-registered ship right next to the cargo vessel), SAR sensors will be able to identify it so further action can be taken.

- There are two main integration methodologies: Data Integration and System Integration. The first consists of the combination of data after it is received in the ground, and the second one combines different platforms at the same time while obtaining the data, to then send to the ground station the data already integrated. One methodology or another should be used depending on the accuracy requirements and type of information. In case only data from vessels with AIS transponders on-board is needed (e.g. **Maritime transport companies**) , a SAR sensor could be used to contrast the information in case of any AIS system malfunction. This is when **Data Integration** would be used, as the combination of data is not required during all the observation. On the other hand, if small vessels, those exempt of having AIS transponders on-board or not registered ones need to be tracked as well, with a Sat-AIS receiver would not be enough. A SAR sensor would be needed to keep track of those dark vessels. This would be the case of **government and state security agencies**, and the methodology used shall be **System Integration**, as a constant combination of data between platforms would be required.

- Nowadays, small companies are becoming more and more interested about EO services, as due to *New Space* principle space is becoming more accessible. With the launch of nanosatellites in VLEO, a huge costs saving can be achieved, therefore allowing companies with not a huge fund to be part of space exploitation.

- VLEO technologies are able to bring huge benefits in the EO field, and combining these platforms with different ones the solutions offered can satisfy several customers and cover all the requirements for different EO applications. Not only a matter of accuracy level is being sorted out with the incorporation of these platforms, but also the concern of the over-saturation of space and pollution caused by rockets are taken into account. Once it has been dealt with all the limitations of the environment at that altitude, VLEO platforms are a promising technology to include in EO missions.

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