Monitoraggio via Satellite dei Flussi Migratori nell’Area del Mediterraneo

(Remote Monitoring of Migrants Vessels in the Mediterranean Sea)

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Abstract

The Mediterranean Sea has been the theatre of intense illegal immigration phenomena in the last decade. Current migration flows mainly originate in North Africa and terminate in the southernmost part of Italy; i.e., in the south coast of Sicily and in minor islands. The number of Mediterranean Sea arrivals is rising at increasing rate in the recent years. Unfortunately, these journeys can end up in tragedies. Moreover, from the Italian and European side, the uncontrolled landing of thousands of migrants per year generates a feeling of danger among citizens.

Due to the central role of Italian economy within the Mediterranean Sea and its geographical collocation, Italy is called to play a key role in the definition of the actions for the development of a proper system for illegal immigration monitoring and tragedies prevention. However, monitoring is currently carried out with means that have only a local area of applicability. Moreover, monitoring illegal immigration, rescuing migrants in
troubles, and health caring these people require a huge use of men and money.

A novel approach to overcome the previous issues is proposed in this work, based on the use of space-based technologies. Being at hundreds of kilometers above the Earth’s surface, artificial satellites permit us to have a global overview over an extended area. Moreover, the possibility of exploiting payloads and satellites that already operate on a regular basis allows the costly development and deployment of *ad hoc* space systems to be avoided. In addition, the development of a proper system architecture relying on the mere processing of satellite images is shown to allow the Authorities to identify possible illegal vessels and to send or re-direct patrols and rescue teams in a more efficient way.

The performances and feasibility of the proposed strategy are assessed using the Italian satellite constellation COSMO-SkyMed as the baseline system for data retrieving. The next step for the future implementation of a space-based illegal immigration monitoring system is described.
Executive Summary

The Mediterranean Sea has been the theatre of intense illegal immigration phenomena in the last decade. The migration flows find their origin in various Countries and are directed toward Italy and European Countries. Historically, southern-east Italy experienced a huge number of landings of migrants coming from the Balkans in the first half of the nineties. More recently, migration flows mainly originate in North Africa and terminate in the southernmost part of Italy, i.e., in the south coast of Sicily and in minor islands. Above all, the situation in Lampedusa is particularly worrying. According to the Italian Ministry of Interior, with the exception of 2007, the number of arrivals in Lampedusa has kept rising at increasing rate since 2003. The figure of illegal entries in 2007 doubled in 2008, when about 31000 arrivals were recorded. The trend of 2009 is leading the number of landings well over the level of 2008.

Due to travel and vessel conditions, these journeys can end up in tragedies. As this manuscript is being written, news report that 73 Eritrean people died at sea during
their risky journey from Africa to Europe. Moreover, from the Italian and European side, the uncontrolled landing of thousands of migrants per year generates a feeling of danger among citizens.

On the other hand, the endless work of the Italian armed forces and non-governmental organizations confirms the great tradition of humanitarian support that is recognized to Italy at international level. Italy is then called to play a key role in the development of the proper architecture for illegal immigration monitoring and tragedies prevention.

However, monitoring illegal immigration, rescuing migrants in troubles, and health caring these people require a huge use of men and money. This implies elevate costs for the armed forces. These costs are loaded on taxpayers. This asks for the definition of innovative cost-effective strategies. Moreover, monitoring illegal immigration is currently carried out with means that have only a local area of applicability. Boats are in fact located either if they are close to other boats or if they are in the field of view of certain instruments (e.g., land radars). A global approach is therefore missing.
Within this context, this work is aimed at assessing the possibility of overcoming the previous issues using a novel approach to monitor illegal immigration in the Mediterranean Sea, relying on the use of space-based technologies. Being at hundreds of kilometers above the Earth’s surface, artificial satellites permit us to have a global overview over an extended area. Moreover, the possibility of exploiting payloads and satellites that have already been developed for other purposes (so avoiding the costly development and deployment of ad hoc space systems), and that are operating on a regular basis, is shown to serve the purpose of illegal immigration monitoring with significant reduction of the operative costs. More specifically, a system architecture is sketched that allows the authorities to identify possible illegal vessels based on satellite images. Consequently, patrols and rescue teams can be sent or re-directed to the suspect target in a more efficient way.

The proposed methodology is based on the use of Synthetic Aperture Radar (SAR) instruments, which are preferred to optical instruments for their versatility, as they also work with clouds and during nighttime.
The state-of-the-art in SAR imagery and the analysis of the satellites operating SAR instruments show that, based on the best compromise between instrument resolution and swath, illegal vessels with a minimum length of about 15 m can be effectively detected from space, with good spatial resolution and revisit time.

The case of COSMO-SkyMed, the largest Italian investment in space systems for Earth observation, is thoroughly analyzed. With its ScanSar operating mode, the orbit performance assessment indicates that, once in its full configuration, COSMO-SkyMed will be able to assure the following worst-case performances:

- the coverage of most part of the Mediterranean Sea area (90%) in 2.9 days;
- a maximum number of 5 accesses to the Mediterranean Sea area per day;
- a maximum revisit time of a point of interest of about 12 hr;
• SAR data download to ground in real-time during acquisition, thanks to the support of Fucino ground station.

In conclusion, the work highlights that the technology to implement an effective space-based illegal immigration monitoring system is available. The use of satellites already operating on a regular basis will allow cost containment and efficiency. The software for image processing, as well as the system architecture, can take advantage of the work carried out at European level for illegal fishery control. The set up of a pilot project is suggested to demonstrate the feasibility and to acquire the proper know-how for the deployment of the final monitoring system.
# Remote Monitoring of Migrants Vessels in the Mediterranean Sea

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Part 1: Generalities

1 Introduction and Statistical Data

1.1 Demographics of Immigration in Italy

Traditionally a country of emigrants, in the last 20 years Italy has become a country of immigration, with about 4.9% of the population fitting that description. Fitting the description to 2009, 3.7 million immigrants live legally in Italy, while estimates for undocumented immigrants vary from 0.8 million to 2 million. The most recent wave of migration has been from surrounding European nations, particularly Eastern Europe, replacing North Africans as a major source of migrants. Around 500,000 Romanians are officially registered as living in Italy, but unofficial estimates put the actual number at double that figure or perhaps even more. As of 2006, migrants came from other parts of Europe (47.75%), North Africa (17.77%), Asia (17.43%), Latin America (8.90%). Smaller groups came from sub-Saharan Africa, and North America [1]. Figure 1 shows the geographical distribution of foreign residents in Italy.
1.2 Illegal Immigration to Italy

Illegal immigration refers to immigration across national borders in a way that violates the immigration laws of the destination country. Illegal immigration may be prompted by the desire to escape civil war or repression in the country of origin. Non-economic push factors include persecution (religious and otherwise), frequent abuse, bullying, oppression, and genocide, and risks to civilians during war. Political motives traditionally motivate refugee flows – to escape dictatorship for instance [2].
In Italy, illegal immigration is fed mainly by *overstayers*, all those foreigners who entered the country regularly, and remain after the expiration of their visa (or, equivalently, their authorization to stay). According to the Ministry of Interior, in 2005 this phenomenon affected 60% of the total number of illegal immigrants in Italy. Another 25% of immigrants arrive illegally from other Schengen countries, taking advantage of internal borderless controls. Only 15% of the total illegal immigration in Italy comes from routes within the Mediterranean Sea [3]. Table 1 summarizes the distribution of illegal immigrants according to the source.

Although the latter way of reaching Italy seems to be marginal with respect to the other two, it involves thousands of people, and, unfortunately, it causes the death of hundreds of people a year. Thus, special attention has to be paid to this kind of illegal immigration.

<table>
<thead>
<tr>
<th>Source</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overstayers</td>
<td>60%</td>
</tr>
<tr>
<td>Shengen</td>
<td>25%</td>
</tr>
<tr>
<td>Mediterranean</td>
<td>15%</td>
</tr>
</tbody>
</table>

**Table 1**: Sources of illegal immigration in Italy in 2005 [3].
1.3 Illegal Immigration to Italy through the Mediterranean Sea

In order to have a clear understanding of the size of the problem (i.e., average number of people involved, recent trends, countries of origin, etc.) in this section we briefly report data of illegal immigration via the Mediterranean Sea of latest years.

A total of 22016 unauthorized immigrants have landed in Italy from the 1\textsuperscript{st} January to 31\textsuperscript{st} December 2006. This represents a slight decrease compared to 2005, when the total number of arrivals was 22,939. Most of the landings took place on the shores of Sicily.

In 2006, 21400 (22,824 in 2005) people landed in Sicily, 243 (19 in 2005) in Apulia, and 282 (88 in 2005) in Calabria. Of these 8146 are of Moroccan nationality, 4200 Egyptian, 2859 Eritrean, and 2288 Tunisian [3]. Table 2 summarizes the number of unauthorized immigration to Italy in the years 2005-2006. The small missing arrivals are relative to either landings occurred on the shores of Sardinia or other Regions of Italy looking out on the Mediterranean Sea.
Table 2: Illegal immigration in Italy in 2005-2006.

<table>
<thead>
<tr>
<th>Year</th>
<th>Sicily</th>
<th>Apulia</th>
<th>Calabria</th>
<th>Italy</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>22824</td>
<td>19</td>
<td>88</td>
<td>22939</td>
</tr>
<tr>
<td>2006</td>
<td>21400</td>
<td>243</td>
<td>282</td>
<td>22016</td>
</tr>
</tbody>
</table>

In 2007, 19,900 people arrived in the Italian islands or the mainland by ship from North Africa. This is a slight decrease compared to 2006. Nevertheless, at least 471 people died or were missing in the same year.

During 2008 it is estimated that over 67,000 people arrived by sea in Europe, about 36,000 have landed in Italy and 2700 in Malta, most of them departing from Libya. Of these, a large majority has applied for asylum and more than half received some form of protection. Table 3 summarizes the trend of total number of arrival in Italy during years 2005-2008.

According to UNHCR (The UN Refugee Agency), about 31,000 people arrived by boat in Lampedusa (see Figure 2) in 2008. Despite this was only a rough estimate, it is significant to assessing that they represent over 85% of the 36,000 immigrants of 2008. Compared to 2007,
arrivals in Lampedusa have registered an increase of approximately 153%. As an example, 1,400 People arrived with two boats to Lampedusa in just one day, 29 November 2008.

<table>
<thead>
<tr>
<th>Year</th>
<th>No. of Arrivals (Italy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>22939</td>
</tr>
<tr>
<td>2006</td>
<td>22016</td>
</tr>
<tr>
<td>2007</td>
<td>19900</td>
</tr>
<tr>
<td>2008</td>
<td>36000</td>
</tr>
</tbody>
</table>

**Table 3:** Total number of arrivals in Italy through the Mediterranean Sea in the years 2005-2008.

These arrivals in Lampedusa continue to rise, according to the Ministry of Interior: 8,800 in 2003, 10,477 in 2004, 15,527 in 2005, 18,047 in 2006. The exception in 2007 with 11,749 entries, but this figure more than doubled in 2008 with 31,000 arrivals (see Table 4, Figure 3). According to the Italian Geographical Society, 2,000 bodies were found by fishermen in the channel of Sicily. On Christmas 1996, off Portopalo, 283 people disappeared in the greatest tragedy in the Mediterranean Sea since the Second World War [7].
For what concerns 2009, the trend is increasing [8]. It has to be noted that up to April 22 more than 6,000 people, about twice those occurring in the same period of 2008, arrived in Italy. A trend which, if confirmed, would lead the landings well over 31,000 of 2008 (which is already a score record if compared to 2007). The trend of first quarter 2009 highlights how the immigration flow does not slow down even more in winter, when weather conditions make it even more dangerous.

**Figure 2:** Lampedusa island and Channel of Sicily.
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<table>
<thead>
<tr>
<th>Year</th>
<th>No. of Arrivals (Lampedusa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>8800</td>
</tr>
<tr>
<td>2004</td>
<td>10477</td>
</tr>
<tr>
<td>2005</td>
<td>15527</td>
</tr>
<tr>
<td>2006</td>
<td>18047</td>
</tr>
<tr>
<td>2007</td>
<td>11749</td>
</tr>
<tr>
<td>2008</td>
<td>31000</td>
</tr>
<tr>
<td>2009</td>
<td>more than 31000*</td>
</tr>
</tbody>
</table>

**Table 4:** Arrivals in Lampedusa in 2003-2009 (*estimated).

**Figure 3:** Arrivals in Lampedusa in 2003-2009 (*estimated).

Another important index that demonstrates the evidence of the increasing unauthorized immigration is the number of people that appealed for political asylum in last years.
Figure 4 shows that, in recent years, the number of people that applied for the political asylum is increasing (2005-2007). In particular, in 2005 there were 9346 applications, 10348 in 2006, and 14053 in 2007.

![Graph showing number of applications to obtain the status of political refugee in Italy during the years 1996-2007 [9].]

**Figure 4:** Number of applications to obtain the status of political refugee in Italy during the years 1996-2007 [9].

1.4 **Illegal Immigration in Europe through the Mediterranean Sea**

Illegal immigration through the Mediterranean Sea is not an issue that concerns the sole Italy. Other European Countries having shores on the Mediterranean Sea have the same problems – Spain above all. This flow causes
very often tragedies. Indeed, according to information gathered between 1988 and 2008, at least 12,012 men, women and children lost their lives trying to reach Europe surreptitiously. In the same period victims were 2511 in the Channel of Sicily, among which 1549 were missing. This happened in the portion of Mediterranean Sea among Sicily, Libya, Egypt, Tunisia, and Malta. Moreover, 70 people have died traveling from Algeria to Sardinia. Along the routes that bring people from Africa to Spain, 4091 people died traveling in the Strait of Gibraltar. In the Aegean Sea, between Turkey and Greece, 895 migrants have lost their lives. Finally, 603 people have died in the Adriatic Sea among Albania, Montenegro, and Italy [10].

2 Problem Analysis

As we have seen, the Mediterranean Sea has been the theatre of intense immigration phenomena in the last decade. The migration flows find their origin in underdeveloped Countries and are directed toward Italy and European Countries. In the first half of nineties, indeed, southern-east Italy experienced a huge number
of landings of migrants coming from the Balkans. This was due to the crisis affecting the Balkan Countries in that period. More recently, migration flows originate in North Africa and terminates in the southernmost part of Italy, i.e., in the south coast of Sicily and in minor islands – Lampedusa over all. We have seen that the yearly number of arrivals in Lampedusa is increasing in an uncontrolled way (see Figure 3).

It has also been cited that reasons generating these uncontrolled flows toward Italy (and European Countries in general) are due to economic crisis (spread poverty, underdeveloped economies, famine), political instability (civil wars, coups, secessions), and persecutions (application to political asylum – see Figure 4).

The central role of Italian economy within the Mediterranean Sea and its geographical collocation make Italy one of the most favorite destinations for migrants. Immigrants aim at improving their conditions, and therefore are strongly motivated to reach Italy either to stay or to travel for northern European Countries.
Nevertheless, from the Italian and European side, the uncontrolled landing of thousands of migrants per year generates a feeling of danger among citizens. This contributes at decreasing the homeland security in the public opinion. This feeling generates more and more episodes of intolerance, racism, and xenophobia.

On the other hand, Italy has a great tradition of humanitarian support that is recognized at international level. This attitude is consolidated thanks to the endless work of the armed forces and non-governmental organizations. These agencies have always shown availability in acting to help unauthorized migrants. This includes monitoring the sea, rescue, aid, care, and work placement.

In any case, monitoring illegal immigration, rescuing migrants in troubles, and health caring these people require a huge use of man and money. This implies elevate costs for the armed forces if we consider the more and more cut budget allocated to these agencies. These costs are loaded again on the citizens, and therefore clandestine immigration generates also a
feeling of economical dissatisfaction as well as social break-up.

Monitoring illegal immigration is currently carried out with means that have a local area of applicability. This is the case of boat detection. Boats are in fact located either if they are close to other boats or if they are in the field of view of certain instruments (e.g., land radars). A global approach is therefore missing as a strategy for illegal immigration monitoring. Moreover, real-time control over a vast area or even over the whole Mediterranean Sea would bring huge benefits, both from a logistic and economical point of view. If this approach were possible, it would allow the identification of unknown harbors where “journeys of hope” find their origins. This would demonstrate that bilateral agreements aimed at repressing unauthorized immigration, signed between European and North-African Countries, are (or are not) violated by the latter.

The technology is mature to re-consider the strategies for illegal immigration monitoring within Mediterranean Sea. A novel strategy is possible considering the available
technology. More specifically, this strategy has to consider:

- a *global view* of the migration flow to assess the places where boats leave. In this way governments would undertake aimed bilateral relations to keep down clandestine immigration.

- *cost* reduction (at least in the long period), together with the reduction of the number of people in charge of controlling territorial waters. This has to be done in order to keep down the costs and optimize the ratio cost/effectiveness of the military body;

- the improvement of the *logistics* following the sighting of the target. In this way it would be possible to coordinate, organize, and optimize the landing in advance, when the repatriation is no more possible;

- the *humanitarian* feature of the control operations in order to help and rescue possible boat occupants in troubles;
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- the increase of *homeland security* of citizens together with a better cognition and perception about the efficiency of the military body;

3 Proposed Solution

This work is aimed at assessing the use of space-based technologies to monitor unauthorized immigration in the Mediterranean Sea. The current state-of-the-art of space missions for Earth observation and remote sensing, together with the nowadays-accessible technology level, allow us to study the feasibility of space missions and space systems devoted to the control of unofficial traffic in the Mediterranean Sea.

Being at hundreds of kilometers above the Earth’s surface, artificial satellites permit us to have a global overview over an extended area, rather than a mere local picture on small portion of sea given by other means operating at sea level. In this context, we assess the possibility of exploiting payloads and satellites that have already been developed for other purposes, and that are operating on a regular basis. This includes using either scientific satellites or other satellites (e.g.,
telecommunication, military, spies, dual-use satellites [11]) to achieve this goal. Moreover, the use of an ad-hoc system will be considered, and pros and cons of this system versus utilization of existing satellites is discussed in detail.

Beside the task of controlling and monitoring waters, the satellite has also to communicate with ground stations for the sake of data download and post-processing of the achieved measurements. Thus, we will consider the performances of the satellites in terms of

- coverage of and accesses to the Mediterranean Sea area;
- revisit time of a specific point of interest;
- ground station access and data download.

In order to clearly discuss the concept proposed, the second part of this report is organized as follows.

**Introduction to SAR instruments.** In this section we will describe the properties of those instruments that mostly fit the requirements of unauthorized ship detection. Both passive (optical) and active (radar) instruments will be
considered. This section is useful to state preliminary requirements that are considered in the performance assessment.

**System architecture.** In this section the mission architecture is described. In particular, the properties of both the space and ground segment will be fixed to let the concept be feasible. Moreover, hints on the post-processing of data and response time will be given.

**Performance assessment of existing satellites.** In this section, the feasibility of using already orbiting satellites is assessed, and their performances for illegal immigration monitoring are evaluated. In particular, we will consider those systems that are both operating on a regular basis and whose instruments fit the requirements previously prescribed. The performance evaluation is devoted to coverage, ground station access, and revisit time.

**Feasibility of ad-hoc systems.** In this section the feasibility of ad-hoc space systems will be considered. Given both the mission requirements and a certain payload, we will discuss the feasibility and convenience
of a dedicated satellite in terms of main properties (orbit, attitude control, propulsion, power generation, costs).
Part 2: Technical Report

4 Introduction to Ship Detection with SAR

Ship detection is a key requirement for unauthorized vessels traffic control, fisheries and for associating ships with oil discharges [24]. Space-based imaging for ship detection and maritime traffic surveillance has often formed part of major research efforts in the fields of automatic target detection and recognition. Two different technological solutions are currently available based on the use of Synthetic Aperture Radar (SAR) imagery and optical instruments, respectively.

Ship detection with satellite based on SAR was first demonstrated by the experimental SEASAT in 1978. With later first-generation satellites such as ERS-1, JERS-1, ERS-2 the field has reached some maturity. With the advent of the second generation of radar satellites such as ENVISAT and RADARSAT-1, ship detection capabilities were once and for all established thanks to advanced specific processing taking advantage of the huge amount of information that can be retrieved from
low level products (see [24] and references therein). SAR imagery is advantageous due to its ability to scan large areas and its independence from cloud and light conditions, individual identification and classification of vessels at a higher detail level remains a difficult task.

Compared to the large amount of investigations on the feasibility of satellite-based SAR for ship detection purposes, far less research and development activity has taken place in automatic detection and classification of vessels using optical imagery than using SAR imagery. This is a consequence of the novelty of the high resolution optical satellite sensors, the problem of clouds, and the fact that the swath of high resolution imagery is relatively small, making it less suitable for surveillance over the oceans.

The main criteria for the instrument selection are:

- a large swath to minimize the time required for the full coverage of the area of interest;
- a high spatial resolution to improve the performances on target detection;
• high versatility to work with various environmental conditions (e.g., in presence of atmospheric disturbances or during nighttime).

However, the first two criteria clash each other: a low spatial resolution is associated to radar and optical instruments with large swaths, and vice versa. Thus, the design or the selection of the instrument aims at the best compromise solution, trading-off between swath and resolution.

![Line of fishing vessels in NE Atlantic RADARSAT satellite](image)

**Figure 5:** A standard image from RADARSAT satellite [14].
The main characteristics of radar instruments for ship detection are listed below.

- Low resolution, ranging typically between 8-50 m;
- Wide swath, up to 400 km width;
- Work with clouds and during nighttime.

A typical SAR image is shown in Figure 5.

The features of optical instruments are instead reported below.

- High resolution, from 10 m down to below 1 m;
- Small covered area, with swath width ranging within 10-60 km;
- Useful only with clear sky and in daytime.

The latter is the feature that most limits the use of optical instrument to detect vessels. Moreover, SAR data associated to vessels produce notable peaks that can be easily detected in an automatic way. For these reasons, SAR instruments are preferred to optical ones. Nevertheless, optical instruments may be helpful for
recognition and double-checking (after SAR is used for detection). A typical optical image is shown in Figure 6. A radar vs optical acquisition of the same boat is illustrated in Figure 7.

![Cargo ships in Istanbul IKONOS satellite](image)

**Figure 6:** An image from IKONOS satellite [14].
**Figure 7**: Radar vs optical. A 216 m long ship imaged with both optical and radar instruments. The instrument corresponding to each image is described in *Table 5* [14].

<table>
<thead>
<tr>
<th>Overview</th>
<th>(O) SPOT 5 m</th>
<th>(R) RSAT 8 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>(O) SPOT 5 m</td>
<td>(R) RSAT 8 m</td>
<td>(O) EROS 1.8 m</td>
</tr>
<tr>
<td>(O) SPOT 2.5 m</td>
<td>(R) RSAT 8 m</td>
<td>(R) RSAT 8 m</td>
</tr>
</tbody>
</table>

*Table 5*: Images in *Figure 7* [14]. (O): Optical; (R): Radar.
The properties of the instruments that have been successively used to detect fishing vessels in [14] are reported in Table 6. RADARSAT and ENVISAT satellites have been used in that study.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Mode</th>
<th>Incid. (deg)</th>
<th>Resol. (m)</th>
<th>Swath (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RADARSAT</td>
<td>SNB</td>
<td>31-46</td>
<td>60</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>W2,W3</td>
<td>31-45</td>
<td>25</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>S5,S6,S7</td>
<td>36-49</td>
<td>25</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Fine</td>
<td>37-47</td>
<td>8</td>
<td>50</td>
</tr>
<tr>
<td>ENVISAT (ASAR)</td>
<td>Wide</td>
<td>17-42</td>
<td>75</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>IM IS5,6,7</td>
<td>36-45</td>
<td>30</td>
<td>64,70,56</td>
</tr>
<tr>
<td></td>
<td>AP IS5,6,7</td>
<td>36-45</td>
<td>30</td>
<td>64,70,56</td>
</tr>
</tbody>
</table>

Table 6: RADARSAT and ENVISAT instruments characteristic used for vessel identification in [12].

Exploiting the effect of polarization, the outcome of SAR imagery can be suitably tuned. For instance, two different polarizations are shown in Figure 8. Although HV polarization appears to be optimal for ship-sea contrast, it produces a low signal level. For this reason, HH polarization is often preferred.
Figure 8: Effect of polarization in SAR imagery [14] (left: HV polarization; right: HH polarization).

In [24] the 5 m resolution panchromatic camera of SPOT-5 is used to detect small ships. It is known indeed that wooden and fiberglass boats cannot be detected with current state-of-the-art SAR imagery. High resolutions cameras may be therefore used either alone or in support to SAR images in order to detect and recognize unknown migrant vessels.

5 System Architecture

The strategy we propose to monitor illegal immigration in the Mediterranean Sea is a modified version of that effectively used either for fishery control [12] or to combat
illegal fishing [13]. This concept is based on the simultaneous use and integration of data coming from two space-based platforms.

A communication satellite makes up the first part of the system architecture. The boats communicate their status (ID, position, velocity, etc.) to this satellite, which download a map of known vessels. This is a cooperative system. We refer to this part as the vessel monitoring system (VMS).

In the second part, all vessels that are present in a portion of sea are identified by post-processing images taken from radar satellites. This is a non-cooperative system, and is referred to as the vessel detection system (VDS).

Data achieved by both VMS and VDS are combined together to obtain a list of identified and unidentified vessels appearing in the processed scene. Unauthorized immigration boats (e.g., smugglers, unauthorized fishing boats, crafts in troubles) can therefore be found among those vessels in the VDS report that are not matched by
the VMS data (it is likely that these boats are non-cooperating).

The so sketched system architecture has been set up and tested during past years by the European Commission’s Joint Research Center (JRC) to use satellite radar imagery to complement VMS for fishing activities monitoring [14]. This work was carried out with several European partners in the IMPAST project [15]. The system architecture is described in detail in the followings.

5.1 The Vessel Monitoring System

Since the 1990’s a cooperative system for the control of fishing activities has been implemented in many countries: the Vessel Monitoring System (VMS). This system is used in commercial fishing to allow environmental and fisheries regulatory organizations to monitor, minimally, the position, time at a position, and course and speed of fishing vessels. They are a key part of monitoring control and surveillance programs at the national and international levels [17].
Detail of VMS approved equipment and operational use varies with the requirements of the nation of the vessel's registry, and the regional or national water in which the vessel is operating. Nevertheless, in principle, the participating fishing ships have a transponder on board, which sends their GPS position plus identification, course and speed to their (flag state) national authorities on an hourly or bi-hourly basis by satellite communication (see Figure 9). In this way, authorities are continuously informed of the global whereabouts of their national fishing fleet. The information is also forwarded to the authorities of the coastal states in which the ships are present. In addition to the regular interval ship reports, some VMS implementations also allow “polling”, i.e., requesting the positions of vessels within a certain geographic area at a certain time [12].
Figure 9: The vessel monitoring system [18].

VMS units principally rely on GPS for position and time information. LORAN may be a backup or complementary technology. They report data to monitoring systems generally using satellite systems from Inmarsat (constellation of geosynchronous communications satellites), Argos (European and US satellites in low Earth polar orbits), ORBCOMM (low Earth orbit satellites) or Qualcomm (access to Iridium satellites).
In the European Union, the VMS is obligatory for fishing ships of 15 meter and longer. By 1999, Europe had 7000 vessels, in excess of 15 meters, under VMS [17]. Since 2005, all Community vessels automatically transmit vessel identification, date, time, position, course and speed either hourly or every 2 hours (if the responsible Fisheries Monitoring Centre can request positions). The only exception is for vessels that operate only inside home waters, and are used exclusively for aquaculture. A recent regulation requires VMS transponders aboard vessels that are not limited to fishing.

It should be noted that the VMS is not the only existing cooperative system for vessel traffic control. It has been developed to monitor fishing vessels globally. Other examples of cooperative systems are [14]:

- Vessel Traffic Service (VTS), for port and coastal traffic control;

- Automatic Identification System (AIS), for merchant ships control (local);
• Long Range Identification and Tracking (LRIT), for merchant ships control (long distance)

• Vessel traffic reports and database.

In summary, by using one (or more) cooperating system for vessel traffic control, authorities can have at their disposal the data of all known vessels with a minimum time delay. This information can be cross-checked with that given by the vessel detection system to detect unidentified (and possibly unauthorized) boats.

5.2 The Vessel Detection System

The literature for the ship detection in Synthetic Aperture Radar (SAR) imagery is wide. There are several algorithms for each of the stages (land masking, pre-processing, prescreening and discrimination) necessary to recognize boats within SAR acquisition data. For a complete and thorough description of these algorithms the reader is remanded to [20] where detection of ship wake is also addressed. In the following, we briefly describe the algorithm developed at JRC (see [12] for details).
Let us consider the standard SAR image reported in Figure 10, which was taken by RADARSAT-ASAR in fine mode (50 km swath, 8 m resolution). This image represents a ship in the strait of Gibraltar.

Figure 10: A RADARSAT-ASAR image in fine mode representing a boat in the strait of Gibraltar (left), and close-up of the boat (right) [14].

An automatic ship detection algorithm can be developed based on a constant false alarm rate (CFAR) approach. In this algorithm, the image is divided into tiles, and the mean and standard deviation of the signal amplitude values within the tiles are calculated. Based on those and on the number of looks of the image product, a CFAR threshold is determined assuming a K distribution for the
pixel values (see Figure 11). Pixels over the threshold are clustered into detected targets using some proximity criteria (see Figure 12).

**Figure 11**: pixel values associated to the tile in **Figure 10**. Some pixels exceed the threshold level (calculated using mean and standard deviation of pixel values) [14].
Prior to the processing, a land mask is applied (Figure 13), and in the estimation of the background mean and standard deviation, very high values are excluded in an iterative way to avoid biasing the background estimation with target pixels. A size and heading estimate of the target is extracted (Figure 14). This detection algorithm takes less than a minute to run on a single radar image on a normal PC [12]. This process is fully automatic. Once the SAR image has been processed, a report of identified vessels is produced.
Figure 13: Example of land mask application [14].

Figure 14: Estimation of size and heading.
The typical output of the VDS includes:

- position (pixel number and row number in the image; latitude and longitude);
- reliability (certain ship, probable ship, probable noise, certain noise);
- estimated length;
- estimated width;
- estimated heading;
- radar cross section;
- detection time;
- maximum pixel value.

In another implementation of this concept [15], the TerraSAR-X images are inspected manually and then analyzed with the automatic ship detection software. The manual analysis consists in carefully inspecting the acquisitions in order to highlight general characteristics of the images as produced by the ScanSAR imaging mode of TerraSAR-X. In particular, the presence of natural
features that could cause problems for the detection of vessels or false alarms and the overall quality of the images are inspected.

In summary, the whole Vessel Detection System is reported in Figure 15.

![Figure 15: Vessel Detection System (entire process).](image)

5.3 VMS and VDS Data Fusion

Once both VMS (cooperating) and VDS (non-cooperating) data have been achieved, the two scene
can be merged together (i.e., intersected) to identify those vessel corresponding to possible unauthorized immigrant boats. It can be assumed, indeed, that the latter are not likely collaborating vessels in the VMS frame. The issue is therefore matching vessels targets (detected via satellite) with VMS position.

In this context, the aspects of possible ship motion, together with time difference between VMS position report and satellite image acquisition, come into play. In the already developed version of this algorithm [12], an uncertainty circle is drawn around each VMS with a radius based on this time difference and an assumed maximum vessel speed. Inaccuracies in the geocoding, which is based on real-time orbit data provided with the image, add extra uncertainty. In case the uncertainty area of the VMS contains one detected target, the two are matched; in this case the VMS is confirmed by the satellite image. In case no detected target is found within the uncertainty radius of the VMS, the VMS is unmatched, which can mean either that the target strength was too small for the radar given the circumstances, or that the VMS position is wrong. (In the
context of compliance monitoring this could mean that the vessel in question is illegally fishing elsewhere.) In case a number of N VMS uncertainty radii overlap and N detected targets lie within the overlap zone, no unique 1:1 correlation can be established. However, this is not a problem as it means all these N VMS and satellite targets are accounted for. In any case, when more satellite targets are found than VMS positions, or when they are found too far from the VMS positions, they are unmatched, signaling the presence of unknown, potentially unauthorized, vessels (see Figure 16 and Figure 17).
Figure 16: A subset (30 x 30 km) of a RADARSAT image representing the Rotterdam port. In this image, pink crosses are AIS (Automatic Identification System) positions, orange crosses are VMS positions, and green circles are VDS (given by satellite SAR) positions [14].
Figure 17: A close-up of the bottom-left part of Figure 16. It can be seen that three vessels are perfectly detectable by both VMS and VDS techniques [14].

The result of this data fusion process can be presented to the authorities in several ways. In [12], a list comparing VMS positions and satellite targets is sent by e-mail, highlighting the discrepancies. The entire process can take 45 minutes (although best times obtained in [12] were 25 minutes). This is fast enough to warn authorities and re-direct patrols and rescue teams to the suspect target.
The strategy described above has been implemented and tested for illegal fisheries detection in [12]. Test campaigns have been carried out using mostly RADARSAT images and, to a lesser extent, also ENVISAT-ASAR. It has been identified that the limiting factor for success is the ability to detect the ships (with an acceptable false alarm rate) against the background sea clutter. For that reason, HH polarisation, shallow incidence angle and high resolution are preferred, but with a swath as large as possible. By experimenting with different modes, it was found that RADARSAT ScanSAR Narrow Far (SNB) is most suitable for monitoring open ocean fishing grounds, which are more extended but where the ships are larger (roughly 35 m and up), whereas Standard beams 5, 6 and 7 (S5, S6, S7) are more suited for monitoring areas closer to the coast, where fishing ships are smaller. As a rule of thumb, it was found that the detection rates become unacceptably low for ships with a length half of the radar resolution or less. RADARSAT Wide mode would be suited for continental and coastal seas, but unfortunately it suffers severely from ghost targets (ambiguities) in the
neighborhood of land. Fine beam (8 m resolution) is suited to find smaller ships (like those used for illegal immigration), but its limited swath (50 km) restricts its use to very pin-pointed studies.

5.4 Guidelines for Migrant Vessels Identification

The system described so far has been successfully applied to detect fishing vessels. Nevertheless, identifying fishing vessels is quite different than monitoring illegal immigration boats. The two scenarios have different features that have to be taken into account. Thus, this system cannot be readily applied to monitor illegal immigration. A list of guidelines that should be considered in implementing a migrant vessel identification system is given below.

• Smaller vessels. It is known that migrants use smaller vessels that those considered above in both VMS and VDS. It has been found that vessel detection is successful when vessel characteristic length is higher than half of the radar resolution. Thus, smaller vessels to identify ask for more accurate radars. In the followings, we restrict our
analyses to a SAR instrument with 30 m resolution and 100 km swath, so allowing vessels with length down to 15 m to be detected. This is the best compromise available between swath and spatial resolution for state-of-the-art SAR instruments.

- **Different materials.** It has been found that vessel detection is successful when boats present large flat metal sheet on top [20]. This produces intense peaks in the pixel values of a radar image, and therefore eases the vessel identification. Migrant boats are usually densely filled by people, and may not expose large metal sheets. The signature of human body presence in the radar image has to be taken into account.

- **Off-shore.** The main task of the proposed system is to identify migrant vessels in order to warn authorities and allow a prompt rescue in case of need. This makes sense only if the detection of vessels is done off-shore, i.e., when the vessel is navigating in international waters. Here traditional identification systems (i.e., land radar, human
inspection, etc.) fail. Moreover, the crowded area close to the coast and ports may rise the chance of having wrong results.

- **Higher speed.** The VMS matches the VDS data quite precisely when detecting fishing vessels. In the method described above, a circle with radius given by maximum vessel speed and time difference (between VMS and VDS data) is drawn about each VMS position. When fishing vessels are anchored during this time difference, the matching occurs at the center of this circle. Dealing with migrant, smugglers, or pirate boats means detecting smaller and possibly more rapid vessels. This may cause uncertainty circles to blow up to unacceptable dimensions.

- **Time delays.** For the reasons above the time delay between VMS and VDS acquisitions must be minimized.

- **Coverage and revisit time.** It is straightforward that to achieve a more complete and more precise monitoring, the covered area must be maximized
while the revisit time must be minimized. This can be done by optimizing the satellite orbits. Moreover, a proper choice of the satellites involved (both the communication satellite selected for VMS and the radar satellite for the VDS) may improve the performances in terms of coverage and revisit time.

- **Passive countermeasures.** The proposed system has to be robust to possible duperies. Indeed, after the initial successful operation, it is expected that potential targets not wanting to be detected will try to sneak by the system. Allowances are therefore to be considered for further upgrades to improve detection capabilities.

6 Overview on Orbit Selection

In this section we give some guidelines for orbit selection of Earth observing missions. The identification of the orbit that best responds to requirements related to mission, system, payload, platform and ground segment characteristics is the main goal of mission analysis. Five parameters must be selected to define the orbital
geometry of a satellite. The set of orbital parameters is usually defined by \((a, e, i, \Omega, \omega)\), where \(a\) is the semi-major axis, \(e\) is the eccentricity, \(i\) is the inclination, \(\Omega\) is the right ascension of the ascending node, and \(\omega\) is the argument of perigee, as shown in Figure 18.

Figure 18: Orbital parameters definition.

For Earth observation missions most of the constraints on the operative orbit come from the spacecraft payloads. As instruments resolution is typically a function of the orbital altitude, a range of admissible orbital altitudes is immediately identified. As an example, in
order to assure a good spatial resolution of SAR instruments, it is necessary to select a low Earth orbit (LEO). Furthermore, as it is usually preferable to have the same accuracy level over the entire orbit, circular orbits are selected, i.e. $e = 0$ and $\omega$ becomes meaningless.

Within the range of altitudes allowed by payloads, the mission analyst selects the nominal value by tradeoffs arising from: orbital perturbation minimization, suitable ground track separation, minimization of the propellant required for satellite de-orbit, minimization of eclipse duration, ground stations access duration maximization, etc.

For most of Earth observation missions it is required that the spacecraft instruments can observe the entire globe, thus global coverage is envisaged. For a LEO satellite this goal can be achieved if the orbital inclination is close to 90°. Furthermore, it is often required that observations are performed at a fixed local time either to constrain the light conditions or avoid unfavorable weather conditions (e.g. for optic instruments). In these cases a Sun-
synchronous orbit (SSO) is selected. A Sun-synchronous orbit is a geocentric orbit which combines altitude and inclination in such a way that an object on that orbit ascends or descends over any given point of the Earth's surface at the same local mean solar time. The surface illumination angle will be nearly the same every time. This consistent lighting is a useful characteristic for satellites that image the Earth's surface in visible or infrared wavelengths (e.g. weather and spy satellites) and for other remote sensing satellites (e.g. those carrying ocean and atmospheric remote sensing instruments that require sunlight). Once the semi-major axis has been fixed based on previous considerations, the orbital inclination for a Sun-synchronous orbit is obtained by

\[ \frac{d\Omega}{dt} = -\frac{3}{2} \frac{J_2}{a} \sqrt{\frac{\mu}{a} \left( \frac{R_{\text{Earth}}}{a(1-e^2)} \right)^2 \cos i} , \]

\[ \frac{d\Omega}{dt} = 0.9856 \text{ deg/day} \]

in which \( R_{\text{Earth}} \) is the Earth’s radius, \( J_2 \) is the first zonal harmonic of the Earth’s gravitational potential, and the \( \Omega \)
time rate is set to enforce Sun-synchronous condition. The nominal value of $\Omega$ is selected in order to satisfy the lighting constraints. If the onboard payloads do not impose any constraints on lighting conditions, the Sun-synchronous condition can be still exploited for spacecraft subsystems optimization: the orbit can be selected to maximize the incoming solar radiation, thus minimizing the required for solar panels area.

LEO satellites are often deployed in satellite constellations, because the coverage area provided by a single LEO satellite only covers a small area that moves as the satellite travels at the high angular velocity needed to maintain its orbit. Many LEO satellites are needed to maintain continuous coverage over an area or to improve the coverage figure achievable by a single satellite. This contrasts with geostationary satellites, where a single satellite, moving at the same angular velocity as the rotation of the Earth's surface, provides permanent coverage over a large area. However, geostationary satellites are not suitable for our purpose due to their distance from Earth’s surface, which would lower the SAR resolution to inadmissible levels for ship detection.
Several LEO satellite constellations are currently orbiting the Earth, which are able to fulfill the requirements of ship detection. Among them, the performances achievable by COSMO-SkyMed constellation, when the mission objective is monitoring the unauthorized migration fluxes in the Mediterranean Sea, will be assessed in the following section. With reference to the considerations previously carried out:

1. COSMO-SkyMed is a constellation of four satellites to assure repeated observations of an area of interest several times a day.

2. The satellites are in LEO to allow SAR imaging with resolution down to meter level.

3. The orbital altitude of the spacecraft is selected to maximize the number of repeated observations.

4. Sun-synchronous dawn-dusk orbits are utilized to minimize the solar panel area required for power generation.
7 Performance Assessment of Existing Satellites

The identified candidate orbit and the selected instrument considerably reduce the set of existing satellites that could be used to retrieve the required data. The attention will be focused naturally on COSMO-SkyMed, which is an Italian Mission co-funded by the Ministry of Defense. However, in the end of the section, the use of other existing missions will be considered as a possible integration of COSMO-SkyMed to increase the overall performances.

7.1 Overview of COSMO-SkyMed

COSMO-SkyMed (COnstellation of small Satellites for Mediterranean basin Observation) is the largest Italian investment in Space Systems for Earth Observation, commissioned and funded by Italian Space Agency (ASI) and Italian Ministry of Defense (MoD). COSMO-SkyMed has been conceived from the beginning as a Dual-Use (Civilian and Defense) end-to-end Earth Observation System, aimed to establish a global service supplying
provision of data, products and services compliant with well-established international standards and relevant to a wide range of applications, such as Risk Management, Scientific or Commercial Applications and Defense or Intelligence Applications.

COSMO-SkyMed space segment consists of a constellation of four Low Earth Orbit mid-sized satellites, each equipped with a multi-mode high-resolution Synthetic Aperture Radar (SAR) operating in X-band and fitted with particularly flexible and innovative data acquisition and transmission equipment [25].

The space segment is supported by a dedicated full-featured Ground Segment infrastructure for managing the constellation and granting ad-hoc services for collection, archiving and distribution of acquired remote sensing data.

COSMO-SkyMed System provides today an asset characterized by full global coverage, all weather, day/night acquisition capability, high resolution, high accuracy (geo-location, radiometry, etc.), high image quality, fast revisit and response time, interferometric and
polarimetric capabilities and quicker-and-easier ordering and delivery of data, products and services.

The system is conceived to pursue a Multi-mission approach thanks to its intrinsic Inter-operability with other EO missions and Expandability towards other possible partners with different sensors typologies to implement an integrated space-based system providing Earth Observation integrated services.

These features designate COSMO-SkyMed as a system capable to provide “Institutional Awareness” in order to make proper decisions in preventing and managing world-wide crisis.
7.1.1 Payload Instrument

Due to the need of many combinations between image size and spatial resolution, the SAR instrument on-board COSMO-SkyMed was chosen as a multimode sensor operating in (see Figure 20):

- A Spotlight mode, for metric resolutions over small images
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- Two Stripmap modes, for metric resolutions over tenth of km images; one mode is polarimetric with images acquired in two polarizations
- Two ScanSAR for medium to coarse (100 m) resolution over large swath

![COSMO-SkyMed SAR Operating Modes](image)

**Figure 20:** COSMO-SkyMed SAR Operating Modes [25].

The sensor imaging operating modes are therefore:

- Spotlight Mode, in which the antenna is steered (both in the azimuth and the elevation plane) during the overall acquisition time in order to
illuminate the required scene for a time period longer than the one of the standard strip side view, increasing the length of the synthetic antenna and therefore the azimuth resolution (at expense of the azimuth coverage). In such configuration the acquisition is performed in frame mode, hence it is limited in the azimuth direction due to the technical constraints deriving from the azimuth antenna pointing. The implementation allowed for this acquisition mode is the Enhanced Spotlight. In the Enhanced Spotlight mode, the spot extension is achieved by an antenna electronic steering scheme requiring the centre of the beam steering to be located beyond the centre of the imaged spot, thus increasing the observed Doppler bandwidth for each target. Such mode is characterized by an azimuth frame extension of about 11 Km, a range swath extension about 11 Km.

- Stripmap Mode, which is the most common imaging mode (e.g. similar to ERS mission one), obtained by pointing the antenna along a fixed

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direction with respect to the flight platform path. The antenna footprint covers a strip on the illuminated surfaces as the platform moves and the system operates. The acquisition is virtually unlimited in the azimuth direction, except for the limitations deriving from the SAR instrument duty cycle (about 600 s, allowing a strip length of 4500+ km). Two different implementation of this mode are available: the Himage and the PingPong. The Himage is characterized by a swath width of about 40 km, an azimuth extension for the standard product (square frame) about 40 Km (corresponding to an acquisition of about 6.5 sec). The PingPong mode is characterized by a swath width value of about 30 km, an azimuth extension for the standard product is about 30 Km (square frame) corresponding to an acquisition of about 5.0 sec

- ScanSAR Mode, which allows larger swath in range with respect to the Stripmap one, but with a less spatial resolution, obtained by periodically stepping the antenna beam to neighboring sub-
swaths. Since only a part of the synthetic antenna length is available in azimuth, the azimuth resolution is hence reduced. In such configuration the acquisition is performed in adjacent strip mode, hence it is virtually unlimited in the azimuth direction, but for the limitations deriving from the SAR instrument duty cycle that is of about 600 s. The two different implementations allowed for this acquisition mode are WideRegion and HugeRegion. In the WideRegion mode the grouping of acquisition over three adjacent subswaths allows achieving ground coverage of about 100 Km in the range direction. The azimuth extension for the standard product is about 100 Km (hence envisaged for the origination of a square frame) corresponding to an acquisition of about 15.0 sec. In the HugeRegion mode the grouping acquisition over up to six adjacent subswaths allows achieving ground coverage of about 200 Km in the range direction. The azimuth extension for the standard product is about 200 Km (hence envisaged for the origination of a
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square frame) corresponding to an acquisition of about 30.0 sec.

7.1.2 Operative Orbit

The constellation consists of 4 medium-size satellites, each one equipped with a microwave high resolution synthetic aperture radar (SAR) operating in X-band, having ~600 km access ground area. The orbit characteristics are summarized in Table 7.

<table>
<thead>
<tr>
<th>Orbit Type</th>
<th>SSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi Major Axis</td>
<td>7003.52 Km</td>
</tr>
<tr>
<td>Inclination</td>
<td>97.86°</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>0.00118</td>
</tr>
<tr>
<td>Argument of Perigee</td>
<td>90°</td>
</tr>
<tr>
<td>LTAN</td>
<td>6:00 AM</td>
</tr>
<tr>
<td>Nominal Height</td>
<td>619.6 Km</td>
</tr>
<tr>
<td>Revolutions/day</td>
<td>14.8125</td>
</tr>
<tr>
<td>Orbit Cycle</td>
<td>16 days</td>
</tr>
<tr>
<td>Number of Satellites</td>
<td>4</td>
</tr>
<tr>
<td>Phasing</td>
<td>90°</td>
</tr>
</tbody>
</table>

Table 7: COSMO-SkyMed orbit parameters [25].
In nominal conditions, the four satellites are equi-phased in the same orbital plane as depicted in Figure 21.

**Figure 21:** COSMO-SkyMed Constallation [25].

The nominal (full sized) constellation orbiting configuration is conceived to achieve the best compromise among cost and performance, providing a global Earth access at constellation level of few hours, with at least two opportunities in one day to access the same target site on the Earth under different observing conditions (incidence angle).
7.1.3 Constellation Deployment

The first launch of COSMO-SkyMed was successfully completed in June 2007, followed by other two successful launches in December 2007 and October 2008. The last launch is scheduled for 2010, allowing the constellation to reach the nominal configuration.

7.2 Performances assessment

7.2.1 Problem modeling and proposed analyses

The analyses described in this section are carried out with the aid of Satellite Tool Kit software (STK). The Mediterranean Sea is our area of interest and COSMO-SkyMed constellation is here considered as the baseline solution for remote monitoring of illegal migration fluxes in the Mediterranean Sea. Figure 22 gives a 3D representation of the constellation based on the orbital parameters given in Table 7 and highlights the area of interest. For each COSMO-SkyMed satellite, two virtual SAR sensors are defined for the assessment of the performances of the SAR instrument onboard. The first one has a rectangular swath of approximately 100 x 100
km, which guarantees the required spatial resolution of 30 m. The sensor swath is shown in Figure 23 in red and it is used to address the coverage analysis. This analysis is aimed at computing the time required for achieving a full coverage of the area of interest. The second sensor has a swath defined by the envelope of the area accessible, at a given instant, by the SAR instrument. The sensor swath is shown in Figure 23 in blue and it is used for revisit time analysis.

Figure 22: COSMO-SkyMed constellation definition.
The revisit time is the most important figure of merit as it identifies the maximum gap between two consecutive observations of a specific point in the area of interest. This figure is directly connected to the response time, which is the time span between the delivery of the image requests by the users and the availability of the ordered data. The response time includes the revisit time and the time required to download the data to ground, to post-process and to deliver them to the users.

The number of accesses per day to the area of interest is another interesting figure of merit, as it is directly related to the number of images of the area that can be obtained in one day.

The last analysis offered is ground station access. Fucino is selected as main ground station due to its favorable geographical collocation close to the Mediterranean area barycenter. The ground station access analysis is aimed at assessing the possibility of sending to ground SAR data during acquisition in order to promptly post-process them for unauthorized vessels identification.
All the analyses are based on the numerical propagation of the constellation orbital dynamics for a three-month window using a gravitational model that considers the gravitational attraction of the Earth up to $J_2$ harmonic. All the other perturbation sources (e.g. higher order harmonics, atmospheric drag, solar radiation pressure) have been neglected as they have minor effects on the figure of merits we are looking at, i.e. Mediterranean Sea coverage, revisit time, and ground station access.

![Figure 23: COSMO-SkyMed SAR swath definition.](image-url)
7.2.2 Coverage Time

Figure 24 and Figure 25 show the coverage analysis of the Mediterranean Sea achievable by the current COSMO-SkyMed constellation (3 satellites) and by the complete constellation (4 satellites). It is apparent that the time to achieve the global coverage is approximately 3 months for both cases. However, the fourth satellite decreases the time required to cover most part of the area. As an example, the three-satellite constellation takes 5.7 days to cover 90% of the area, whereas the same result is achieved in 2.9 days by the complete constellation. The performed analysis underlines that at least three months of continuous SAR acquisition over the Mediterranean Sea are required to obtain a complete overview of the routes followed by vessels of clandestine migrants. Note that this three-month interval represents a lower limit as

1. Illegal immigration is not a continuous activity (for this reason its detection differs from the problem of identifying unauthorized fishing boats); as a consequence, a global picture of the
Mediterranean Sea does not necessarily delivers meaningful information on migration routes.

2. Global coverage analysis assumes that COSMO-SkyMed SAR imaging is continuously available for migration detection purposes; i.e., the service is not shared with other customers.
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Figure 24: Mediterranean Sea coverage % for the current COSMO-SkyMed constellation.
Figure 25: Mediterranean sea coverage% for the COSMO-SkyMed complete constellation.
7.2.3 Revisit Time

Figure 26 and Figure 27 show the color maps of the maximum revisiting time over the Mediterranean Sea. These maps are obtained by computing the figure of merit for a set of points separated by 1 deg both in longitude and latitude. Interpolation is then used to gain a smooth representation between grid points.

The current constellation guarantees a maximum revisit time of approximately 35 hr. This means that:

1. In a worst case scenario the response time to obtain a SAR image of a specific region of the Mediterranean Sea is more than 35 hr because we need to add the time required to download, post-process, and deliver the image.

2. If a suspicious boat is detected, again, it might take more than 35 hr to obtain a new useful SAR image of the same boat.

Point 2 is even more complicated because immigrant boats move on routes unknown a-priory; thus, it could be difficult to exactly determine the region the constellation
should look at in the subsequent observation. Note also that for some routes the maximum revisit time is almost comparable with the trip time. As a consequence, the probability of getting two images of the same boat is rather small. Nevertheless, the performance assured by the current constellation can be considered as appropriate in the framework of performing checks over the Mediterranean Sea area, based on single observations and aimed at improving the logistics behind authority actions on unauthorized vessels.

The system performance is greatly improved when the four-satellite constellation (or complete constellation) is considered: the maximum revisit time lowers to approximately 12 hr, as shown in Figure 27. With this value it could be possible to obtain two SAR images of a suspicious boat, and a sufficient SAR imaging frequency of a specific area of interest is guaranteed. Furthermore, check effectiveness would greatly take advantage of the presence of the fourth satellite, even when only one image is demanded.
The considerations carried out so far considered the worst-case scenario. Table 8 summarizes the average and optimal values of the number of accesses to the Mediterranean Sea area and the revisit time figures for both the current and the complete COSMO-SkyMed constellation.

<table>
<thead>
<tr>
<th>Number of access per day</th>
<th>Revisit time [hr]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum</td>
</tr>
<tr>
<td>Current Constellation</td>
<td>5</td>
</tr>
<tr>
<td>Complete Constellation</td>
<td>5</td>
</tr>
</tbody>
</table>

**Table 8:** COSMO-SkyMed optimal and average access number and revisit time figures.

The following considerations can be carried out:

1. Average figures are significantly better than the worst-case ones. Revisit times of approximately 8.90 and 6.67 hr guarantee good performances for specific area monitoring.
2. The minimum revisit time of 0.39 hr occurs when two subsequent satellites can perform SAR imaging of the same area. In this case boats tracking is possible.

3. The fourth satellite does not improve significantly either the maximum value of accesses per day or the minimum revisit time. On the other hand, the complete constellation guarantees better average performances.
Figure 26: Mediterranean Sea maximum revisit time for current COSMO-SkyMed constellation.
Figure 27: Mediterranean sea maximum revisit time for complete COSMO-SkyMed constellation.
7.2.4 Ground Station Access

Fucino ground station is located at 41° 58´ N and 13° 35´ E. Figure 28 shows ground station access for a single COSMO-SkyMed satellite obtained by setting a constraint of minimum elevation angle of 5°. It is apparent that the access area highlighted in magenta includes the Mediterranean Sea, proving that each satellite can download SAR data to ground in real-time during acquisition. All the satellites belonging to the constellation have same ground station access characteristics. Table 9 shows that, on average, a ground station access lasting 535 s is achieved. Gaps analysis shows that the maximum gap between two consecutive accesses is roughly equal to one day, whereas the average value is less than half day. This means that a satellite has, on average, more than one ground station access during either the ascending or descending phase of the orbit.

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Access [s]</td>
<td>640</td>
<td>535</td>
</tr>
<tr>
<td>Gap [s]</td>
<td>87018</td>
<td>31652</td>
</tr>
</tbody>
</table>

**Table 9**: Summary of ground station gaps and access.
Figure 28: Fucino ground station access.
7.2.5 Modified COSMO-SkyMed and Augmented Constellation

We now analyze how the performances change if the fourth satellite of COSMO-SkyMed is inserted into a different orbit, e.g. in a midday-midnight Sun-synchronous orbit. We refer to this constellation as modified COSMO-SkyMed constellation. With respect to the complete constellation we obtain that:

1. The maximum number of access per day is 7, but the average value is still 3.59.

2. The maximum revisiting time rises to 24 hr, whereas the minimum and the average values do not change significantly.

3. The time required for Mediterranean Sea coverage lowers to 10 days.

From the previous considerations we can conclude that the complete COSMO-SkyMed constellation is optimally designed to minimize the worst-case revisit time, i.e. is optimal from the response time point of view.
The possibility of improving the performances by including SAR images obtained by an additional satellite already in orbit is now considered. ENVISAT satellite with orbital parameters of Table 10 is used for the purpose of building an augmented COSMO-SkyMed constellation.

<table>
<thead>
<tr>
<th>( a ) [km]</th>
<th>( e )</th>
<th>( i ) [deg]</th>
<th>LTDN [hh:mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7159</td>
<td>( \approx 0 )</td>
<td>98.5</td>
<td>10:00</td>
</tr>
</tbody>
</table>

**Table 10**: ENVISAT orbital parameters (LTDN is the local time of descending node) [26].

By repeating the computation of the figures of merit discussed in Section 7.2.3 and comparing the results of the augmented constellation with the nominal complete one, we can conclude that:

1. worst-case and minimum revisit time values remain unchanged;
2. the average revisit time lowers to 5 hr;
3. the maximum and average number of accesses rise to 7 and 4.72, respectively;
4. the time for global coverage decreases to 46 days.

It is apparent that, whenever possible, it is useful to add other SAR satellites to COSMO-SkyMed ones in order to increase the efficiency of Mediterranean Sea monitoring system.

8 Feasibility of ad-hoc Systems

In this section the feasibility of designing and deploying an ad-hoc space mission will be analyzed considering the candidate instruments identified above and the performances of existing systems.

As it has been clearly shown by the performances achievable by the COSMO-SkyMed Constellation in the previous section a multi-spacecraft constellation is required to allows performances adequate for the proposed system. The development of an ad-hoc system will be necessary only if it is not possible to acquire the required information from the COSMO-SkyMed payload with the desired frequency. However, the design of a completely disjoined system will be highly inefficient if a
single satellite is considered and cost ineffective if a constellation is deployed.

In the following of this section the performances of a single satellite system is analyzed to demonstrate the inadequacy of such system with respect to COSMO-SkyMed. However, the results presented can give an hint of the deterioration of the performances achievable if only a single satellite of the COSMO-SkyMed is considered available for the proposed application.

The development of an ad-hoc system will be valuable only if the new satellite is used to augment the COSMO-SkyMed constellation, as demonstrated again in the performance evaluation above. For this reason, a few words are dedicated to the possible solution for the spacecraft bus available on the market for Earth Observation satellites, both in case of a SAR Payload and of a Panchromatic Camera Payload.

8.1 Performance Assessment

For the performance assessment of a single satellite system, the orbital parameters of a single COSMO-
SKyMed satellite are considered, as the orbit has been designed to allow good performances in the observation of Italy and the Mediterranean Sea with a SAR payload. The Orbital parameter are reported in Table 7. The ground station considered for the computation of the accesses is Fucino as in the case of COSMO-SkyMed because it is located exactly in the center of the Mediterranean Sea, allowing the best compromise for the download of Payload data.

The figures of merit considered in the performance assessment of the single satellite solution are the same used in the COSMO-SkyMed Analysis: Coverage Time, Revisit Time and Ground Station Access.

8.1.1 Coverage Time

Figure 29 shows the coverage analysis of the Mediterranean Sea achievable by a single satellite orbiting in the COSMO-SkyMed operative orbit. It is apparent that the time to achieve the global coverage is approximately 3 month as in the case of the complete COSMO-SkyMed Constellation. However a single satellite solution can cover about 90% of the
Mediterranean Sea in about 18 days which is clearly worse than the performance achievable by the complete constellation.
Figure 29: Single satellite Mediterranean Sea coverage %.
8.1.2 Revisit Time

Figure 30 shows the color map of the maximum revisiting time over the Mediterranean Sea of the single satellite solution.

As in the case of the full COSMO-SkyMed constellation performance evaluation, this map is obtained by computing the figure of merit for a set of points separated by 1 deg both in longitude and latitude. Interpolation is then used to gain a smooth representation between grid points.

The single satellite solution guarantees a maximum revisit time of approximately 65 hr, and an average one of about 26.8 hr.

Table 11 summarizes the average and optimal values of the access number and revisit time figures for the single satellite solution and for the complete COSMO-SkyMed constellation.
<table>
<thead>
<tr>
<th></th>
<th>Number of access per day</th>
<th>Revisit time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum</td>
<td>Average</td>
</tr>
<tr>
<td>Single Satellite</td>
<td>2</td>
<td>0.89</td>
</tr>
<tr>
<td>Complete Constellation</td>
<td>5</td>
<td>3.59</td>
</tr>
</tbody>
</table>

**Table 11:** Single satellite solution optimal and average access number and revisit time figures, compared to COSMO-SkyMed complete constellation.

Analyzing this figure of merit it is clear that a single satellite solution is not feasible for the proposed application if considered alone. The very long revisit time will not allow a successful monitoring of a certain region of the Mediterranean Sea, as a single vessel can complete its journey in the time gap between two successive acquisitions over the same area. However, in the framework of performing random checks over the Mediterranean Sea area, the single satellite solution can provide sufficient performance in terms of revisit time, allowing almost one access per day.
Figure 30: Single satellite Mediterranean Sea revisit time.
8.1.3 Ground Station access

The ground Station access of the single satellite solution are exactly the same as those reported in the COSMO-SkyMed performance assessment section, as the Orbital Parameters considered are kept unchanged. A summary of the results is reported in Table 9.

8.2 Space segment feasibility

The technological solutions related with the development of the space segment for an ad-hoc mission, which extends the performances of the proposed system, are briefly analyzed in this section in terms of possible satellite bus for the identified payload instrument categories.

8.2.1 Satellite Bus

The proposed ad-hoc system should be developed to be integrated in an existing network of satellites operating SAR instruments over sun synchronous orbits. The more efficient approach to the development of a Platform for this kind of satellite is to base the design on existing
multi-purpose platform already designed and optimized for Earth observation missions, such as the PRIMA Bus for SAR Application or the Proteus LEO Platform for optical applications, both developed by ThalesAlenia Space.

The PRIMA (Piattaforma Riconfigurabile Italiana Multi Applicativa) Bus is a high adaptability multi-mission bus that can be configured to carry a variety of payloads and can be utilized for different classes of missions. The PRIMA Bus based Spacecraft (S/C) is a 3-axis stabilized satellite placed directly into an earth orbit by the launcher. The highly customizable configuration feature of PRIMA, allows a significant degree of freedom on the Payload design and mission planning, permitting the utilization of standard modules to obtain a mission dependant configuration. PRIMA has been developed in order to include a wide range of European, US, and other foreign countries equipment suppliers, in order to be independent from market supply restrictions.

The PRIMA bus has been flown on COSMO-SkyMed and RADARSAT-2 and recently has been chosen for the
Sentinel-1 mission, all with SAR instruments; hence this platform has a history of use in SAR missions. The Sentinel-1 spacecraft dimensions in the stowed configuration are: 3.9m x 2.6m x 2.5m and has a launch mass of about 2,300 kg, with a design life of 7 years. This platform, which is based on the COSMO-SkyMed design, may fit into Vega, allowing the use of European Developed launcher.

The Proteus LEO Platform is a highly standardized platform which suits all specific needs of the payloads in every field of application, be it science, earth observation, telecommunications, navigation, or environment.

Proteus has been used on satellites in various fields of applications such as programs Jason-1 (CNES/ NASA Jpl), Calypso (CNES/ NASA Larc), Jason-2 (CNES/ NASA/ EUMETSAT/ NOAA), Corot (CNES), SMOS (CNES/ ESA) et MEGHA TROPIQUES (CNES/ ISRO)

The Proteus LEO Platform allows bringing to orbit Payload up to 300 kg and 300 W; It provides mass memory of 2 gigabits, S-band telemetry with a data rate of 690 kbps and it is designed for sun synchronous orbits
with altitude between 600 and 1500 km. The attitude performances assure pointing accuracy from 0.02 to 0.05 depending on mission requirements. The Platform has been designed for a life span of around 5 years typical of LEO missions and it is compatible with all the small launchers in the categories of 500 to 1000 kg launched mass.

The main benefits resulting from the adoption of standard platforms are related to the fight-proven reliability of the platform with excellent in-orbit demonstrated performances, and with the rapid and secure development which guarantees a cost-effective solution with low cost-adaptation to the specific needs of various missions.

9 Conclusions and Recommendations

9.1 Conclusions

This report is conceived as a feasibility study on the possibility to monitor illegal immigration in the Mediterranean Sea using space-based technology. The social, scientific, and technological issues of the
implementation of such a system have been discussed. More specifically, in the first part of the report, a picture on the current status of the immigration in Europe and Italy via Mediterranean Sea is given. In the second part, the technical features of the devised system are illustrated. First, the remote sensing via SAR instruments is described, as this technology is deemed mature and suitable for our purpose. The system architecture is then described. In principles, this is based on the combination of data coming from two space-based systems: the cooperating Vessel Monitoring System, and the non-cooperating Vessel Detection System. As this architecture has proven to be successful for the identification of fishing vessels, guidelines for tailoring it to migrant vessels identification are discussed. In the remaining sections of the technical part, the performances of both existing and ad hoc systems have been evaluated. This is accomplished with space mission analysis tools. An overview of orbit selection principles is given, and then the performances of the Italian SAR constellation COSMO Sky-Med are evaluated. The results achieved are promising: COSMO-SkyMed
constellation assures performances that are in agreement with the prescribed requirements. This is meant in terms of Mediterranean Sea coverage, access, and revisit time. Thus, among the space platforms operating on a regular basis, COSMO-SkyMed is the preferred constellation for the implementation of the proposed concept. Moreover, COSMO-SkyMed is equipped with the third generation of SAR, and is therefore capable of reproducing appropriate radar imageries for accurate vessel identification. A discussion on the implementation of dedicated space systems ends the technical part. In author’s view, this is not the preferred solution as the improvement of the performances deriving from the use of a dedicated system is not worth the cost of development, production, and deployment. However the development of a dedicated system can be envisaged to increase the performances achievable with the existing constellations.

For what concerns the SAR properties, a wide variety of these instruments is embarked on remote sensing satellites, and tailored versions can be even designed to match the requirements of a certain mission. Among the
other features, the resolution and the swath width are the most important ones for the purpose of ship detection. It would be desirable to have the finest resolution with the largest possible swath. Nevertheless, these two properties are in opposition each other: high resolution corresponds to narrow swath width, and vice versa. In the report we have assumed the following values:

- 30 m resolution;
- 100 km swath.

As a rule of thumb, the fixed resolution allows the detection of boats having length down to 15 m. This is the best-deemed compromise between swath and resolution, although smaller vessels may flee from the proposed detection system. For instance, if one selects a finer resolution (but reduces the swath), the detection capability is improved (but the revisit times become longer). On the other hand, if one increases the swath (but reduces the resolution), only large vessels – not likely to be those used by migrants – can be detected.
The assumed values for resolution and swath correspond also to those currently available on COSMO-SkyMed. It has been assessed that this constellation can assure the following worst-case performances:

- the coverage of most part of the Mediterranean Sea area (90%) in 2.9 days;
- a maximum number of 5 accesses to the Mediterranean Sea area per day;
- a maximum revisit time of a point of interest of about 12 hr;
- SAR data download to ground in real-time during acquisition, thanks to the support of Fucino ground station.

These performances fit the requirements ensuing from migration flows monitoring. In particular, the coverage and the revisit time obtained are relevant.

Beside the technical properties, the proposed concept is cost-effective for the following reasons:

- It uses technology that is already available;
• The space segment makes use of satellites that are already orbiting and working on a regular basis;

• The necessary SAR imageries are already available.

Moreover, with the proposed concept the whole efficiency in the management of illegal immigrant is improved. For instance, as the position of vessels is known well in advance with respect to traditional systems, rescue teams and patrols can be re-directed more efficiently. This will likely reduce tragedies and will serve at organizing the logistics in advance.

9.2 Recommendations

From the discussion above, it is clear that the first, obvious recommendation pertains to SAR technology. We recommend to promote research programs for finding technological solutions that allow for instruments with larger swaths and finer resolutions.

The proposed system can be used also for other purposes, rather than for the mere detection of migrant
vessels. In particular, smuggling, illegal fishing, oil spilling, and piracy (among other) can be detected with no dedicated modifications to the system. Moreover, the monitoring activity is not constrained to the sole Mediterranean Sea area, but rather it can be done everywhere using the same space segment. In this way the system increases the possible returns, making it even more worth to implement.

We conclude this report by stressing the importance of implementing the proposed concept. In particular, a pilot project would be suitable for both testing the feasibility of the concept and acquiring the necessary know-how. This project will analyze the data that are already available from the Italian COSMO-SkyMed mission, and will be focused on the design of algorithms, architectures, and systems necessary to deploy an integrated tool for monitoring unauthorized immigration and other illegal activities.
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